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The Gulf of Finland assessment

Mika Raateoja and Outi Setälä (eds)

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ABSTRACT

This assessment on the environmental state of the Gulf of Finland in 1996 – 2014 was produced by together over 100 scientists from Estonia, Finland, and Russia in the context of the Gulf of Finland Year 2014. The thematic year aimed at – and succeeded in – giving additional value for the protection and restoration of the Gulf of Finland environment by enhancing political presence and interaction between the private sector, decision-makers, and citizens.

This assessment concentrates on the past development and the current state of the Gulf of Finland environment and pressures affecting it. The themes include climate in the Gulf of Finland area, Gulf of Finland physics, geology and geodiversity, eutrophication, hazardous substances, biodiversity, fishes and fisheries, non-indigenous species, marine litter, underwater soundscape, maritime traffic and its safety, and environmental valuation. Each chapter also delivers expert opinions and recommendations for the future.

Keywords: Gulf of Finland, Finland, Estonia, Russia, trilateral cooperation, state, environmental state, long-term development, long-term trend, eutrophication, nutrients, loading, hazardous substances, environment health, marine litter, plastic litter, microplastic, underwater sound, maritime traffic, Gulf of Finland Year, biodiversity, geology, geodiversity, environmental valuation, environmental economics, fish, fishery, fisheries, alien species, non-indigenous species, hydrography, climate.

TIIVISTELMÄ

Yhteensä yli sata suomalaista, venäläistä ja virolaista tutkijaa on osallistunut tämän Suomenlahden ympäristön tilaa vuosina 1996–2014 koskevan arvioinnin tuottamiseen. Arvio kokoaa yhteen Suomenlahti 2014 -teemavuoden tulokset. Teemavuoden tavoitteena oli kiinnittää poliittista huomiota Suomenlahden ympäristön suojeluun sekä parantaa yhteistyötä yksityisen sektorin, päättäjien ja kansalaisten välillä. Tavoite myös saavutettiin: ymmärrys meren tilasta ja toiminnasta sekä meren tilaa parantavista toimista lisääntyi.

Arviointi keskittyy Suomenlahden ympäristön tilan kehitykseen ja nykytilaan sekä niihin paineisiin, joita merialueeseen kohdistuu. Teemoja ovat mm. Suomenlahden alueen ilmasto, Suomenlahden fysikaaliset ja geologiset ominaisuudet, rehevöityminen, haitalliset aineet, luonnon monimuotoisuus, kalat ja kalastus, vieraslajit, meren roskaantuminen, merenalainen äänimaailma, meriliikenne ja sen turvallisuus sekä ympäristön arvottaminen. Kappaleissa on myös asiantuntijoiden kommentteja ja suosituksia meren tilan parantamiseen.

Asiasanat: Suomenlahti, Suomi, Viro, Venäjä, kolmikanta, tila, ympäristön tila, pitkäaikaiskehitys, pitkäaikaissarja, rehevöityminen, ravinne, kuormitus, haitalliset aineet, ympäristön terveys, meriroska, muoviroska, mikromuovi, vedenalainen ääni, meriliikenne, Suomenlahtivuosi, biodiversiteetti, monimuotoisuus, geologia, geodiversiteetti, ympäristön arvo, ympäristöekonomia, kala, kalastus, vieraslaji, ilmasto

SAMMANDRAG

Denna bedömning av miljöns tillstånd i Finska viken åren 1996–2014 gjordes i samarbete mellan över 100 forskare från Estland, Finland och Ryssland under Finska vikens år 2014. Målet med temaåret – vilket också uppnåddes – var att främja skyddet och återställandet av miljön i Finska viken genom att öka den politiska närvaron och samarbetet mellan den privata sektorn, beslutsfattarna och medborgarna.

I denna bedömning fokuserar man på den tidigare utvecklingen och det nuvarande läget av miljön i Finska viken samt de miljötryck som påverkar havsområdet. Teman som tas upp är klimatet i området kring Finska viken, Finska vikens fysik, geologi och geodiversitet, övergödning, farliga ämnen, biodiversitet, fiskarter och fiske, främmande arter, marin nedskräpning, undervattensljudlandskapet, sjöfarten och dess säkerhet samt miljövärderingen. Varje kapitel innehåller även expertutlåtanden och rekommendationer för framtiden.

Nyckelord: Finska viken, Finland, Estland, Ryssland, trilateralt samarbete, tillstånd, miljöns tillstånd, långsiktig utveckling, långsiktig trend, eutrofiering, närsalter, belastning, farliga ämnen, miljöhälsa, marint skräp, plastskräp, mikroplast, undervattensljud, sjöfart, Finska vikens år, biodiversitet, geologi, geodiversitet, miljövärdering, miljöekonomi, fisk, fiskeri, främmande arter, icke-inhemska arter, hydrografi, klimat.

KOKKUVÕTE

Hinnang Soome lahe keskkonnaseisundile aastatel 1996-2014 koostati 2014. Aastal Soome lahe teema-aasta kontekstis enam kui 100 Eesti, Soome ja Venemaa teadlase koostöös. Teema-aasta eesmärk, mis edukalt täideti, oli anda lisaväärtust Soome lahe keskkonna kaitsmisele ja taastamisele suurendades poliitilist kohalolekut ja suhtlust erasektori, otsustajate ja kodanike vahel.

Hinnangu puhul on keskendutud Soome lahe keskkonna varasematele arengutele, praegusele olukorrale ning mõjuteguritele. Käsitletud teemade hulgas on Soome lahe piirkonna kliima, Soome lahe füüsikaline ja geoloogiline mitmekesisus, eutrofeerumine, ohtlikud ained, bioloogiline mitmekesisus, kalad ja kalandus, võõrliigid, merepraht, veealune helimaastik, mereliiklus ja selle ohutus, keskkonna hindamine. Igas peatükis sisalduvad ekspertarvamused ning soovitused tulevikuks.

Võtmesõnad: Soome laht, Soome, Eesti, Venemaa, kolmepoolne koostöö, seisund, keskkonnaseisund, pikaajaline areng, eutrofeerumine, toitained, koormus, ohtlikud ained, keskkonnatervis, mereprahi, plastpraht, peened plastosakesed, veealune müra, laevaliiklus, Soome lahe aasta, bioloogiline mitmekesisus, geoloogia, geoloogiline mitmekesisus, keskkonnahindamine, keskkonnasäästlik majandus, kalad, kalapüük, kalandus, võõrliigid, sissetungivad liigid, hüdrograafia, kliima

РЕЗЮМЕ

Данная оценка состояния окружающей среды Финского залива в 1996 – 2014 гг. была совместно подготовлена более чем ста учеными из Эстонии, Финляндии и России в рамках проекта «Год Финского Залива-2014». Цель тематического года, которая в итоге была достигнута, состояла в том, чтобы принять дополнительные меры по защите и восстановлению окружающей среды Финского залива путем увеличения политического взаимодействия между частным сектором, директивными органами и местными жителями.

В этом отчете содержатся сведения о прошлом развитии и текущем состоянии окружающей среды Финского залива, а также приводятся факторы, влияющие на нее. Темы отчета включают климат в районе Финском заливе, физические характеристики залива, геологию и геологическое разнообразие, сведения об эвтрофикации, опасных веществах, биоразнообразии, рыбах и рыбном промысле, чужеродных видах-вселенцах, загрязнении моря мусором, шумовом фоне в море, морском трафике и его безопасности, а также оценку стоимости объектов окружающей среды. Кроме того, в каждом разделе представлены мнения и рекомендации экспертов на будущее.

Ключевые слова: Финский залив, Финляндия, Эстония, Россия, трехсторонне сотрудничество, состояние, экологическое состояние, долгосрочное развитие, эвтрофикация, биогенные вещества, нагрузка, опасные вещества, здоровье окружающей среды, морской мусор, микромусор, микропластик, подводный шум, морские перевозки, Год Финского залива, биоразнообразие, геология, георазнообразие, экологическая оценка, экономика природопользования, рыбы, рыболовство, рыбное хозяйство, чужеродные виды, вселенцы, гидрография, климат.

EXTENDED SUMMARY

The main findings of this assessment are reported here in a nutshell.

Climate in the Gulf of Finland area

The Baltic Sea is located between marine temperate and continental sub-arctic climate zones. The moist and relatively mild marine air mass from the North Atlantic and the Russian continental air mass counteract with each other and produce the highly variable climate in the Baltic area.

The latest Major Baltic Inflow through the Danish Straits appeared in December, 2014. In the end, the inflown waters did not reach the Gulf of Finland (GOF). However, the old stagnant waters occurring in the deeps of the Northern Gotland Basin were pushed forward, and consequently, waters rich in nutrients and poor in oxygen were observed in the deepest layers of the western GOF in January, 2016. By the end of May, 2016, however, the deep water condition had returned to quite average one, and thus the boosting effect of this process on the algal biomasses of the GOF will most likely be moderate.

An interannual variation in the seasonal maximum ice extent in the GOF was considerable, and there was no clear trend in the severity of winters in the GOF area during the assessment period. Nor was there any trend to note in the average sea level in the GOF. An increasing trend was noted in the river runoff during the assessment period. Runoff was, however, abnormally low in 2003, which had its consequences, e.g., in the eastern GOF. The total nitrogen load from the catchment followed the pattern in the river runoff, and hence, has not decreased during the assessment period.

Gulf of Finland physics

The GOF has intrinsic characteristics to experience deep-water oxygen deficiency driven by hydrographic features. In the western and middle GOF, the salinity stratification has strengthened in the deep areas since the 1990's due to an increase in the near-bottom salinity. Having a halocline in these areas has become more a rule than an exception during the assessment period. This, in turn, has increased the occurrence of hypoxic events in these areas.

Because the northern part of the GOF is shallower, the near-bottom oxygen conditions are generally better there than in the deeper southern part. However, in isolated trenches oxygen conditions can be poor in the northern GOF, too. In 2014, the oxygen-poor waters originating from the Northern Gotland basin entered deep into the middle GOF. Consequently, the waters of the GOF below the depth of 70 m were hypoxic or anoxic from spring to autumn, while in the shallower areas the conditions were normoxic.

Prevailing circulation pattern in the GOF – an eastward flow in the southern GOF and a westward flow in the northern GOF – is based on the prevailing wind direction from south-west and on earth rotation, but is not a constant feature. Instantaneous currents almost totally mask the long-term mean circulation pattern.

In the deep layer of the GOF, an obvious reduction in pH took place in 1990–2010. The average reduction rate at the time period was about 0.02 units/year. The trend, however, levelled out after 2010.

Geology & geodiversity

The seafloor topography of the GOF is very diverse in the Baltic Sea scale. Topographically variable seafloor environment leads to patchy sediment distribution and supports heterogeneous habitats.

The Russian shoreline of the GOF suffers heavily from erosion; over 40% of the shores are seasonally eroded. Milder winters since 2004 with delayed freezing have increased the susceptibility of the coast for erosion, as storms hit the coast harder if sea ice is absent.

The recent hydro-technical activities in the Neva Bay have significantly disturbed sedimentation patterns and benthic communities of the eastern GOF. The system is very slowly reversing back to its state prior to alterations.

Heavy metal input into the GOF started to decline in the mid-1980's. Consequently, heavy metal concentrations in the sediment have generally declined during the recent decades. Despite this trend, there are still areas where concentrations are still relatively high.

Eutrophication

The eutrophication state of the GOF is amongst the highest of all basins of the Baltic Sea, but has generally shown a declining trend, especially after the early 2000's.

The total phosphorus load from the catchment has decreased, although irregularly; the point-source load since 2005 and the riverine load, preceded by a strong increase, since 2011. Especially the waste water management in St. Petersburg has influenced on the former, and the management of the industrial phosphorus inputs into the River Luga on the latter.

The changes in the land-based phosphorus load do not explain the large variation in the phosphorus stock in the GOF water. Water intrusions rich in phosphorus originating from the Northern Gotland basin and the benthic phosphorus processing play major roles in this variation. These processes are ultimately controlled by wind and air pressure patterns of the Baltic area.

The internal nutrient dynamics lead to highly variable nutrient conditions that strongly affect the trophic status of the GOF and have the potential to largely mask the effect of the land-based nutrient load reductions. In addition to the internal processes, the River Neva flow affect the nutrient status of the Neva Estuary. Consequently, the temporal patterns of both nitrogen and phosphorus in the water were characterized by large recurring fluctuations throughout the assessment period.

Decreasing phosphorus trends were observed in the Finnish coastal area and in the Neva Estuary since the early 2000's, while no phosphorus trends could be detected for the middle and western offshore GOF. Increasing nitrogen trends appeared in the western and middle offshore areas, although they levelled out in the late 2000's.

In many parts of the GOF, chlorophyll a concentration as a proxy for phytoplankton biomass increased in the late 1990's – the early 2000's as a manifestation of intensified benthic release of phosphorus. This development levelled out in the early 2000's and turned to a decrease during the assessment period due to decreasing deep water phosphorus storages. This appeared in the offshore waters, and especially in the Finnish coastal waters and the eastern GOF, where also decreased phosphorus loading contributed to the positive development.

Hazardous substances

Despite of the restrictions in use and observed declines in some of the monitored substances, the people around the GOF are still exposed to persistent hazardous substances, mainly due to fish consumption.

