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Loss of Large Bivalves in the Rivers of the Southern Primorye (Russian Far East) in Summer and Autumn of 2021

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Abstract—Mass mortality of Unionidae from the genera *Middendorffinaia, Buldowskia,* and *Sinanodonta* was observed in the plain rivers of the south of Primorsky Krai (south of the Russian Far East) in the abnormally hot and low-water summer–autumn season of 2021. *Nodularia douglasiae* (Griffith et Pidgeon, 1833) was the most resistant and thus least affected species, the species from the genera *Sinanodonta* and *Middendorffinaia*, the least resistant and the most affected.

Keywords: Primorsky Krai, rivers, Bivalvia, *Nodularia*, *Middendorffinaia*, *Buldowskia*, *Margaritifera*, Unionidae mortality, climate change, high water temperature, anthropogenic pollution

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INTRODUCTION

In the past few decades, the nature of our planet has been destroyed at an incredible rate, and freshwater ecosystems are among the most vulnerable. According to forecasts, in the near future, the impact of climatic factors on the ecosystems of the globe will increase [1]. Climate change affects the natural cycles of floods, namely, flood strength increases, but the probability of showers during the dry season decreases (i.e., there are more extremes) [2]. In particular, in the southern Far East (Primorye), heavy rains occurred in August and September 2020, including those caused by two typhoons. No typhoons were registered in summer and autumn of 2021; according to weather forecasters, this has not happened for more than 10 years in Primorye. The last time a long period with no typhoons in the region was observed was in 2010.

During a strong flood, quantitative depletion of phyto- and zoobenthos takes place; it may end with total destruction of riverine benthic communities. At low water content, water heating increases; larvae of some amphibiotic insects, gastropods, and other invertebrates actively develop during this period. Against the background of a long low water period and at high water temperatures, bacterial decomposition of organic substances (for example, leaf litter buried at the bottom of a reservoir) is activated. High water temperature reduces the partial pressure of oxygen, which causes the death of rheophilic organisms. The resistance of hydrobionts to many adverse environmental factors, including anthropogenic pollution, depends on the saturation of water with oxygen.

At low water level, it is convenient to study large Bivalvia and other benthic organisms, since these aquatic organisms become available for direct collection and accounting. Taking into account the low water level of river systems in the study region in 2021, it was decided to assess the current state of populations of large bivalve mollusks, especially the species included in the latest edition of the Red Data Book of Russia: *Middendorffinaia mongolica* (Middendorff, 1851), *Middendorffinaia sujfunensis* Moskvicheva et Starobogatov, 1973, and *Buldowskia cylindrica* Moskvicheva, 1973 (family Unionidae), and *Dahurinaia dahurica* (Middendorff, 1850) (family Margaritiferiidae) [3], and to assess their ability to survive in extreme conditions of a dry season.

MATERIALS AND METHODS

The studies were carried out in June–November 2021 and April–June 2022 in the south of Primorsky Krai in the basins of the Knevichanka River (basin area of 476 km^2, the right tributary of the Artemovka River, flowing into the Ussuri Bay of the Sea of Japan) and Razdolnaya River (basin area of 16,830 km^2, flowing into the Amur Bay of the Sea of Japan), including the Komarovka River (basin area 1490 km^2, left tributary of the Razdolnaya River, Ussuriysky District), the Rakovka River (basin area of 812 km^2, right tributary of the Komarovka River, Mikhailovsky District), and Kiparisovka River (left tributary of the Razdolnaya River, Nadezhdinsky District) (Fig. 1a). The entire study area is included in the ecoregion

