УДК 504.422:57.047

© *Е. В. Волощук*[1,2], *А. А. Максимов*[3]
[1]Санкт-Петербургский филиал Института океанологии им. П. П. Ширшова РАН
[2]Российский государственный гидрометеорологический университет, г. Санкт-Петербург
[3]Зоологический институт РАН, г. Санкт-Петербург
ketrin492006@mail.ru

ОЦЕНКА ВЛИЯНИЯ БИОТУРБАЦИОННОЙ АКТИВНОСТИ ПОЛИХЕТ *MARENZELLERIA ARCTIA* НА СОДЕРЖАНИЕ ВЕЩЕСТВ В ДОННЫХ ОТЛОЖЕНИЯХ ВОСТОЧНОЙ ЧАСТИ ФИНСКОГО ЗАЛИВА

Статья поступила в редакцию 07.03.2017, после доработки 11.05.2017.

Бентосные организмы способны оказывать значительное влияние на геохимические процессы в донных отложениях за счет выкапывания нор и туннелей, которые затем разрушаются или засыпаются, поглощения и экскреции отложений, вспахивания поверхностных грунтов и т. д. В работе исследуется влияние биотурбационной активности видов-вселенцев полихет *Marenzelleria arctia* на содержание органического углерода, валовое содержание железа и марганца в твердой фазе донных отложений в восточной части Финского залива. Содержание химических соединений в донных отложениях, а также численность и биомасса полихет были получены в ходе экспедиции РГГМУ в июле 2016 г. Применение методов статистического анализа позволило выявить закономерности распределения химических веществ в условиях различной численности полихет. Было установлено, что на станциях с более высокой плотностью поселения полихет наблюдается более низкое содержание органического вещества, железа и марганца твердой фазы донных отложений. Напротив, на станциях с низкой численностью червей, содержание этих веществ выше. Можно заключить, что биотурбационная деятельность полихет способствует увеличению минерализации органического вещества и уменьшению его захоронения, а также, вероятно, способствует более интенсивному расходованию оксидов/гидроксидов Fe и Mn при окислении органического вещества.

Ключевые слова: бентосный слой, биотурбация, Финский залив.

E. V. Voloshchuk[1,2], *A. A. Maximov*[3]
[1]Saint-Petersburg Branch of the P. P. Shirshov Institute of Oceanology of RAS, Russia
[2]Russian State Hydrometeorological University, Saint-Petersburg, Russia
[3]Zoological Institute of RAS, Saint-Petersburg, Russia

ASSESSMENT OF INFLUENCE OF *MARENZELLERIA ARCTIA* BIOTURBATION ACTIVITY ON SUBSTANCES CONTENT IN THE SEDIMENTS OF THE EASTERN GULF OF FINLAND

Received 07.03.2017, in final form 11.05.2017.

Benthic organisms can significantly influence the geochemical processes in the sediments by digging burrows and tunnels, which are then destroyed or backfilled, by absorption and excretion of sediments, plowing of surface soil etc. This work is dedicated to assessment of influence of invasive polychaetes *Marenzelleria arctia* activity on organic carbon content, total contents of iron and manganese in the solid phase of bottom sediments in the Eastern part of the Gulf of Finland. The content of chemical compounds in the sediments, abundance and biomass of polychaetes were obtained during the research cruise of RSHU in July 2016. Statistical analysis of field data allowed to reveal the peculiarities in distribution of chemicals depending on polychaetes population. Stations with higher polychaetes density were found to correspond to the lower content of organic matter, iron and manganese in the solid phase of sediments. In contrast, at stations with low Marenzelleria population the contents of these substances are higher. It can be concluded that bioturbation

Ссылка для цитирования: *Волощук Е. В., Максимов А. А.* Оценка влияния биотурбационной активности полихет Marenzelleria Arctia на содержание веществ в донных отложениях восточной части Финского залива // Фундаментальная и прикладная гидрофизика. 2017. Т. 10, № 2. С. 34—40.

For citation: *Voloshchuk E. V., Maximov A. A.* Assessment of influence of Marenzelleria Arctia bioturbation activity on substances content in the sediments of the Eastern Gulf of Finland. *Fundamentalnaya I prikladnaya gidrofizika.* 2017, 10, 2, 34—40.