The levels of dioxin and dioxin-like PCBs in fish have decreased from the very high values of the past, but still may exceed the maximum allowable level for human consumption. Due to biomagnification in the food web the concentrations of mercury may also occasionally exceed the threshold levels for human food in large predatory fish. Furthermore, sprat and herring should not be used as feed in aquaculture without refinement.

Polybrominated diphenyl ethers (PBDE) and perfluorinated compounds (e.g., PFOS) as well as tributyltin (TBT) mainly occur in relatively low concentrations in fish, but the risks they pose are difficult to estimate due to scarce spatial and temporal data and no information on their biological effects. More hot-spots are likely to be found in the vicinity of cities and harbours. These compounds also currently lack maximum allowable concentrations in food.

The organotin concentrations in the sediment surface are lower than those measured in the 1980's – the 1990's. This is most likely caused by the combined effect of sedimentation of less-polluted material, and degradation and/or dissolution of the settled TBT.

Increased maritime traffic has resulted in frequent oil spills in the GOF but their number and volume have decreased in the recent past due to improved surveillance.

Only recently we have come to realize that pharmaceuticals are a highly relevant environmental issue in spite of the fact that their use and subsequent release in the environment has been continuous for decades. Hormones, anti-inflammatory drugs, and antidepressants, to name a few, have been found in the effluent waters of waste water treatment plants. Knowledge about their environmental fate and effects on the ecosystem is piling up slowly.

Biodiversity

Although the salinity range in the GOF limits a number of species inhabiting it, biodiversity is increased by the existence of various environmental gradients and high geodiversity, which creates an array of habitat types suitable for specific communities. Also, various human induced pressures create additional gradients across the GOF.

The late-summer total phytoplankton biomass predominantly increased between the two monitoring periods in 1980/1993–2005, and 2005–2014. Whether there was a decreasing trend in biomass during the most recent decade – alike in Chl *a* – could not be assessed because the former period included times prior to the phytoplankton biomass increase around the turn of the millennium.

Cyanobacterial biomasses were generally decreasing during the assessment period, and to a larger extent in the eastern GOF. Especially, the numbers of a cyanophyte *Nodularia spumigena* – an icon of eutrophication – have decreased compared to the level of the late 1990's – the early 2000's. For zooplankton, on the other hand, no major trends could be detected. The observed variations seem to be mostly caused by long-term oscillations in salinity.

A drastic community change has taken place in deep soft sediments. The Baltic clam *Macoma baltica*, the amphipods (*Monoporeia* and *Pontoporeia*), and the isopod *Saduria entomon* have disappeared from the deep bottoms of the GOF, and been replaced by a community almost entirely dominated by the non-indigenous polychaete *Marenzelleria* spp. The decline of the native community was not, however, caused by the invasion by *Marenzelleria*. More probably, the native community suffered from eutrophication and anoxia, while the hypoxia-tolerant *Marenzelleria* spp. is able to survive in these conditions. The native community has by far shown no sign of returning to the areas from where it once disappeared. The shallow water benthic communities of the GOF, in turn, are relatively well developed, and currently only locally affected by water quality issues.

Certain seabird species have increased markedly during the assessment period. The population of barnacle goose that has nested for instance in Finland only since 1981, has now increased to 4 000–5 000 pairs. The population increase has been particularly intense in the GOF. The great cormorant returned to the GOF as a breeding species after an absence of two centuries, and now the population has increased to about 6 000 pairs.

The numbers of grey seal and ringed seal are developing to opposite directions. In the early 1980's, the numbers of grey seal in the GOF were still low, but the population has been steadily recovering since then. Ringed seal was counted in thousands in the GOF in the 1980's, but the population suffered a dramatic decline in the 1990's due to poor breeding conditions. Harbour porpoise is very rarely sighted in the GOF and do not seem to form a viable population here.

Fisheries & the value of the Gulf of Finland

In the GOF, fishery has to a large degree compensated the weakened top-down control of pelagic fish by marine mammals and cod. This has led to changes in the pelagic fish community structure.

The changes in herring, sprat and cod stocks in the GOF depend on fishing pressure and changes in the ecosystem function both in the GOF and in the Gotland Basin. Cod is a predatory species, which, whenever abundant, is able to control the abundances of herring and sprat. Low abundance of cod and climatic conditions favorable for reproduction of sprat in the 1990's enabled an increase of sprat abundance in the GOF. Relatively high sprat and herring abundance compared to the zooplankton production induced a severe competition for food resources within and between these species. Consequently, weight-at-age of herring decreased substantially in the 1980's – the 1990's, and has remained at a low level since then. Weight-at-age of sprat decreased, too, but sprat abundance has remained at a relatively high level.

The state of wild salmon stocks in the GOF area is critical, mainly due to damming and other physical changes in the spawning rivers, eutrophication, and overfishing in the sea. Smolt (young salmon ready to migrate to the sea) releases are carried out to compensate for the lost natural reproduction. The number of smolts from natural reproduction in rivers draining into the GOF is currently only one tenth as compared to the releases of hatchery-reared smolts.

Ecosystem services denote benefits which people obtain from ecosystems. Valuation of ecosystem services is needed for sustainable use and conservation of the marine resources. In addition to catches, fish stocks support substantial recreational services, the value of which can greatly exceed the value of commercial catches. Valuation of these services is challenging since both provisioning service (fishery) and cultural service (recreational angling) should be taken into account.

The GOF ecosystem provides a huge number of other less tangible ecosystem services. Many of those, such as clean water for swimming and for other recreational purposes, are outcomes of complicated ecosystem processes. Even though assigning a value for these intermediate services is challenging, the final services that cannot be bought from shops, but of which consumers still enjoy, can be valued.

Non-indigenous species

The GOF is one of the highest risk areas in the Baltic Sea for non-indigenous species introductions. Although low salinity and temperature limit the number of successful establishments, a low number of native species and thus available ecological niches have facilitated establishments of alien species. Altogether 38 alien species have been recorded in the GOF. The GOF hosts various alien species from several taxonomic groups, including phytoplankton and zooplankton species as well as littoral shallow water invertebrates and fish.

There are two widely spread species in the GOF: a cladoceran *Cercopagis pengoi* and a polychaete *Marenzelleria* spp. *C. pengoi* was found in the GOF for the first time in 1992. Its abundance has increased from the 1990's to the present, and it is less abundant in the easternmost GOF. It affects the pelagic food web through effective predation on smaller zooplankton, food competition with native invertebrates and planktivorous fish, and as a food source for several fish species. The deep bottoms of the GOF suffer from frequent hypoxic events that prevent steady zoobenthic communities from developing. This facilitated the entry of the hypoxia-tolerant *Marenzelleria*. It was first spotted in the GOF in 1990, and has become the dominant component of the soft-bottom communities during the assessment period.

Marine litter

Marine litter, and especially plastic litter, is one of the most ubiquitous environmental problems in both marine and freshwater environments, receiving increasing public attention and causing a lot of concern. Based on monitoring campaigs, most of the beach litter in the GOF is composed of plastic, while the most common litter types in the seafloor are glass bottles, glass fragments, and aluminum cans.

Litter causes harm to a variety of marine organisms particularly because of entanglement and ingestion of litter items. Microlitter, in turn, can be ingested by, e.g., filter-feeding organisms and bottom feeding animals. Ingested microplastics cause internal mechanical damage, and induce chemical problems caused either by their intrinsic chemical characteristics or by harmful compounds absorbed onto microplastic items. It is not yet known whether marine microplastics will turn out to be a health hazard for humans, but is surely that for marine life.

Underwater soundscape

Underwater sound can be classified to sounds of natural and anthropogenic origins. The effect of the anthropogenic noise on marine ecosystem depends on i) the characteristics of sound, ii) sound propagation losses, iii) the ratio of anthropogenic sound pressure to the natural one, and iii) the spatial and temporal sensitivity of the local ecosystem. The first two we know, the third is under consideration, and the fourth is almost unknown.

Most of the sound pressure at sea comprises of background noise that has many different sources, most of which are natural. In the Baltic Sea, the temporal patterns of the wave height and the received sound pressure were well correlated confirming the importance of the contribution of waves in the overall noise. On the other hand, the studies in the Baltic Sea have revealed that the ship passage is easily heard underwater at a distance of at least 1.5 km.

Depending on circumstances, even the softest anthropogenic underwater noise can cause marked harm on the ecosystem's functioning.

Maritime traffic and its safety

The GOF has always been an important fairway; it is one of the areas in the world subject to most dense traffic.

The volume of maritime traffic in the GOF has recently increased mainly due to the opening of new ports in Russia. Especially, the transportation of oil through the GOF has increased extremely rapidly. The freight volume in the GOF is forecasted to grow by 50 to 110 million tonnes by 2030.

In spite of the dense traffic and large volume of dangerous goods transported in the GOF, the number of accidents, such as groundings and collisions, has decreased. The most frequent failure behind grounding accidents is human error either in communication or judgment.

The annual nitrogen oxide emissions into the Baltic Sea from the maritime traffic equals 10 to 12% of the total atmospheric nitrogen load, that is, 2 to 3% of the total nitrogen load.

Should a chemical accident happen, the most harmful chemicals for human health have quite opposite properties to those that are most hazardous for water biota. For human health, the most hazardous chemicals are those that are very reactive, forming gas clouds. From the environmental point of view, the most hazardous chemicals are those that are persistent and have a high solubility, staying in the water column.

The GOF area is unique and sensitive, where any pollution by oil or a chemical agent most likely has significant consequences endangering the nature. Thus, the appropriate level of preparedness needs to be maintained and preventive actions taken.

CONTENTS

FROM THE EDITORS

You are holding at your hand (virtually, at least) one of the main products of the Gulf of Finland Year 2014: the assessment of the environmental state of Gulf of Finland (GOF), logically named as the Gulf of Finland Assessment. From the very beginning, we aimed to write a unique assessment that would not mimic anything that had been done before, would assess the chosen topics in an unprecedented detail, and would be used as a reference for years to come. In other words: the assessment with a capital "T". It is for your judgment to decide how we have succeeded in doing this.

This assessment supports the Gulf of Finland Declaration that delivers to the decision-making level the most essential management measures for improving the health of the GOF. In addition, it defines outlines for the protective work and sustainable use of the GOF. While this assessment serves as the basic information package to support the declaration, the Gulf of Finland Roadmap lists the concrete steps that are advised to take to improve the state of the GOF.

The preparation of an assessment this heaven-embracing was challenging to organize in such a way that all the necessary topics would be covered by the best experts available, let alone that the message would be truly trilateral. The assessment was built on the thematic chapters, for each of which we were looking for one chief scientist. We managed to find a group of people who were willing to contribute to the task, maybe not quite knowing what they had involved in. After all, we gave these persons an enormous task to build the trilateral writing team, to divide the tasks within the team – and what was probably the most challenging task – to integrate the products from the team in a timely manner. After all this, they were faced with editors' complaints. The persons, who are greatly acknowledged, are in alphabetical order: Pekka Alenius, Aarno Kotilainen, Maiju Lehtiniemi, Kari Lehtonen, Jaakko Mannio, Jakub Montewka, Kai Myrberg, Jukka Pajala, Heikki Peltonen, Heikki Pitkänen, Eija Rantajärvi, Outi Setälä, and Markku Viitasalo. The list of the co-writers of the chapters was way too long to be placed here, but you can find those names placed in the chapters. Naturally, these people are sincerely thanked for their contributions.

This publication would not have seen the light of day without the efforts from theme editor Riitta Autio, Erika Várkonyi (layout, graphics), Saara Reinimäki (the secretariat's front in the publishing business), Riku Lumiaro (photos), and Marco Nurmi (GIS-products). Also our Russian front, Alexander Antsulevich, is greatly acknowledged of his coordinating work within the Russian institutes.

For the last but certainly not the least; the Gulf of Finland Year 2014 would never have taken place in such vast proportions as it finally realized, and definitely would not have been as successful as it was, without the GOF2014 secretariat's continuing efforts, relentless self-challenging, and the working morale that sometimes seemed to be never-exhausting. The far-sightedness of the visionary project leader Kai Myrberg may not be forgotten, but especially we wish to emphasize the role of the GOF2014 secretary, Ljudmila Vesikko: the secretary with a capital "T".

All in all, thinking of the enormous efforts of so many people and so many final absolute definite deadlines, we editors are astonished that this day actually came: the assessment is here in its final form. Enjoy!

27.6.2016, the crowded coffee room at the seaward end of the 2nd floor,
SYKE building, Helsinki

Mika Raateoja and Outi Setälä

FOR THE READER

One of the ways to persuade people to be involved in this process was to make sure that the people can use their contribution as a reference. As you may well see, each thematic chapter forms its own coherent whole. In shorter chapters, the contributors' list is right there in the start of the whole chapter, while in longer chapters the lists are placed in the sections. This enables easy referencing to the particular chapter (and we wish you will do so, too) and the writers can include their contribution to these sections also into their CVs. This is very handy.

The chapters end with general conclusions and suggestions for the future. Even if you are not into some of the topics, or you are just in a hurry, we would suggest scrolling through at least these main points. There are certain info-boxes in the text that cover novel aspects, interesting cases, or just something good to know of. You can ignore them without the main message being obscured in any way. Enjoy!

