Marine Pollution Bulletin 61 (2010) 149–155

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Principal processes within the estuarine salinity gradient: A review

Irena V. Telesh *, Vladislav V. Khlebovich

Zoological Institute of the Russian Academy of Sciences, Universitetskaya Embankment 1, St. Petersburg 199034, Russia

A R T I C L E   I N F O

Keywords:
Definition of an estuary
Salinity gradient
Critical salinity
Zooplankton
Neva Estuary
Baltic Sea

A B S T R A C T

The salinity gradient is one of the main features characteristic of any estuarine ecosystem. Within this gradient in a critical salinity range of 5–8 PSU the major biotic and abiotic processes demonstrate non-linear dynamics of change in rates and directions. In estuaries, this salinity range acts as both external ecological factor and physiological characteristics of internal environment of aquatic organisms; it divides living conditions appropriate for freshwater and marine faunas, separates invertebrate communities with different osmotic regulation types, and defines the distribution range of high taxa. In this paper, the non-linearity of biotic processes within the estuarine salinity gradient is illustrated by the data on zooplankton from the Baltic estuaries. The non-tidal Baltic Sea provides a good demonstration of the above phenomena due to gradual changes of environmental factors and relatively stable isohalines. The non-linearity concept coupled with the ecosystem approach served the basis for a new definition of an estuary proposed by the authors.

1. Introduction

Organisms inhabit the aquatic environments with total mineralization ranging from few milligrams of salts per liter (e.g. in lakes with granite beds in Karelia and Kola Peninsula) to ca. 300 g l^{-1} in water bodies of the arid climate zone (e.g. the Dead Sea, or Liman Kuyalnik in the Black Sea). Within such a broad range of mineralization of natural waters, at certain salinities the major biotic and abiotic processes demonstrate non-linear dynamics of change in rates and directions. In estuaries, such zones appear where the fresh (riverine) and saline (marine) waters mix. As the ecotone areas between marine and freshwater habitats estuaries are characterized by the unique combination of physical, chemical and biological features, and are distinguished by exceptionally high productivity (Alimov, 2007). Together with a function of natural evolutionary and biogeographic barriers (Khlebovich, 1974, 1990), estuaries are serving as both pollution sources for the open sea and marginal filters for the polluted runoff from the river drainage basin (Lisitzin, 1999; Schiewer, 2002). The intensity of the above-mentioned functions of estuarine ecosystems is defined to great extent by the estuarine salinity gradient.

2. Salinity gradient and definition of an estuary

When considering any estuary worldwide certain generalizations can be applied among which a gradient of environmental conditions is the major common feature (Elliott and McLusky, 2002). Among those conditions, salinity is the main environmental factor which plays a decisive role and defines structural and functional characteristics of aquatic biota in estuaries. As transition areas and one of the main physiographic forms to be included under the term "transitional waters" (European Communities, 2000) estuaries play an important filtering role for dissolved and particulate matter as well as for their associated compounds, operating as sinks of organic matter and nutrients (de Jonge et al., 2002).

However, despite an intensive research into the estuarine, coastal and shelf ecology and related disciplines there is still a lack of comprehensive definition of an estuary as well as any universal classification of this type of water systems is not yet available (Elliott and McLusky, 2002). Continuality of these transitional water ecosystems can be considered as the major reason for such state of the arts. As concluded recently by McLusky and Elliott (2007), "there will always be a problem of defining types within a continuum and it remains to be seen whether the differences in use will have any repercussions – legal, administrative or environmental".

Estuaries have various shapes and sizes and can be called by many names: bays, lagoons, harbors, and inlets or sounds (McLusky and Elliott, 2004). However, it is of note that in general the terms "estuary", "lagoon" and "river delta" are geo-morphological characteristics, and they may have no relation to the salinity factor (e.g. in case the "estuaries" of large lakes are under discussion). Real estuarine, i.e. brackish water, ecosystems are formed where the marine waters meet with fresh waters, and the salinity gradient appears: in lagoons, deltas and estuaries of rivers inflowing the seas. Avoiding, however, a detailed debate on the typology of

* Corresponding author. Fax: +7 812 328 2941.
E-mail address: itelesh@zin.ru (I.V. Telesh).

0025-326X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2010.02.008

estuaries in general (see Day, 1951; Ketchum, 1951; Pritchard, 1967; Khlebovich, 1965, 1974, 1986; Kinne, 1971; Fairbridge, 1980; Bulger et al., 1993; Meire and Vincx, 1993; Pethick, 1993; Dyer, 1996; Lisitzin, 1999; Conley et al., 2000; Elliott and McLusky, 2002; DEH-GSA, 2006, and many others) we will concentrate here on the biologically relevant aspects of such a definition. In this respect, the decisive characteristics of an estuary is the mixing of saline and fresh waters – a process which creates a salinity gradient that defines specificity of physical, chemical and biological features, and their interactions in these transitional ecosystems (Khlebovich, 1986, 1990). Strictly speaking, *an estuarine ecosystem develops everywhere in the conditions of the salinity gradient*. Flora and fauna of these ecosystems is rather peculiar and continuous flow-through of allochtonous organic matters favours high rate of productivity process in this environment (Khlebovich, 1965, 1974; Van Beusekom and de Jonge, 1994; Golubkov et al., 2003; Telesh, 2004).