DOI: 10.7868/S2073667317020058.

activity of polychaetes increases organic matter mineralization and reduces its burial, and also, probably, contributes to a more intensive consumption of Fe and Mn oxides/hydroxides in organic matter oxidation.

Key words: benthic layer, bioturbation, Gulf of Finland.

Metabolism in the sediments and distribution of dissolved compounds in the pore water are controlled by balance processes of organic matter decomposition and transport [1, 2]. This balance can be disturbed, if sediments are inhabited by bioturbating organisms, whose activity leads to changes in physico-chemical characteristics of soils [3—6]. The process of bioturbation is a set of disturbances in sediments caused by activities of living organisms [7]. These processes include the digging of burrows and tunnels, which are then destroyed or backfilled, ingestion of soil and formation of faeces, ploughing up of bottom surface, construction of mounds and digging of craters. The process of bioturbation involves the mixing of both solid and liquid phase of the sediments, increasing the porosity of soils, oxygen penetration depth and, hence, the area of oxygen and sediments contact (area of the oxidized layer).

Bioturbation increases the speed of mineralization process due to mechanical splitting of detritus particles and oxidation of organic substances penetrating into the bottom sediments. In addition to mixing of sediments, the development of bacterial mineralization of organic substances is accelerated (fig. 1).

As a result of sediments mixing by benthic organisms, oxidized compounds move deeper into the ground and reduced substances diffuse upward. This process leads to the increase in the average depth of organic matter mineralization [8]. There exists a positive correlation between the rate of organic matter mineralization and density of macroorganisms population as shown by Karlson et al. and Van der Bund et al. [9, 10].

However, only physical mixing of sediments is not enough to increase mineralization; presence of oxygen in the bottom waters and its easy transport are of greater importance [11].

The study of organic matter mineralization in the bottom of the Gulf of Finland is an actual target in conditions of deteriorating state of the Gulf of Finland. Hypoxia ($O_2 < 2$ ml L^{-1}) and anoxic conditions (absence of O_2) are often observed in the bottom of the Gulf in the summer period leading to animals' death and formation of «dead zones». The mechanism of hypoxia in the Gulf of Finland is associated with two main factors: the physical processes that determine the establishment of vertical water stratification and biological supply of organic matter to the bottom. Owing to the stratification of water, the supply of oxygen to the bottom layers stops, and organic substances accumulated on the bottom «consume» the remains of O2, which leads to the formation of hydrogen sulphide. Currently, active sediment bioturbators in the Gulf of Finland are polychaetes *Marenzelleria* spp. [12, 13] (more likely *Marenzelleria arctia* (*M. arctia*)), that were recently found in the Baltic Sea. These polychaetes burrow into the ground deeper than native species of benthic invertebrates, exerting significant influence on biogeochemical processes at the bottom. Estimates of polychaetes effect on nitrogen and phosphorus fluxes have been carried out in many works [5, 9, 12—17], while the effect of *M. arctia* on the content of organic carbon, iron and manganese in sediments is poorly known [18].

In the marine environment iron and manganese in the solid phase of sediments occur predominantly in the form of oxides /hydroxides, which participate in anaerobic oxidation of organic matter. At the same time, their contribution to organic matter oxidation can be very significant, reaching 21—78 % in the bottom sediments of the Skagerrak Strait (the maximum contribution of manganese oxides is 5—14 % in this case) [19]. However,

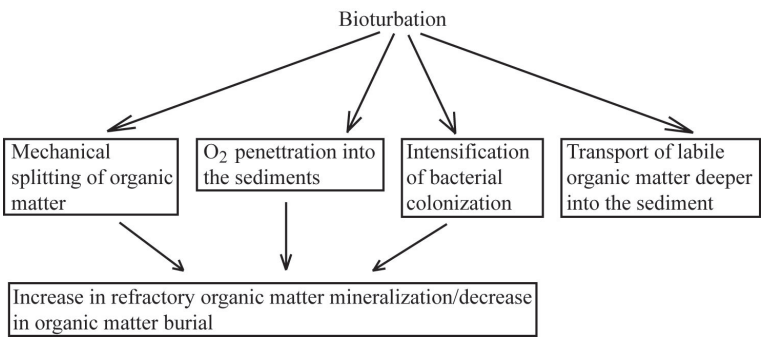

Fig. 1. Influence of bioturbation on organic matter recycling in sediments.

the presence of bioturbators in bottom sediments significantly reduces (up to 0 %) contribution of manganese oxides [11] due to the greater availability of molecular O_2. Manganese oxides can also be used to oxidize iron [11].