THE TRILATERAL ENVIRONMENTAL COLLABORATION OF THE GULF OF FINLAND

The trilateral environmental collaboration of the Gulf of Finland

Kai Myrberg, Ljudmila Vesikko, Mika Raateoja, Vilma Hakala
Finnish Environment Institute

History

The path towards the international collaboration to protect the marine environment of the Gulf of Finland (GOF) dates back in 1955 when Finland and the Soviet Union established the mutual terms of collaboration in the fields of science and technology. One outcome was the launch of the environmental collaboration of the GOF in 1968, based on the proposal by the scientists of Leningrad and Tallinn. Consequently, a joint working group, focusing on the study of pollution upon the GOF and the functioning of the GOF's ecosystem, was established. Thus, the foundation for the environmental collaboration within the GOF was built almost half a century ago. The group worked until the dissolution of the Soviet Union in 1991.

Estonia, Finland, and Russia initiated the collaboration again in 1992, following logically the work of the former joint working group. Up to this time it had become clear that science had veered off on its own path and become somewhat separated from the environmental management work carried out by HELCOM and by the Ministries of the Environment. It was necessary to help science and management to work closer together and to supplement each other; the trilateral collaboration in the 1990's drew attention to finding practical solutions to environmental problems, having more concrete goals than before.

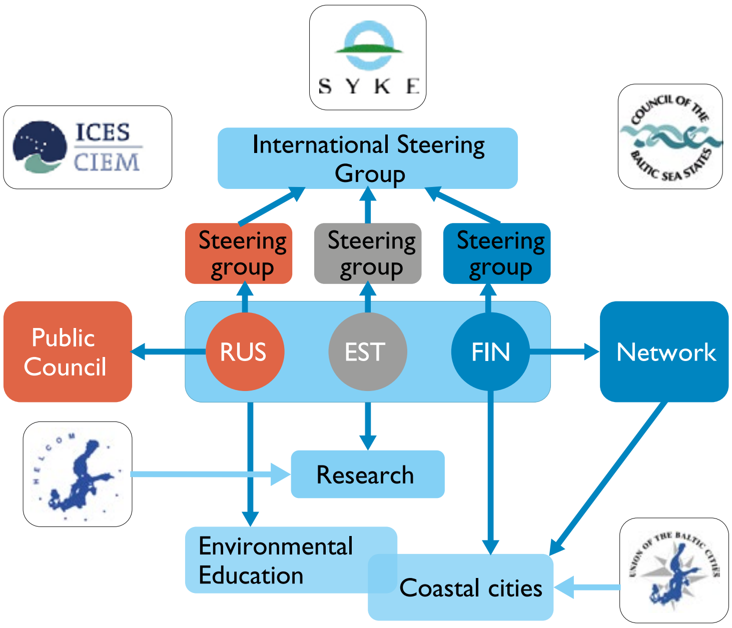
The first official GOF year was organized in 1996. The main motivation to organize the thematic year was to stop the deterioration of the GOF, which had reached an alarming level by then. Furthermore, there were no guidelines at that time for the accuracy of the analytical performance in the environmental front. The year was officially initiated in Pskov on the 11th of January, 1996. The delegations from the Ministries of the Environment of Estonia, Finland, and Russia signed the declaration to stress their aims to gain a more precise insight

Photo: Wikipedia Commons.

into the environmental state of the GOF and the nutrient loads into it. Furthermore, it was seen necessary to establish projects that would improve the environmental protection and maritime safety. The common research program was formed as well; the topics were as follows: 1) research on the state of the GOF and its changes, 2) clarification of the pollution loads and possibilities to reduce them, and 3) the introduction of a joint data bank and unrestricted data exchange. In retrospect, the two first items were at least partially implemented but the last one failed. The Gulf of Finland Year 1996 was needed to re-start the collaboration between the three countries in the new political environment. However, the year only committed a limited number of environmental decision-makers and scientists to discuss the environmental condition of the GOF. There was practically no interaction with the non-governmental organizations or citizens.

After the first GOF year, the work continued mainly in the form of the low-profile annual scientific seminars in Estonia and Finland. Since the year 2000, a trilateral round-table seminar was additionally organized during the Baltic Sea Days in St. Petersburg. The common conclusions from these meetings have covered a wide range of topics (for details, see Rintala and Myrberg 2008). To emphasize one of those here, there was a need to re-shape the trilateral collaboration by making its work more focused for the needs of the decision-makers and the public.

The state of the GOF was a growing concern already in the 1970´s when the previous Finnish research vessel named as “Aranda” sailed its waters. Photo: Finnish Institute of Marine Research.



The organization of the GOF2014. The practical coordination of the GOF2014 was carried out by the project secretariat in Marine Research Centre of Finnish Environment Institute along with the national coordination bodies in Estonia and Russia. Source: SYKE.

Towards the Gulf of Finland year 2014

It is elementary that the latest scientific information is available to support the environmental decision-making process. Even more than before, there is a need for up-to-date information concerning the pressures on and state of the GOF ecosystem. How will we optimally focus our resources for the protection and restoration of the sea in the future? The idea of the second GOF year surfaced from the scientific community. The Gulf of Finland Year 2014 (GOF2014) was tailored to give additional value for the protection and restoration of the GOF environment in terms of enhanced political presence as well as through better communication and interaction with the private sector, environmental decision-makers, politicians, and citizens.

The decision to organize the GOF2014 was finally made in December, 2010. The Ministry of the Environment of Finland and the international research community took the initial steps and soon the corresponding ministries in Estonia and Russia became involved in the planning process. As long time had gone since the first GOF year and a lot had been done ever since, it was high time to assess the environmental state of the GOF, only having a broader view this time. The idea from the very beginning was not only to involve scientists but to have public and decisions-makers also onboard.

After high-level negotiations in 2011–2013, the GOF2014 got an official status in Estonia, Finland, and Russia. Furthermore, the Ministers of the Environment and the Minister of Natural Resources and Environment signed a memorandum of understanding that committed the governments to implement the GOF2014 and carry out shared actions.

What was the GOF2014?

The GOF2014 was a common Estonian, Finnish, and Russian project involving experts, governments, and people. It gave a unique opportunity to analyze the ecological status of the GOF and the pressures on it in detail, and to form a common plan for the sustainable use of the GOF.

Two future decision-makers get to know the wonders of the GOF's environment during the open days on board Aranda in the Port of Kotka on the 25th of July, 2014. Photo: Saara Reinimäki.

Within the umbrella of the GOF2014, environmental collaboration was established at various levels linking stakeholders in Estonia, Finland, and Russia. The work at the highest level involved the Ministries of the Environment, the Ministry of Natural Resources and Environment, and various steering groups. The Ministries were committed to implement the GOF2014 at a high political level. In Finland, the Ministry of Foreign Affairs and the Parliament of Finland played a crucial role, too. The action program was directed by the international steering committee including experts and officials from all three countries. In addition, the riparian countries had their own national steering groups that included representatives from ministries and research institutes.

The next level included environmental education (camps, schools, teachers, educational material, youth declarations), and collaboration with the coastal cities, the private sector, and the non-governmental organizations. Within the umbrella of the GOF2014, the riparian countries organized events for public councils and for the public in the coastal cities, forums for decision makers, not forgetting media happenings. Together there were more than 250 different events in 2014.

Research within the GOF2014

Research collaboration included research meetings and forums, a common research plan, and steps taken forward in the monitoring scheme of the GOF (the trilaterally integrated monitoring activity, the establishment of the trilateral data bank, and steps towards more fluent data exchange).

The research was organized around five key research themes (eutrophication and the climate change were overarching themes):

- **Bio- and geodiversity:** mapping and protecting the biological and geological diversity of the GOF
- **Fish and fisheries:** the use of fish stocks in a sustainable way to secure fishing in the future
- **Pollution and Ecosystem health:** the effects of anthropogenic chemical contaminants on the health of organisms and ecosystem
- **Maritime spatial planning:** sustainable use of sea areas considering both the nature, and all the different actors related to the use of the sea
- **Marine safety:** the prevention of and preparedness for accidents in harsh conditions

Youth declaration during the meeting of the national Public Councils in St. Petersburg on the 19th of September, 2014. Photo: Ljudmila Vesikko.

The research collaboration produced updated information for decision-makers about the most urgent and cost-effective measures to improve the state of the GOF. This information was disseminated to various stakeholders and will be used as a guideline for implementing EU directives, HELCOM Baltic Sea Action Plan, Convention on Biological Diversity, bilateral agreements, and collaboration between the EU and Russia. Of the scientific outcomes of the GOF2014, scientific articles (a special issue in Journal of Marine Systems), and various reports on the state of the GOF (such as the one you have at your hand) deserve to be mentioned.

Impact of the GOF2014

Any attempt to evaluate the impact of the GOF2014 at this point would hardly make justice to the project as the legacy of successful high-level collaborations, such as this one, tends to persist long into the future. Nevertheless, it can be noted that the GOF2014 further strengthened, and in some respects re-defined, the trilateral environmental collaboration – an achievement that is even more respectable taking into account the geopolitical situation at the time of the project.

The GOF2014 increased public awareness and communication among different stakeholders, and supported the ecosystem-based decision-making. The work of numerous people done for the GOF2014 clearly responded to an existing demand, as can be concluded from the list of the patrons: the presidents of the republic Mr. Toomas Hendrik Ilves, Mr. Sauli Niinistö, and Mr. Vladimir Putin.

Future of the trilateral work

The GOF2014 is over and the trilateral work returns in a way back to ordinariness, only having a much stronger basis than before. In early 2016, the Ministers of the Environment, and the Minister of Natural Resources and Environment signed a Declaration of the Co-operation until 2020 to protect the legacy of the GOF2014. A trilateral co-ordination committee and a scientific expert group will be established. The situation is profoundly different from the past when the collaboration mainly leaned on the efforts of the individual scientists acting on institutional mandates or on their personal interests. A common monitoring programme will be carried out, and the research topics will be chosen among the most topical problems. Furthermore, the the Gulf of Finland

Maritime traffic will remain as the biggest environmental threat for the GOF. Photo: Petri Tuohimaa (SYKE photo bank).

Road Map will be regularly updated to deliver the most concrete suggestions from the scientific community to the decision-making level how to improve the state of the GOF.

The work of the trilateral collaboration is still surely needed. Even though we now have evidence that the anthropogenic pressure to the GOF in the form of nutrients has somewhat eased up, a new mechanism has come to our attention that has a potential to compensate for the evident load reductions: the climate change. Now that the degrading impact of the classical hazardous substances is slowly retrieving, a new list of substances has emerged that will have unpredictable and probably not less deleterious consequences to the ecosystem. Moreover, there are substances like pharmaceuticals that have for a long time found their way into the GOF. However, only recently we have come to realize their harmful effect. The tonnages in the maritime cargo transport in the GOF keep on rising with no levelling off in sight. As long as the human aspect plays a marked role in the traffic coordination, the logical conclusion is that the major accident is just a question of time. We can only hope that this will not concern any oil tanker. The ever-growing maritime traffic also serves as the spreading vector for non-indigenous species. As the wide array of the ecosystem services will become a more in-demand commodity as time goes by, a proper implementation of a truly basin-wide maritime spatial plan will become imperative in a relatively short time frame.

The trilateral collaboration has shown its resilience towards political storms. The Ukraine crisis did not leave fatal fingerprints on the GOF2014 project. The crisis produced tension in the high political level, which was related to the wider development of world politics. Still, it seemed for the writers that the environmental front wanted to show its ability and willingness to collaborate as ever. Despite the crisis, key events of the GOF2014 and the joint research of the three countries were carried out according to the plans. Co-operation between scientists, environmental educators, and other actors was extremely fluent. For some part, networks got even better. These observations draw a promising view over the future trilateral collaboration; the environment and its integrity seem not to be a political tool within the GOF area – as they should not be.

References

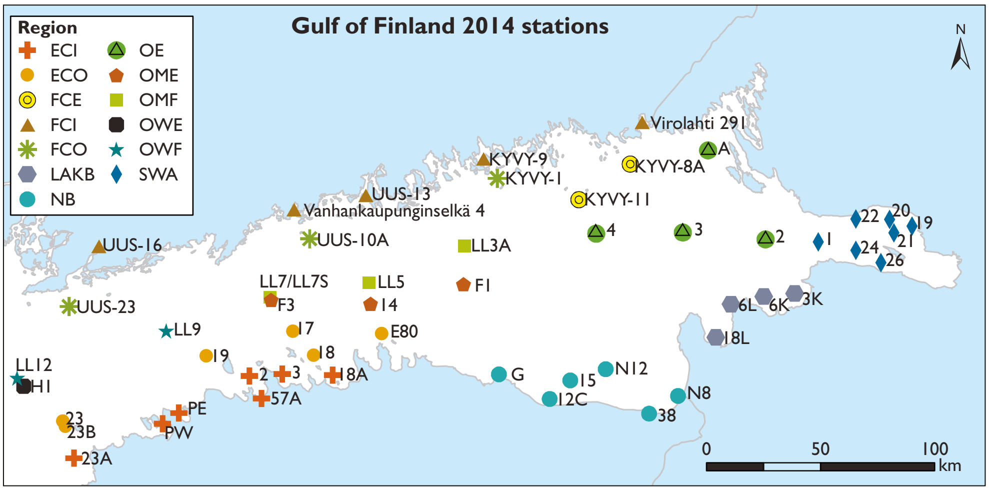
Rintala J-M, Myrberg K (Eds) (2008). The Gulf of Finland. Finnish-Russian-Estonian cooperation to protect the marine environment. History and prospects for the future. Ministry of the Environment of Finland.

