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Macrophyte thicket ecosystems in the Neva Bay: a response to hydraulic construction impact

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The first stage results (2016–2020) of the scientific research programme of macrophyte thickets ecosystems (so-called "reed beds") in the Neva Bay of the Gulf of Finland have been summed up. The programme is carried out by the environmental design company "Eco-Express-Service" LLC (initiator, coordinator, sponsor and main executor) with the participation of a group of St. Petersburg biologists. Observations are carried out at 16 model parcels of thickets (the area of each plot is about 1 km^2). Maps of phytocenoses, fish spawning places, migratory stopovers for aquatic and semi-aquatic birds, as well as summary maps of the resulting ecological value were compiled.

According to main indicators, the macrophyte thickets ecosystems that have appeared before and during Saint Petersburg Flood Prevention Facility complex construction (1979–2011) turned out to be the most environmentally valuable. The last ones have some advantages, since they are still less dense, more mosaic, and therefore available for fish and birds settlement not only along the periphery of plant massifs, but also inside them. Younger thickets that have appeared in new biotopes in the past decade are much less actively used by the biota, but they represent a valuable reserve for future macrophyte thickets ecosystems. The sensitivity of macrophyte thickets to hydraulic works and their consequences increases with the age of thickets: the youngest ecosystems formed under the conditions of technogenic impact are the most resistant. On the whole, it should be noted that macrophyte thickets are highly resistant to hydraulic works, except their direct mechanical destroying. The projective cover degree of biotopes by vegetation depend much less on the ongoing hydraulic works, than on the general trend of its technogenic succession.

Keywords: macrophytes thickets, reed bed, Neva Bay, Eastern part of the Gulf of Finland, hydraulic works, aerial survey.

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Зарослевые экосистемы Невской губы: реакция на гидростроительство

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Подведены итоги первого этапа (2016–2020 гг.) научной программы комплексных исследований экосистем макрофитных зарослей (так называемых «плавней») Невской губы Финского залива. Программа выполняется эколого-проектной компанией «Эко-Экспресс-Сервис» (инициатор, координатор, спонсор и основной исполнитель) при участии группы санкт-петербургских биологов. Наблюдения ведутся на 16 эталонных участках плавней (площадь каждого – около 1 км^2). Составлены карты фитоценозов, нерестилищ рыб, миграционных стоянок водоплавающих и околоводных птиц, а также сводные карты результирующей экологической ценности.

По всем основным показателям наиболее экологически ценными оказались плавни, возникшие ещё до начала сооружения комплекса защитных сооружений Санкт-Петербурга от наводнений или в ходе его строительства

(1979–2011 гг.). Последние имеют некоторые преимущества, поскольку пока ещё менее плотны, более мозаичны и потому доступны для освоения рыбами и птицами не только по периферии растительных массивов, но также и внутри их. Более молодые заросли, возникшие в новых биотопах в истекшее десятилетие, используются биотой значительно менее активно, однако представляют собой ценный резерв будущих полноценных плавней. Чувствительность зарослевых экосистем к гидротехническим работам (ГТР) и их последствиям закономерно возрастает с возрастом плавней: наиболее молодые экосистемы, сформировавшиеся в условиях техногенного воздействия, наиболее к нему устойчивы. В целом же следует отметить высокую устойчивость макрофитных зарослей к воздействию ГТР, за исключением их прямого механического уничтожения. Показатели проективного покрытия биотопов растительностью зависят от ведущихся ГТР гораздо меньше, чем от общего хода её техногенной сукцессии.

Ключевые слова: заросли макрофитов, плавни, Невская губа, восточная часть Финского залива, гидротехнические работы, аэрофотосъёмка.

The aquatic vegetation of shallow waters in the Neva Bay (NB) and Eastern Gulf of Finland (EGoF) create special ecosystems (reed beds). Their environmental role is important and multifaceted. They stabilize the shore and coastline soils, favour for purifing waters, serve as edificators and regulator of diverse zoocenoses. Many fish species spawn here, in macrophyte thicket ecosystems, and then juveniles immediately grow up there [1–5].

Aquatic and semi-aquatic birds use macrophyte thicket ecosystems for their life existence, nesting and rest during seasonal migrations [6–10]. The Neva Bay is one of the most important water areas in the North-West of Russia in this regard [11–13]. This is the place where main branches of the White Sea – Baltic migration route converge. The rest in shallow water areas of the Neva Bay during migrations (especially spring) is very important and vital for aquatic and semi-aquatic birds. This is the key to their successful further flight to the harsh northern conditions of the north and north-west of the European part of Russia. Therefore, the protection of resting places for migratory birds there has global and priority environmental importance. As a result, numerous specially protected natural areas of the Neva Bay are primarily focused on this task and are confined precisely to shallow waters overgrown with macrophytes.