It is known that distribution of manganese in sediments depends not only on the intensity of bioturbation, but also on the benthic organic carbon (C_{org}) flux and oxygen concentration in the overlying water [4]. The formation of iron hydroxides occurs faster than manganese, and strongly depends on the pH value multiplying with its growth [20].

The results of field observations in the Eastern part of the Gulf of Finland indicate a slight variation in the iron and manganese content in the upper (0—3 cm) sediment layer during the period 2001—2009. Thus, according to the data of Fokin and Frumin [21], the average iron content varied within 3.25—3.76 %, and for manganese — 0.066—0.082 %. In this paper, the effect of *M. arctia* activity on mineralization of organic matter is investigated. In addition, the relationship between bioturbation of polychaetes and iron and manganese content in the solid phase of the sediments is revealed.

Materials and methods

Collection and processing of data. Scientific cruise in the Eastern Gulf of Finland was organized in July 2016 by Russian State Hydrometeorological University. During the cruise 7 stations were studied. Sediment samples were taken by Borutsky grab and cut into layers 1—2.5 cm thick. The maximum thickness of the sampled ground was from 8 to 12.5 cm. In the solid phase of the sediments, organic matter content was determined as the loss in ignition. It was assumed that carbon is 50 % of organic matter mass. In addition, the total content of iron (ΣFe) and manganese (ΣMn) were determined by X-ray fluorescence on the EDX-800P spectrometer.

To determine the biomass and abundance of *M. arctia*, 3 sediment samples were taken from Van-Win grab at the studied stations (capture area of 0.025 m2). Sediments were washed through a sieve of 0.4 mm mesh size. The residue was fixed with 4 % formalin. Further processing was made in a laboratory.

Statistical analysis of observational data. Mean abundance of *M. arctia* at 7 stations is 1380 ind./m^2 with average absolute deviation (AAD) 634 ind./m^2. To assess the effect of bioturbation on organic carbon content, and the total content of iron and manganese in the solid phase of sediments, the studied stations were divided into three groups: high (population > 2014 ind./m^2, more than mean value + AAD), medium (range of abundances within the mean ± AAD) and low (< 746 ind./m^2, density less than mean value — AAD) polychaetes population. Since the greatest impact of polychaetes is observed in the bioturbation zone, calculation of average values of compounds in each of the three selected groups was carried out to depths of 3.5—5 cm, which corresponds to the two upper layers of the samples. The significance of differences in the samples was determined with respect to the group with a high *M. arctia* population using the Student's t-test at a significance level of $\alpha = 0.05$ [22]. The regularities of joint distribution of C_{org}, ΣFe, and ΣMn content in the sediments at different stations regardless of polychaetes density were determined by the cluster analysis. The analysis was performed in STATISTICA 6.0 program using the Ward method, with Euclidean distance measure. The thickness of the described layer was also 3.5—5 cm.

Results and discussion. In the considered period, in the upper 0—3.5/5 cm layer of sediments, measured concentrations of organic carbon in the solid phase ranged from 2.14 to 6.75 % (mean 4.69 %), of iron 2.21—2.87 % (2.56 %); manganese concentrations varied significantly — from 0.07 to 0.76 % (0.21 %). Oxygen conditions in the bottom layer, which has substantial effect on bioturbation process, were favorable: O_2 content varied from 3.40 to 4.55 ml L^{-1} (there was no data for 2F station).

Results of measurements of polychaete abundance and biomass at the stations as well as allocation of station groups are shown on fig. 2 and in table 1.

Average contents of chemicals in the groups of low, medium and high *M. arctia* population are presented in table 2.