THE GOF2014 DATASET

The GOF2014 dataset

A part of the results of this assessment is based on the newly-established GOF2014 dataset. This unique dataset compiles for the first time monitoring data on water quality and biology from Estonia, Finland, and Russia. Data providers:

- Estonia: Estonian Marine Institute (EMI), Marine Systems Institute, Tallinn University of Technology (MSI)
- Finland: Finnish Environment Institute (SYKE), South-East Finland Centre for Economic Development, Transport and the Environment (KASELY), Uusimaa Centre for Economic Development, Transport and the Environment (UUDELY), City of Helsinki Environment Centre (HELSINKI)
- Russia: North-West Interregional Territorial Administration for Hydrometeorology and Environmental Monitoring (HYDROMET)



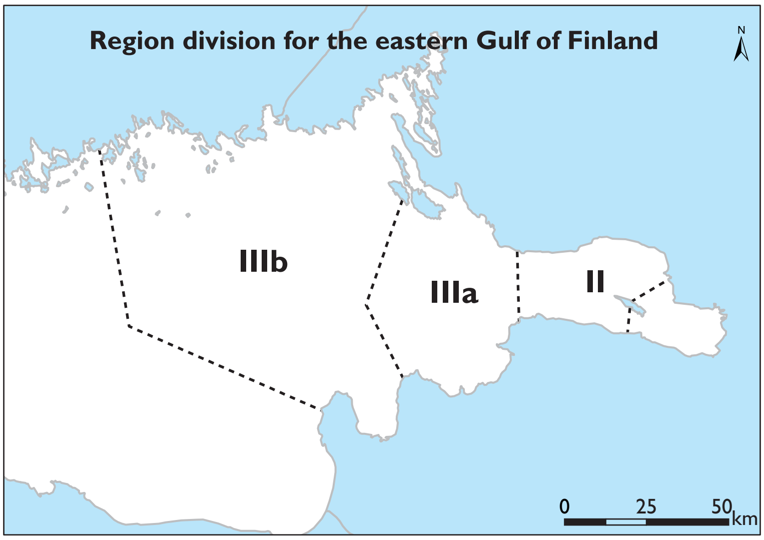
GOF2014 station map. ECI = Estonian Coast In, ECO = Estonian Coast Out, FCE = Finnish Coast East, FCI = Finnish Coast In, FCO = Finnish Coast Out, LAKB = Luga and Koporye Bays, NB = Narva Bay, OE = Offshore East, OME = Offshore Middle EST, OMF = Offshore Middle FIN, OWE = Offshore West EST, OWF = Offshore West FIN, SWA = Shallow Water Area. Graph: Marco Nurmi.

Photo: Finnish Institute of Marine Research.

The strategic numbers:

- Data span 1996–2013 (i.e., since the Gulf of Finland Year 1996)
- ≥ 15 monitoring stations per country, chosen by the countries
- All HELCOM depths (depending on the parameter and station depth)
- Parameter list (depending on the station)
    - Secchi-depth
    - Salinity, temperature
    - Oxygen concentration, pH
    - NH_3-N, NO_2-N, NO_2-N+NO_3-N, TOTN, PO_4-P, TOTP, silicate
    - Chlorophyll a
    - Phytoplankton species distribution, abundance, and biomass
    - Zooplankton species distribution, abundance, and biomass
    - Zoobenthos species distribution, abundance, and biomass

The dataset or parts of it can be used for any scientific, educational, or communicational purpose without any fee or cost. Finnish Environment Institute currently coordinates the delivery of the dataset.



Region map over the eastern GOF. The division is used in the chapter Eutrophication. Source: Russian State Hydrometeorological University. Graph: Marco Nurmi.

CLIMATE IN THE GULF OF FINLAND AREA

Climate in the Gulf of Finland area

Pekka Alenius1), Kai Myrberg2), Petra Roiha1), Laura Tuomi1), Heidi Pettersson1), Urmas Lips3)

1) Finnish Meteorological Institute
2) Finnish Environment Institute
3) Marine Systems Institute, Tallinn University of Technology

The elongated, narrow and relatively shallow Gulf of Finland (GOF) is the easternmost basin in the Baltic Sea (BS), surrounded by the countries Estonia, Finland, and Russia. Its western boundary has historically been defined to follow the line Põõsaspea – Osmussaar – City of Hanko (Witting 1910). It locates in a geographical box of 59°11′N / 22°50′E and 60°46′N / 30°20′E (Alenius et al. 1998, Leppäranta and Myrberg 2009).

Even in the BS scale, the GOF is a relatively small basin. Its length is about 400 km and its width varies in the western and middle parts from 48 km between Tallinn and Porkkala peninsula to 135 km between Narva Bay and Kotka. Its volume of 1 103 km^3 and the surface area of 29 948 km^2 are about 5 % of the volume and about 7.5 % of the surface area of the BS. Nevertheless, it has a relatively large impact on the BS by its drainage area – 420 990 km^2, that is, about one fourth of the total drainage area of the BS – and associated voluminous river runoff.

Baltic Sea on the roof of Europe

High latitude seas show strong heat fluxes to the atmosphere as long as the surface is ice-free during the fall and winter. On the other hand, the transport of warm air from lower latitudes by intensive cyclone activity, if this is to happen, compensates for this heat loss. This transport is especially strong to the central and northern Europe because the Gulf Stream and its extension bring heat to these areas. As a result, the mean atmospheric temperature in the BS area is much higher than anywhere else at corresponding latitudes. There is no other area in the world where growing of grain is possible at latitudes higher than 60°N.

Photo: Riku Lumiaro.

The BS is located between marine temperate and continental sub-arctic climate zones, in a geographical box of 54°N / 9°E and 66°N / 30°E. The moist and relatively mild marine air mass from the North Atlantic and the Russian continental air mass counteract with each other, and thus produce the highly variable climate in the BS area.

The climate is shaped by the strength of the westerlies and the location of the polar front. Together they express considerable seasonal and inter-annual variation on the climate. The BS lays on the prolongation of the North Atlantic storm track and therefore low pressure systems come frequently into the BS area bringing in warm air masses and reducing the temperature difference between the northern and southern latitudes. The westerlies are particularly important in heat dissipation in the winter when the temperature difference between the marine and continental air masses is at its largest.

It is the westerlies that most often makes the best swells for surfers in the GOF. Photo: Riku Lumiaro.

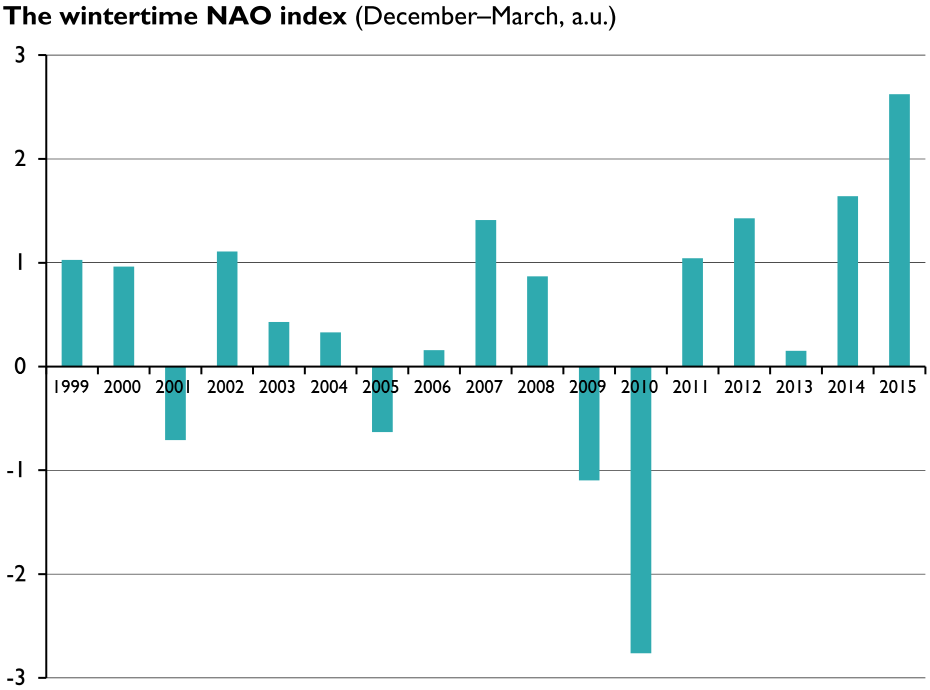


Figure 1. Wintertime NAO-index in 1999–2015. Source: Hurrell and National Center for Atmospheric Research staff (2015).

The southern and western parts of the BS belong to the Central European mild climate zone in the westerly circulation. The northern part typically locates at the path of the polar front, which separates the cold arctic air mass from the warmer and moister air masses in the south. The polar front fluctuates over the BS area during the winter; the central part of the BS, including the GOF, can be either in the mild or the cold side of the front depending on the year. During the summer the front is located farther in the north.

During warm summers and cold winters the air pressure field is smooth and winds are weak, and blocking high pressure situations are a common feature. During such periods the weather can be very stable for several weeks.

Atmospheric oscillations

Low-pressure systems that come from the Atlantic Ocean largely control the large-scale weather conditions in the BS and in the GOF. The intensity of the westerlies is described by the North Atlantic Oscillation (NAO) index that is based on the difference of the normalized sea level pressure between Lisbon (Portugal) and Stykkisholmur (Iceland, Fig. 1). The NAO index is positive when there is a high pressure area in the south and a low pressure area in the north. Westerly winds prevail and winters are typically much warmer than on the average over most of Europe. When the index is negative there is a high pressure area in the north and a low pressure area in the south. The winds blow mostly from northerly and easterly directions, and the mean wintertime temperatures are much below normal, like it was in 2010 and 2011. In the summertime, winds tend to be weaker and the role of local features, such as the land-sea breeze, is larger. A specific Baltic Sea Index has been developed to better describe the specific conditions in the BS (Lehmann et al. 2002, Dippner et al. 2012).

Major Baltic Inflow (MBI)

It is not uncommon that storms – forcing oceanic water to flow into the BS in large quantities – overtake the Baltic area in the early winter. Therefore, the wintertime NAO index that describes the NAO in December–March has been used to indicate the intensity of saline water exchange between the North Sea and the BS. The distance from the observation sites in the southern BS that detect MBIs to the entrance to the GOF is around 950 km along the deep trenches. The incoming waters make this travel in about seven months.

The recent MBIs were reported in 1993 and 2003, and the latest appeared in December 2014 (Mohrholz et al. 2015). Since its entry in the BS, strict attention has been drawn on its advancement. In the end, the inflown waters did not reach the GOF. In December 2015, the remnants of the inflow were detected in the Eastern Gotland Basin, but not in the Northern Gotland Basin (Andersson 2015). The inflown waters, however, succeeded in pushing forward the old stagnant waters of the deeps of the Gotland Basin. Thus, a large volume of water poor in oxygen and rich in nutrients was there in place at the entrance area to the GOF to be possibly transported into the GOF (by processes described in the chapter Eutrophication, Fig. 2). This indeed happened prior to the Finnish winter monitoring cruise held in January 2016 (Finnish Environment Institute 2016). The boosting effect of this process on the high-summer algal biomasses of the GOF will hardly be pronounced; the deep water phosphorus inventory in the western and middle GOF in May 2016, as measured on board R/V Aranda, was somewhat larger than the long-term average but not exceptional (Mika Raateoja, pers. comm.).

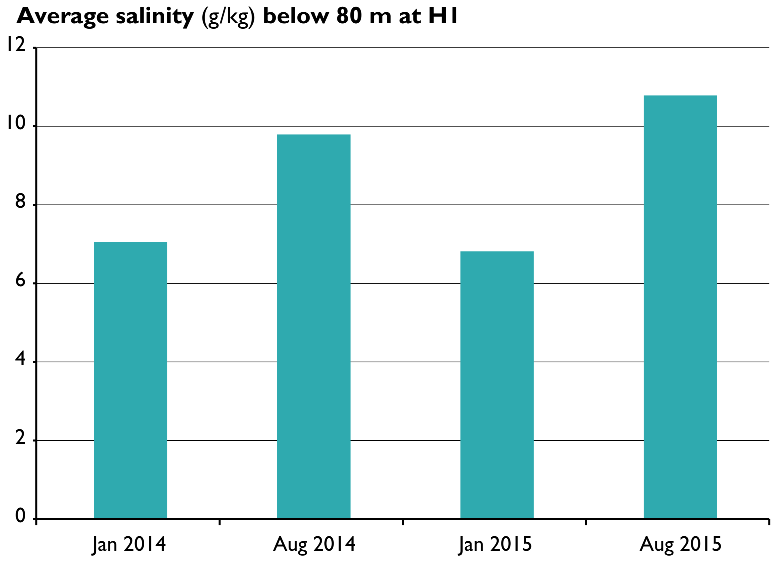


Figure 2. The average salinity below 80 m at station H1 at the entrance to the GOF. Superimposed to the seasonal variation there is a marked difference in the deep-layer salinity between the late-summers of 2014 and 2015. Source: Marine Systems Institute.

