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ORIGINAL PAPERS

# The Hydrological, Hydrochemical, and Microbiological Characteristics of Amur Bay during the Summer Monsoon

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**Abstract**—An integrated hydrological and microbiological survey of Amur Bay in July 2022 showed that the levels and distribution of values of the thermohaline and hydrochemical parameters indicate the effect of the summer monsoon and river runoff. Under southerly winds, there was a setdown of the water surface along the western coast, which resulted in a decrease in temperature by 0.3–1°C and an increase in salinity by 2.6 PSU relative to those near the eastern coast. At the same time, a setup effect with blocking of freshened and warm, nutrient-enriched surface waters was observed in the northeastern part of the bay. These favorable conditions caused phytoplankton blooms accompanied by high concentrations of chlorophyll *a* (up to 6–9 μg/L) and oxygen saturation of water (up to 120%). In the near-bottom layers of this sector, hypoxia with oxygen concentrations lower than 5% was observed as a consequence of developing eutrophication. According to the results of microbiological testing, the waters of Amur Bay in the summer of 2022 were classified as mesosaprobic, enriched in organic compounds, with accumulation of organic matter prevailing over its degradation. The biological pollution of water was indicated by the high abundance of bacteria of the sanitary indicator group, which exceeded the maximum permissible concentration; the activity of plant communities was indicated by a high abundance of phenol-resistant microorganisms. Oil pollution was detected only in vicinities of sources of petroleum hydrocarbons: an oil terminal and a junction railway station. The low abundance of metal-resistant microorganisms indicated the insignificance of specialized (technogenic) pressure on the waters of the bay at the sampling time.

**Keywords:** CTD data, hydrochemical analysis, microbial indication, Amur Bay, Sea of Japan, southern monsoon

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## INTRODUCTION

Amur Bay is a semi-enclosed northwestern part of the Peter the Great Bay, Sea of Japan. On the west, it is bounded by the mainland coast; on the east, by the Muravyov-Amur Peninsula coast and by Russky, Popov, Reineke, Rikord, Tsivolko, and Zheltukhin islands extending southwest from it. From the southern boundary (the imaginary line from Cape Bryus to Zheltukhin Island), the bay cuts 70 km deep north into the mainland coast. In the northern part of the bay, it receives the water of the Razdolnaya River, the second largest river in southern Primorsky krai after the Tumen River; in the northeastern part, the Schmidtovka and Bogataya rivers; in the northwestern part, the small Amba, Barabashevka, and Narva rivers. The seabed of the bay is a depositional plain slightly sloping offshore. The depth of the bay increases smoothly from 0 to 53 m, with an average of 15 m. A strip of shallow, to a 5-m depth, water stretches along the apex of the bay (which is 1–5 km in width) and along the northwestern coast. The southeastern coast of the bay is mountainous; the western and northern coasts are low-land almost all along their stretch, sometimes waterlogged, with a sandy shore. One characteristic feature of the underwater topography of Amur Bay, as well as Ussuri Bay, is a large, sublatitudinally oriented seabed threshold. In Amur Bay, the threshold, rising 8–15 m above the seabed, is referred to as the Muravyevsky threshold. The threshold extends from the southern tip of the Peschany Peninsula to Russky Island. Due to the threshold, almost all solid matter

[†] Deceased.

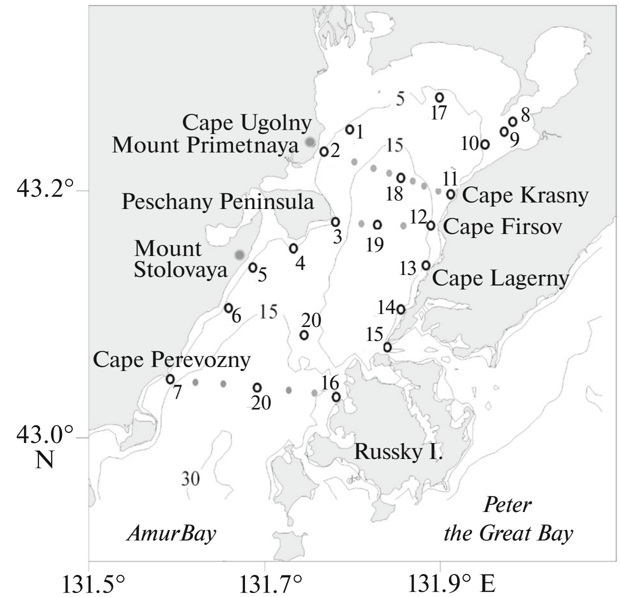


**Fig. 1.** The seabed topography of Amur Bay (isobaths 5, 15, and 30 m) and the arrangement of hydrological and microbiological stations (dots with numerals).

discharged from the Razdolnaya River accumulates in the northern part of the bay [5, 13, 17, 19].

Among water bodies in the Far Eastern seas of Russia, Amur Bay is one of the most productive; it is exposed to a pronounced anthropogenic pressure [12, 14, 18, 25, 29, 31, 32]. The large port of Vladivostok is situated on its coast, and the industrial city of Ussuriysk is within its catchment basin. Agriculture is developed in the Razdolnaya River valley. The bay is characterized by intensive shipping traffic; various port structures and ship repair facilities, an oil terminal, and a fish processing plant are operated on its shores. Nevertheless, a substantial portion of the coast is used for recreation, which causes a high abundance of allochthonous microorganisms in the environment, with their pool including also opportunistic and pathogenic microflora [3, 27]. As a result, the bay area is exposed to increased anthropogenic pressure and requires continuous monitoring of the condition of the environment and biota [28].

In this study, we focused on the hydrological and hydrochemical parameters of the water column and on the microbiological control of the surface waters in the bay.

The aim of our study, based on data of CTD profiling of water column and microbial indication of surface water, was to evaluate the current condition of the surface waters in Amur Bay in the summer season.