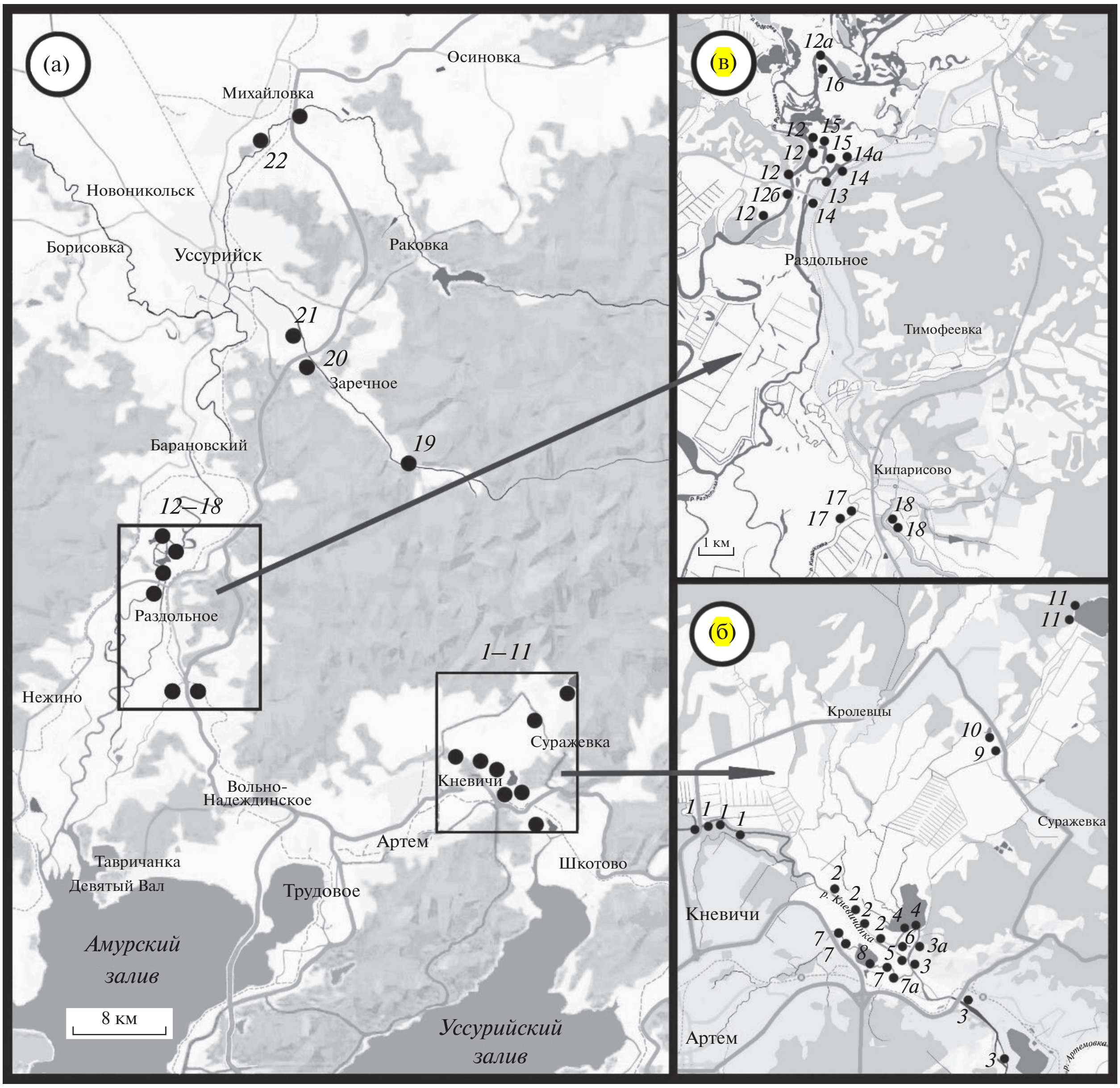

Fig. 1. Schematic map of the sampling area (a), including the Knevichanka River basin (b) and Razdolnaya River basin (c): *1–3* – the channel of the Knevichanka River (*1* – forest area, *2* – meadow area upstream the Lake Krolevetskoe, *3* – meadow area downstream the Lake Krolevetskoe); *4* – Lake Orlovskoye; *5* – active drainage channel; *6* – drainage channel, lined with an earthen dam; *7* – Orlovka River; *8* – Lake Orlovskoye; *9* – Ivnyanka River (polluted riverbed); *10* – a lake on the Ivnyanka River near Zavodskoe village; *11* – reservoir; *12* – the main channel of the Razdolnaya River; *13* – left branch of the Razdolnaya River; *14* – backwaters of the Razdolnaya River; *15* – oxbow lake; *16* – quarries; *17* – Kiparisovka River; *18* – irrigation canal near the Kiparisovo village; *19* – Komarovka River downstream of Kondratenovka village; *20* – Lake Banevurovo; *21* – backwater of the Komarovka River at the Raduzhnoye sports complex; *22* – Rakovka River.

"Ussuri broad-leaved and mixed forests of temperate climate", belonging to the biome "broad-leaved and mixed forests of temperate climate" (https://ecoregions2017.appspot.com/).

In the Knevichanka River basin, the riverbed was surveyed within the river valley up to about 15 km upstream of the confluence of the Knevichanka River with the Artemovka River, two drainage canals (operating and now lined with an earthen dam), the Orlovka River (right tributary of the Knevichanka River), lakes Orlovskoe and Krolevetskoe, the Ivnyanka River (flows into Lake Krolevetskoe), including a lake near the Zavodskoe village and a reservoir in the mountainous part of the river basin. In the lower reaches of the Knevichanka River, three sites were surveyed: the upstream site, located within the broad-leaved forest (11–15 km upstream of the confluence with the Artemovka River), and two downstream sites, located in an open meadow area, respectively upstream and downstream of Lake Krolevetskoe (Fig. 1b).

At the lower reaches of the Razdolnaya River, the mollusks were sampled at Razdolnoe village in the main channel along the 8-km transect, in the left branch of the river channel (about 300 m below Razdolnaya station), as well as in backwaters, oxbow lakes, and quarries. In the Kiparisovka River, we explored the channel and irrigation canal near Kiparisovo village; in the Komarovka River, the foothill section of the channel near Kondratenovka village, Lake Banevurovo, and backwaters of the river near the Raduzhnoye sports complex, in the Rakovka River, a channel in the vicinity of Mikhailovskoe village (Fig. 1c).

It should be emphasized that all studied water bodies were distinguished by a high diversity and a significant population density of large bivalve mollusks from the Unionidae family from 3 to 4 decades ago [4–15]. In particular, the Razdolnaya River and its floodplain reservoirs, as well as the Kiparisovka River with a reclamation canal near Kiparisovo village, was inhabited by numerous representatives of the genera *Nodularia, Middendorffinaia, Buldowskia,* and *Sinanodonta;* the channel upstream was the locality of *Anemina* (*Buldowskia) zatrawkini* Martynov et Tshernyshev, 1992 [11], later redefined as *Buldowskia suifunica suifunensis* (Shadin, 1938) [16]. The lower reaches of the Komarovka and Rakovka rivers, as well as their floodplain water bodies, were inhabited by mollusks from the genera *Buldowskia* and *Sinanodonta,* the middle reaches of these rivers, species from the genus *Middendorffinaia*. In addition, at the upper reaches of the Komarovka River, within the Ussuriysky State Reserve, a large population of the Dahurian pearl mussel *Margaritifera dahurica* (Middendorff, 1850) (family Margaritiferidae) lived [15]. (Nowadays, in the Komarovka River, this species is preserved only at the middle reaches, near Kondratenovka village [17].) At the bottom of the basin Knevichanka River, including the Lake Krolevetskoe, genus *Buldowskia* prevailed, including *B. cylindrica,* for which one of the backwaters of the river downstream Lake Krolevetskoe was designated as a type locality [12]. Rarely, in the lower reaches of the Knevichanka River, representatives of the genera *Middendorffinaia, Sinanodonta* and brackish mollusks *Corbicula japonica* Prime, 1864 (family Corbiculidae) have been found. In turn, the Orlovka River was abundantly populated by *Buldowskia suifunica* (Lindholm, 1925) [16, pl. 65, 68].

