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Article

Long-term Changes of Growth Rates and Shell Bioerosion of the Japanese Scallop related to Tumen River Discharge

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Abstract : The purpose of this study was to determine changes in the growth rates and the degree of shell bioerosion exhibited by endolithic organisms of the Japanese scallop family, *Patinopecten* (*Mizuhopecten*) *yessoensis*, on the coast of Furugelm Island (Peter the Great Bay, northwest of East Sea = Sea of Japan) over the last three decades. The areas studied are affected by Tumen (Tumangang) River run-off, which is enriched by organic matter and polluting agents. It was found that the linear growth rates of the Japanese scallops living along the coasts of Furugelm Island have decreased over the last three decades. The degree of bioerosion of scallop shells has significantly increased for the same period. These phenomena may be explained by a gradual increase in bottom sediment silting, organic enrichment and pollution of the areas being studied. It was found that the degree of scallop shell bioerosion increased with the scallop's age. At present, in each age group, the shells of the scallops sampled from the muddy sand showed greater erosion than the shells of individuals collected from the sandy substrate.

Key words : bioerosion, ecology, organic pollution, scallops, sediment.

1. Introduction

Organic enrichment of sediments in coastal areas is increasing worldwide (Rosenberg 1985; Nixon 1995). The main source of both particulate and dissolved organic loads, as well as fine-grained mineral particles in shallow waters is river silt deposits. One of the largest rivers on the west coast of the East Sea (= Sea of Japan) is the Tumen (= Tumangang) River, whose drainage basin is situated in China, North Korea and Russia (Fig. 1). Its waters are enriched by organic matter and polluting agents (Prozorova and Kavun 1999) due to the presence of industrial plants (Korean chemical plant and Chinese carton factory) and agricultural farms on its banks. The river water is discharged into the sea between Russia and Korea. The coastal water currents at the river estuary transport the pollutants from the river to the Korean coast in the winter and to the Russian coast, including Posyet Bay and the territory of the Russian State Marine Reserve in the summer (Vyshkvartsev and Lebedev 1997; Grigorjeva and Moshchenko 1998). Previous studies have demonstrated that in Posyet Bay, at a depth of up to 25 m, the number and biomass of many benthic species had decreased for 1956-1983, and the predominant species had changed in this bay due to siltation of sediment (Golikov *et al.* 1986). It was shown that the main source of organic matter and contaminants in the area studied results from Tumen River run-off (Moshchenko *et al.* 2001; Shulkin *et al.* 2001; Vanin *et al.* 2000). The direct effect of the Tumen River discharge on the chemical composition of the coastal waters has been established for dissolved copper, the concentration of which is elevated along the seacoast and in the sea waters to the north of the river mouth (Tkalin 1999). In the area situated north of Tumen River mouth, contamination of the bottom sediments by organic carbon, heavy metals, organochlorine pesticides (DDT and hexachlorcyclohexane, HCH) and hydrocarbons is determined by the dissipation of the river aleuro-pelite material (Shulkin *et al.* 2001).

The major part of polluting river effluent and organic matter settles and is accumulated in bottom sediments.

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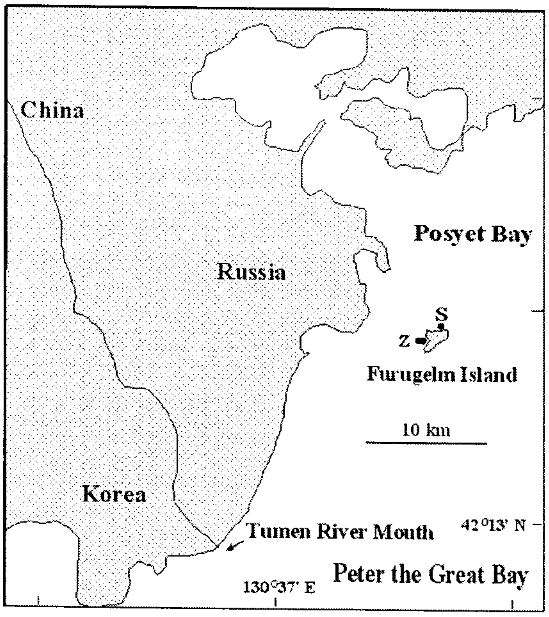

Fig. 1. Schematic map of the sampling sites near Furugelm Island in Peter the Great Bay (East Sea = Sea of Japan). Z is Zapadnaya Bight and S is Severnaya Bight.