Considering the existing concepts of ecosystem functioning (Alimov, 2003) we infer that the approach to classification of estuaries on the basis of hydrographic parameters linked to ecological transformations (Lisitzin, 1999; Jay et al., 2000) and related to the ecosystem functioning modes can be accepted as the most relevant one. This approach rests on description of characteristic spatial–temporal modifications of both structural components as well as biogeochemical processes in estuarine ecosystems (Telesh, 2006b; Elliott and Quintino, 2007; Telesh et al., 2008). From this point of view, in a very general way *an estuary being a trans-boundary region between river and sea where the fresh and saline waters mix can be defined as a specific semi-enclosed water body which ecosystem is characterized by a variety of inter-related biotic and abiotic structural components naturally undergoing change in space and time, along with intensive chemical, physical and biological processes exposed against a salinity gradient*.

3. The critical salinity concept and non-linearity of biological processes in estuaries

Species composition and richness of fauna were among the first biological characteristics investigated in relation to the gradual change in salinity. In the tideless Baltic Sea with relatively stable isohalines and smooth salinity gradient in the bays and estuaries Remane (1934) showed the Artenminimum zone (area with minimum species number) within the narrow salinity range of 5–8 PSU. Within this salinity range the relative number of true brackish water species reached maximum while species richness of organisms of freshwater or marine origin was sloping to minimum. Zenkevitch (1959) revealed the similar Artenminimum zones in the Azov and Caspian Seas. Those findings provided arguments for considering the 5–8 PSU zone as an area of "critical salinity" where the two major types of fauna (marine and freshwater) meet and co-exist wherever the smooth water salinity gradient is present (Khlebovich, 1962, 1974), and Kinne (1971) has coined for this zone a term "horohalinicum".

By combining the Remane curve with the data of Hedgpeth (1959) on species richness in hyperhaline water bodies Khlebovich (1962) compiled a general scheme demonstrating how species number and composition of fauna changes within a broad range of salinity in natural waters (Fig. 1). This scheme witnesses for the exceptional importance of the critical salinity zone and also for the fact that major structural characteristics of animal communities demonstrate uneven change mode against the gradual salinity transformation.

The concept of critical salinity of 5–8 PSU is not just pointing to a "border line" between the oligo- and mesohaline ecological zones (Venice System, 1959). This specific water area separates marine

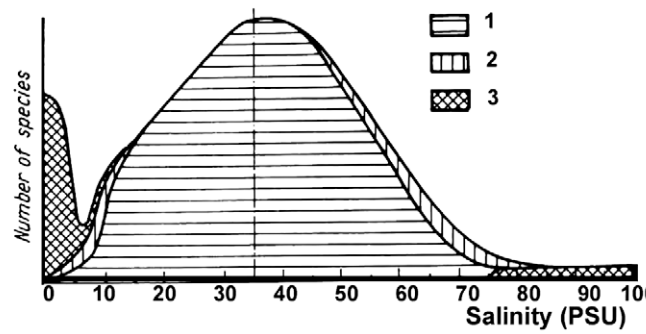

Fig. 1. Number of marine animal species (1), brackish water and euryhaline animal species of marine origin (2), and freshwater species (of freshwater origin, 3) (after Khlebovich (1962, 1969)).

and freshwater faunas due to inability of marine poikilo-osmotic organisms to live in a freshwater environment inhabited only by those invertebrates that are capable of hypertonic regulation providing high salinity of body liquids. In fact, the sense of hyper-osmotic regulation is in providing the internal salinity of organisms at the level not lower than 5–8 PSU (Khlebovich, 1974). In this context, the term "internal salinity" is valid due to high similarity of ion composition of biological liquids (blood plasma, lymph, and hemolymph) and oceanic water. A curious illustration to this similarity is the historical fact that during the World War II, in the hospitals of the blockaded Leningrad (now Saint Petersburg, Russia) as well as in Great Britain the diluted and sterilized sea water was used as a substitution of blood plasma (Khlebovich, 2007).

Thus, the narrow salinity range of 5–8 PSU acts not only as an ecological "border" but also as a physiological and evolutionary barrier. Even for those organisms which cross this critical salinity zone in their life cycle (e.g. widely euryhaline or migrating upstream–downstream) it occurs to be the upper or the lower limit of reproduction, and here the trend of physiological processes, especially the salt-water regulation, is radically changed (Khlebovich, 1990). After millions of years of evolutionary development a number of higher marine taxa such as Echinodermata and Ascidia have not acquired a physiological mechanism allowing them to overcome this narrow barrier zone and penetrate into fresh waters. Other originally marine groups that had successfully populated the fresh water environments became hyper-osmotic and formed new large taxa: Oligochaeta, Pulmonata and Pisces. Some of such taxa returned into sea waters but they have kept their hypotonic regulation and the level of internal salinity acquired in fresh waters (for the possible evolutionary schemes of osmotic relations see Khlebovich (2007)).

4. Chemical and physical processes in the salinity gradient

Interactive chemical processes involving the removal or addition of a dissolved constituent in estuarine waters have been inferred from non-linear regressions of the dissolved constituent when plotted against a conservative index of mixing such as salinity or chlorinity (Morris et al., 1978). This non-linearity may be attributed to variability of composition and fluxes of fresh water over time scales comparable to the water residence time in estuary, or subsidiary inputs of different waters because rivers discharge into the estuaries fresh waters of different chemical composition that can additionally vary in seasonal aspect (Wetzel, 2001).

The change in ion ratio in water plays a decisive role in chemical processes within the salinity gradient. In sea waters the ion ratio is stable, and the Knudsen rule allows determination of major ions and total salinity on the basis of data on a single ion concentration.

However, when river and sea waters mix in the estuaries the question arises how the ion ratio changes, or what is the lower salinity level when the Knudsen rule is still valid?