It is important to recall that large Bivalvia in the basins of the Knevichanka and Razdolnaya rivers were sporadically studied throughout the 20th century; in the 1980s, the largest collections of mollusks were obtained with participation of one of the authors of this article (V. Bogatov). In subsequent years, there were one-time visits of specialists to water bodies; as a result, the first red flags indicating the degradation of bivalve mollusk habitats were noted. For example, the pearl mussels *Dahurinaia dahurica* disappeared from the bottom community during the survey in 2000 and 2008 at the upper reaches of the Komarovka River. During the survey in 2011, no representatives of the genus *Middendorffinaia*, which dominated here previously, were found in the main channel of the Razdolnaya River near Razdolnoe village in the composition of the malacofauna. In the same period, the absence of bivalve mollusks was noted in the Kiparisovka River and in the reclamation canal near Kiparisovo village.

In 2021, mollusks were collected from the same water bodies as in the 1980s, except a lake and a reservoir on the Ivnyanka River, where the composition of the malacofauna was studied for the first time. The mollusks and shells were collected manually or using a large-mesh net and a rake-shaped scraper. The mollusks were counted quantitatively by total scraping of a certain area of the bottom to a depth of 1.5–2.0 m, as well as by manual collection in shallow waters. As a rule, when quantifying living specimens of mollusks, they were returned back to their habitat. In total, about 40 live bivalves and more than 400 empty shells were collected. V.V. Bogatov identified the mollusks and photographed them. In order to assess the degree of eutrophication of water bodies, the dominant species of algae in the surface bacterial films were taken into account. T.V. Nikulina determined the microalgae.

In 2021, at the main sampling sites, the water temperature was measured and the pH level and the content of ammonium nitrogen (NH_4) in the water were determined using the Value-Test and Ammonium/Ammonia-Test, respectively (Sera Werke, Germany). In addition, in April–June 2022, at low water conditions, a control survey of sampling sites was performed. During these surveys, the carbonate hardness of the water (kH) and the content of phosphates (PO_4) in the water were measured and evaluated using Sera Werke test systems, kH Test and Tetra Test PO_4, respectively (Tables 1 and 2).

RESULTS

The Knevichanka River basin. During the study period, in the main riverbed of the Knevichanka River, its working drainage channel, Lake Krolevetskoe, and in the Orlovka River (Fig. 1b, *1–8*), only representatives of the genus *Buldowskia* were found. In the second half of August 2021, death of these mollusks was recorded, while in June of the same year it was still possible to meet live bivalves. Undoubtedly, the main reason for the mass death of *Buldowskia* was associated with a long abnormally warm summer period, when the water temperature in reservoirs and streams did not decrease below 28–30°C for a long time under conditions of extremely low water shortage.

Table 1. Hydrochemical characteristics at stations in the basin of the Knevichanka River

Sampling site (station no.)	Coordinates, N/E	Date, time of collection	Water temperature, °C	pH	kH	NH_4, mg/L	PO_4, mg/L
Knevichanka river, forest zone (1)	43°25′19″/132°11′82″	20.10.21, 16-30	6.0	6.5–7.0	–	1.0	–
Ibid.	43°25′22″/132°12′11″	25.05.22, 10-00	18.5	7.0	6.0	5.0	5.0
Knevichanka River, upstream the lake (2)	43°25′19″/132°11′82″	20.10.21, 11-30	6.0	7.0	–	1.0	–
Ibid.	43°23′54″/132°14′99″	25.10.21, 14-00	7.0	7.0	–	5.0	–
–″–	43°23′37″/132°15′33″	25.05.22, 15-00	24.0	9.0	3.0	0.5	0.5
Knevichanka River, at the discharge from treatment facilities (3a)	43°23′18″/132°16′15″	25.05.22, 12-30	21.0	7.5	6.0	>10.0	10.0
Knevichanka River, downstream treatment plants (3)	43°23′07″/132°16′08″	20.10.21, 14-00	10.0	7.5–8.0	–	10.0	–
Ibid.	Ibid.	25.05.22, 12-00	23.0	7.5	4.0	5.0	5.0
Channel of the Knevichanka River, at the mouth (5)	43°23′08″/132°16′04″	15.09.21, 11-00	19.5	–	–	–	–
Orlovka River (7 a)	43°23′02″/132°15′67″	26.10.21, 10-00	6.0	7.5	–	0.0	–
Ibid.	Ibid.	25.05.22, 14-00	22.0	8.0	5.0	0.0	0.0
Ivnyanka River, contaminated site (9)	43°26′30″/132°18′08″	20.10.21, 15-20	8.0	7.5	–	5.0–10.0	–
Ibid.	Ibid.	25.05.22, 11-30	16.0	7.0	3.0	5.0	5.0–10.0
Lake on the Ivnyanka River (10)	43°26′56″/132°17′77″	20.10.21, 15-40	7.0	7.5	–	0.0	–
Ibid.	Ibid.	25.05.22, 11-00	19.0	7.5	4.0	0.0	0.0

Quantitative counts of empty shells of *Buldowskia,* resulted by the death of mollusks, evidenced by their extremely uneven distribution over biotopes. In particular, in the Knevichanka River, in the upper forest zone (Figs. 1b, *1*; 2a), during total fishing from the shore to a depth of 1.5 m, only 1–2 shells were collected for every 10 m of the channel, on a plain treeless area (Fig. 1b, *2;* 2b), 5–9 shells each. The very low density of bivalves in the forest zone is explained by the fact that the river bottom was covered with a dense layer of rotting leaf litter in 2021 (Fig. 2c), which has been preserved since autumn 2020. It is clear that the leaf cover of the soil is easily washed away during floods, but when the low water period is long, leaf litter remains on the ground, thereby reducing the habitat of mollusks. Downstream, outside the forest zone, there was no continuous cover of the bottom with leaf litter, which obviously ensured a higher abundance of bivalves.