Therefore, the most serious ecological consequences of the gradual organic enrichment and pollution of adjacent areas to the river mouth should probably be expected in the biotope on benthos. It was fair to choose the benthic commercial Japanese scallop, *Patinopecten* (*Mizuhopecten*) *yessoensis* (Jay, 1956), as the main focus of this study. Usually, it is difficult to understand is what is to be considered "normal" for the population studied in a single survey, especially when the changes in environment are slow. Consequently, only long-term monitoring carried out over a number of years may help to identify the quality changes in the populations caused by natural impacts (Meyer-Reil and Köster 2000).

The most intensive sedimentation (mud accumulation) is discovered in the bottom depression to the west of Furugelm Island (Moshchenko *et al.* 2001; Vanin *et al.* 2000) in the study area. Due to protection of this depression by a stony submarine ridge (depths <20 m), situated northwest of Furugelm Island and joining the northwest part of the island with the mainland (continent), it is possible to see a gradual accumulation of the polluting aleurite-pelite fractions originating from run-off in the bottom sediment of the depression and surrounding area (Ozolinsh and Klimova 1991). All these events gradually alter the environment near Furugelm Island and may affect the benthic Japanese scallop populations. Moreover, the river run-off influence is found on Zapadnaya Bight, which is situated to the west of this island, as opposed to Severnaya Bight found to the north of the island and somewhat separated from the zone of the main river's influence by a stony submarine ridge. Therefore, the two populations of Japanese scallops living in Zapadnaya and Severnaya Bights were compared.

The external surface of the upper (left) valve of the Japanese scallop bears a thin microsculpture with detectable daily and weekly growth layers, and their width and appearance change seasonally (Silina 1978, 1995, 1996). This peculiarity allowed us to determine the age of each specimen studied and reconstruct its linear growth rate in retrospect. This method affords us an opportunity to investigate the long-term growth of wild scallops in the natural environment. Therefore, the purpose of the present study is to determine changes in the scallop growth rates, the degree of scallop shell bioerosion by endolithic organisms in the Japanese scallop populations inhabiting Zapadnaya and Severnaya Bights of Furugelm Island (Peter the Great Bay, northwest of the East Sea = Sea of Japan) over the last three decades.

2. Materials and methods

Study area and sample collection

The Japanese scallops were sampled by SCUBA diving from muddy sand (depth 12-15 m) in Zapadnaya Bight (in 1974, 1976, 1980, 1981, 1998, 2000 and 2001) and from sand (depth 10-12 m) in Severnaya Bight (in 1976, 1979, 1980, 1981, 1995, 1996, 1998, 1999 and 2001) of Furugelm Island, which is located about 20 km north of the mouth of the Tumen River (Fig. 1). Additionally, in 1998 at Zapadnaya Bight, Japanese scallops were collected from sand (depth 6-8 m) for comparison of the growth rates and shell bioerosion of individuals inhabiting different bottom sediments. Each sample contained 50-150 scallops.

The studied sites of Zapadnaya Bight differ only slightly in terms of temperature and salinity. In 1996-1999, near the bottom, the water temperature ranged from −1.3 to 19.3°C and from −1.2 to 18.7°C at a depth of 6-8 and 12-15 m, respectively (Moshchenko *et al.*, 2001; authors' data). Annual variations of water salinity were from 32.7 to 33.6 $g.kg^{-1}$ and from 33.0 to 33.8 $g.kg^{-1}$ at a depth of 6-8 and 12-15 m, respectively. In Severnaya Bight, near the bottom at the study site the water temperature was slightly lower in summer (< 17.8 °C) than at the study sites in Zapadnaya Bight. Water salinity ranged from 32.8 to 33.7 $g.kg^{-1}$ at a depth of 10-12 m in

Severnaya Bight over the course of the year (Grigorjeva 2001; Moshchenko *et al.*, 2001; authors' data). In studying the open area near Furugelm Island, the direction and velocity of the water current caused by wave and tidal action varied significantly, from 10-15 to 50-60 $cm.s^{-1}$ in the water column to a 0-15 m depth (Vanin *et al.*, 2000; Moshchenko *et al.*, 2001). A density of phytoplankton was less than 250,000 $cells.l^{-1}$, with diatoms being dominant (over 80% of total phytoplankton density). The abundance and species composition of phytoplankton have practically shown no change in the study area over the last decades (Konovalova 1979; Orlova *et al.*, 2001).