## MATERIALS AND METHODS

A hydrological and hydrochemical survey of the condition of the waters in Amur Bay was carried out on July 2–3, 2022. Observations included profiling of the water column with an autonomous CTD profiler at 35 hydrological stations and taking water samples from the surface layer at the 21st of them for microbial indication. The water sampling sites (station numbers are provided in Fig. 1), which were selected taking the alleged sources of pollution into account, were mainly in the shallow waters along the western (stns. 1–7) and eastern (stns. 8–16) shores. The background stations (stns. 17–21) were selected along the axial line of the bay, where the depth reached 25 m. Additional stations, designed to clarify the distribution of values of the controlled parameters, where only CTD profiling was performed, were set on three transverse transects: from Mount Primetnaya to Cape Krasny (stns. 2, 18, and 11), from Peschany Peninsula to Cape Firsov (stns. 3, 19, and 12), and from Cape Perevozny to Cape Mikhailovsky on RusskyIsland (stns. 7, 21, and 16) (Fig. 1).

The water column of the bay was profiled using an autonomous Rinko ASTD102 profiler (JFE Advantech Co. Ltd., Japan) that measures temperature, pressure, salinity, turbidity of water, concentrations of chlorophyll *a*, and dissolved oxygen with a frequency of 10 Hz. The metrological specifications of the ASTD102 profiler declared by the manufacturer are listed in Table 1. Based on the results of processing of primary CTD data using our original software [11], we obtained a series of values of the water parameters with an optimum step of 0.5 m in depth for subsequent analysis.

The coordinates of the hydrological stations were determined with a Garmin eTrex GPS receiver. Weather conditions were analyzed using data retrieved from the meteorological data archive for WMO_ID 31960, which contains continuous fixed-time (eight times a day) observations at the Vladivostok-Gora weather station [1].

The coordinates of the sampling stations for microbiological analysis are listed in Table 2. Water samples were collected from the surface layer (10–20 cm) into sterile plastic containers, transported to the laboratory in compliance with GOST [6], and analyzed before the shelf-life of the samples expired.

The total abundance of colony-forming saprophytic heterotrophic microorganisms per 1 mL water was estimated by the method of ten-fold dilutions followed by inoculation of a nutrient medium for marine microorganisms, supplemented with 1.5% agar, with these aliquots being done in triplicate [15, 33]. Abundance of oligotrophic bacteria per 1 mL water was estimated by the same method on a solid Mills'nutrient medium modified for marine microorganisms [10]. Oil- and phenol-resistant microorganisms were determined on a starvation medium supplemented with oil

**Table 1.** The metrological specifications of an autonomous RinkoASTD102 CTD profiler

| Parameter | Range | Accuracy | Resolution | Response time, s |
|---|---|---|---|---|
| Temperature, °C | –5 to +40 | 0.01 | 0.001 | 0.2 |
| Conductivity, mS/cm | 0–65 | 0.01 | 0.001 | 0.2 |
| Pressure, dbar | 0–1000 | 0.3 | 0.02 | 0.2 |
| Salinity, PSU* | 2–40 | 0.02 | | |
| Turbidity, NTU** | 0–1000 | 2% | 0.03 | 0.2 |
| Chlorophyll *a* concentration, μg/L | 0–400 | 1% | 0.01 | 0.2 |
| Oxygen concentration, mg/L | 0–20 | 0.4 | 0.001 | 1 |

*Practical salinity unit [34].
**Nephelometric turbidity unit (1 NTU = 1 mg/L (kaolin)).

**Table 2.** The coordinates of stations, time of water sampling for microbial indication, and values of the parameters measured with an ASTD102 profiler in the surface layer of Amur Bay, July 2–3, 2022

| Stn. no. | Date | Time | Latitude, N | Longitude, E | *T*, °C | *S*, PSU | Chl, μg/L | $O_2$ | | Turb, NTU |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | dissolved, mg/L | saturation, % | |
| 1 | July 3 | 10:52 | 43°15.0′ | 131°47.7′ | 20.81 | 23.29 | 2.6 | 7.3 | 94.1 | 1.6 |
| 2 | July 3 | 10:38 | 43°14.2′ | 131°46.0′ | 20.49 | 24.55 | 1.7 | 7.3 | 94.3 | 0.8 |
| 3 | July 2 | 12:46 | 43°10.5′ | 131°46.9′ | 19.84 | 25.09 | 1.9 | *6.7* | *85.8* | 1.3 |
| 4 | July 2 | 12:18 | 43°9.2′ | 131°44.0′ | 19.1 | 27.48 | 1.7 | 7.3 | 92.8 | 0.6 |
| 5 | July 2 | 11:58 | 43°8.5′ | 131°41.4′ | 18.3 | 28.58 | 2.2 | 7.4 | 93.6 | 1.7 |
| 6 | July 2 | 11:38 | 43°6.4′ | 131°40.0′ | 18.6 | 29.27 | 1.5 | 7.5 | 95.7 | 0.4 |
| 7 | July 2 | 10:56 | 43°2.82′ | 131°35.28′ | *17.88* | **30.68** | *0.8* | 7.5 | 95.5 | 0.5 |
| 8 | July 3 | 12:43 | 43°15.46′ | 131°58.91′ | 22.6 | 18.32 | **5.7** | **7.8** | **100** | **3.4** |
| 9 | July 3 | 11:58 | 43°14.94′ | 131°58.43′ | **23.01** | 17.31 | **7** | **8.4** | **108.2** | 2.4 |
| 10 | July 3 | 13:31 | 43°14.2′ | 131°57.0′ | 22.94 | *16.08* | **6.1** | **8.7** | **111.1** | 2.1 |
| 11 | July 3 | 9:30 | 43°11.98′ | 131°54.9′ | 21.23 | 20.01 | **5.6** | **7.7** | **98.9** | 1.7 |
| 12 | July 2 | 13:37 | 43°10.4′ | 131°53.3′ | 21.12 | 22.44 | 1.9 | 7.6 | 96.5 | 0.9 |
| 13 | July 2 | 13:54 | 43°8.4′ | 131°53.4′ | 20.24 | 26.52 | 2.6 | 7.6 | 97.2 | 1 |
| 14 | July 2 | 14:17 | 43°6.2′ | 131°51.5′ | 19.58 | 28.3 | 1.7 | 7.6 | 96.5 | 0.5 |
| 15 | July 2 | 14:35 | 43°4.37′ | 131°50.6′ | 19.51 | 28.66 | 1.7 | 7.5 | 96.8 | 0.5 |
| 16 | July 2 | 9:38 | 43°2.0′ | 131°47.2′ | 18.25 | 29.52 | 1.2 | 7.4 | 93.5 | 0.4 |
| 17 | July 3 | 11:30 | 43°16.7′ | 131°54.0′ | 21.59 | 18.49 | **9.7** | **9.6** | **123.2** | 2.8 |
| 18 | July 3 | 9:51 | 43°12.3′ | 131°52.9′ | 20.62 | 23.29 | 2.4 | 7.6 | 97.4 | 0.7 |
| 19 | July 2 | 13:12 | 43°10.4′ | 131°50.0′ | 20.84 | 22.47 | 2.6 | 7.6 | 96.7 | 1.1 |
| 20 | July 2 | 9:19 | 43°5.0′ | 131°45.0′ | 18.69 | 28.75 | 1.8 | 7.4 | 94.3 | *0.5* |
| 21 | July 2 | 10:14 | 43°2.55′ | 131°41.5′ | 18.58 | 27.67 | 1.8 | 7.4 | 93.6 | 0.9 |