The most significant retreat of *Buldowskia* was observed in the Orlovka River (Fig. 1b, *7*), where the abundance of shells turned out to be one of the highest among the studied water bodies. For example, on September 3, 2021, on a 25-m section of the channel (43°23′02″ N, 132°15′67″ E; Fig. 2d), at a river width of 7–8 m and a depth of up to 1.6–1.7 m, 56 empty shells were collected (Fig. 2e). Their length ranged from 6.3 to 9.8 cm, age, from 2.0–2.5 to 4.0 years (the age of one shell was 1 year). Empty shells of *Buldowskia,* similar in age composition, were found in the bed

Table 2. Hydrochemical characteristics of water at stations in the basin of the Razdolnaya River

Sampling site (station no.)	Coordinates, N/E	Date, time of collection	Water temperature, °C	pH	kH	NH_4, mg/L	PO_4, mg/L
Razdolnaya River, above the quarry (12a)	43°35′04″/131°53′79″	05/20/22, 11-40	21.0	8.5	3.0	0.0	0.5
Razdolnaya River, at the bridge (12b)	43°33′03″/131°53′23″	05/20/22, 16-00	20.0	8.5	3.0	0.0	0.5
Backwater nearby Razdolnoe station (14a)	43°33′46″/131°54′60″	05/20/22, 15-00	27.0	7.5	3.0	0.0	0.5
Oxbow lake nearby Razdolnoe station (15)	43°33′50″/131°54′01″	05/20/22, 14-00	22.5	7.5	4.0	0.0	0.0
Quarry near the Razdolnaya River (16)	43°34′66″/131°53′98″	05/20/22, 12-50	22.0	7.5	3.0	0.0	0.0
Channel at Kiparisovo village (18)	43°27′83″/131°55′27″	05/20/22, 10-30	21.5	6.5	3.0	0.0	0.5
Komarovka River, downstream Kondratenovka River (19)	43°38′39″/132°09′56″	29.10.21, 12-00	6.0	7.0	–	0.0	–
Ibid.	Ibid.	11/19/21, 11-00	3.0	7.0	–	0.0	–
″	″	04/29/22, 13-00	6.5	6.5–7.0	3.0	0.0	0.0
Lake Banevurovo (20)	43°43′15″/132°03′10″	06/22/22, 11-00	18.5	7.5	4.0	0.0	0.0
Komarovka River, backwater, near Raduzhnoe sport complex (21)	43°45′19″/132°02′25″	06/22/22, 12-00	21.5	7.0	2.0	0.0	0.0
Rakovka River (22)	43°53′74″/132°00′50″	29.10.21, 16-00	7.0	7.5	–	5.0	–
Ibid.	Ibid.	06/22/22, 14-00	21.5	7.0	3.0	1.0	2.0

of the Knevichanka River below Lake Krolevetskoe, while in the middle reaches of the river (upstream of Lake Krolevetskoe), the age of the collected mollusks did not exceed 2 years. All the mollusks collected upstream of Lake Krolevetskoe were identified as *Buldowskia suifunica,* while at the lower reaches of the channel, these were *B. suifunica* and *B. cylindrica.*

Another large settlement of *Buldowskia* was found in the estuarine section of the drainage canal (43º23'08" N, 132º16'04" E; Fig. 1b, *5*). During the total harvest of this biotope (10-m long, 5–6-m wide, down to 0.8-m deep) on September 15, 2021, 51 empty shells were collected, their length varied from 4.7 to 5.5 cm, age, from 2 to 3 years. Based on morphological features, all shells were identified as *Buldowskia cylindrica* [16, pl. 70].

It should be noted that numerous remains of large *Sinanodonta* shells were found in the stratum of muddy soil at a depth of about 2 m in the Knevichanka River upstream of Krolevetskoe Lake in 2021. Only the anterior part of the shell, submerged in the soil, had survived, while its posterior part washed by water had already disappeared (Fig. 2f). If we take into account the rate of shell corrosion (2 years or more), then the extinction of these mollusks could occur no later than 2019 or earlier. The finds of "fresh" empty shells of *Buldowskia suifunica* (all of them were 2-year-olds) in the same section of the channel may serve as an indirect confirmation of the time of this event. Probably, during the death of *Sinanodonta,* the death of *Buldowskia* occurred as well. The last species was able to restore its population partially by 2021, while mollusks of the genus *Sinanodonta* disappeared from the Knevichanka River, apparently already irrevocably.

Regard must be paid to the fact that representatives of *Sinanodonta* were widespread in the basin of the Knevichanka River in the past, since some fragments of the shells of these mollusks were collected in the riverbed both upstream and downstream of Lake Krolevetskoe, in drainage channels, as well as in the Orlovka River. At the same time, during the freezing period in 2021, living *Sinanodonta schrenckii likharevi* Moskvi-