In 1998, for grain-size analysis, the bottom sediments were excavated by five pans in the 0.09 m^2 (each) to a depth of 0-2 cm at different places of the bights. All sediment samples were dry-sieved through 0.1, 0.25, 0.5, 1.0, 5.0, 7.0 and 10.0 mm mesh screens. Particle-size distribution for sediment samples was expressed as % particle dry weight within each size category.

Measurement of growth rates and shell bioerosion

The age and individual linear growth of each scallop during its lifetime was determined retrospectively from daily and weekly growth layers in the microsculpture of the external surface of the upper valve according to the method suggested earlier by Silina (1978).

The area of each scallop valve, which was occupied by endolithic organisms (with boreholes on the outer surface) and of a dark brown color, was determined in transmitted light, from the inner side of the valve, using a transparent palette with a 1 × 1 mm grid. The degree of bioerosion of the scallop valve was calculated as %-proportion of this area to all valve areas. The degrees of shell bioerosion were compared for scallops sampled at Zapadnaya Bight between 1974-1976 and in 1998, and at Severnaya Bight in 1979 and 1998. The comparison of the degrees of shell bioerosion for scallops from different bottom sediment types were carried out at Zapadnaya Bight in 1998.

Statistics

Prior to the statistical analysis, all data were tested for normality of variance among the different groups by using a Kolmogorov-Smirnov test. A two-way ANOVA (the year of scallop sampling and scallop age determination, with independent parameters) was used to test the mean values of the shell heights. A t-test was conducted to identify significant differences between both the mean values of the shell heights and the mean values of the degrees of shell bioerosion (for the age of each scallop) for different pairs of years for the survey. The significance criterion was $P < 0.05$.

Linear regressions for the degree of bioerosion of the upper valve on shell height were calculated for 9-year-old (as the most numerous age class everywhere) scallops inhabiting Zapadnaya and Severnaya Bights. The significance criterion for coefficients of correlation was $P < 0.01$.

3. Results

It was found that during all periods of observation, the linear growth rates of Japanese scallops living near the coasts of Furugelm Island were high for the species in comparison to the scallop populations inhabiting other places of Peter the Great Bay (Silina and Pozdnyakova 1986; Silina 1990). However, they have declined slightly over the last three decades (Tables 1 and 2). A two-way ANOVA test has revealed significant differences ($F = 30.5$, $df = 3$, $P < 0.01$) between scallop growth rates in different years of sampling. From the t-test, significant differences

Table 1. Changes of the linear growth rates of the Japanese scallop, *Patinopecten (Mizuhopecten) yessoensis,* at the depths of 12-15 m in Zapadnaya Bight of Furugelm Island (Peter the Great Bay, Sea of Japan = East Sea) during 27 years.

Age (years)	Shell height (mean ± s.e.), mm			
	1974, 1976	1980, 1981	1998	2000, 2001
1	52.3 ± 0.4	52.8 ± 0.4	52.0 ± 0.3	52.1 ± 0.4
2	102.3 ± 0.5	102.6 ± 0.4	101.4 ± 0.4	100.7 ± 0.4
3	127.2 ± 0.5	127.1 ± 0.4	126.9 ± 0.5	125.9 ± 0.5
4	143.3 ± 0.6	143.0 ± 0.5	142.6 ± 0.6	141.7 ± 0.5
5	153.7 ± 0.5	153.6 ± 0.7	152.5 ± 0.6	151.0 ± 0.6
6	159.8 ± 0.6	159.1 ± 0.8	157.1 ± 0.6	155.7 ± 0.6
7	161.5 ± 0.7	160.3 ± 0.7	158.2 ± 0.6	157.8 ± 0.7

Table 2. Changes of the linear growth rates of the Japanese scallop, *Patinopecten (Mizuhopecten) yessoensis,* at the depths of 10-12 m in Severnaya Bight of Furugelm Island (Peter the Great Bay, Sea of Japan = East Sea) during 23 years.