Khlebovich (1968) analyzed the data of Wittig (1940) cited by Schlieper (1958) on the concentration of calcium ions of freshwater origin within the salinity gradient along the "transect" from the North Sea to the Baltic estuaries. The results proved that the ion Ca/Cl ratio was stable within the salinity range from 34 through 7 PSU below which the relative amount of "freshwater" Ca ions was drastically increasing. Similar salinity limits were registered also for the calcium ions in the White Sea, and the curves for other ions "behaved" in a comparable way (Khlebovich, 1968, 1974).

Some hydro-chemical parameters related to nutrient concentrations demonstrate the dynamics within the salinity gradient that was linked with the processes of mineralization and consumption by biota. Thus, at salinities close to critical level of 5 PSU in the Caspian Sea coastal waters the silicon consumption/excretion ratio reverses due to replacement of freshwater diatoms by the marine species of these algae (Khlebovich, 1990). Concentration of phosphorus compounds is known to be conservative at salinities 5–8 PSU while at lower salinities these compounds are labile. As demonstrated by Anikeyev et al. (1987) in experiments with heavy metals in sea water diluted by fresh water the essential modification in their "behaviour" takes place at critical salinities 5–8 PSU.

The change of charge in particles drawn by water which occurs at the same critical salinity level is one of the most prominent physical phenomena in the salinity gradient (Pravdič et al., 1981). This change of charge would result in varying mode of sediment formation on either side of the critical salinity barrier due to increased flocculation which, in turn, influences other physical characteristics of water, e.g. transparency (Gordeev, 1983; Khlebovich, 1990). As shown by Van Beusekom and de Jonge (1994), dynamics of suspended matter concentration in the Ems Estuary (North Sea) exposed maximum fluctuations at critical salinity values (Fig. 2).

Thus, the non-linearity of biological, chemical and physical processes within a narrow salinity range around 5 PSU is the most characteristic feature of the estuarine salinity gradient. However, certain shifts in the lower and upper limits of the critical salinity zone are quite common. For instance, Deaton and Greenberg (1986) showed that the most abrupt change in the relative Ca content of seawater diluted with either natural fresh water or low Ca water often occurs below salinity 2 PSU. These authors concluded on the higher importance of changes in the total osmotic pressure in aquatic animals compared to changes in ionic composition. These results do not contradict with the critical salinity concept developed by Khlebovich (1962, 1965, 1968, 1969, 1974, 1986, 1990). Together with the latter and other findings, the conclusions drawn by Deaton and Greenberg (1986) stressed the complexity of biogeochemical processes in estuaries, variability of biotic/abiotic interaction modes in continual transitional waters of different types, and ambiguity of conventional zoning. This was additionally proved by Aladin (1983) who showed that in the "chain" World Ocean – Caspian Sea – Aral Sea the horohalinicum zone expanded and shifted towards higher salinity values (Fig. 3), meanwhile it was registered that the chlorinity in those three cases remained stable (Khlebovich, 1990).

Biological data from the Baltic coastal waters reflected the exceptional significance of lower salinities in the estuarine ecosystems of this brackish sea (Gasiūnaitė, 2000; Telesh, 2004) which to certain extent supports the idea of Deaton and Greenberg (1986) about the specific importance of low-salinity zone of 1–2 PSU.