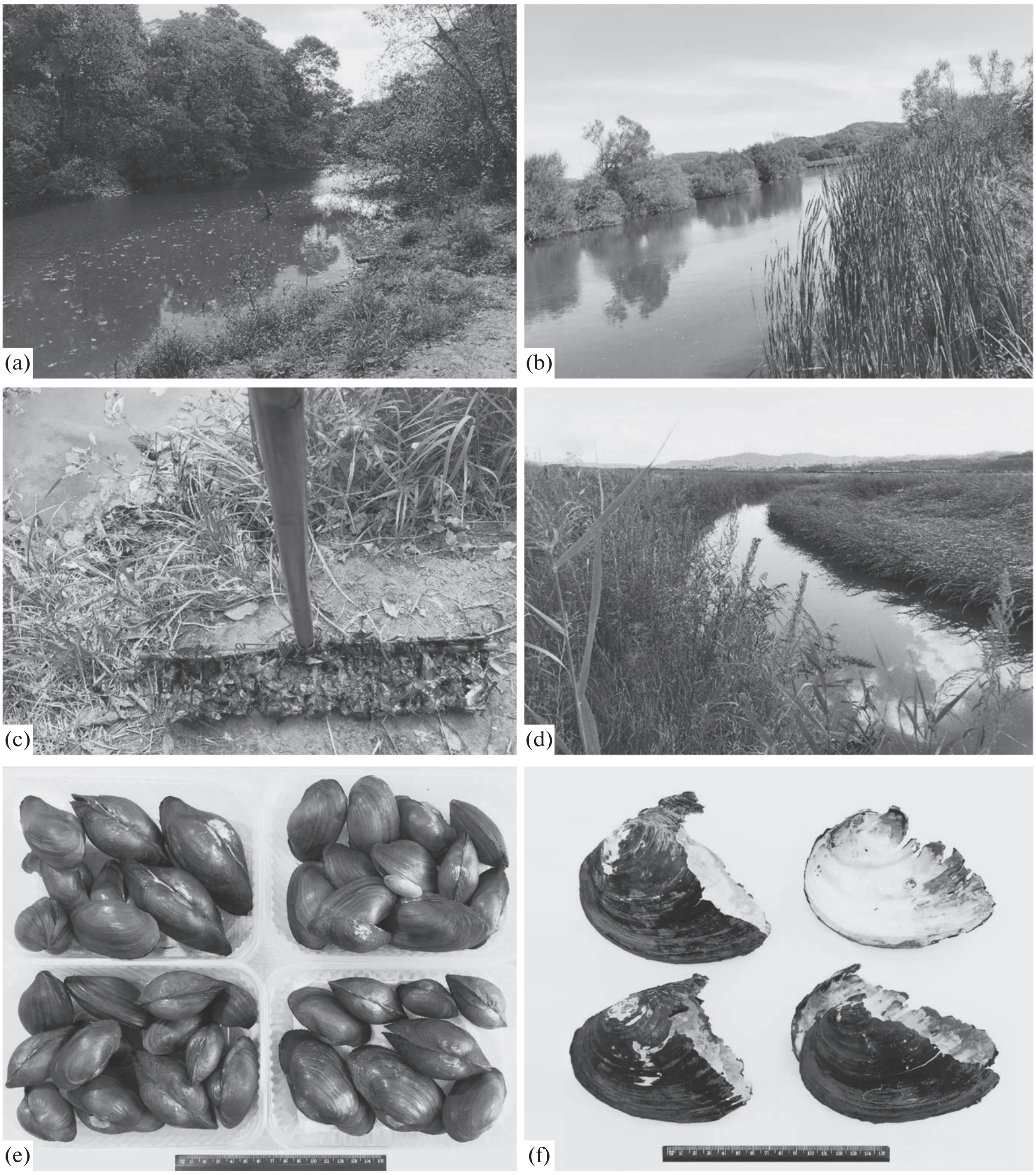

Fig. 2. Basin of the Knevichanka River: a – the Knevichanka River in the area of the forest zone (September 2021); b – the Knevichanka River at the lower reaches (August 2021); c – leaf litter collected in September 2021 from the bottom of the Knevichanka River in the forest zone from a depth of 1.5 m (the site is shown at Fig. 2a); d – the Orlovka River in the lower reaches (photo taken September 3, 2022); e – empty shells of *Buldowskia suifunica* (Lindholm, 1925), collected September 3, 2022 on the section of the Orlovka River (Fig. 2d); f – remains of *Sinanodonta* shells collected in the Knevichanka River from about 2-m depth in August 2021 (Fig. 2b).

cheva, 1973 were found in a small weakly flowing lake near Zavodskoe village (43°26′56″ N and 132°17′77″ E; Fig. 1b, *5*), connected to the Ivnyanka River by an unnamed channel flowing from the lake. This lake turned out to be a refugium for three nominative *Buldowskia* species: *B. suifunica, B. flavotincta* (Martens, 1905) [16, pl. 72, *18, 19*], and *B. fuscoviridis* (Moskvicheva, 1973) [16, tab. 73, *8–16*], which have successfully survived here, apparently, through more than one abnormally hot period. It is noteworthy that the mollusks concentrated mainly in the coastal area of the steep coast of southern exposure, where the water temperature was 2–3°C or even lower than in the shallows, the ammonium and phosphates were almost absent here (Table 1). At the same time, this lake has been cut off from the Krolevetskoe lake ecosystem for many years due to the toxic waters of the Ivnyanka River: the water in the river is polluted with waste from a poultry farm, it has an increased content of ammonium and phosphates (Table 1).

The section of the drainage canal (43°23′24″ N, 132°15′80″ E), isolated from the main channel of the Knevichanka River, turned out to be another refugia for *B. suifunica*. Here, mollusks were concentrated under the steep southern coast at a depth of 0.4–0.6 m. Shells were not found on the opposite bank of the canal. It is possible that this refugium and similar reservoirs may become sources for the restoration of *Buldowskia* settlements in the Knevichanka River in the future, in conditions of high water.

During the study period, the reservoir, located in the mountainous part of the Ivnyanka River basin and characterized by cool water (the temperature in August did not exceed 24–26°C in shallow areas), was inhabited by *Nodularia douglasiae* (Griffith et Pidgeon, 1833). This mollusk was apparently introduced into this reservoir during its stocking. No other representatives of Unionidae were found here. There were no signs of oppression of mollusks in the reservoir either.

The Razdolnaya River basin. During a survey in 2021, dense settlements of *Nodularia douglasiae,* which showed good resistance to elevated water temperatures throughout the abnormally warm growing season, were observed in the channel of the Razdolnaya River, as well as its backwaters and large pits (Fig. 1c). Mollusks were mainly concentrated under the coast near the water's edge, where they reached their maximum density (up to 150–200 ind./m^2). Currently, the state of populations of this species does not cause concern. For example, control accounting of *N. douglasiae,* carried out in May 2022 in a large quarry upstream of Razdolnoye village (Fig. 1c, *16*), has revealed a high density of bivalves in the coastal zone (about 180–200 ind./m^2 and even more). In addition, a high proportion of the mollusks of new generation was noted everywhere, amounting to 10–15% of the total number of mollusks.