Hydraulic and construction works in EGoF have actively been carried out during last decades. Firstly, the largest and most influential for the ecosystem of the Neva Bay object should be mentioned – the Saint Petersburg Flood Prevention Facility complex (FPFC) [14, 15]. Moreover, new port complexes have been created there. Plural artificial land plots have arisen and now are creating. New approach navigation channels have been constructed. Since both old and new navigation canals are constantly being covered with soil, their operation also requires regular dredging.

It is clear that all these processes have a more or less negative impact on the marine environment, including macrophyte thickets. The key factors for the biota of thickets are seabed violation (biotopes destruction) and sedimentation. At the same time, macrophyte thicket ecosystems can lose their functions listed above, which are significant regionally and even globally [16, 17].

The closer a specific macrophyte thickets area is to the place of hydraulic works, the stronger and more obvious their negative impact is. However, actually this influence has a more complex and ambiguous character, which manifests when the spatial scales of its assessment change. Thus, the FPFC construction changed the local hydrological regime and led to the active growth of macrophyte thickets [2, 18, 19].

The mechanism of this peculiar autocompensation of macrophyte thickets resources has not been sufficiently studied. It is only clear that the final balance of negative, neutral and positive effects of hydraulic construction for macrophyte thicket ecosystems is dynamic, complex, spatially extremely heterogeneous and varies significantly depending on spatial limits of the assessment [20, 21].

This manuscript presents some results of a comprehensive research programme "Macrophyte thicket ecosystems of the Neva Bay". This programme is developed, being coordinated and implemented by the environmental design company "Eco-Express-Service" with the participation of experts from leading scientific organizations of St. Petersburg.

The main purpose of the work was to assess the resources of macrophyte thicket ecosystems of the Neva Bay and to identify the patterns of their technogenic dynamics.

Materials and methods

A system of so-called "model parcels" of macrophyte thickets was developed and used in

order to solve these tasks. These areas were selected according to the concept that complex of model parcels should reflect all main possible combinations of the following three factors gradations: vegetation age; technogenic impact degree; location: near FPFC (as the main environment-forming hydraulic structure for the studied water area) or far from it (i. e. outside of its direct impact).

Three thicket age gradations were studied (examples at Figure 1): 1 – thickets that have been formed before the FPFC construction ("old macrophyte thicket ecosystems"); 2 – thickets that have appeared during FPFC construction (1979–2011 [10]) ("middle–aged"); 3 – thickets that have appeared after the FPFC was fully built and put into operation.

Hydraulic works impact level (both ongoing and already completed, but retaining their aftereffect on the ecosystem) was also divided into three gradations: a – strong; b – moderate, but significant; c – not reliably distinguishable from the general background anthropogenic impact.

Finally, the names of model parcels located far from FPFC and near it include capital letters A and B, respectively.

It turned out that 14 out of 18 theoretically possible combinations of these factorial gradations really exist (Table). The area of each model parcel is about 1 km^2. Moreover, two additional model parcels of the same size characterized by the maximum biodiversity indicators were observed (16 plots in total). All model parcels were observed according to a unified general scheme annually, starting from 2016 (Figure 2, see color insert IV).

An environmental monitoring of model parcels system included 3 comprehensive assessments per year. All main characteristics that determine a value of "ecosystem services" were evaluated every year at each model parcel: indicators of aquatic vegetation state, hydrological, hydrochemical, hydrobiological, ornithological, and ichthyological indicators as well. Moreover, vegetation observations using a quadcopter were also carried out. They covered not only model parcels, but also the surrounding vegetation with a total area of more than 35 km^2.

Results and discussion

At present, results about aquatic vegetation, avifauna and juveniles of phytophilous fish species can already be presented.

Aquatic vegetation. "Old" macrophyte thickets (appeared before the construction of the FPFC began) have a well–defined zonal distribution. They are usually formed by single-layer and multilayer macrophyte groups with a predominance of 2–3-layered vegetation zones. Mostly these thickets are dense and stable. Possibilities for their further expansion have been exhausted.

These thickets are characterized by the largest projective cover degree of the water surfaces (PCW) (far from FPFC – up to 71%, near FPFC – up to 66%). At the same time, submerged vegetation far from FPFC is mainly refer to

1 2 3

Fig. 1. Characteristic macrophyte communities of three identified age gradations (explanations in the text)

Table

A matrix of 14 realized combinations of macrophyte thickets' age, technogenic impact level and location relative to the FPFC

Factors gradations	A			B		
	a	b	c	a	b	c
1	A1a	A1b	A1c	—	B1b	—
2	A2a	A2b	A2c	—	B2b	—
3	A3a	A3b	A3c	B3a	B3b	B3c

Note: cells indicate corresponding names of the established model parcels; a blank – the hypothetical combination has not been implemented.