Here and in Tables 3–5, the highest values are highlighted in bold; the lowest values, in Italics. The letter designations are as follows: *T*, water temperature; *S*, salinity; Chl, chlorophyll *a* concentration; Turb, turbidity.

or phenol as the only source of carbon for bacterial growth to a final concentration of 0.1% [21]. The abundance of metal-resistant forms in the community of heterotrophic culturable microorganisms was estimated using selective media prepared on a nutrient medium for marine microorganisms with metal salts added at concentrations inhibiting the growth of sensitive bacterial forms. Chlorides of the heavy metals Zn, Cu, Cd, Ni, and Pb were used as additives [7, 8]. Sanitary indicator microorganisms, such as bacteria of the *Escherichia coli* group (common coliform bacteria), were detected using the selective Endo medium. Catalase-positive and oxidase-negative Gram-negative bacteria were also determined [21]. The data obtained through laboratory testing were processed by the generally accepted statistical methods.

## RESULTS

According to the data that we obtained using the profiler at the water sampling stations (Table 2), the water temperature in the surface layer varied from 17.9 to 23°C, with the lowest value occurring off Cape Perevozny and the highest value in the shallow water between Cape De-Friz and the Okeanskaya railway station. The spatial distribution of salinity had the opposite pattern, varying from 16 to 30.7 PSU. However, the pool of stations with the lowest salinity and maximum turbidity of water (up to 3.4 nephelometric turbidity units, NTU) was concentrated in the northeastern sector of the bay, while the water at the southern stations was more salty and transparent (less than 1 NTU). The concentrations of chlorophyll *a* and dissolved oxygen reproduced the turbidity stratification, varying from 0.8 to 9.7 μg/L and from 6.7 to 9.6 mg/L, respectively. The maximum oxygen saturation of the water reached 123% at the northernmost station 17.

The total abundance of heterotrophic bacteria varied from $3 \times 10^2$ to $9 \times 10^4$ CFU/mL, although concentrations greater than $10^4$ CFU/mL were observed at most stations. The abundance of oligotrophic bacteria was markedly lower, varying from 10 to $10^4$ CFU/mL with a predominance of $10^2$ CFU/mL. Bacteria of the *E. coli* group were detected at 10 out of the 21 stations. Their maximum concentration, which was higher than $10^2$ CFU/mL, was recorded from the eastern coast, in the area of the Pervaya Rechka River (Cape Lagerny) and between Skrebtsov Island and Cape De-Friz, and from the western coast, south of the Barabashevka River estuary (stn. 6). Anaerobic bacteria were absent at one-third of the stations; at sites of their dominance, the abundance was higher than $10^2$ CFU/mL (Table 3).

The simultaneous detection of saprophytic and oligotrophic bacteria and a comparison of their abundances showed the degree of mineralization of organic matter and provided a quantitative characteristic: the oligotrophy index, with its value indicating the degree of the enrichment of the habitat in nitrogen-containing organic matter and the intensity of its mineralization [15]. Values of the index higher than 0.01 were recorded from six stations (Table 3).

Bacteria growing on the medium with crude oil occurred in samples from eight stations; the abundance of oil destructors was higher than $10^2$ CFU/mL at only four of them. Phenol-oxidizing bacteria were present almost everywhere; at half of the stations their abundance was higher than $10^2$ CFU/mL. Metal-resistant microorganisms were rare and in small quantities: Cu-resistant bacteria were not detected; Pb-resistant bacteria were found at only one station; Ni-resistant at two; Zn-resistant at eight; and Cd-resistant at nine stations (Table 4).