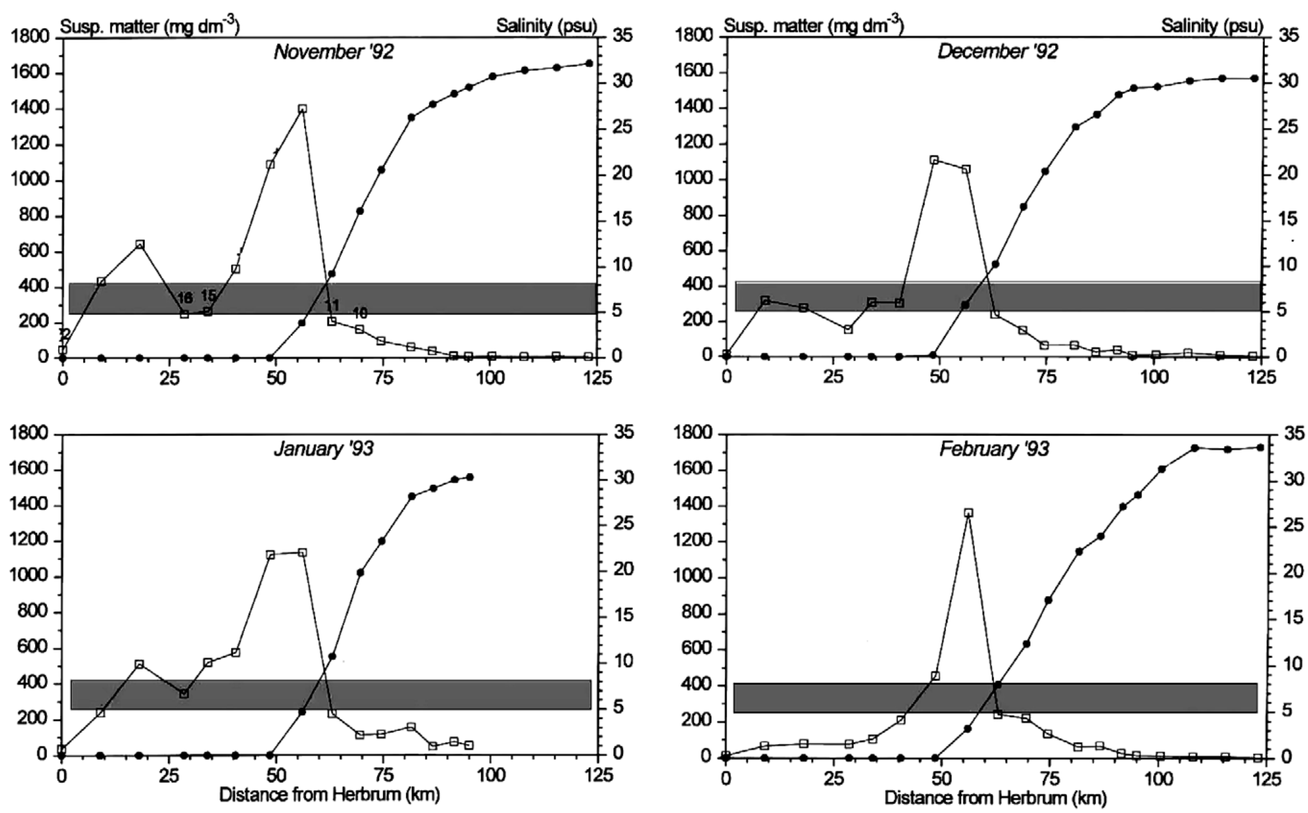

Fig. 2. Longitudinal distribution of salinity (closed symbols) and suspended matter (open symbols) in the Ems Estuary, gray stripe indicates the critical salinity zone (after Van Beusekom and de Jonge (1994), with additions).

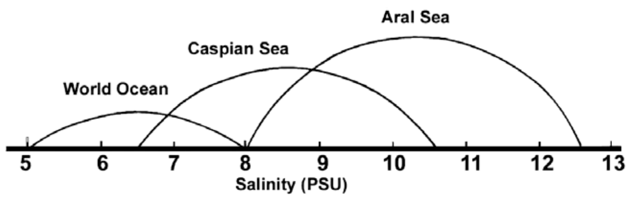

Fig. 3. Horohalinicum zones in the World Ocean, Caspian and Aral seas (modified from Aladin (1983)).

5. Case study: zooplankton of the Baltic estuaries

Zooplankton is an important component of any estuarine ecosystem suitable for investigating the non-linearity of biotic processes within a salinity gradient. Zooplankton species composition and diversity, abundance, population structure and productivity of pelagic communities change under the impact of environmental conditions thus providing information on pelagic food web transformation, organic matter turnover and energy fluxes through the ecosystem, water pollution, and eutrophication processes (Telesh, 2006a,b).

Plankton communities in different Baltic estuaries are influenced by a number of common environmental and anthropogenic factors: the increase in nutrient loading, water pollution, invasions by non-indigenous species of plants and animals, and changes in hydrological regime due to construction activities, thus demonstrating common structural features and functional characteristics (Telesh, 2001, 2004; Telesh and Heerkloss, 2002, 2004; Olenin, 2005; Telesh et al., 2008). In order to evaluate the effects of gradual changes of environmental parameters on estuarine plankton we investigated alterations of species richness, diversity and abundance of zooplankton communities in the Neva Estuary (Gulf of Finland, the Baltic Sea) in the gradient of salinity.

Zooplankton species diversity is one of the important ecosystem characteristics which is defined “internally” by biotic components (food resources, competition, predation) and “externally” by abiotic parameters: origin, location and geomorphology of water body, its size, chemical and physical conditions (Telesh, 2006b). Among the latter, water chemistry plays a decisive role. We analyzed zooplankton species richness in the water system: Lake Ladoga (fresh) – Neva River (fresh) – Neva Bay (upper Neva Estuary, fresh) – Gulf of Finland (lower Neva Estuary, 1–4 PSU) – central Baltic Sea (7–8 PSU). The results showed gradual (exponential) increase of zooplankton species richness in the waters with lower mineralization (Table 1, Fig. 4), and the slope was the steepest at the conventional “border” in brackish waters with salinity values below 4 PSU (Telesh, 2006b).

Short-term analyses of spatial variation, as well as long-term studies of zooplankton diversity and species richness within a low-scale salinity gradient (e.g. in the salinity range ⩽ 0.1–4 PSU) in the Neva Estuary provided similar results (Telesh, 1987, 1996, 2006a,b). Relation of zooplankton species diversity to water salinity was exposed by a dome-like curve (Fig. 5) where maximum values of Shannon–Wiener index (⩾3) corresponded to salinity range of 0.32–2.81 PSU (Telesh, 2004). As shown earlier, such dome-like curves are not factor-specific; they are typical effects of different environmental factors impacting zooplankton community parameters, and they are defined by the alteration of the community structure (Ivanova, 1997).

Table 1
Species richness of Ciliates, Rotifera, Cladocera and Copepoda in the central Baltic Sea (Hernroth and Ackefors, 1979, but see Telesh et al., 2009), Gulf of Finland (Silina, 1997), Neva Bay (Telesh, 1987), and Lake Ladoga (Den’gina and Sokolova, 1968; Telesh, 1996).

Organisms	Baltic Sea	Gulf of Finland	Neva Bay	Lake Ladoga
Ciliates	No data*	36	90	90
Rotifera	10	135	170	220
Cladocera	5	57	89	70
Copepoda	11 (27**)	48	45	34

* But see Telesh et al. (2009).
** According to Remane and Schlieper (1971), there are 27 species of Harpacticoida (additionally to other copepods).

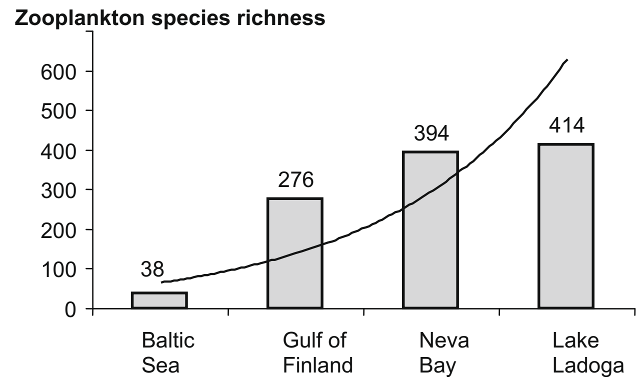

Fig. 4. Total zooplankton species richness (including Ciliates, Rotifera, Cladocera and Copepoda) in the central Baltic Sea (Hernroth and Ackefors, 1979, but see Telesh et al., 2009), Gulf of Finland (Silina, 1997), Neva Bay (Telesh, 1987), and Lake Ladoga (Den’gina and Sokolova, 1968; Telesh, 1996).