Age (years)	Shell height (mean ± s.e.), mm			
	1979-1981	1995	1998	1999, 2001
1	52.0 ± 0.4	51.5 ± 0.3	51.6 ± 0.4	51.4 ± 0.4
2	99.8 ± 0.5	97.1 ± 0.4	95.5 ± 0.4	95.3 ± 0.5
3	124.3 ± 0.6	119.4 ± 0.4	119.3 ± 0.5	118.8 ± 0.4
4	140.9 ± 0.7	138.9 ± 0.5	139.3 ± 0.4	137.9 ± 0.6
5	151.0 ± 0.7	149.3 ± 0.4	149.1 ± 0.7	148.5 ± 0.5
6	157.3 ± 0.8	155.5 ± 0.4	155.1 ± 0.7	153.2 ± 0.7
7	160.1 ± 0.8	157.7 ± 0.5	156.9 ± 0.7	155.2 ± 0.7

for the mean values of the shell heights were observed only in scallops sampled at Zapadnaya Bight between 1974-1976 and 2000-2001, and in scallops sampled at Severnaya Bight between 1979-1981 and 1999-2001 (pairs for each age group, $P < 0.01$). These differences were achieved during the first two years of scallop life; further, the differences did not increase (compare Tables 1 and 2 for respective years of sampling).

The results showed that for last three decades, the degree of bioerosion in scallop shells has considerably increased (Table 3 and 4). It was found that the degree of bioerosion of the upper valves rose significantly as the age of scallops increased. Significant statistical differences were revealed between scallop samples taken at Zapadnaya Bight between 1974-1976 and in 1998 from the same bottom sediment types and compared by t-test for each scallop age group separately. In terms of population, the lower valves of the scallops were eroded at an average of 0.1 ± 0.0% and 3.6 ± 0.3% between 1974-1976 and 1998, respectively. Similarly, significant statistical differences were found between the scallops sampled from sand at Severnaya Bight in 1979 and 1998. At Severnaya Bight, the lower valves of the scallops were eroded at an average of 0.0 ± 0.0% and 0.1 ± 0.0% in 1979 and 1998, respectively. The degree of shell bioerosion was obviously higher for scallops sampled at Zapadnaya Bight than it was for Severnaya Bight, both at the beginning and at the end of the study period (compare Tables 3 and 4 for each scallop age group). A paired t-test (for each scallop age group) revealed significant statistical differences between the mean values of the degrees of shell bioerosion of scallops sampled from

Table 3. Changes of the degree of the bioerosion of the upper valves of the different aged Japanese scallop, *Patinopecten (Mizuhopecten) yessoensis*, at the various bottom sediment types in Zapadnaya Bight of Furugelm Island (Peter the Great Bay, Sea of Japan = East Sea) for 25 years. Note: Scallops at some ages are absent in the samples.

Age (years)	Portion of the upper valve area eroded by endolithic organisms (mean ± s.e.), %		
	1974, 1976	1998	1998
	Muddy sand, 12-15 m depth	Sand, 6-8 m depth	Muddy sand, 12-15 m depth
1	-	-	0.6 ± 0.2
2	-	-	3.5 ± 0.8
3	4.9 ± 0.8	-	9.0 ± 0.9
4	6.5 ± 1.0	9.7 ± 0.9	15.4 ± 1.1
5	10.4 ± 1.2	19.9 ± 1.0	25.1 ± 1.2
6	14.8 ± 1.5	27.2 ± 1.2	35.2 ± 1.2
7	20.1 ± 1.7	36.4 ± 1.4	48.2 ± 1.4

Table 4. Changes of the degree of the bioerosion of the upper valves of the different aged Japanese scallop, *Patinopecten (Mizuhopecten) yessoensis*, living on the sand at the depth of 10-12 m in Severnaya Bight of Furugelm Island (Peter the Great Bay, Sea of Japan = East Sea) for 20 years. Note: Scallops at some ages are absent in the samples.

Age (years)	Portion of the upper valve area eroded by endolithic organisms (mean ± s.e.), %	
	1979	1998
1	0.0 ± 0.0	-
2	0.0 ± 0.0	0.7 ± 0.2
3	0.1 ± 0.0	1.8 ± 0.3
4	0.3 ± 0.1	6.6 ± 0.7
5	1.0 ± 0.2	14.5 ± 1.0
6	-	23.2 ± 1.2
7	-	30.4 ± 1.4