## DISCUSSION

The observations were carried out for 2 days with abnormally warm weather, when the air temperature reached 26°C at noon (Fig. 2a), which is typical of the southern monsoon [4]. During the first day of the survey (July 2), when operations were carried out in the southern part of the study area (including the transect from Cape Peschany to Cape Firsov), and on the previous day, the speed of the southerly wind reached 5–7 m/s. Under its action, a water setdown effect was formed along the mainland coast, which was manifested as low temperatures and increased salinity of waters, despite the substantial precipitation (190 mm) in June and the abundant discharge of the Razdolnaya, Amba, and Barabashevka rivers. For example, on the southern transect, in the surface layer near Cape Perevozny, the water temperature and salinity were 17.88°C and 30.7 PSU (stn. 7, Table 2); near Cape Mikhailovsky, 18.25°C and 29.5 PSU; and on the transect from Cape Peschany to Cape Firsov, respectively, 19.8°C and 25.1 PSU and 21.1°C and 22.44 PSU. On the following day, the survey, which began in calm weather, continued under a gradual strengthening of the southerly wind (Fig. 2b). The distribution pattern of values of the thermohaline parameters persisted. Thus, off the mainland coast near Mount Primetnaya (stn. 2), despite the effect of the Razdolnaya River discharge, we observed colder (20.5°C) and saltier (24.5 PSU) water than off the eastern coast, near the Sedanka River estuary (22.9°C and 16 PSU) and near Cape Krasny (21.5°C and 20 PSU). Such parameters as turbidity and concentrations of chlorophyll *a* and oxygen clarified the pattern of the effect of dynamic processes on the surface layer of Amur Bay. A patchy increase in turbidity caused by coastal upwelling (Figs. 3a–3c) was observed along the western coast and spread as a continuous field over the northern shallow area of the bay. Simultaneously, in the east and northeast, an increase in the chlorophyll *a* and oxygen contents was caused by the wind-induced setup effect.

The set down effect was more pronounced in the distribution of all the environmental parameters on the axial and three transverse transects (Figs. 4a, 4b, 5a–5c). The transect located south of the Muravyevsky threshold between Cape Mikhailovsky and Cape Perevozny (Fig. 1), unlike the others, was influenced by the open and fresher waters of Peter the Great Bay. This was manifested as an increased salinity of 29–32 PSU of the surface 5-m layer compared to the salinity in the waters north of the threshold, which was by 2–3 PSU lower (Fig. 4b). The setdown effect near the western coast was clearly visible as a characteristic bending of isotherms and isohalines. The corresponding intensive rise of waters from the lower lay-

**Table 3.** The abundance of ecological and trophic groups of microorganisms and oligotrophy index in surface waters of Amur Bay, July 2–3, 2022

| Stn. no. | Abundance of microorganisms, CFU/mL | | | | Oligotrophy index |
|---|---|---|---|---|---|
| | CHM | O | BECG | Anaerobic | |
| 1 | $(4.8 \pm 0.22) \times 10^4$ | $(3.0 \pm 0.13) \times 10^2$ | 0 | $(3.9 \pm 0.14) \times 10$ | <0.01 |
| 2 | $(3.8 \pm 0.31) \times 10^4$ | $\mathbf{(1.3 \pm 0.13) \times 10^4}$ | $(3.2 \pm 0.14) \times 10$ | 0 | 0.34 |
| 3 | $(6.4 \pm 0.14) \times 10^3$ | $(1.4 \pm 0.11) \times 10$ | 0 | $(4.2 \pm 0.22) \times 10$ | <0.01 |
| 4 | $(8.5 \pm 0.23) \times 10^3$ | $(8.7 \pm 0.13) \times 10$ | 0 | $(2.7 \pm 0.23) \times 10$ | 0.01 |
| 5 | $(3.5 \pm 0.21) \times 10^3$ | $(3.7 \pm 0.18) \times 10^2$ | 0 | 0 | 1.05 |
| 6 | $\mathbf{(9.4 \pm 0.14) \times 10^4}$ | $(1.4 \pm 0.13) \times 10$ | $\mathbf{(2.8 \pm 0.12) \times 10^2}$ | $(1.4 \pm 0.13) \times 10$ | <0.01 |
| 7 | $(2.8 \pm 0.32) \times 10^4$ | $(1.1 \pm 0.31) \times 10$ | 0 | $\mathbf{(5.7 \pm 0.13) \times 10^2}$ | <0.01 |
| 8 | $(3.3 \pm 0.13) \times 10^4$ | $(5.3 \pm 0.13) \times 10$ | $(8.7 \pm 0.22) \times 10$ | 0 | <0.01 |
| 9 | $(2.4 \pm 0.14) \times 10^4$ | $(1.1 \pm 0.14) \times 10$ | $(4.4 \pm 0.21) \times 10$ | $\mathbf{(1.7 \pm 0.18) \times 10^2}$ | <0.01 |
| 10 | $(3.5 \pm 0.23) \times 10^4$ | $(1.5 \pm 0.23) \times 10$ | $\mathbf{(4.6 \pm 0.13) \times 10^2}$ | 0 | <0.01 |
| 11 | $(1.5 \pm 0.21) \times 10^4$ | $(7.5 \pm 0.2) \times 10^3$ | $(1.1 \pm 0.11) \times 10$ | 0 | 0.5 |
| 12 | $(1.4 \pm 0.18) \times 10^4$ | $(1.1 \pm 0.11) \times 10$ | $(7.3 \pm 0.12) \times 10$ | $(2.7 \pm 0.23) \times 10$ | <0.01 |
| 13 | $\mathbf{(8.8 \pm 0.22) \times 10^4}$ | $(1.2 \pm 0.18) \times 10^2$ | $\mathbf{(1.3 \pm 0.17) \times 10^2}$ | $\mathbf{(4.6 \pm 0.23) \times 10^2}$ | <0.01 |
| 14 | $(2.3 \pm 0.31) \times 10^3$ | $\mathbf{(4.3 \pm 0.11) \times 10^3}$ | 0 | $(1.7 \pm 0.22) \times 10$ | **1.86** |
| 15 | $(2.4 \pm 0.14) \times 10^3$ | $\mathbf{(3.4 \pm 0.11) \times 10^3}$ | 0 | $(1.3 \pm 0.23) \times 10$ | 1.41 |
| 16 | $\mathbf{(7.5 \pm 0.36) \times 10^4}$ | $(1.5 \pm 0.36) \times 10$ | 0 | 0 | <0.01 |
| 17 | $(4.5 \pm 0.24) \times 10^4$ | $(1.5 \pm 0.24) \times 10^2$ | $(5.1 \pm 0.28) \times 10$ | $(4.9 \pm 0.27) \times 10$ | <0.01 |
| 18 | $\mathbf{(7.4 \pm 0.31) \times 10^4}$ | $(6.4 \pm 0.21) \times 10^2$ | $(2.1 \pm 0.31) \times 10$ | 0 | <0.01 |
| 19 | $\mathbf{(9.8 \pm 0.26) \times 10^4}$ | $(3.4 \pm 0.17) \times 10^2$ | 0 | $(3.5 \pm 0.35) \times 10$ | <0.01 |
| 20 | $(8.3 \pm 0.33) \times 10^2$ | *$(1.1 \pm 0.33) \times 10$* | 0 | $(7.0 \pm 0.22) \times 10$ | 0.01 |
| 21 | *$(3.4 \pm 0.21) \times 10^2$* | $(3.9 \pm 0.18) \times 10^2$ | 0 | $(3.9 \pm 0.32) \times 10$ | 1.14 |