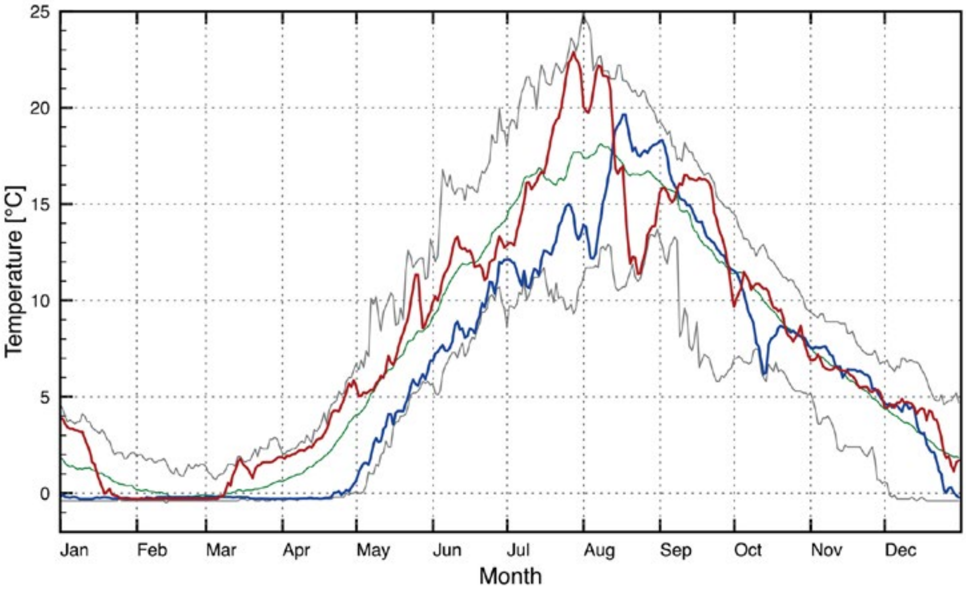


Figure 3. Annual course of SST at Harmaja weather station off Helsinki in 1996 (blue) and in 2014 (red) in comparison to average (green), minimum, and maximum values in 1996–2014. Source: Finnish Meteorological Institute.

Temperature

The annual course of the sea surface temperature (SST) in the middle GOF in the Gulf of Finland Year 1996 was very different from that in the Gulf of Finland Year 2014 (Fig. 3). The year 1996 was cooler than normal until the early August, while the spring in 2014 was warm but the summer was changeable. There appeared to be no clear changes in the lengths of the seasons during the assessment period between the two Gulf of Finland Years. With regard to the timing of the changes, however, spring and summer seemed to have a tendency to start earlier since 1996. This trend levelled off in the mid-2000's, however (data not shown).

Wind patterns

The wind conditions in the BS area are determined by general atmospheric circulation over the Northern Europe. The area belongs to the zone of westerlies. Typically, a strong zonal circulation type exists in the area, introducing eastward moving cyclones. This set-up is superimposed by the inter-annual atmospheric variation as described by the above-mentioned NAO-index. The latitudes where the GOF is located experience a great seasonal variability in the insolation, which in turn affects the wind patterns.

The wind regime of the open GOF is governed by south-west winds that are predominant in the entire BS area (Fig. 4). Locally, western and eastern winds blowing along the GOF are also relatively frequent. Moderate (6 to 10 m/s) and strong winds (> 10 m/s) blow mostly from the south / the south-west on the northern coast, but on the southern coast more often from the south-west / the west. South-east winds are infrequent and relatively weak (Soomere and Keevallik 2003).

Measurements on board vessels and at lighthouses reveal that the average wind speed is considerably greater in the open GOF than on the coasts (Niros et al. 2002). To upscale, the mean wind speed during the most violent storms is 2 to 3 m/s lower in the GOF than in the Gotland Basin. The strongest winds blow from the south or the south-west; the three-hour average wind speed may reach 25 m/s once in a century. Eastern winds are confined to a narrow direction span and may reach 23 m/s (Soomere and Keevallik 2003).

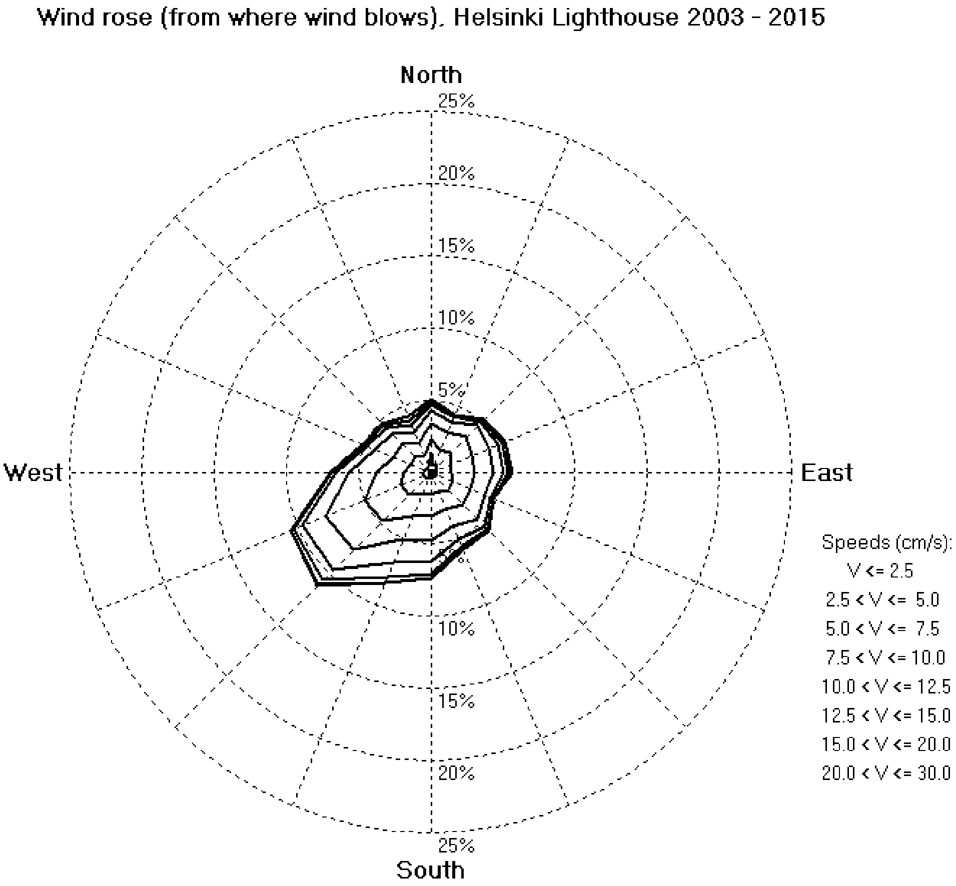


Figure 4. The wind rose at the Helsinki lighthouse in 2003–2015. The prevailing wind direction is from south-west due to the low-pressure systems coming from the North Atlantic. The directional distribution of the wind gets the narrower the higher the wind speed is. The heaviest winds usually blow almost along the GOF from south-west. The strongest winds are experienced during the wintertime, while the wind directions vary more in the summer. Source: Finnish Meteorological Institute.

The local winds have a relatively large role in the summertime when the large-scale wind patterns are relatively weak. The frequent and relatively strong afternoon winds observed along the northern coast in typical summer conditions reflect the interplay of the basic flow, sea breeze, and the geometry of the GOF (Savijärvi et al. 2005). The meanders of the sea breeze, amplified by the unidirectional basic flow, may become evident in the southern coast as relatively strong south-west winds are located on the northern coast.

River runoff

The average annual river runoff into the GOF was 114 km^3/year in 2014 (Johansson 2015) that is about one tenth of the GOF's volume. In earlier studies (data from the 1950's and the 1960's) the value was estimated to be 110 to 115 km^3/year (Mikulski 1970, Mikulski 1972).

The eastern GOF receives the largest single freshwater inflow to the BS via the River Neva. The River Neva (monthly discharge in 1996–2014: mean (min–max) of 2432 (861–3650) m^3/s) overruns with ease the next largest rivers flowing into the GOF; the River Narva 398 (131–949), the River Kymijoki 304 (87–743), and the River Luga 104 (14–634) m^3/s. The annual mean discharge of all the four rivers is about 100 km^3/year,

Although being a small sea, the BS can present storms of respectable severity. Photo: Riku Lumiaro.

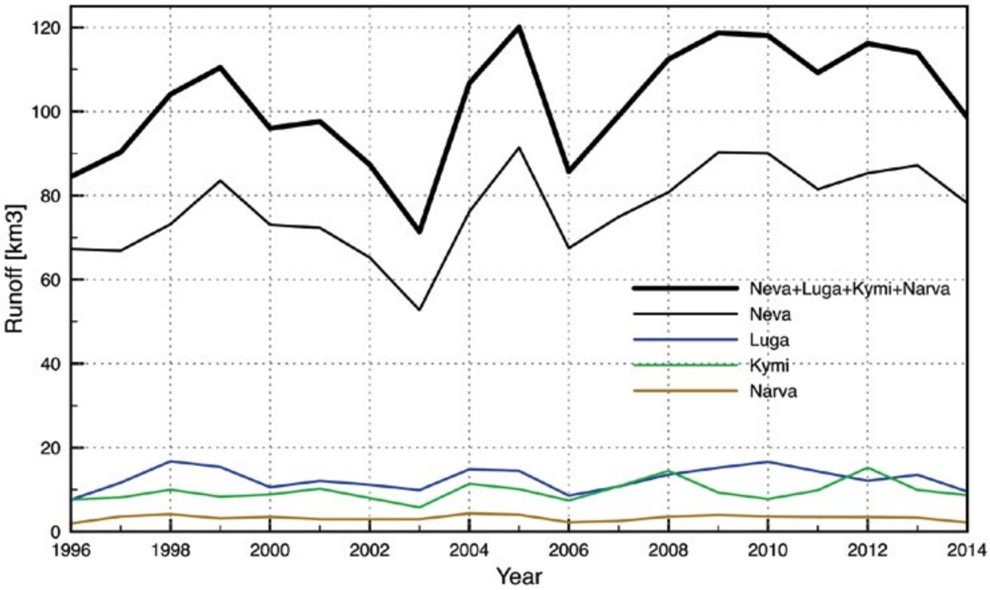


Figure 5. The runoffs of the River Neva, the River Narva, the River Kymijoki, and the River Luga to the GOF as a function of time. Source: Finnish Meteorological Institute.

which constitutes 89 % of the total river runoff into the GOF (Fig. 5). River Neva alone contributes 67 % of the river runoff into the GOF.

Generally, there has been an increasing trend in the river runoff during the study period, but the trend is non-linear (Fig. 6). Runoff was abnormally low in 2003. The temporal variation in the runoff is large, thus contributing to short-term salinity variations in the GOF.

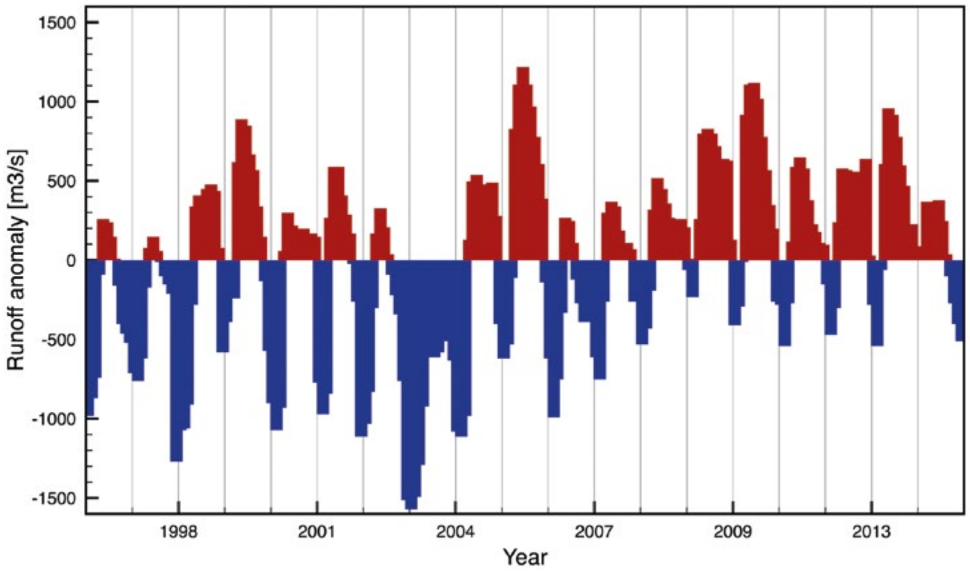


Figure 6. Anomaly of the monthly average runoff of the River Neva, as compared to the mean of 1996–2014. Source: Hydromet.