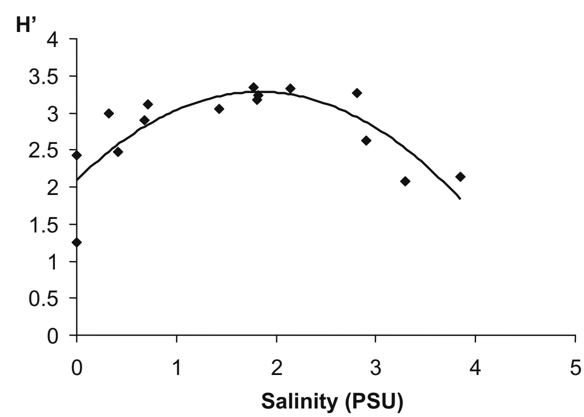

Fig. 5. Shannon–Wiener species diversity index (H′) for zooplankton in relation to water salinity in the Neva Estuary (modified from Telesh (2004)).

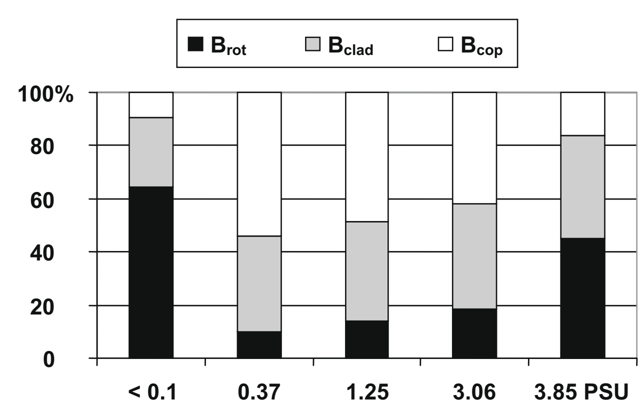

Fig. 6. Variation in zooplankton community structure (% of total biomass) within the salinity gradient in the Neva Estuary (modified from Telesh (2006a)).

In the Neva Estuary, the zooplankton community structure varied regularly within a salinity gradient ranging from below 0.1 to ca. 4 PSU (Fig. 6). With the growing salinity, the share of rotifers in the total zooplankton biomass decreased to minimum (10%) at 0.37 PSU, and then was increasing significantly to ca. 45% at salinity 3.85 PSU due to massive development of euryhaline rotifers, mainly *Keratella cohlearis baltica*. Copepods demonstrated the reverse dynamics; however at salinities above 3 PSU the dominant freshwater copepods from the genera *Mesocyclops* and *Thermocyclops* were partly replaced by the brackish water *Acartia* species. The species composition and relative role of Cladocera in the total zooplankton biomass within the studied salinity range varied insignificantly (Fig. 6). The general transformation of zooplankton community, however, resulted in the pronounced decrease of zooplankton biomass with the increasing salinity within the investigated salinity gradient (Telesh, 2004).

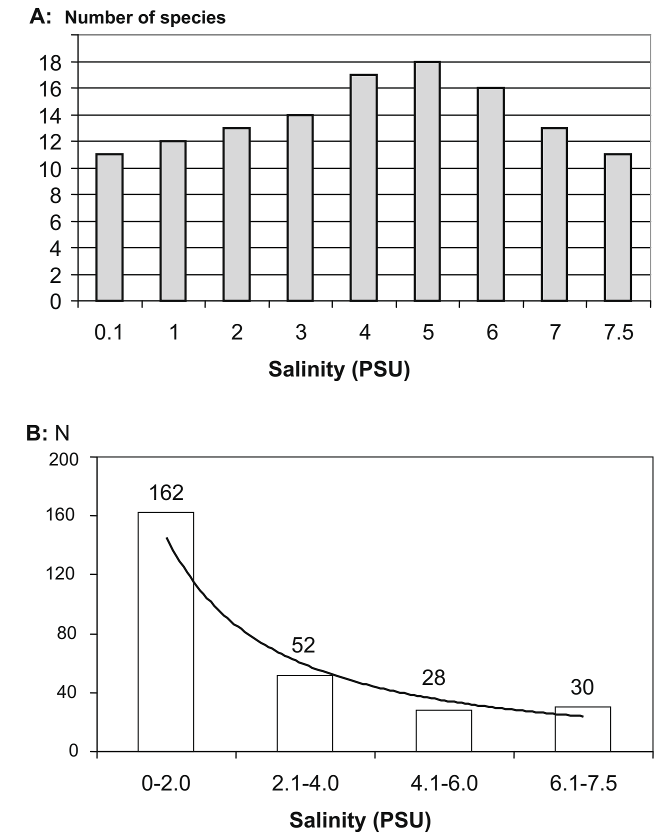

Fig. 7. Variation in species richness (A: number of species) and density (B: *N*, ind./l) of planktonic crustaceans averaged for the salinity zones within the salinity gradient in the Curonian Lagoon (compiled using the data from Gasiūnaitė (2000)).