The letter designations are as follows: CHM, colony-forming saprophytic heterotrophic microorganisms; O, oligotrophic microorganisms; BECG, bacteria of the *Escherichia coli* group.

ers to the surface led to the transport of fine silt fractions and was accompanied by an increase in turbidity near the seabedall along the western slope segment of the transect. A location with an increased chlorophyll *a* concentration at its center was apparently caused by the multidirectional dynamics of surface waters.

The manifestation of the setdown effect near the eastern coast of Amur Bay is presumably caused by local orography features. With a predominantly south-southeasterly wind (recorded at the Vladivostok-Gora weather station), the upwelling effect should also be observed near Russky Island, but the mountainous terrain of the island markedly attenuates it in the nearshore zone. Nevertheless, it was present and was manifested as a salinity increase and a temperature decrease at an intermediate station of the southern transverse transect (Figs. 4a, 4b). The configuration of the isolines of the controlled parameters on the northern transects confirmed the above-described hydrodynamics caused by southerly winds: the setup of waters from south to north with their obvious setdown along the western coast and a less pronounced flow from the opposite side. Such multidirectional dynamics is man-

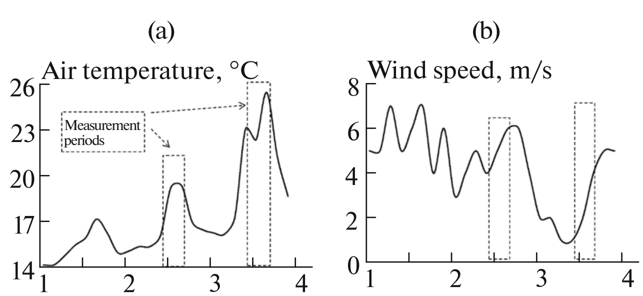


**Fig. 2.** The air temperature (a) and wind speed modulus (b), July 1–3, 2022 (according to [1]).

**Table 4.** The abundance of indicator groups of microorganisms in surface waters of Amur Bay, July 2–3, 2022

| Stn. no. | Abundance, CFU/mL | | | | |
|---|---|---|---|---|---|
| | Phenol-resistant | Oil-resistant | Cd-resistant | Zn-resistant | Ni-resistant |
| 1 | (8.9 ± 0.17) × 10 | (2.5 ± 0.25) × 10 | 0 | 0 | 0 |
| 2 | **(4.9 ± 0.14) × 10$^2$** | 0 | (6.0 ± 0.33) × 10 | (4.6 ± 0.21) × 10 | 0 |
| 3 | (6.0 ± 0.33) × 10 | 0 | (1.1 ± 0.24) × 10 | (2.0 ± 0.13) × 10 | (1.2 ± 0.11) × 10 |
| 4 | (2.0 ± 0.15) × 10 | (3.0 ± 0.22) × 10 | 0 | 0 | 0 |
| 5 | 0 | (1.8 ± 0.24) × 10$^2$ | 0 | 0 | 0 |
| 6 | (1.3 ± 0.23) × 10$^2$ | 0 | 0 | **(7.9 ± 0.16) × 10** | 0 |
| 7 | (1.1 ± 0.13) × 10 | **(3.7 ± 0.14) × 10$^3$** | 0 | 0 | 0 |
| 8 | (2.6 ± 0.11) × 10$^2$ | (9.0 ± 0.23) × 10$^2$ | (7.9 ± 0.31) × 10 | **(9.2 ± 0.33) × 10** | 0 |
| 9 | **(4.5 ± 0.24) × 10$^2$** | 0 | (3.0 ± 0.21) × 10 | (7.0 ± 0.31) × 10 | 0 |
| 10 | (2.0 ± 0.25) × 10 | (4.0 ± 0.18) × 10 | 0 | 0 | 0 |
| 11 | **(4.7 ± 0.22) × 10$^2$** | 0 | **(9.2 ± 0.17) × 10** | **(8.7 ± 0.15) × 10** | 0 |
| 12 | (1.2 ± 0.17) × 10$^2$ | 0 | (2.0 ± 0.11) × 10 | 0 | **(2.8 ± 0.2) × 10** |
| 13 | (3.7 ± 0.14) × 10$^2$ | **(2.6 ± 0.11) × 10$^3$** | 0 | (5.9 ± 0.18) × 10 | 0 |
| 14 | (3.2 ± 0.31) × 10$^2$ | 0 | 0 | 0 | 0 |
| 15 | (1.7 ± 0.12) × 10$^2$ | 0 | (3.1 ± 0.12) × 10 | (2.0 ± 0.13) × 10 | 0 |
| 16 | (3.0 ± 0.11) × 10 | 0 | 0 | 0 | 0 |
| 17 | (9.7 ± 0.21) × 10 | 0 | 0 | 0 | 0 |
| 18 | (2.9 ± 0.31) × 10$^2$ | (3.0 ± 0.22) × 10 | (7.5 ± 0.31) × 10 | 0 | 0 |
| 19 | **(4.3 ± 0.27) × 10$^2$** | 0 | (2.9 ± 0.17) × 10 | 0 | 0 |
| 20 | (2.0 ± 0.12) × 10 | 0 | 0 | 0 | 0 |
| 21 | (1.3 ± 0.22) × 10 | 0 | 0 | 0 | 0 |