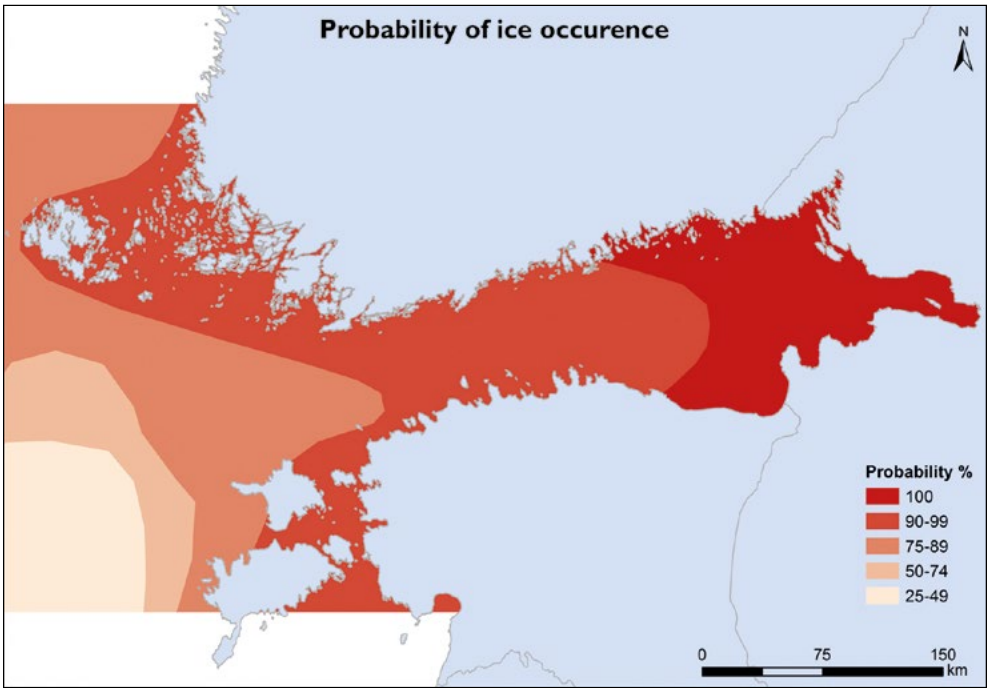


Figure 7. Probability of ice occurrence (%) in the GOF. Graph: Marco Nurmi.

Ice conditions

The GOF is one of the four BS basins – in addition to the Bay of Bothnia, the Bothnian Sea and the Gulf of Riga – where ice is formed every winter (Fig. 7). Sea ice is present in the GOF on the average for five months each winter, usually from December to April. The average freezing date is the 1st of December in the Neva Bay, and the last drift ice floes, observed off Vyborg, have typically melted by the 1st of May (Feistel et al. 2008). The ranges of the freezing and ice break-up dates are the 15th of November to the 15th of January and the 15th of April to the 15th of May, respectively.

The ice season in the GOF gets more severe towards the east and the north. In mild winters, only the area east of the Narva–Kotka line freezes. In normal winters, the entire GOF becomes ice-covered, and in harsh winters the entire GOF can be covered with landfast ice. The ice reaches its maximum extent in February or March. The maximum

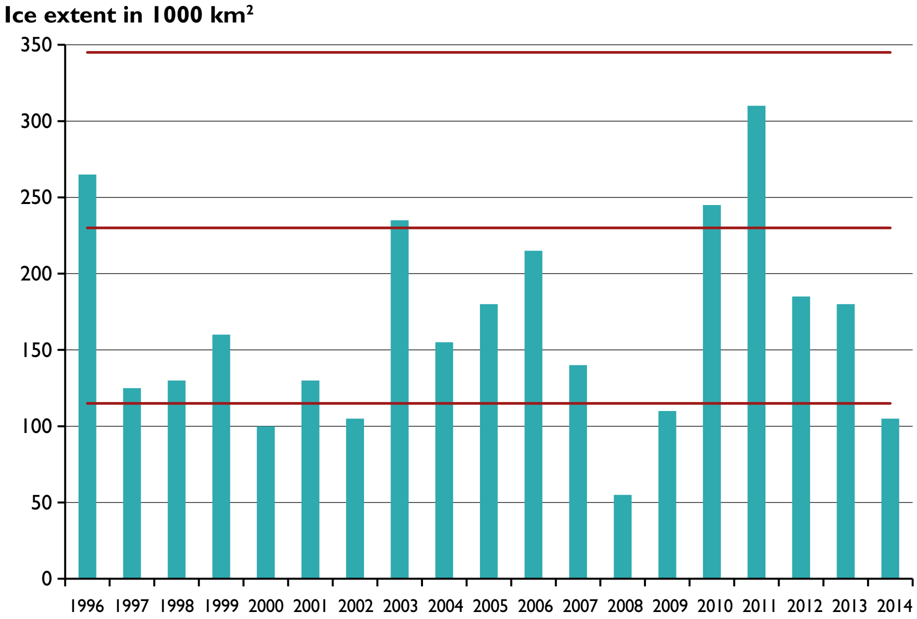


Figure 8. The maximum annual ice extent of the BS in 1996–2014. The national ice services in the BS have agreed to classify the winters into four severity categories: mild, normal, severe, and extremely severe. The horizontal lines classify the boundaries between the categories; a mild winter has the annual maximum ice extent < 115 000 km^2 and a severe winter > 230 000 km^2. An extremely severe winters has the coverage > 345 000 km^2. The present classification is based on data from winters 1960/1961–2009/2010. Source: Ice service, Finnish Meteorological Institute.

annual thickness of coastal fast ice varies from 30 to 80 cm near Vyborg and in the Neva Bay, depending on the severity of the winter.

The annual maximum ice extent is used to describe the severity of the winter (Seinä and Palosuo 1996, Fig. 8). Following the classification of the winter severity, the Gulf of Finland Year 1996 was the second most severe winter in our study period and the Gulf of Finland Year 2014 was the third mildest. There is no significant trend in the severity of the winters in this time frame; instead, the variation was considerable.

The winter 2013–2014 was a mild winter with ice only in the eastern GOF and in the Finnish coast (Fig. 9). The Estonian coast remained ice-free during the entire winter.

The ice conditions are not evenly distributed in the GOF. The heat inflow due to the easterly coastal current from the Northern Gotland Basin and the predominance of south / south-west winds may keep the Estonian coastal area free of ice throughout the winter. The north – south asymmetry of the ice conditions is enhanced by the coastal morphology, which supports a broad, landfast ice zone along the northern coast, but supports almost no fast ice at the southern coast.

The width of the landfast ice zone in the coastal areas depends on bottom topography; islands and grounded sea ice ridges stabilize the ice sheet, and it can be stationary for most of the ice season. The edge of the landfast ice in the GOF is close to the 10 m isobath (Leppäranta 1981).

Wave climate

The elongated and at times narrow shape of the GOF affects the surface wave field by forcing the waves to concentrate on certain directions (Kahma and Pettersson 1994, Pettersson 2004). This has consequences for the net surface drift via the Stokes drift that is associated to the wave field.

The wave climate in the middle GOF showed a behavior similar to the Northern Gotland Basin (Fig. 10). January was calmer than usually, followed by spring and

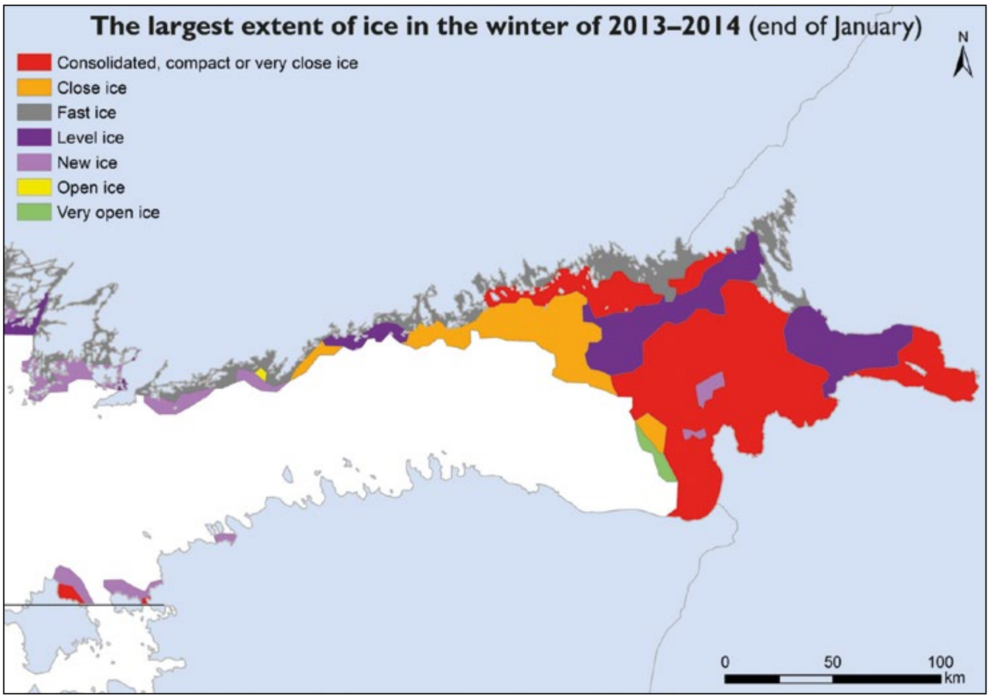


Figure 9. The largest extent of ice in the GOF in the winter 2013–2014. The maximum thickness of the ice was 20 to 25 cm. Source: Ice Service, Finnish Meteorological Institute. Graph: Marco Nurmi.

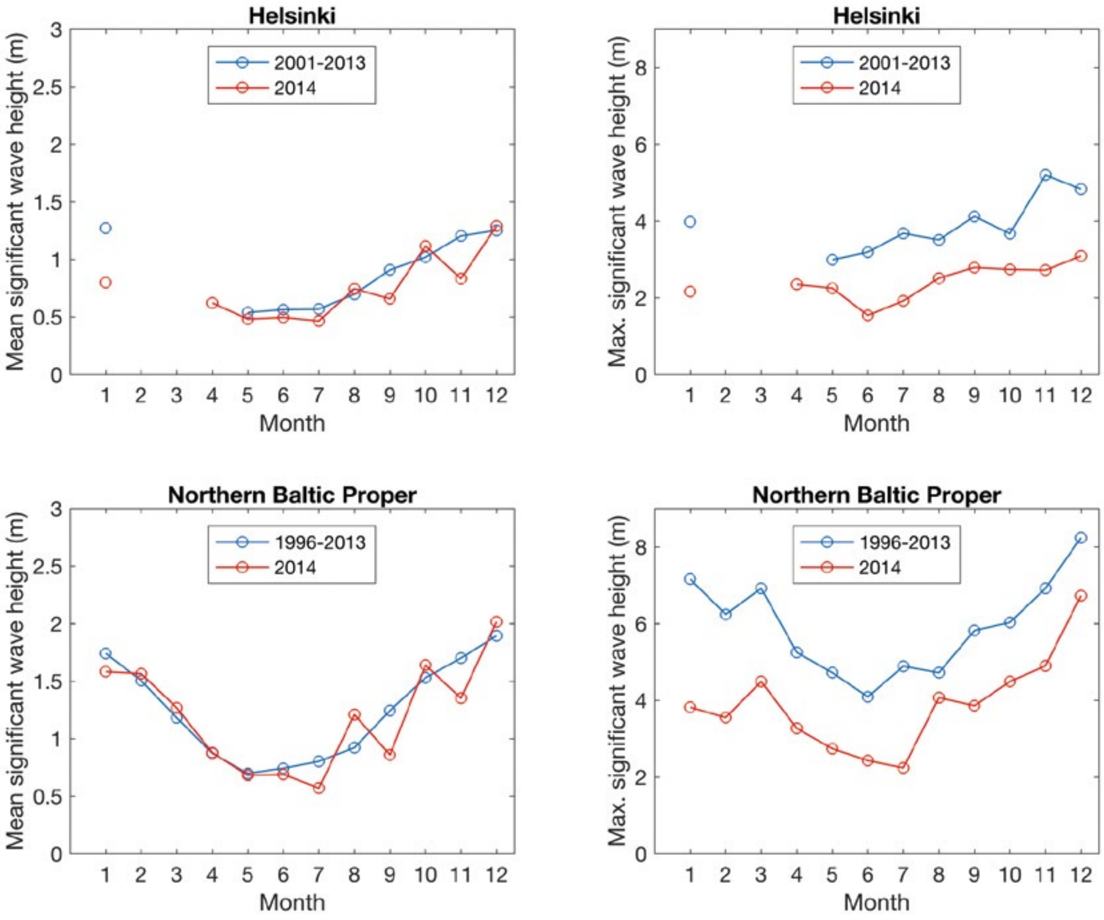


Figure 10. The monthly means (left panels) and maxima (right panels) of the significant wave height at the wave buoy stations off Helsinki (59°57'N, 25°14'E) and in the Northern Gotland Basin (59°15'N, 21°00'E). Significant wave height represents the mean wave height (trough to crest) of the highest third of the waves. Source: Finnish Meteorological Institute.