According to the results presented in table 2, in conditions of high *M. arctia* density, C_{org} content is on the average 2.4 times lower in comparison with the low population group. This is apparently due to both the direct consumption of organic substances by worms and deeper penetration of oxygen into the sediments due to the more intensive bioturbation and, consequently, more intensive oxidation of carbon. In addition, as abundance of polychaetes increases, content of iron and manganese decreases (for the content of manganese, the differences in the mean values are not statistically significant). Apparently, due to bioturbation, the contribution

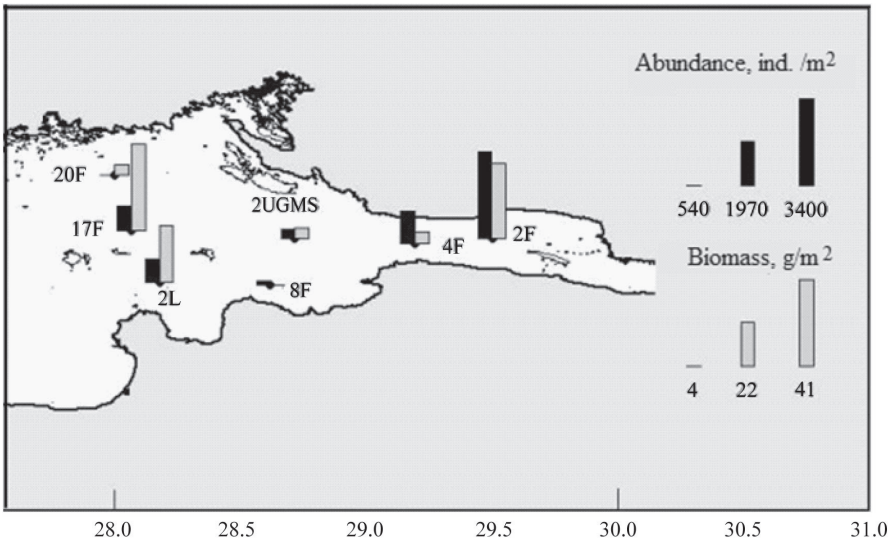

Fig. 2. Abundance and biomass of polychaetes *M. arctia* in the Eastern Part of the Gulf of Finland in July 2016.

Table 1

Allocation of station groups by M. arctia abundance

Characteristic of abundance	Station	Depth, m	Abundance, ind./m^2	Biomass, g/m^2
Low	8F	29	640	3.9
	20F	46	540	8.44
Medium	2UGMS	36	820	8.16
	17F	49	1340	40.88
	2L	33	1340	38.4
	4F	28	1580	8.72
High	2F	21	3400	36.16

Table 2

Mean values (±AAD) of C_{org}, ΣFe and ΣMn in the sediment solid phase in the groups of high, medium and low abundance of polychaetes *M. arctia*

Component / Characteristic of abundance	Low	Medium	High
Corg, %	5.56 ± 1.17*	4.89 ± 0.63*	2.17 ± 0.02
ΣFe, %	2.69 ± 0.11*	2.57 ± 0.17	2.27 ± 0.06
ΣMn, %	0.40 ± 0.26	0.14 ± 0.06	0.08 ± 0.01

Significant differences with respect to the group with high polychaetes population are marked by *.

of Fe and Mn oxides/hydroxides to organic matter oxidation on the bottom increases leading to decrease in their content.

Fig. 3 shows the dendrogram of stations classification for the content of sediment chemicals, while the characteristics of abundance and biomass of polychaetes were not considered as a parameter for clustering. The stations were divided into 4 clusters. The allocation of clusters on the dendrogram is to some extent subjective. Nevertheless, it is quite justified to allocate four clusters, as it is clear from table 3, that 2 clusters have extremely low (3rd) and high (1st) values of all three chemical characteristics. In this case, the maximum (3rd cluster) and minimum (1st) polychaetes density correspond to these groups. In clusters 2 and 4, the content of substances is average between the 1st and 3rd clusters, and polychaetes population also does not very much, but the biomass ratio is large (varies by a factor of 5) (table 3). Apparently, this could determine significance