Cu-resistant microorganisms were not found; Pb-resistant microorganisms were recorded only from stn. 6 at an abundance of (2.1 ± 0.1) × 10.

ifested as increased turbidity and concentrations of chlorophyll *a* and oxygen at the axial transect stations (Figs. 5a–5c).

An analysis of the distribution of chlorophyll *a* and oxygen saturation of waters showed their high levels (>2 μg/L and >80%, respectively) within the upper 5-m layer (Figs. 5a, 5c), which indicated intensification of the phytoplankton bloom. The decrease in the oxygen content to 50% or less in the near-bottom layer north and south of the Muravyevsky threshold indicated the onset of total development of seasonal hypoxia. Its annual presence in the waters of Amur Bay is explained by the eutrophication effect [9, 25] which, by the time of the survey, had already become pronounced in the northeastern shallow-water area (Skrebtsov Island to the Sedanka River estuary) due to the monsoon-induced setup of water. Here, a microalgae bloom in the surface layer caused a chlorophyll *a* concentration of 6–9 μg/L, a percentage of oxygen saturation of water higher than 100%, and an almost complete lack of oxygen in the near-bottom layer (<5%). Better environmental conditions (70–80% oxygen) were observed in the intermediate water layer at the axial and transverse transects.

Heterotrophic bacterioplankton is one of the major components of aquatic ecosystems, with more than 40% of the total carbon flux in planktonic trophic chains passing through it. Heterotrophic microorganisms contribute to the degradation of organic matter and provide self-purification of water masses; saprobity of water is estimated by their abundance [16, 20, 22]. The abundance of colony-forming saprophytic heterotrophic microorganisms in the surface waters of Amur Bay was distributed almost evenly from station to station (Table 3). It ranged from $10^3$ to $10^5$ CFU/mL and was mainly $10^4$ CFU/mL, which characterized the waters as mesosaprobic, enriched in organic matter. This distribution was obviously caused by intensive recreational activities and the influx of organic matter, both of autochthonous and allochthonous origins, including domestic wastewater. According to the data we obtained, the highest levels of saprotrophic bacteria abundance (>5 × $10^4$ CFU/mL) were recorded not only from the sites of evident sources of pollution (opposite the Barabashevka River estuary, with a large

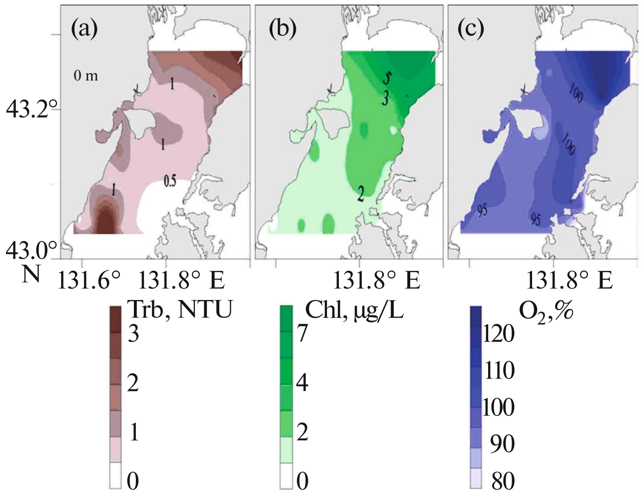


**Fig. 3.** The distribution of turbidity (a), chlorophyll *a* concentration (b), and dissolved oxygen content (c) in the surface layer of Amur Bay, July 2–3, 2022. The letter designations here and in Figs. 4 and 5 are as follows: *T*, water temperature; *S*, salinity; Chl, chlorophyll *a* concentration; Turb, turbidity.

settlement upstream; near Cape Lagerny, where domestic wastewater from the Pervorechensky District of Vladivostok is accumulated; and near Cape Mikhailovsky, next to which a mud bath and mariculture farms in Voevoda Cove are located) but also from the stations of the axial transect in the northern part of the bay. The highest abundance of saprotrophic bacteria (about $10^5$ CFU/mL) found here was probably caused by a combined effect of the main sources of pollution: the Razdolnaya and Schmidtovka rivers and the collectors of the Severnaya sewage treatment system in the area of the De-Friz Peninsula and Tsentralnaya sewage treatment system in the area of the Vtoraya Rechka River estuary. The multidirectional pattern of these hydrodynamic processes also contributed to this high abundance.

A low abundance of saprotrophic bacteria ($<3 \times 10^3$ CFU/mL) was observed in the near-shore water off the Shkot Peninsula (stns. 14 and 15), where domestic wastewater is not discharged. The surface waters near the Peschany Peninsula and south of it had a rather low abundance of colony-forming saprophytic heterotrophic microorganisms ($<10^4$ CFU/mL). The lowest their concentration ($3.4 \times 10^2$ CFU/mL) was found at the southernmost station of the axial transect.