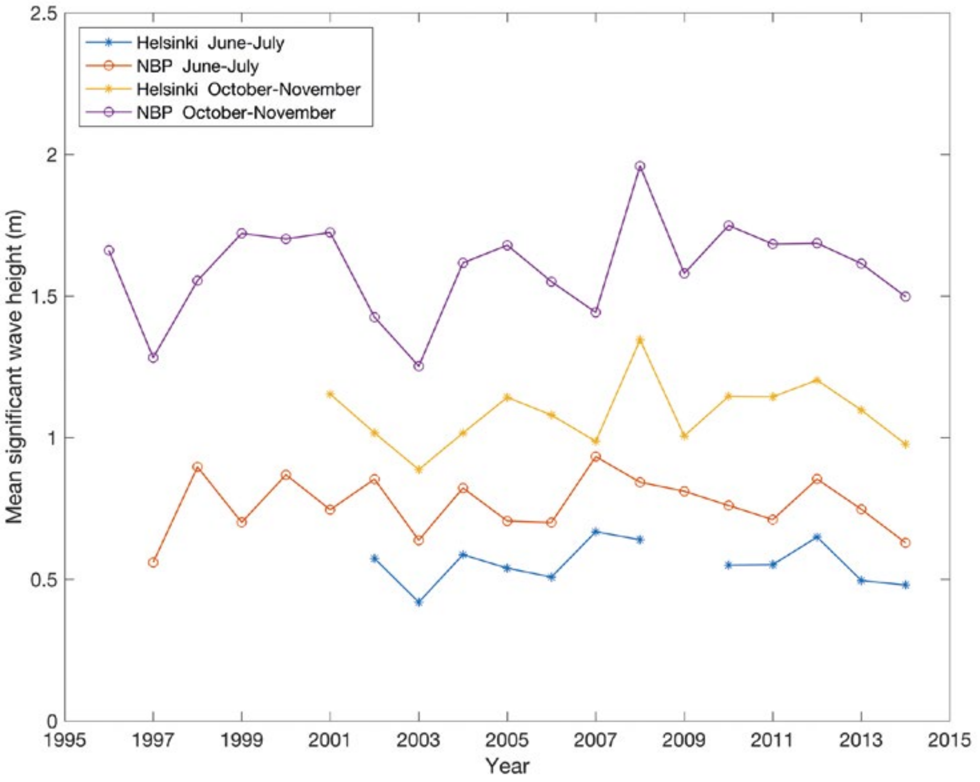


Figure 11. The annual means of the significant wave height in June–July and in October–November. NBP = Northern Baltic Proper, that is, Northern Gotland Basin. Source: Finnish Meteorological Institute.

early summer typical for the season. Clearly calmer and slightly rougher months than typically met alternated from July to December. The highest significant wave heights remained well below the highest measured values. At the station off Helsinki, the highest significant wave height during the measurement period in 2014, 3.1 m, was recorded on the 3rd of December. At the station in the Northern Gotland Basin, the highest significant wave height, 6.7 m, was recorded on the 10th of December.

The period of instrumental wave measurements in the BS is not yet long enough for studying possible trends in the wave climate; since 1996 / 2002 no clear changes have been detected (Fig. 11). The monthly average values of the significant wave height in the Northern Gotland Basin and off Helsinki exhibit a similar seasonal pattern but different magnitudes; wave height tends to be greater in the Northern Gotland Basin than in the offshore GOF, and during the autumn than the summer.

Sea level

Two processes shape the long-term sea level change of the BS, only they operate on opposite directions (Johansson et al. 2001). The land uplift, being largest in the Quark area, lowers the mean sea level in reference to the land whereas the global eustatic sea level rise does the opposite. At present these processes almost compensate each other in the GOF (Fig. 12). Future scenarios suggest that the relative sea level change in the GOF would be + 29 cm (min–max –22 to +92 cm) in 2000–2100 (Johansson et al. 2014).

A comparison of the Gulf of Finland Years 1996 and 2014 to the long-term data shows that no exceptional cases in sea level were reached in either of the years. Exceptional cases were observed between these years, however. The most extreme sea level event, referenced to the theoretical mean sea level, on the Finnish coast was observed in the 9th of January in 2005, producing not only the highest value of the study period but also the all-time record-breaking value. The extremes of sea level variation tend to occur in the tips of the bays. In this case, the maximum values of +132 to +197 cm (from Hanko to Hamina) were overrun by a value of +239 cm in St. Petersburg.

Where is the shoreline? The coasts of the western and middle GOF experienced the most severe flood within living memory in 2005. Helsinki on the 9th of Jan. Photo: Riku Lumiaro.

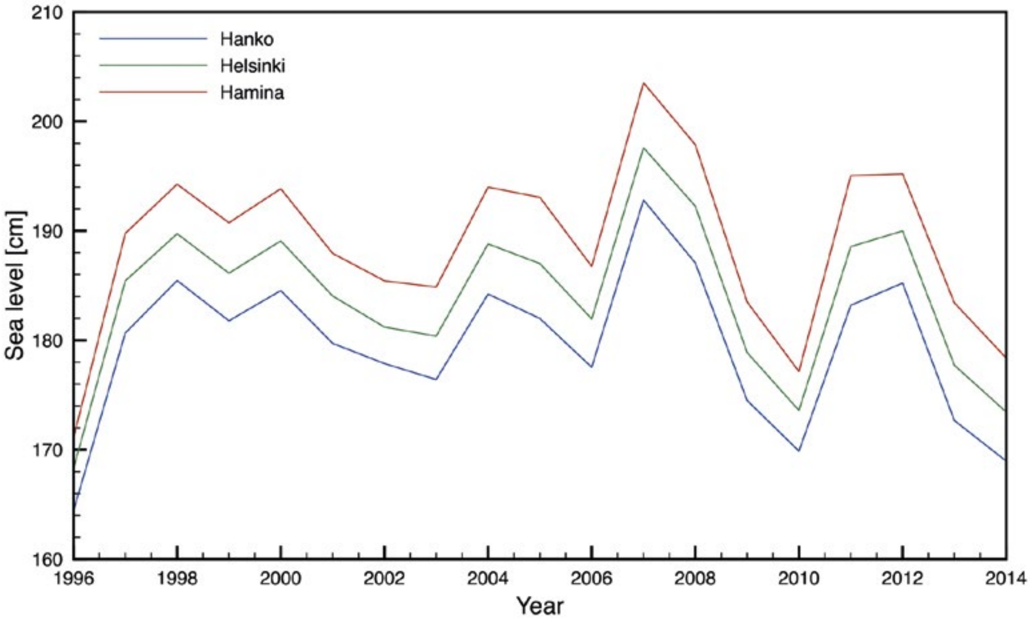


Figure 12. Annual averages of sea level along the Finnish coast of the GOF relative to the reference points of the sea level stations. Note: this scale is not commensurate to the theoretical mean sea level. Source: Finnish Meteorological Institute.

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Gulf of Finland physics

*Pekka Alenius1), Kai Myrberg2), Petra Roiha1), Urmas Lips3), Laura Tuomi1), Heidi Pettersson1),
Mika Raateoja2)*

1) Finnish Meteorological Institute
2) Finnish Environment Institute
3) Marine Systems Institute, Tallinn University of Technology

This chapter describes the past development and the current state of the basic physical features of the Gulf of Finland (GOF) between the 1st and the 2nd Gulf of Finland Years, i.e, in 1996–2014.

Salinity

The GOF possesses features that are characteristic for large estuaries. It can be regarded as a transition zone from virtually fresh waters of the Neva Bay to brackish waters of the Gotland Basin. As there is no sill between the GOF and the Gotland Basin, no specific water masses, isolated by topography, exist in the deeper part of the GOF. A continuous fresh water inflow at the landward end is opposed by a wedge of more saline water entering the deeps of the GOF at the seaward end. On top of this scheme there is strong vertical mixing, although it is reduced by halocline in the deeper parts of the GOF and by seasonal thermocline throughout the GOF (Alenius et al. 1998, Myrberg 1998, Soomere et al. 2008).

The salinity increases westwards and southwards in the GOF. The surface salinity ranges from fresh water at the mouth of the River Neva to 6 to 6.5 g/kg in the west. In the bottom layer, salinity is typically higher. In the western GOF where a halocline exists, it ranges from 7 to 9 g/kg, and occasionally > 10 g/kg. In the middle GOF the range is 5 to 8 g/kg, and in the east from 0 to 5 g/kg (Fig. 1).

Photo: Riku Lumiaro.

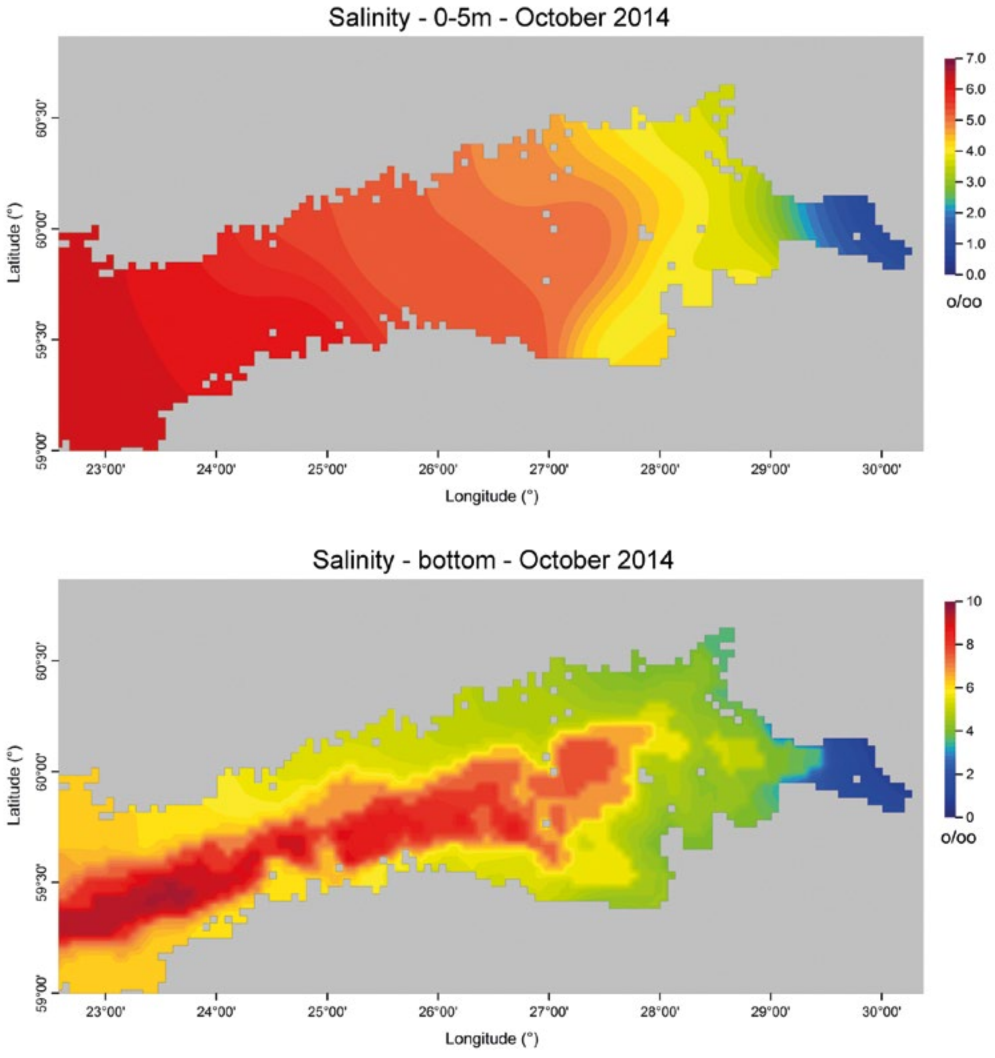

Figure 1. Salinity distribution (‰ equivalent to g/kg) in the surface layer (upper panel) and bottom layer (lower panel) in the GOF in October 2014. Source: SYKE database.

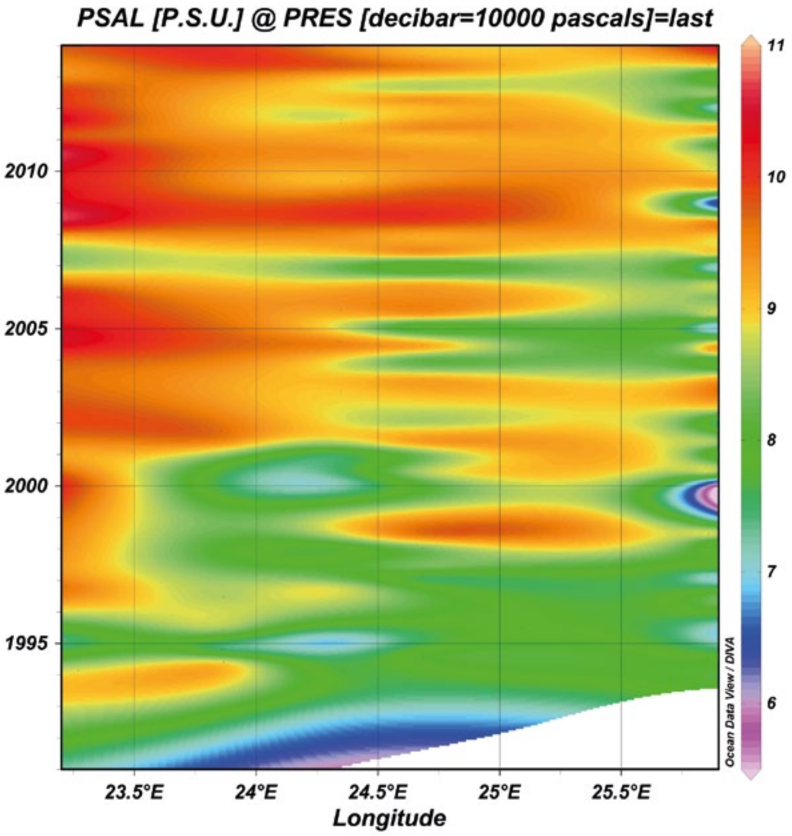

Figure 2. Near-bottom salinity (practical salinity unit PSU equivalent to g/kg) as a function of longitude and time at deep stations in the western and middle GOF. Source: Finnish Meteorological Institute and Marine Systems Institute.

The geographical variation in salinity is controlled by i) topography allowing the advection of water masses of the Northern Gotland Basin to enter the GOF, ii) wind-induced and convective mixing, iii) and the water budget of the GOF. In the vertical, salinity variation is i) at its largest in the bottom layer, and ii) the more pronounced, the deeper is the area. These features determine the location and strength of halocline in the GOF.