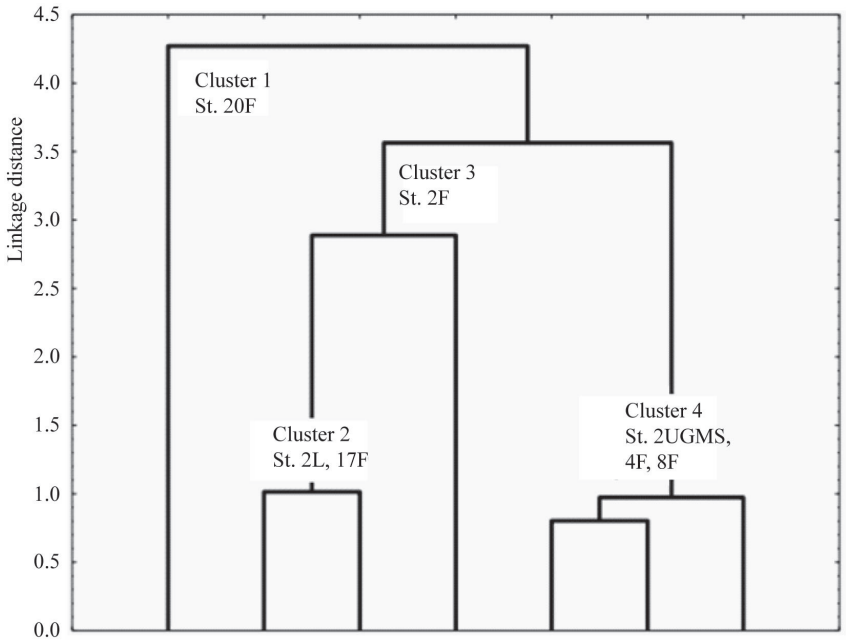

Fig. 3. Dengrogram of stations classification.

of differences in C_{org} content in these two groups, since larger individuals dig out larger holes, which can facilitate rapid delivery of O_2 to the sediments.

The dendrogram also shows that the closest to each other are stations in the 4th cluster, but the characteristics of station 20F are the most different from those at other stations: mean organic carbon content here is the largest (6.73 %), as well as iron and manganese contents (table 3), so cluster 1 is combined with the rest of the group in the last turn. Significance of differences in contents of chemicals was estimated between clusters 2 and 4, which correspond to the average density of polychaetes. Significant differences were obtained only in organic matter content.

The allocation of stations into clusters as a whole coincided with physiographic zonation of the Eastern Gulf of Finland [23]. For example, station 2F is located in the eastern shallow area, in the zone of the Shepelev accumulative region. The stations of the 4th cluster are under the influence of the Neva river flow and are located within the Shepelev and Seskara accumulative areas. Shepelev sedimentation basin stores the bulk of the Neva River's solid flow, which passes through the Neva Bay. Stations 2L, 17F (cluster 2) and station 20F (cluster 1) are located in the deep water area.

Partly the differences in substances content between various regions can be explained by the peculiarities of quantitative distribution of *M. arctia*, namely, the higher density of worms at the eastern stations due to dynamics of polychaetes invasion, spreading in the Gulf of Finland eastwards [24, 25]. As a rule, at the initial stages of invasion, there is a sharp increase in population of invasive species, and then there is some decrease

Table 3

Average values of C_{org}, ΣFe and ΣMn content in the clusters; abundance and biomass of *M. arctia*

Cluster/characteristics	1	2	3	4
C_{org}, %	6.73	5.24*	2.17	4.30*
∑Fe, %	2.8	2.49	2.27	2.68
∑Mn, %	0.66	0.12	0.08	0.16
Polychaetes abundance, ind./m²	Low	Medium	High	Medium
	540	1340	3400	1013
Polychaetes biomass, g/m²	8.4	34.6	36.2	6.9

Significant differences in C_{org}, ΣFe and ΣMn contents between the 2nd and 4th clusters are marked by*.

and stabilization of their density at a lower level. The higher population of worms in the eastern shallow area is due to the later penetration of *M. arctia* into the tip of the Gulf.

Definitely, the differences cannot be uniquely attributed solely to bioturbation of sediments by polychaetes. The content of chemicals in the sediments could be affected by the peculiarities of hydrological regime in different areas of the Gulf. In particular, because of the shallow water at stations of the eastern area, the resuspension of sediments by autumn storms, apparently, contributes to the decrease in the fraction of small-sized particles in sediments, causing a lower content of organic substances there. However, content of substances was also significantly different in the deepwater region, even at closely located stations with different polychaete abundances (stations 17F and 20F), which indicates a noticeable effect of worm activity.