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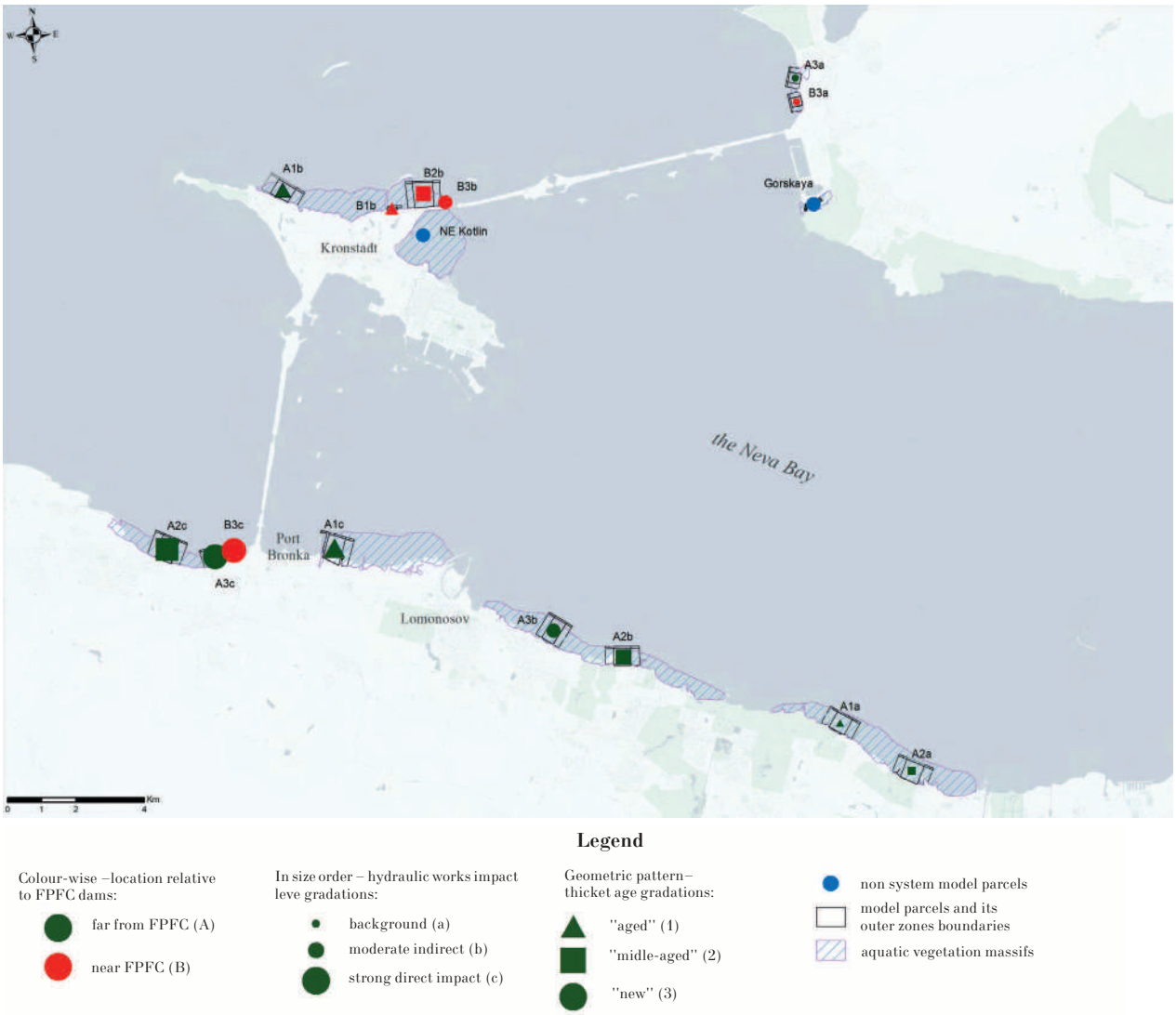
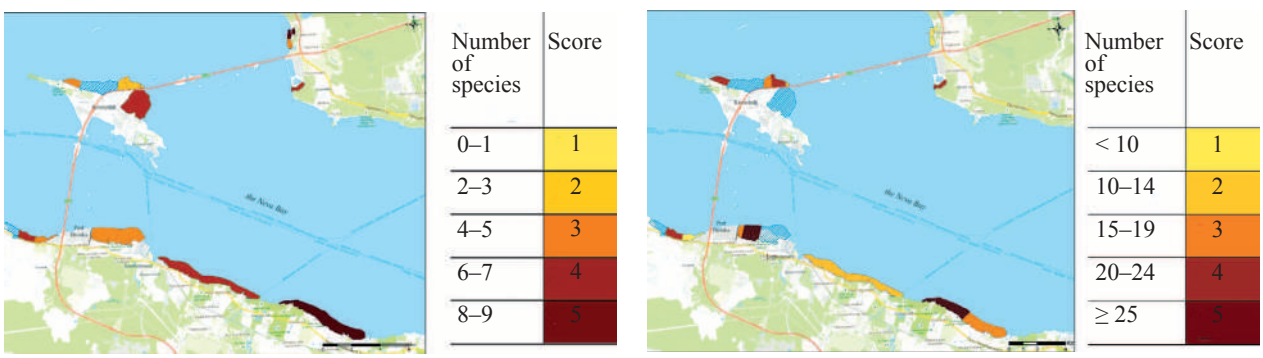