The opposite pattern was observed for the state of populations of representatives of genera *Sinanodonta* and *Buldowskia*. In particular, on August 20, 2021, only empty *Sinanodonta* shells were collected in the left channel of the Razdolnaya River (Fig. 1c, *13*), at a depth of about 1.5 m, and in a large oxbow lake, opposite the Razdolnoye station (Fig. 1c, *15*), where these mollusks were collected in the early 2000s commonly. Now, only separate semi-decomposed fragments of their shells were found in the silt. In the Razdolnaya River basin, similar fragments were also found in some nameless oxbow lakes and Lake Banevurovo (Fig. 1a, *20*). Apparently, the disappearance of representatives of *Sinanodonta* from the composition of the malacofauna of the lower part of the basin of the Razdolnaya River is sustainable, which undoubtedly requires the development of special methods for their protection and reproduction in the entire South Primorsky region.

At the end of August, in the Razdolnaya River and its backwater, only a few living specimens of *Buldowskia* were found, which were extremely inactive during the sampling period, apparently, due to the high-water temperature (about 29–34°C in shallow water). In addition, single living *Buldowskia* were collected in the oxbow lake near Razdolnoe village and in some worked-out quarries connected to the river. At the same time, no living *Buldowskia* were found in the listed biotopes as early as late autumn 2021. Control sampling of mollusks at these sites in May 2022 confirmed the absence of these bivalves.

During the study, the bivalve mollusks were totally absent in the Kiparisovka River and its irrigation canal (Fig. 1c, *17, 18*). In addition, no representatives of *Middendorffinaia* were found at all sample sites nearby Razdolnoe village; the disappearance of this species from the lower reaches of the Razdolnaya River was recorded back in the 1990s. It is obvious that the reduction of the range of these pearl mussels is happening today. In particular, the mass death of *M. sujfunensis* was observed in the second half of 2021 on an extended section of the Rakovka River near Mikhailovka village (Fig. 1a, *22;* Fig. 3); the water had a putrefactive odor here in August–September, which indicated the predominance of anaerobic processes of decomposition of organic matter; in calm areas, the surface of the watercourse was covered with a community of floating duckweed *Lemna* (Fig. 3a). Empty shells of *M. sujfunensis* were distributed extremely unevenly and were mainly concentrated under the gently sloping banks on the stretches. In one of these areas along the right bank, about 5-m long (Fig. 3a), 82 empty shells of *M. sujfunensis* were found (Fig. 3b), their length ranged from 4.3 to 7.6 cm, age, from 3 to 8 years. It is important to note that live specimens of *M. sujfunensis* were not found during a thorough control examination of an approximately 50-m transect of the Rakovka River (June 22, 2022); at the same time, two live specimens of *Buldowskia suifunica* (3 years old, 4.2- and 4.6-cm long) were collected.

Attention is drawn to the fact that a *Middendorffinaia mongolica* population living in the middle semi-mountainous section of the Komarovka River (Fig. 1a, *19*), characterized by a gravel-pebble bottom with boulders, had no signs of oppression; the water temperature in the river in summer did not exceed 22–25°C, pH = 7.5, and ammonium nitrogen was absent, in contrast to the plain rivers (Table 2). Here, in the deep section of the rift (about 2-m deep), 12 living

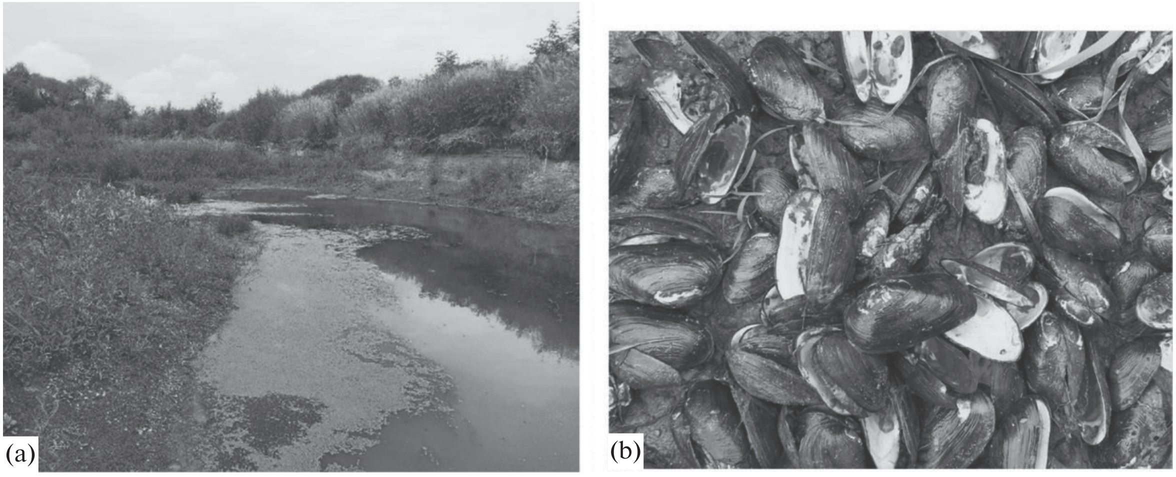

Fig. 3. The Rakovka River (Razdolnaya River basin, south of Primorsky Krai): a – river in the middle course in September 2021 (a community of a floating plant of duckweed *Lemna* is visible in the coastal area); b – empty shells of *Middendorffinaia mongolica* (Middendorff, 1851) collected in the Rakovka River in June 2022 (the site is shown on the left photo).

specimens of *Dahurinaia dahurica* were recorded. Apparently, the outflow of cold under-stream waters contributed to the safety of these mollusks in the conditions of the hot season. At the same time, due to the larvae of caddis flies *Stenopsyche marmorata* Navas, 1920 that developed under low water conditions, shells of most live mollusks *M. mongolica* were used by larvae to fasten their trapping nets, so the bivalves were immobilized, which caused increased mortality of mollusks in winter [18].

The populations of *M. sujfunensis* and *B. suifunica* were in a relatively good state in the backwater of the Komarovka River (silty sediments) near the Raduzhny sports complex (Fig. 1a, *21*). At the time of sampling, the water temperature in the backwater was 25–27°C, while *M. sujfunensis* concentrated at a depth of more than 0.7 m in the area of thickets of water chestnut *Trapa natans* (L., 1758), whose leaves blocked the penetration of sunlight into water, and *B. suifunica,* in open areas at a depth of 0.1–0.5 m. A re-examination of the biotope in June of 2021 confirmed the presence of live mollusks, including juveniles of *M. sujfunensis* generation of 2021.