The abundance of oligotrophic microflora varied within a wider range, from 10 to $10^4$ CFU/mL, although at most stations it was no higher than $10^2$ CFU/mL. The greatest abundance of oligotrophic bacteria ($>10^3$ CFU/mL) was recorded from stations along the Shkot Peninsula and off Mount Primetnaya (Table 3).

For ecological monitoring of aquatic ecosystems, quantitative data on contents of saprophytic and oligotrophic microorganisms in the microflora of a water body are used to identify the pattern of the processes of accumulation and destruction of organic matter [15]. Saprophytic microflora in water bodies is the most active participant in degradation of organic sub-

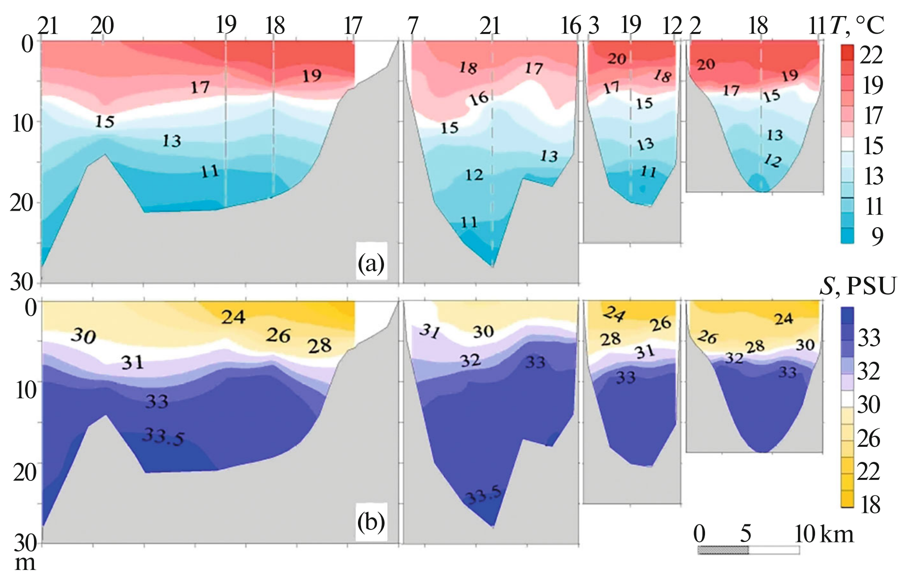


**Fig. 4.** The distribution of water temperature (a) and salinity (b) in the water column of the bay along the axial transect, July 2–3, 2022. Stations located at the intersection of the transects are indicated by vertical dotted lines.

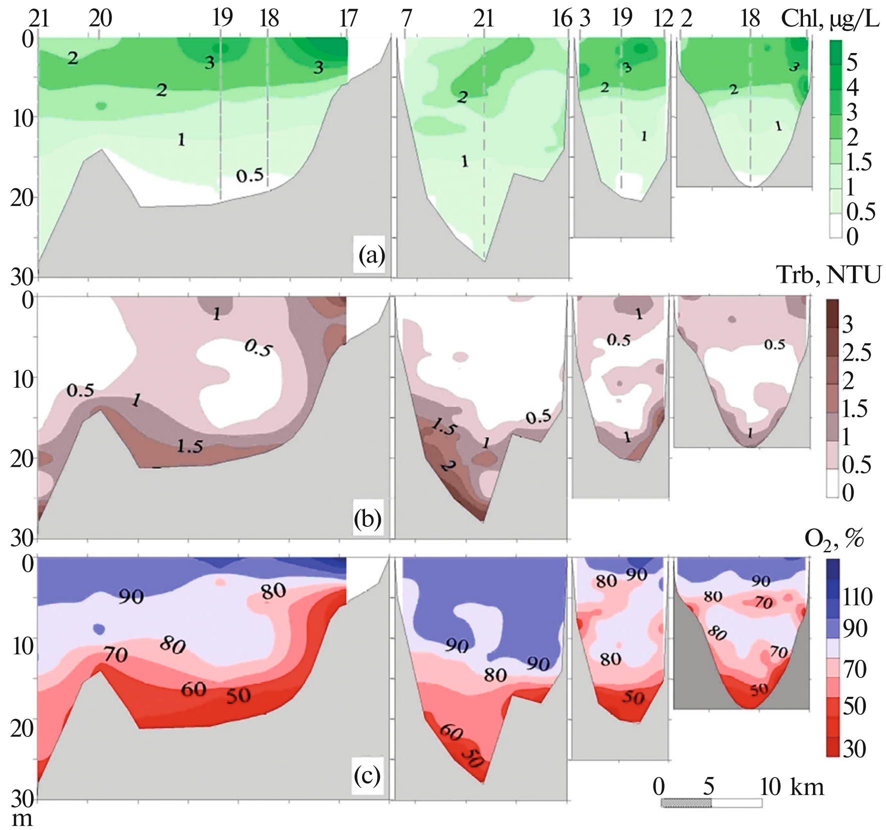


**Fig. 5.** The distribution of chlorophyll *a* concentration (a), turbidity (b), and dissolved oxygen content (c) in the water column of the bay along the axial transect, July 2–3, 2022.

stances, a reliable and rapid indicator of the qualitative direction of many environmental processes. In our study, the oligotrophy index, which characterizes the degree of mineralization of organic matter, was higher than unity at only two stations (Table 3). Thus, over most of the waters, the accumulation of organic matter prevailed over its destruction in the biocenosis of the surface layer, and self-purification processes occurred at a low rate.

Bacteria of the *E. coli* group were identified at half of the stations, which indicated biological contamination of the waters in the bay. The highest abundance of bacteria (>$10^2$ CFU/mL) of this group was recorded from the area near the Barabashevka River estuary, opposite the Sedanka River estuary, and off Cape Lagerny (Table 3).