Comparison of these data with results from other Baltic estuaries and lagoons revealed the commonness of the above-mentioned regularities for the zooplankton community transformations within the low-scale salinity gradient, regardless of the specificity of different Baltic coastal waters. For instance, similarly to Neva Estuary, species richness of planktonic crustaceans in the Curonian Lagoon was the highest in the central area of the lagoon (Fig. 7A), and the crustaceans density dynamics exposed the tendency to decrease within the salinity gradient similar to that in the Neva Estuary (Fig. 7B). It is of interest that the maximum species richness of crustaceans (ca. 20 species) was registered in the Curonian Lagoon at salinities 4–7 PSU (Gasiūnaitė, 2000) which coincided to great extent with the classical critical salinity level (5–8 PSU) and thus may be considered either as contradiction to Remane's Artenminimum concept or/and as support for the idea of shift/expansion of horohalinicum zones in the estuarine regions of different seas (Fig. 4). In the Neva Estuary, maximum of zooplankton species richness (exceeding 270 species) and the highest zooplankton productivity was observed at salinities below critical level (Golubkov et al., 2003; Telesh, 2004) which is in agreement with McLusky and Elliott (2004) who emphasized the complexity of biological and related chemical processes in the uppermost parts of estuaries, in low-salinity regions (Fig. 8).

6. Conclusion

Within the estuarine salinity gradient, the "nucleus" of an estuary is formed in the critical salinity zone of 5–8 PSU where the major chemical, physical and biological characteristics and processes demonstrate non-linear dynamics. The concept of critical salinity establishes the universal character of this barrier zone that separates the main fauna complexes and ecological groups of aquatic organisms which represent various types of cellular and biochem-

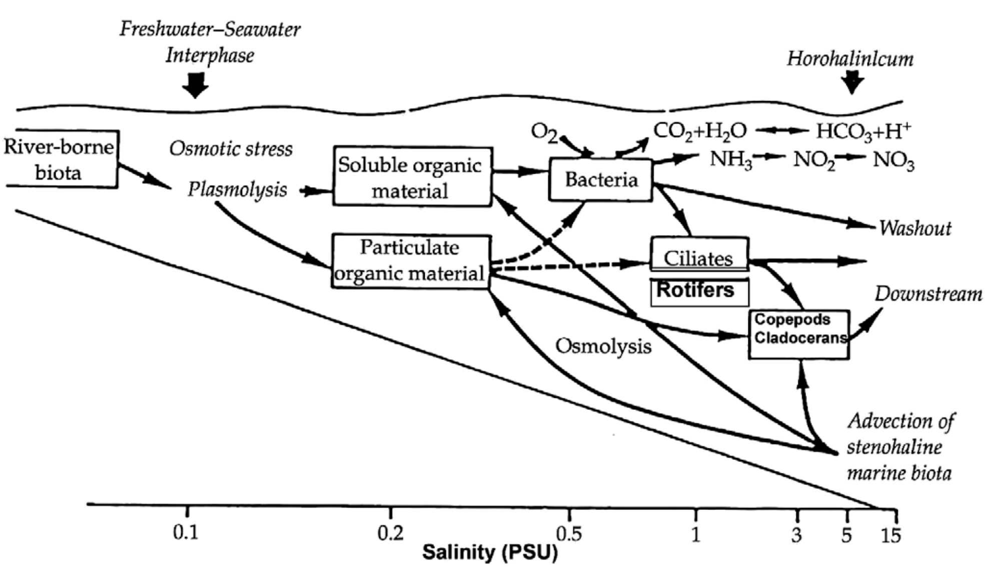

Fig. 8. Biological and related chemical processes in the low-salinity regions of estuaries (from McLusky and Elliott (2004), with additions).

ical homeostasis. The horohalinicum zone hosts the living organisms with broad range of environmental tolerance; most often it is characterized by exceptionally high productivity and the latter fact should provide strong motivation for scientists to research into the *processes* of formation and *functioning* of estuarine ecosystems. However, results of only few of such ecosystem-based studies of estuaries that use functional approach are available so far; thus, application of the basics of theory of ecosystem functioning to estuarine ecology is still at its early stage. Although there are just a limited number of water basins in the world where the salinity gradient may be observed at a comparatively large distance, the Baltic Sea is one of such unique natural "laboratories" with an extended critical salinity zone characterized by a certain spatial–temporal stability. Further investigation and quantification of the non-linearity of biological processes within the salinity gradient can shed more light on estuarine ecosystem functioning and favour detecting natural environmental perturbations in estuaries versus the anthropogenic stress.

Acknowledgements

The authors acknowledge financial support of the Russian Foundation for Basic Research (Grants 04-04-49207, 05-04-90588, 08-04-00486, 10-04-00558), grant for the Leading Scientific School on Production Hydrobiology from the Russian Ministry of Education and Science (1993.2008.4), and Russian Programs "Biological Resources" and "Biodiversity".

References

Aladin, N.V., 1983. On displacement of the critical salinity barrier in the Caspian and Aral seas, the Branchiopoda and Ostracoda taken as examples. Zoological Journal (Moscow) 62 (5), 689–694 (in Russian, English summary).

Alimov, A.F., 2003. Towards a Theory of the Functioning of Aquatic Ecosystems. Backhuys Publishers, Leiden, The Netherlands. p. 130.

Alimov, A.F., 2007. Theory of Ecosystem Functioning: Application to Estuarine Ecology. Abstracts of the Symposium ECSA42 "Estuarine Ecosystems: Structure, Function and Management", 16–22 September 2007. Svetlogorsk, Russia. pp. 8–9.

Anikeyev, V.V., Volkov, A.A., Lobanov, A.A., Sapozhnikov, Yu.A., Khova, S.L., Shumilin, E.N., 1987. Heavy metals conduct during marine and river waters mixing. Influence of the salinity background on the transformation of Cr, Fe, Zn and Mn. Radiochemistry 4, 554–561 (in Russian).