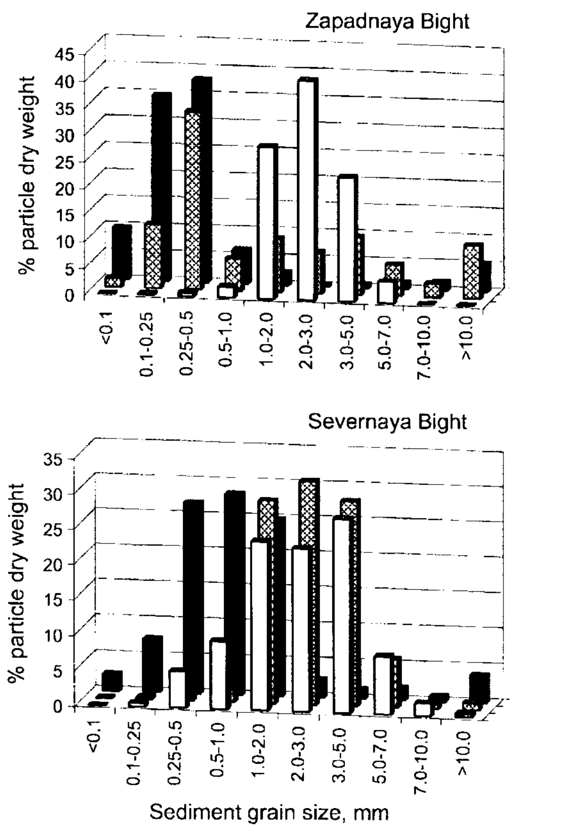

Fig. 2. The bottom sediment composition at the different depths in Zapadnaya and Severnaya Bights of Furugelm Island (Peter the Great Bay, East Sea = Sea of Japan) in 1998.

similar bottom types at Zapadnaya and Severnaya Bights in 1998.

In 1998, it was revealed that the content of fine-grained fractions increased, and the content of coarse-grained particles decreased in the bottom sediments with the increase in the depth of bights (Fig. 2). The isobaths were practically parallel with the coastlines in both bights. In Zapadnaya Bight, the scallop collection site that was situated at a depth of 12-15 m was muddier than other study sites placed at a depth of 6-8 m. The bottom sediment composition was less variable in Severnaya Bight than in Zapadnaya Bight. In Severnaya Bight, the bottom sediments contained sand particles only 0.1-5.0 mm in diameter (Fig. 2). In Zapadnaya Bight, the scallop growth rates were slightly (by 1-2 mm) slower for scallops inhabiting the site with bottom sediments contained about of 10% of muddy particles <0.1 mm (Fig. 2, depth of 12-15 m), than those in which scallops were living on sand at a depth of 6-8 m. At the same time, there was no significant statistical difference (t-test for each scallop age group, $P = 0.10$-0.06) in the mean values of the shell heights of the scallops living at a depth of 6-8 and 12-15 m. However, from a two-way ANOVA test ($F = 87.5$, $df = 1$, $P < 0.0001$) and t-test (for each scallop age group, $P < 0.001$) significant differences were observed in the degree of shell bioerosion among the scallops living on sand and on muddy sand at Zapadnaya Bight. In each age group, the shells of the scallops sampled from muddy sand were more eroded than the shells of the scallops collected from the sand (Table 3, columns of 1998).

A linear regression for the degree of bioerosion of the upper valve on the scallop shell height revealed the statistical significance of this relationship. It was found that shell bioerosion adversely affects the growth of the scallops inhabiting both sand and muddy sand (Fig. 3).

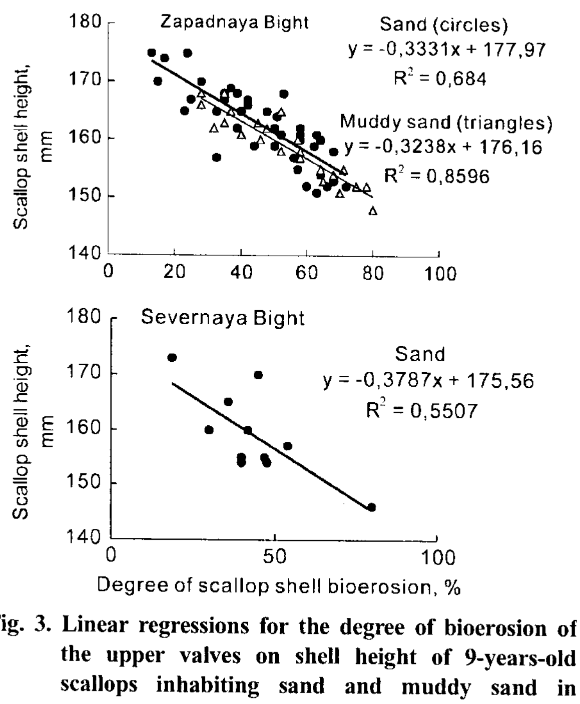

Fig. 3. Linear regressions for the degree of bioerosion of the upper valves on shell height of 9-years-old scallops inhabiting sand and muddy sand in Zapadnaya Bight and sand in Severnaya Bight (Peter the Great Bay, East Sea = Sea of Japan).