Fig. 2. System of model parcels



a b

Fig. 3. Examples of macrophyte thickets zoning results according to their fishery (a) and ornithological (b) value: a – a score assessment of the studied spawning areas according to fish juveniles species richness, b – a total number of bird species recorded during spring migrations (scores)

semi-submerged vegetation with floating leaves and occupies little additional area. However, the projective cover degree of the bottom (PCB) near FPFC is supplemented by submerged vegetation significantly, locally exceeding 98%. Additional projective cover degree of the bottom by submerged vegetation (PCad = PCB – PCW) far from FPFC is maximum up to 25%, near FPFC – up to 33%.

Projective cover degrees (both PCW and PCB) are the most stable at "old" macrophyte thickets, ranges of projective cover degree temporal changes are minimal over the entire observation period.

It should be also noted their unexpectedly high resistance to anthropogenic impact, apart from a direct mechanical extermination: indicators of projective cover degree do not almost depend on the impact level.

"Middle-aged" macrophyte thickets (formed during the FPFC construction) are perennial equilibrium-succession macrophyte communities with a predominance of simple 1–2-layered vegetation groups. A density and homogeneity of these thickets is less than old macrophyte thickets have, but gradually increases. They continue to expand, occupying the surrounding biotopes.

"Middle–aged" macrophyte thickets at a "background" level of technogenic impact are comparable to "old thickets (PCW up to 65%) in terms of projective cover degree, however, PCW of "middle-aged" macrophyte thickets are significantly less than "old" ones at "moderate" and "strong" impacts (PCW far from FPFC is not more than 31%).

Submerged vegetation extends rather far beyond spatial limits of semi-submerged vegetation and vegetation with floating leaves and occupies a larger additional area than in case of "old" thickets (PCW and PCB differ more significantly). Additional projective cover degree of the bottom by only submerged vegetation (PCad) for thickets far from FPFC is up to + 16%, and near FPFC – up to 73% in some places.

The temporal stability of projective cover degree is much less than in case of "old" thickets, ranges of projective cover degree temporal changes are higher.

"New" (or "young") macrophyte thickets (formed after the completion of FPFC construction) are perennial pioneer macrophyte communities with a predominance of simple 1-layered vegetation groups. They occupied a small percent of suitable biotopes and actively expand.

They are characterized by the smallest projective cover degree – both by dominants (which are poor here) and total projective cover degree.

Projective cover degree of the water surfaces (PCW) is minimal: it varies from 2 to 12% in thickets far from FPFC and from 2 to 25% in thickets near FPFC.

Projective cover degree by submerged vegetation here is much higher than by semi-submerged vegetation (PCB exceeds PCW 1.5–4 times in thickets far from FPFC and by 2–7 times in thickets near FPFC). Additional projective cover degree of the bottom by only submerged vegetation (PCad) in thickets far from FPFC reaches + 29% in some places, and in thickets near FPFC – up to + 23%.

The temporal variability of projective cover degree is maximum for "new" thickets (a range of PCB fluctuations is equal to or exceeds average values).

Submerged vegetation is less sensitive than semi-submerged vegetation in case of hydraulic works impact and recovers faster. Moreover, even a weakly expressed direct dependence on the hydraulic impact level is characteristic for "new" thickets.

As a whole, the projective cover degree of the water surface (PCW) is in a clear direct relationship with the thickets age.

The additional projective cover degree of the bottom by submerged vegetation demonstrates an inverse dependence on thickets age and a direct dependence on proximity to FPFC.