Bulger, A.J., Hayden, B.P., Monaco, M.E., Nelson, D.M., McCormick-Ray, M.G., 1993. Biologically-based estuarine salinity zones derived from a multivariate analysis. Estuaries 16, 311–322.

Conley, D.J., Kaas, H., Møhlenberg, F., Rasmussen, B., Windolf, J., 2000. Characteristics of Danish estuaries. Estuaries 25, 820–837.

Day, J.H., 1951. The ecology of South African estuaries. I. A review of estuarine conditions in general. Transactions of the Royal Society of South Africa 33 (1), 53–91.

De Jonge, V.N., Elliott, M., Orive, E., 2002. Causes, historical development, effects and future challenges of a common environmental problem: eutrophication. Hydrobiologia 475 (476), 1–19.

Deaton, L.E., Greenberg, M.J., 1986. There is no horohalinicum. Estuaries 9 (1), 20–30.

DEH-GSA (Department of Environment and Government of South Australia), 2006. Draft Estuaries Policy and Action Plan. <http://www.environment.sa.gov.au/coasts/estuaries.html> (revision 21.02.06).

Den'gina, R.S., Sokolova, M.F., 1968. On the Species Composition of Zooplankton of Lake Ladoga. Biological Resources of Lake Ladoga. Nauka, Leningrad, pp. 117–129 (in Russian).

Dyer, K.R., 1996. The definition of the Severn estuary. Proceedings of the Bristol Naturalists' Society 56, 53–66.

Elliott, M., McLusky, D.S., 2002. The need for definitions in understanding estuaries. Estuarine, Coastal and Shelf Science 55, 815–827.

Elliott, M., Quintino, V., 2007. The Estuarine Quality Paradox, Environmental Homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Marine Pollution Bulletin 54, 640–645.

European Communities, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities 43 (L327), 75.

Fairbridge, R.W., 1980. The estuary: its definition and geochemical role. In: Olausson, E., Cato, I. (Eds.), Chemistry and Geochemistry of Estuaries. John Wiley, New York, pp. 1–35.

Gasiūnaitė, Z.R., 2000. Coupling of the limnetic and brackish water plankton crustaceans in the Curonian Lagoon (Baltic Sea). International Review of Hydrobiology 85, 653–661.

Golubkov, S.M., Alimov, A.F., Telesh, I.V., Anokhina, L.E., Maximov, A.A., Nikulina, V.N., Pavel'eva, E.B., Panov, V.E., 2003. Functional response of midsummer planktonic and benthic communities in the Neva Estuary (eastern Gulf of Finland) to anthropogenic stress. Oceanologia 45 (1), 53–66.

Gordeev, V.V., 1983. River Drainage to the Ocean and Its Hydrochemical Features. Nauka, Moscow, p. 160 (in Russian).

Hedgpeth, J.W., 1959. Some preliminary considerations of the biology of inland mineral waters. Archivio di Oceanografia e Limnologia 11 (Suppl.), 111–141.

Hernroth, L., Ackefors, H., 1979. The Zooplankton of the Baltic Proper. A Long-Term Investigation of the Fauna, Its Biology and Ecology. Report to the Institute of Marine Research, p. 260.

Jay, D.A., Geyer, W.R., Montgomery, D.R., 2000. An ecological perspective on estuarine classification. In: Hobbie, J.E. (Ed.), Estuarine Science: A Synthetic Approach to Research and Practice. Island Press, Washington DC, pp. 149–176.

Ivanova, M.B., 1997. Influence of Active Water Reaction and Total Mineralization on the Zooplankton Community Formation in Lakes with Values of these Parameters Close to Extreme. Reaction of Lake Ecosystems on the Changing Biotic and Abiotic Conditions, St. Petersburg, pp. 71–86 (in Russian).

Ketchum, B.H., 1951. The flashing of tidal estuaries. Sewage and Industrial Wastes 23, 198–209.

Khlebovich, V.V., 1962. Peculiarity of water fauna composition in relation to the salinity of the medium. Zhurnal Obshchei Biologii 23 (2), 90–97 (in Russian).

Khlebovich, V.V., 1965. Physiology of Euryhalinity: Critical Salinity of the Environment and Inner Medium. Voprosy Gidrobiologii (Moscow), pp. 440–441 (in Russian).

Khlebovich, V.V., 1968. Some peculiar features of the hydrochemical regime and the fauna of mesohaline waters. Marine Biology 2 (1), 47–49.

Khlebovich, V.V., 1969. Aspects of animal evolution related to critical salinity and internal state. Marine Biology 2 (4), 338–345.

Khlebovich, V.V., 1974. The Critical Salinity of Biological Processes. Nauka, Leningrad, p. 236 (in Russian).

Khlebovich, V.V., 1986. On biological typology of the estuaries of the USSR. Proceedings of the Zoological Institute Academy of Sciences USSR 141, 5–16 (in Russian, English summary).

Khlebovich, V.V., 1990. Some physico-chemical and biological phenomena in the salinity gradient. Limnologica (Berlin) 20 (1), 5–8.

Khlebovich, V.V., 2007. Levels of homeostasis. Priroda (Moscow) 2, 61–65 (in Russian, English summary).

Kinne, O., 1971. Salinity – animals – invertebrates. In: Kinne, O. (Ed.), Marine Ecology, vol. 2 (part 2). Wiley Interscience, London, pp. 822–995.

Lisitzin, A.P., 1999. The continental-ocean boundary as a marginal filter in the World Oceans. In: Gray, J.S., Ambrose, W., Jr., Szaniawska, A. (Eds.), Biogeochemical Cycling and Sediment Ecology. Kluwer Academic Publishers, Dordrecht, pp. 69–103.