The fragmentary information available in the literature on geochemistry of bottom sediments over the past years also indicates the changes that have occurred after the invasion of *M. arctia*. For instance, in 1950s and 1980s the C_{org} content in silty sediments of the Shepelev and Seskara accumulative regions (clusters 3 and 4) was 5—6 % [26, 27]. At present such organic carbon concentrations were registered only at stations with low population of polychaetes.

***

The results of sampling at 7 stations in the Eastern part of the Gulf of Finland demonstrate that at stations with higher abundance of polychaetes *M. arctia* the lower organic carbon content of the solid phase of bottom sediments is observed. In contrast, at stations with low worm population, the content of C_{org} is higher. It was concluded that bioturbation activity of polychaetes increases the mineralization of organic matter and reduces its burial. Consumption of organic compounds by worms also contributes to its decrease.

In terms of higher polychaetes abundance lower content of ΣFe and ΣMn of the solid phase was observed, apparently, due to more intensive use of oxides/hydroxides of these substances in organic matter oxidation at the bottom. However, the differences in content of ΣFe and ΣMn in different groups in some cases were not statistically significant.

The more detailed study of polychaetes effect on the changes in bottom sediments requires the increase in number of sampling stations, that will also improve the accuracy of the results.

This work was funded by the project COCOA of BONUS program.

References

1. *Jahnke R., Richards M., Nelson J.* et al. Organic matter remineralization and porewater exchange rates in permeable South Atlantic Bight continental shelf sediments. *Cont. Shelf Res.* 2005, 25, 1433—1452.
2. *Jørgensen B. B., Boudreau B. P.* Diagenesis and sediment–water exchange. In: Boudreau B. P., Jørgensen B. B. (eds) The benthic boundary layer: transport processes and biogeochemistry. *Oxford University Press, Oxford,* 2001. P. 211—244.
3. *Welsh D.* T. It's a dirty job but someone has to do it: the role of marine benthic macrofauna in organic matter turnover and nutrient recycling to the water column. *Chem Ecol.* 2003, 19, 321—342.
4. *Aller R. C.* Bioturbation and remineralization of sedimentary organic matter: Effects of redox oscillation. *Chemical geology.* 1994, 114, 331—345.
5. *Norkko J., Reed D. C., Timmermann K.* et al. A welcome can of worms? Hypoxia mitigation by an invasive species. *Global Change Biology.* 2012, 18, 2, 422—434.
6. *Sandnes J., Forbes T., Hansen R., Sandnes B., Rygg B.* Bioturbation and irrigation in natural sediments, described by animal-community parameters. *Mar. Ecol. Prog. Ser.* 2000, 169—179.
7. *Boudreau B. P.* Diagenetic models and their implementation: modeling transport and reactions in aquatic sediments / Bernard P. Boudreau. Berlin; Heidelberg; New York; Barcelona; Budapest; Hong Kong; London; Milan; Paris; Santa Clara; Singapore; Tokyo: *Springer,* 1996.
8. *Herman P.M.J., Middelburg J.J., Van de Koppel J., Heip C.H.R.* Ecology of estuarine macrobenthos. *Adv. in Ecol. Res.* 1999, 29, 195—240.
9. *Karlson K., Hulth S., Ringdahl K., Rosenberg R.* Experimental recolonisation of Baltic sea reduced sediments: survival of benthic macrofauna and effects on nutrient cycling. *Mar. Ecol. Prog. Ser.* 2005, 294, 35—49.
10. *Van der Bund W. J., Olafsson E., Modig H., Elmgren R.* Effects of the coexisting Baltic amphipods *Monoporeia affinis and Pontoporeia femorata* on the fate of a simulated spring diatom bloom. *Mar. Ecol. Prog. Ser.* 2001, 212, 107—115.
11. *Ferro I., Van Nugteren P., Middelburg J. J., Herman P.M.J., Heip C.H.R.* Effect of macrofauna, sediment ventilation and particle reworking on sedimentary iron and manganese pools in a mesocosm experiment. *Vie et Milieu.* 2003, 53, 211—220.
12. *Eremina T. R., Voloshchuk A. A., Maximov A. A.* Assessment of biogeochemical changes in the sediments of the Eastern part of the Gulf of Finland due to invasion of polychaetes *Marenzelleria spp.* on observational data and modeling results. *Izvestiya RGO.* 2016, 148, 1, 55—71 (in Russian).
13. *Maximov A. A., Eremina T. R., Lange E. K., Litvinchuk L. F., Maximova O. B.* Regime shift in ecosystem of the Eastern Gulf of Finland due to invasion of polychaetes *Marenzelleria arctia. Oceanology.* 2014, 54, 1, 52—59.