DISCUSSION

In the summer period of 2021, under the conditions of a long-lasting low water content, the water in the studied reservoirs warmed up to extremely high values by the end of July, amounting to 28–30°C in the riverbed, and exceeding 32–35°C in shallow waters, and unusually high-water temperatures continued to be observed in the region through September. In particular, on September 3, the water temperature in the Orlovka River in the daytime was 28°C, on September 15, 22°C. At the lower reaches of the Knevichanka River, on September 9 in the daytime, the water temperature in the coastal zone was 24–26°C, on September 15, about 21–22°C, and on October 8, about 14°C.

In August 2021, a mass death of large bivalve mollusks from the genera *Middendorffinaia, Buldowskia,* and *Sinanodonta* was noted in the lowland rivers of the region*,* obviously due to the high-water temperature. A subsequent hydrochemical survey of water bodies (Tables 1, 2) evidenced that in some cases, the death of mollusks was facilitated by pollution of watercourses with organic substances, including from the treatment facilities of Artyom. In general, in the channels of the Knevichanka and Rakovka rivers, an increased content of ammonium nitrogen in the water (NH_4, 5–10 mg/L) was found everywhere, while the water pH during this period ranged from 7.5 to 8.5. It should be noted that ammonium itself is not toxic; however, at an elevated pH level (above 7.0), this ion transforms into ammonia (NH_3), which is a highly toxic substance. This undoubtedly contributes to increased mortality of aquatic organisms. At the same time, ammonium nitrogen was not detected (for example, in Orlovka River and reservoirs in the vicinity of Razdolnoe village); however, a total death of bivalves also occurred here, which confirmed the role of temperature as the leading factor that caused the death of aquatic organisms.

It is necessary to pay attention to the fact that there was no mass development of algae in the water column during the hot summer in the surveyed reservoirs. At the same time, algobacterial film had formed on the water surface (for example, on the plain section of the Knevichanka River near Knevichi village and in Lake Orlovskoe) in August–October (Fig. 4a, b); such a film usually forms at low water exchange and high temperature [19]. When examining a film from the Knevichanka River, ten species of diatoms, euglenoids, and protococcal algae were identified, of which

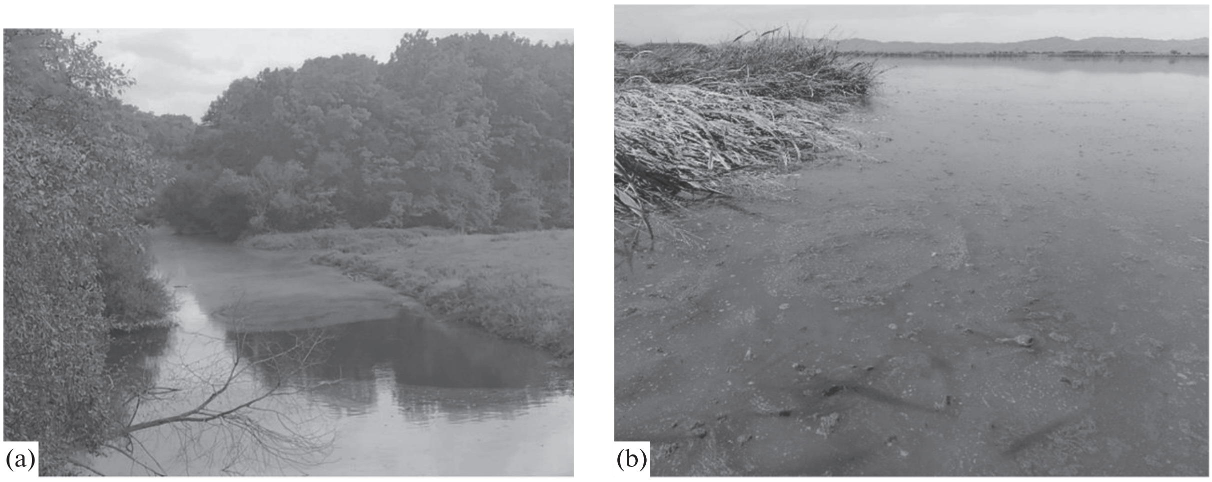

Fig. 4. Algobacterial film: a – the Knevichanka River (forest zone, photo taken September 10, 2021); b – Lake Orlovskoe, (photo taken October 8, 2021).

seven species belonged to the Protozoa division (class Euglenophyceae). Two species, diatom *Nitzschia palea* (Kützing) W. Smith (indifferent to salinity and pH, alpha-beta meso-saprobe) and *Trachelomonas planctonica* Swirenko (indifferent to salinity and pH, beta-oligo-meso-saprobe) dominated in the algal community. In addition, a mass accumulation of bacteria was found in the film (chain-shaped colonies, presumably streptococci), and branching mycelia of actinomycetes (heterogeneous group of Gram-positive bacteria). The ecological characteristics of the algobacterial film were predetermined by algae indifferent to salinity and pH of the environment (with the exception of mesohalobic *Euglena viridis* Ehrenberg), while the saprobic characteristics of algae changed from beta-oligo-meso-saprobic to poly-saprobic.

In Lake Orlovskoe, ten species of algae were identified as well in a film; three diatom species dominated: *Navicula* sp. (with unknown ecological characteristics), *Nitzschia palea* (indifferent to salinity and pH, alpha-beta meso-saprobe), and *Tryblionella acuminata* W. Smith (mesohalobe, alkaliphile, beta-poly-saprobe). The ecological characteristics of the algobacterial film were predetermined by algae, mesohalobic, and salinity-indifferent species, alkaliphilic and indifferent to the active reaction of the environment, with various saprobic characteristics, from oligo-xeno-saprobe to beta-poly-saprobe. In addition to algae, the laboratory processing of the material revealed the presence of "flakes" of organic origin, colored brown, dark brown, and black.