4. Discussion

It is difficult to blame any particular cause that resulted in gradual reduction of the scallop growth rates during the period of this study. Although the data for the grain-size and chemical composition of bottom sediments in 1974-1995 in the bights studied are absent in the literature, previous investigations have demonstrated that the main source of the bottom sediments in the area studied is a result of solid discharge from the Tumen River (Vanin *et al.* 2000). According to the data of the Chinese scientists, the main polluting agent in Tumen River water is organic matter (Zhu *et al.* 1998). The mean accumulation rate of sediments in the river is 3 $cm.year^{-1}$, and annual river discharge is about 5.7 km^3. Therefore, it is reasonable to suggest that permanent river run-off leads to gradual sediment siltation, organic enrichment and pollution of the bottom sediments in the study area, situated in the vicinity of the river mouth. Earlier, it was shown that the great amount of organic matter in the bottom sediments had a negative impact on the growth rates of the Japanese scallop (Silina and Ovsyannikova 1995).

Scallop growth rates have declined, but the degree of shell bioerosion has increased over the last three decades. A possible explanation for this development of scallop shell endolithic organisms is the fact that an increased organic content in bottom sediment is advantageous for the growth of bacteria, which improves food potential for detritus feeding polychaete worms of the *Polydora* genus (Fauchald and Jamars 1979; Zhukova and Radashevsky 1995), which constitute the bulk of endolithic organisms burrowed in the shells of the scallop species studied (Sato-Okoshi and Nomura 1990). In 1998, total organic carbon was about 3 and 15 $mg.g^{-1}$ of dried weight for sand and muddy sand sediments, respectively, in Zapadnaya Bight; and about 1 $mg.g^{-1}$ of dried weight for sand sediments, in Severnaya Bight, where the river discharge impact on the bottom sediment composition weakened considerably (Vanin *et al.* 2000; Moshchenko *et al.* 2001; Shulkin *et al.*

2001). Therefore, the degree of scallop shell bioerosion is lower for populations living at Severnaya Bight than for populations inhabiting Zapadnaya Bight, and in Zapadnaya Bight, the shells of the scallops living on muddy sand showed greater erosion than shells of individuals found in sand.

The discovery that shell bioerosion adversely affects the growth of scallops and that there was an increase in the degree of shell bioerosion over the last three decades can explain one of the reasons for the decrease in scallop growth in the study area for this period. Another possible reason for scallop growth reduction is the gradual increase of complex (heavy metals and organic toxicants such as hexachlorocyclohexane isomers, DDT and others) pollutants in the area situated north of the Tumen River mouth (Tkalin 1999; Shulkin 2001; Shulkin *et al.* 2001).

It is necessary to expect a further increase of bioerosion in scallop shells and a gradual reduction in scallop growth rates due to permanent river run-off and, additionally, the presence of the bottom depression between Furugelm Island and the mainland (continent) at the area studied, where there is a gradual accumulation of fine-grained particles enriched by organic matter and polluted contaminants. An amplification of economic activity in the river drainage basin, for example, as a result of economic development of the area of the Tumen River (TREDA, Tumen River Economic Development Area), will result in the deterioration of the state of the Japanese scallop populations living in vicinity of the river mouth. According to this project, one of the largest transportation junctions is to be created in the river basin. The realization of this project will entail an increasing flow of anthropogenic pollutants to adjacent areas of Russia and Korea. Therefore, this study is a necessary step in investigating the possible consequences of the realization of such large-scale economic projects as TREDA. Besides, the Japanese scallop is a harvested and cultivated species in the area studied. The findings of this study suggest that it is reasonable to expect that the environment in the area adjacent to the Tumen River mouth will become increasingly less favourable for the scallop populations, especially at sites nearby the bottom depression. This event is particularly important in managing the ground cultivation of such commercial scallop species as the Japanese scallop in the area studied.

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