14. *Voloshchuk E. V., Eremina T. R., Ryabchenko V. A.* Modeling of biogeochemical processes in the sediments of the Eastern part of the Gulf of Finland by means of diagenetic model. *Fundam. Prikl. Gidrofiz.* 2015, 8, 4, 106—113 (in Russian).
15. *Urban-Malinga B., Warzocha J., Zalewski M.* Effects of the invasive polychaete *Marenzelleria spp.* on benthic processes and meiobenthos of a species-poor brakish system. *J. of Sea research.* 2013, 80, 25—34.
16. *Hietanen S., Laine A. O., Lukkari K.* The complex effects of the invasive polychaetes *Marenzelleria spp.* on benthic nutrient dynamics. *J. of Exper. Mar. Biol. and Ecol.* 2007, 352, 89—102.
17. *Maximov A., Bonsdorff E., Eremina T.* et al. Context-dependent consequences of *Marenzelleria spp.* (Spionidae: Polychaeta) invasion for nutrient cycling in the Northern Baltic Sea. *Oceanologia.* 2015, 57, 342—348.
18. *Voloshchuk E., Eremina T., Isaev A.* Assessment of bioturbation activity of *Marenzelleria spp.* in the eastern Gulf of Finland. Abstract book of the EMECS'11 SeaCoasts XXVI conference: Managing risks to coastal regions and communities in a changing world. August 22—27 2016, *Saint-Petersburg, Russia.* P. 69.
19. *Canfield D. E., Thamdrup B., Hansen W.* The anaerobic degradation of organic-matter in Danish coastal sediments — iron reduction, manganese reduction, and sulfate reduction. *Geochimica et Cosmochimica Acta.* 1993, 57, 3867—3883.
20. *Millero F. J., Sotolongo S., Izaguirre M.* The kinetics of oxidation of Fe(II) in seawater. Geochim. *Cosmochim. Acta.* 1987, 51, 793—801.
21. *Fokin D. P., Frumin G. T.* Content and distribution of metals in sediments of the Eastern Part of the Gulf of Finland (according to the Federal monitoring 2001—2009). *Obshchestvo. Sreda. Razvitie.* 2011, 1, 210—214 (in Russian).
22. *Gordeeva S. M.* Practicum on «Statistical methods of processing and analysis of hydrometeorological information». *SPb., RGGMU,* 2010. 74 p. (in Russian).
23. *Pitkänen H.* Nutrient dynamics and conditions in the eastern Gulf of Finland: the regulatory role of the Neva estuary. *Aqua Fennica.* N 21 (2). 1991. P. 105—115.
24. *Maximov A. A.* The long term dynamics and current distribution of macrozoobenthos communities in the Eastern Gulf of Finland, Baltic Sea. *Russian Journal of Marine Biology.* 2015, 41, 4, 300—310.
25. *Maximov A., Nygård H., Kotta I.* Benthic communities. Deep bottoms. The Gulf of Finland assessment. *Reports of the Finnish Environment Institute.* 2016, 27, 204—207.
26. *Alferovskaya M. M.* Chemical composition of Gulf of Finland sediments. *Izhv. GosNIORH.* 1969, 65, 321—327 (in Russian).
27. *Maximov A. A.* The role of Monoporeia affinis (Lindstrom) (Crustacea; Amphipoda) in bottom communities of the Eastern part of the Gulf of Finland. Dissertation of candidate of biological sciences. *SPb, Zoologicheskiy institute RAN,* 2000 (in Russian).