At present, it is difficult to interpret the obtained data via direct impact of the algobacterial film on the hydrobiological regime of water bodies. At the same time, the very fact of film formation with a predominance of eurybiont algae on the water surface indicates an unfavorable hydroecological regime of watercourses or stagnant water bodies, which may be accompanied by negative consequences for the life of many hydrobionts.

It should also be noted that in the lowland rivers of the region, under conditions of extremely weak flow, mass development of the floating duckweed *Lemna* sp. was observed in calm areas (Fig. 3a). Moreover, in small stagnant water bodies, duckweed completely covered the water surface during this period, blocking the sunlight necessary for the development of algae. It is obvious that the presence of developed communities of duckweed in river systems indicates an ongoing dry season, which seems to be an extremely rare case under monsoon climate conditions. Apparently, this phenomenon may adversely affect the vital activity of rheophilic organisms. In particular, in the Rakovka River, main accumulations of shells of dead *Middendorffinaia* were confined to the calm areas covered with duckweed.

When assessing the factors associated with the mortality of mollusks in rivers flowing into marine systems, it is necessary to take into account the possibility of penetration of saline sea waters into the habitat zone of freshwater Unionidae at extremely low water content. As the temperature and salinity of water increase, the concentration of oxygen decreases rapidly. In particular, the penetration of saline waters of the Ussuri Bay of the Sea of Japan into the lower reaches of the Knevichanka River is indicated by the finds of shells of brackish-water basket clams of genus *Corbicula* (up to about 12 km upstream of the mouth of the Artemovka River), as well as barnacle shells (*Balanus* spp., suborder Balanomorpha), found on the valves of *Buldowskia cylindrica,* collected in the drainage channel of the Knevichanka River [16, pl. 70, *14–18*], which is located 9 km upstream of the Artemovka River mouth.

It is indicative that there was no death of freshwater mollusks in the foothill areas of river ecosystems, where the temperature regime was not extremely high and where no ammonium nitrogen in the water was registered. For example, on the foothills of the Komarovka River, where the flow was steady (about 0.3–0.8 m/s), rheophilic *Middendorffinaia mongolica* had no signs of oppression. In addition, in the area of the settlement of the Dahurian pearl mussel *Margaritifera dahurica,* outcrops of cold groundwater were recorded, which undoubtedly contributed to the survival of mollusks not only in the hot summer season, but also in winter, protecting these biotopes from freezing. It is also important that live mollusks were found in areas of floodplain reservoirs closed from direct sunlight at the end of the abnormally hot season, in particular, in the backwater of the Komarovka River, Lake Banevurovo, an oxbow lake of the Knevichanka River, the lake on the Ivnyanka River near Zavodskoy village (basin of the Knevichanka River), etc.

Our data allow us to state that there were several periods of local extinctions of large bivalve mollusks in the last past 2–3 decades in the south of the Primorsky Krai, as evidenced by the current state of the populations of these bivalves in water bodies and streams compared to the period of the 1980s. In particular, over the past 30 years or so, bivalve mollusks have completely disappeared from the Kiparisovka River and from the associated irrigation canal. In addition, mollusks from the genera *Middendorffinaia* and *Sinanodonta* disappeared in this period from the lower reaches of the Razdolnaya River and its oxbow lakes, although these groups of bivalves dominated here in the 1980s and the first half of the 1990s. A death of *Sinanodonta* was recorded in the lower reaches of the Knevichanka River about 3–4 years ago. Representatives of the genus *Buldowskia* have sharply reduced their numbers everywhere. In the oligotrophic streams, the population of the Dahurian pearl mussel *Margaritifera dahurica* disappeared in the early 2000s from the upper reaches of the Komarovka River, while in the middle semi-mountainous section of this river a small settlement has still been preserved, numbering several dozen individuals.

Apparently, the previous cases of the disappearance of mollusks from aquatic ecosystems in the south of the Far East could be caused by local pollution of the aquatic environment by the waste of the agroindustrial complex, runoff from the sand pits developed in the floodplain of the Razdolnaya River, and industrial discharges or transboundary pollution. At the same time, the mass death of mollusks that occurred in the summer–autumn season of 2021 is the first recorded case of mollusk death in the Russian Far East, caused exclusively by climatic factors, enhanced by anthropogenic pollution in certain water bodies.

It should be noted that in other regions of the Russian Federation, there has also been a decrease in the number of bivalve mollusks in recent decades, mainly due to pollution of surface waters or due to the reduction of suitable habitats. For example, the range of the European pearl mussel *Margaritifera margaritifera* (L., 1758) has decreased significantly [20]. Alongside with that, warm-water genus *Sinanodonta* has penetrated into the water bodies of Western Europe, European Russia, and Siberia from the southern regions of Asia after 2010 [21, 22]. In recent years, *Dreissena polymorpha* (Pallas, 1771) has successfully invaded the water bodies of Western Siberia (Pyshma River) [23], this causes deep concern, since this species may adversely affect the operation of hydraulic structures in the Ob-Irtysh basin.

Taking into account the ongoing heating of the northern part of the Eurasian continent [24], the mass extinction of large bivalve mollusks, at least in the boreal region of the globe, will undoubtedly continue, as well as a significant shift in the ranges of warm-water mollusk species to the north. The dramatic decline in populations of large Bivalvia observed in different regions of the world has made these invertebrates one of the most endangered taxonomic groups worldwide. The findings clearly show that the application of an integrated approach that combines conservation measures with actions aimed at eliminating the causes of habitat changes (such as reducing freshwater pollution, including the entry of pollutants from the catchment with surface runoff, and protecting floodplain water bodies as potential refugia for Unionidae and other hydrobionts) will help to maintain and possibly restore the biodiversity of freshwater mollusks. In some cases, it is necessary to apply more stringent measures for the protection and restoration of water bodies, which would take into account not only pollution of water bodies, but also climate change [25].

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COMPLIANCE WITH ETHICAL STANDARDS

All applicable ethical standards were followed when working with live mollusks.

Conflict of Interest

The authors declare that they do not have a conflict of interest.

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SPELL: OK