An analysis of the abundance of bacteria growing on the medium with crude oil showed that the waters in most of Amur Bay were not contaminated by petroleum hydrocarbons. At eight stations, the abundance of oil-resistant microorganisms was higher than 10 CFU/mL; at the stations near the Okeanskaya railway station, near the oil depot in the area of the Pervaya Rechka River, and off Cape Perevozny, their abundance reached $10^3$ CFU/mL (Table 4). At the two former stations, this technogenic effect was expected, and the maximum amount of petroleum products detected in the southernmost and seemingly least polluted part of the area was probably explained by sampling too close to the shore, where signs of regular loading and unloading activities were obvious.

During the study, it turned out that the entire area of the bay was exposed to phenol pollution to a greater or lesser extent; concentrations of phenol-resistant organisms reached 5 × $10^2$CFU/mL (Table 4). The main, but not relevant in our case, technogenic sources of phenols are facilities of the pulp and paper and woodworking industries [24] and the use of organochlorine pesticides. It is known that macrophytic algae can themselves become a natural source of phenols, while fecal sterols can be an anthropogenic source [23, 30]. Since phenols are hazardous pollutants considered as highly toxic substances, the abundance of phenol-resistant microorganisms, even at $10^2$ cells/mL, indicates that the environment is significantly polluted [7].

Determination of abundance of metal-resistant microorganisms classified as heterotrophic allows assessment of the level of specialized pressure on the surface waters of the bay. While the contents of ions of

**Table 5.** The approximate criteria of water pollution by heavy metals based on microbiological characteristics [8]

| Microbiological characteristic | Pollution | | | |
|---|---|---|---|---|
| | background (<MPC) | insignificant (≈MPC) | noticeable (1–3MPC) | substantial (>3MPC) |
| CHM (cells/mL) | $< 10^3$ | $10^3–10^4$ | $10^4–10^5$ | $>10^5$ |
| MI | | | | |
| Cd | <0.01 | 0.01–0.1 | 0.1–9 | >9 |
| Cu | <10 | 10–46 | >46 | No data |
| Pb | <10 | 10–46 | >46 | No data |
| Zn | <0.1 | 0.1–10 | 10–46 | >46 |
| Ni | <0.1 | 0.1–10 | 10–46 | >46 |
| Co | <1 | 1–20 | 20–46 | >46 |

The letter designations are as follows: MPC, maximum permissible concentration of heavy metals in water (for fishery water bodies); MI, microbial index, % of abundance of colony-forming saprophytic heterotrophic microorganisms.

the heavy metals Cd, Pb, Ni, and their complexes in the water mainly indicates a technogenic effect on the environment, the presence of Cu and Zn indicates an anthropogenic effect [26]. The results of the microbiological testing showed low values of abundance of metal-resistant microorganisms and their mosaic pattern of distribution (Table 4). Metal-resistant bacteria were not detected at ten stations. The most widespread ecological and trophic groups identified at most of the stations were Cd- and Zn-resistant microorganisms whose abundance, however, was not higher than 10 CFU/mL. No Cu-resistant microorganisms were detected. Pb-resistant bacteria were found in minimum quantities at one station (near the Barabashevka River estuary).

To proceed from microbiological data to environmental assessment of degree of pollution of marine waters by heavy metals, a scale is used on which the microbial index (the percentage proportion of a specific metal-resistant group among colony-forming saprophytic heterotrophic microorganisms) is compared to the maximum permissible concentration (MPC) of heavy metals for fishery water bodies [2]. The microbial index clearly shows the degree of resistance of the community to effects of pollutants (Table 5). After recalculating the absolute abundance of metal-resistant groups to be expressed in terms of microbial indices and comparing them to the Dimitrieva's scale for pollution assessment [7], we observed a relatively uniform background for all metal-resistant bacteria, which indicates concentrations of heavy metals not exceeding background values.

## CONCLUSIONS

The results of an integrated hydrological and microbiological survey of Amur Bay on July 2–3, 2022 showed a substantial effect of the summer monsoon and river runoff on the condition of the environment and its quality. The long-term effect of the southerly wind with a speed of up to 7 m/s was manifested, primarily, as a characteristic setdown of the water surface along the western coast. Here, despite the preceding abundant precipitation and a great volume of inflowing fresh water (discharged from the Razdolnaya, Amba, and Barabashevka rivers), the recorded temperature was lower by 0.3–1°C and the salinity increased to 2.6 PSU compared to those on the opposite side of the bay. Accordingly, in the northeastern sector of the bay, a setup effect was observed, which contributed to limiting of surface waters freshened by river runoff with a characteristic increase in water temperature by 3–5°C, which reached 23°C, and a decrease in salinity to 17–18 PSU. The nutrient-enriched water of the surface layer facilitated the active phytoplankton bloom (with a concentration of chlorophyll *a* up to 6–9 μg/dm$^3$) and oxygen saturation (more than 100%). Simultaneously, hypoxia with reduced oxygen concentrations (less than 5%) was observed in the near-bottom layers of this sector, which indicated the development of eutrophication.

According to the results of microbiological control, the waters of Amur Bay during the survey in the summer of 2022 were categorized as mesosaprobic, enriched in organic compounds; the processes of accumulation of organic matter in them prevailed over its degradation. At most stations, high abundances of bacteria of the sanitary indicator group were recorded, which indicates biological contamination of waters. Phenol-resistant microorganisms were found at all stations with no exception; oil pollution was detected in marked quantities only at stations located near the oil depot and the Okeanskaya railway station. As follows from the analysis of the distribution of metal-resistant microorganisms, at the time of sampling, the level of specialized (technogenic) pressure on the surface waters of the bay was insignificant: the microbial indices corresponding to the relative abundance of metal-resistant microorganisms were at a minimum, which indicated metal concentrations not exceeding the background levels.


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## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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