McLusky, D.S., Elliott, M., 2004. The Estuarine Ecosystem: Ecology, Threats and Management, third ed. University Press, Oxford. p. 214.

McLusky, D.S., Elliott, M., 2007. Transitional waters: a new approach, semantics or just muddying the waters? Estuarine, Coastal and Shelf Science 71, 359–363.

Meire, P., Vincx, M. (Eds.), 1993. Marine and estuarine gradients. Netherlands Journal of Aquatic Ecology 27, 71–496.

Morris, A.W., Mantoura, R.F.C., Bale, A.J., Howland, R.J.M., 1978. Very low salinity regions of estuaries: important sites for chemical and biological reactions. Nature 274 (5672), 678–680.

Olenin, S., 2005. Invasive Aquatic Species in the Baltic States. Klaipeda, p. 42.

Pethick, J.S., 1993. Shoreline adjustments and coastal management: physical and biological processes under accelerated sea level rise. The Geographical Journal, 162–168.

Pravdič, V., Jednačak-Biscan, J., Juracič, M., 1981. Physico-Chemical Parameters Describing the Role of Particulate Material in Estuarine Waters. River Inputs to Ocean System. UNEP and UNESCO, Switzerland. pp. 188–196.

Pritchard, D.W., 1967. What is an estuary: a physical viewpoint. American Association for the Advancement of Science 83, 3–5.

Remane, A., 1934. Die Brackwasserfauna. Zoologischer Anzeiger 7 (Suppl.), 34–74.

Remane, A., Schlieper, C., 1971. Biology of Brackish Water, second revised ed. John Wiley and Sons Inc., New York – Toronto – Sydney. p. 372.

Schiewer, U., 2002. Recent changes in northern German lagoons with special reference to eutrophication. In: Schernewski, G., Schiewer, U. (Eds.), Baltic Coastal Ecosystems: Structure, Function and Coastal Zone Management. Springer-Verlag, Berlin, pp. 19–30.

Schlieper, C., 1958. Physiologie des Brackwassers. Die Binnengewässer 22, Stuttgart, pp. 217–348.

Silina, N.I., 1997. Zooplankton and its participation in the biotic turnover. In: Davidan, I.N., Savchuk, O.P. (Eds.), International Project "Baltica", Issue 5: Ecosystem Models. Assessment of the Modern State of the Gulf of Finland, Gidrometeoizdat, St. Petersburg, pp. 390–404 (in Russian).

Telesh, I.V., 1987. Planktonic rotifers and crustaceans. In: Winberg, G.G., Gutelmakher, B.L. (Eds.), Neva Bay: Hydrobiological Investigations. Nauka, Leningrad, pp. 81–103 (in Russian).

Telesh, I.V., 1996. Species composition of planktonic Rotifera, Cladocera and Copepoda in the littoral zone of Lake Ladoga. Hydrobiologia 322, 181–185.

Telesh, I.V., 2001. Zooplankton studies in the Neva Estuary (Baltic Sea): a brief excursion into history. Proceedings of the Estonian Academy of Sciences, Biology and Ecology 50, 200–210.
Telesh, I.V., 2004. Plankton of the Baltic estuarine ecosystems with emphasis on Neva Estuary: a review of present knowledge and research perspectives. Marine Pollution Bulletin 49 (3), 206–219.
Telesh, I.V., 2006a. Impact of biological invasions on the diversity and functioning of zooplankton communities in the Baltic estuarine ecosystems (a review). Izvestiya Samarskiy Scientific Center RAS 8, 220–232 (in Russian).
Telesh, I.V., 2006b. Species Diversity and Functioning of Zooplankton Communities in Lakes, Rivers and Estuaries. Abstract of the Doctoral Dissertation. St. Petersburg, p. 45 (in Russian).
Telesh, I.V., Heerkloss, R., 2002. Atlas of Estuarine Zooplankton of the Southern and Eastern Baltic Sea. Part I: Rotifera. Verlag Dr. Kovač, Hamburg. p. 90 (with CD).
Telesh, I.V., Heerkloss, R., 2004. Atlas of Estuarine Zooplankton of the Southern and Eastern Baltic Sea. Part II: Crustacea. Verlag Dr. Kovač, Hamburg. p. 118 (with CD).
Telesh, I.V., Golubkov, S.M., Alimov, A.F., 2008. The Neva estuary ecosystem. In: Schiewer, U. (Ed.), Ecology of Baltic Coastal Waters, Ecological Studies 197. Springer-Verlag, Berlin Heidelberg, pp. 259–284.
Telesh, I., Postel, L., Heerkloss, R., Mironova, E., Skarlato, S., 2009. Zooplankton of the Open Baltic Sea: Extended Atlas. BMB Publication 21 – Meereswissenschaftliche Berichte 76, Warnemünde, pp. 1-290.
Van Beusekom, J.E.E., de Jonge, V.N., 1994. The role of suspended matter in the distribution of dissolved inorganic phosphate, iron and aluminium in the Ems estuary. Netherlands Journal of Aquatic Ecology 28 (3–4), 383–395.
Venice System, 1959. Symposium on the classification of brackish waters, Venice, April 8–14, 1958. Archivio di Oceanografia e Limnologia 11 (Suppl.), 1–248.
Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems, third ed. Academic Press. p. 1006.
Wittig, H., 1940. Über die Verteilung des Kalziums und der Alkalini i9n der Ostsee. Kieler Meeresforschung, Bd. 3 Hf 2, 460–496.
Zenkevitch, L.A., 1959. The classification of brackish-water basins as exemplified by the seas of the USSR. Archivio di Oceanografia e Limnologia 11, 53–61.