Fish juveniles. The most productive spawning areas of phytophilous fish species were revealed, mapped and studied at Strelna, Znamenka, Peterhof, Limuzi, in the mouth part of the bay near Gorskaya station and on Kotlin Island, at thickets on the northwestern coast of Kotlin Island and in the area of the 1st Northern Fort, as well as a macrophyte thicket model parcel of adjoining reservoir in Aleksandrovskaya Bay (example at Figure 3a, see color insert IV).

The greatest impact on fish juveniles relative abundance distribution within thickets model parcels and between different types of massifs can be made by bottom sediments type, the presence of *Nuphar lutea* (L.), *Stratiotes aloides* L. and abundance of filamentous algae (mostly species from the division Chlorophyta) and of filamentous Cyanobacteria in the plant communities, thickets age and projective cover degree, as well as a model parcels location relative to hydraulic works impact degree.

"Old" and "middle-aged" thickets were found to be the most attractive for the spawning of phytophilous fishes. "Middle–aged" thickets are characterized by greater accessibility of an inner part of vegetation massif, give the greatest

spawning surface and rather effective shelters for juveniles. Since "old'' thickets are the densest, most fish species (partial except for *Gasterosteus aculeatus* L.) can use only their external border for spawning. "New'' thickets, on the contrary, are still not dense enough and can't provide a sufficient spawning substrate. They are suitable mainly only for juveniles fattening.

A number of regularities have been established for various phytophilous fish species juveniles' spawning and feeding characteristics distribution over thickets of different age, structure and different levels of anthropogenic impact. The influence of various soil and vegetation characteristics on spawning rates is being studied.

Avifauna. The use of macrophyte thickets by aquatic and semi-aquatic birds during seasonal migrations and nesting was studied (example at Figure 3b, see color insert IV). According to four-year observation results, some conclusions can be characterized by significant interannual differences, spatio-temporal dynamics of bird communities and a probabilistic nature of discrete observations results.

Unfortunately, the Neva Bay is gradually losing its value as a place of one of the most important migratory stopovers for aquatic and semi-aquatic birds on the White Sea – Baltic migration route due to the anthropogenic transformation of the water area and coasts. Birds' abundance there gradually continues to decline in spring. And probably it has never been very high in autumn in recent decades.

At the same time, spring stopovers are still important for birds migrating to taiga and Arctic Region. Spring stopovers remain more numerous and rich in species than autumn ones.

Littoral macrophyte thickets remain the most important nesting place for many species of semi-aquatic birds in summer. A species diversity of birds breeding in thickets is great, and many rare, protected species are bringing out nestlings in the Neva Bay (including model parcels).

"Old" macrophyte thickets were the most attractive for birds at all stages of the annual cycle (during both the nesting period and seasonal migrations). "Middle-aged" macrophyte thickets were also used by aquatic and semi-aquatic birds and turned out to be quite comparable with the "old" ones according to a number of indicators. Their advantage apparently is a lower density and a presence of open water gaps there. It makes "middle-aged" macrophyte thickets more convenient for birds taking off and landing, as well as getting food. "New" macrophyte thickets almost did not attract aquatic and semi-aquatic birds.

The model parcel adjacent to the port Bronka was significantly inferior to other "old" and "middle-aged" parcels in according with all indicators. The port Bronka impact on birds has a local character, more or less appears in a radius of 200 m from its boundaries, and requires special further researches. No negative impact of the FPFC dam and its economic activities on birds has been identified.

Conclusions

Obtained results summary confirm that "middle-aged" macrophyte thickets (formed during the FPFC construction) are already comparable to the "old" thickets in terms of the level of "ecosystem services" or even prevail them due to the greater variety of conditions they create. This is facilitated to a large extent by the lower density of "middle-aged" macrophyte thickets, the significantly greater angularity of their boundaries, and the abundance of gaps with open water inside the plant massifs. It makes them more convenient both for birds (takeoff and landing, foraging, nesting are facilitated) and for phytophilous fish species (access for spawning and for juveniles within the massif, and not only along its periphery, is facilitated). "New", recently emerged thickets are a promising resource for macrophyte thickets, but they still almost do not attract aquatic and semi-aquatic birds at this stage of their development. They are also used sporadically by fish and so far only for growing period of juveniles, but not for spawning.

Finally, we noted one more significant result. In fact, a very important precedent has been created – a large, comprehensive scientific and research environmental programme was independently proposed, developed and is being implemented by a non-governmental company with the involvement of leading specialists from specialized government organizations. Hopefully, this will serve as a useful example for environmentally responsible business and attract followers.

The results of the first stage of the programme implementation are presented in detail in the monograph [22].

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