The seasonality in near-bottom salinity – higher values in the summer and lower values in the late autumn to winter – is a characteristic feature. In the late autumn to winter, alterations / reversals of dominant estuarine circulation (Elken et al. 2003) in combination with enhanced convection can lead to the collapse of stratification in large areas of the GOF (Liblik et al. 2013). Episodic advection events from the Northern Gotland Basin are superimposed to this general pattern.

In the large scale, near-bottom salinity has increased since the 1990's (Figs. 2 and 3, Liblik and Lips 2011), being probably a manifestation of an intensified estuarine circulation (Elken et al. 2003) and the occurrence of Major Baltic Inflows at longer intervals than before.

Stratification

The density stratification is determined by the vertical distribution of temperature and salinity. In the GOF, like in the BS but unlike in the World Ocean, salinity mostly determines stratification of water masses, not forgetting a seasonal thermocline in the summer.

Thermocline

In the winter, temperature is near to the freezing point in the surface layer and no seasonal thermocline exists. In the summer, there is a warm surface mixed layer, below

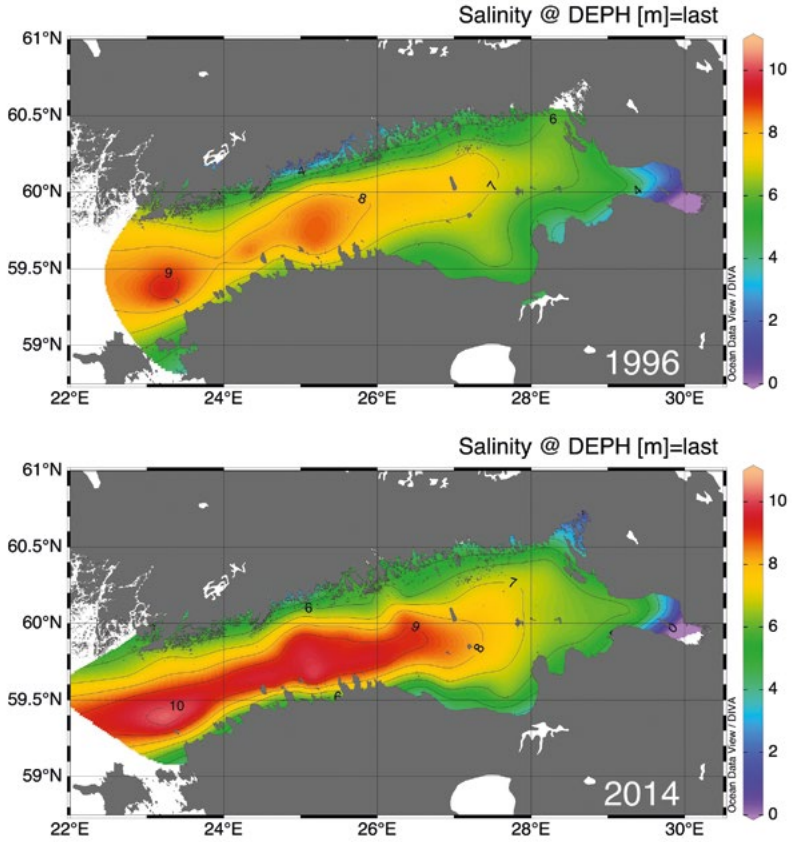

Figure 3.
Near bottom salinity (g / kg) in 1996 (above) and 2014 (below). Source: Finnish Meteorological Institute.

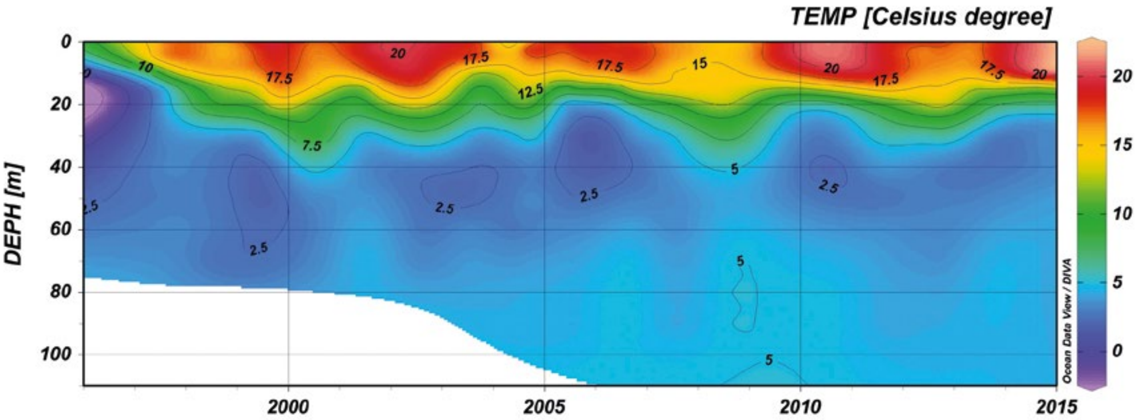

Figure 4. Temperature as a function of depth and time at station LL7 in July–August. Source: Pekka Alenius.

which there is thermocline. The average depth of the surface mixed layer in the summer was 12.8 m in 1987–2008, deepening from 11.4 m in June to 14.9 m in August (Liblik and Lips 2011). The summertime thermocline depth has slightly increased between the Gulf of Finland Years (Fig. 4).

Halocline

Halocline plays a crucial role in the overall stratification and mixing. It prevents vertical mixing of water beyond its location. The halocline locates usually at a depth of 60–80 m in the Gotland Basin and thus extends into the deepest parts of the western and middle GOF. If we define the vertical salinity gradient necessary for a prominent halocline to be ≥ 0.07 g/kg per metre, then the average halocline depth in the western and middle GOF was 67 m in 1987–2008 (Liblik and Lips 2011). At the same time,

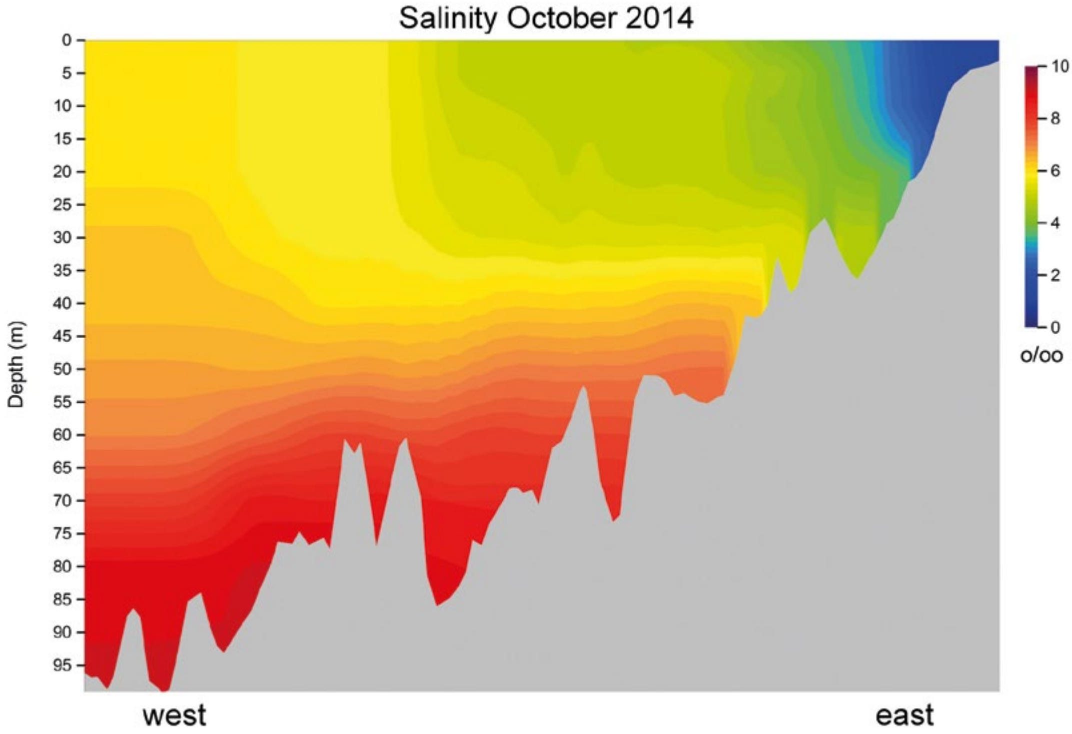

Figure 5. Salinity cross-section through the GOF in October 2014. Source: SYKE database.

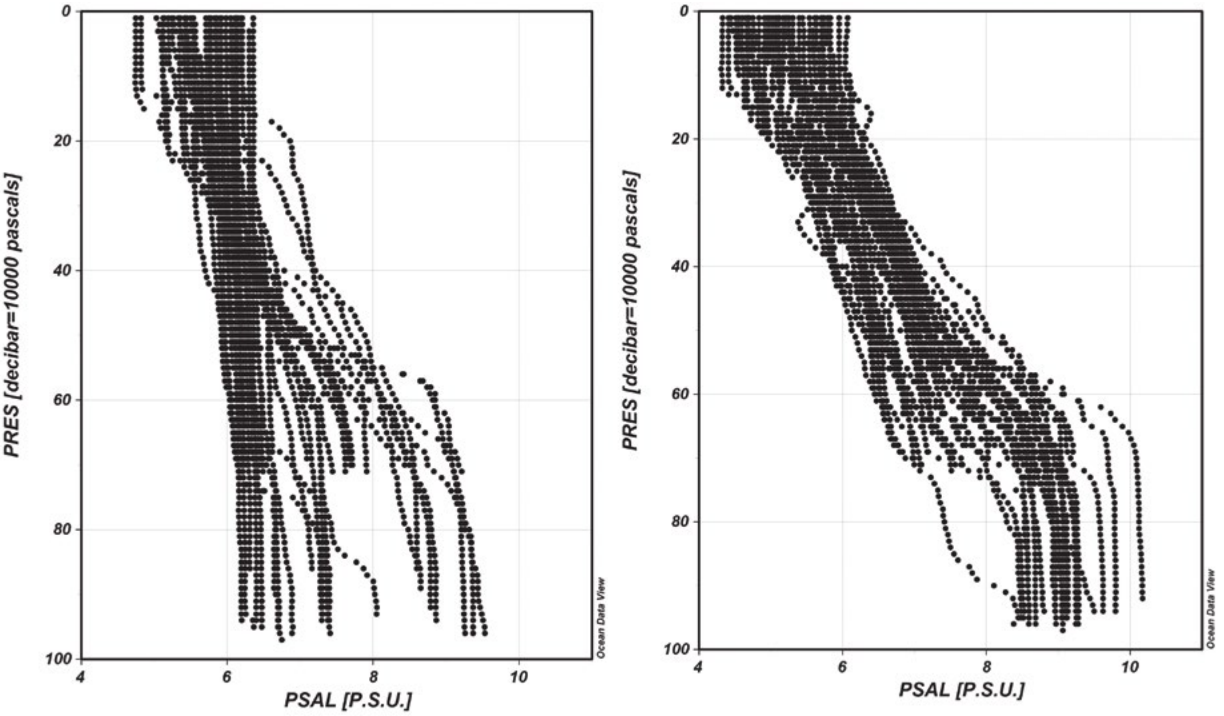

Figure 6. Salinity (practical salinity unit PSU equivalent to g/kg) as a function of pressure (desibar equivalent to one metre in depth) at LL7 in the winter (left) and in the summer (right). Source: Finnish Meteorological Institute.

the occurrence of halocline in these areas has become more a rule than an exception (Liblik and Lips 2011). The renewal of the deep waters in those parts of the GOF covered by halocline largely relies on the advection from the Northern Gotland Basin.

The strength of salinity stratification decreases towards the east, and halocline eventually vanishes in the shallower eastern areas due to the massive fresh water input by the River Neva and strong mixing (Fig. 5). In the eastern GOF, there is no permanent halocline and salinity increases approximately linearly with depth. Halocline is missing in the shallow coastal areas, too. In these areas, strong wind events are able to mix the entire water column particularly at times without thermocline.

Salinity stratification varies between the winter and the summer (Fig. 6). Enhanced vertical mixing processes in the autumn and the early winter break the stratification and renew the deep waters of the GOF. As a result, the difference between surface and bottom salinities in the winter is 1.5 to 2 g/kg. In the summer, the stratification strengthens and vertical mixing is gradually hindered, and the difference between surface and bottom salinities rises up to about 4 g/kg. Similarly to the observed changes in the near bottom salinity, the salinity stratification weakened in the 1980's – the mid-1990's, and has strengthened ever since (Liblik and Lips 2011).

Water circulation

The water masses change continuously in the GOF. The average circulation pattern is cyclonic (counter-clockwise) with eastward flow at the southern part and westward flow in the northern part (Fig. 7). A quite persistent (up to 50 %) inflow takes place near the southern coast. The rest of the GOF harbors a compensating outflow. It is highly persistent (up to 80 %) near the surface and below it, locating slightly north of the central axis of the GOF.

This description of cyclonic circulation pattern is a simplification, and is based on the prevailing wind direction from the south-west and on earth rotation. The true circulation is much more variable and depends on the local short-term wind conditions. Already classical studies (Witting 1912, Palmén 1930, Hela 1952) elucidated

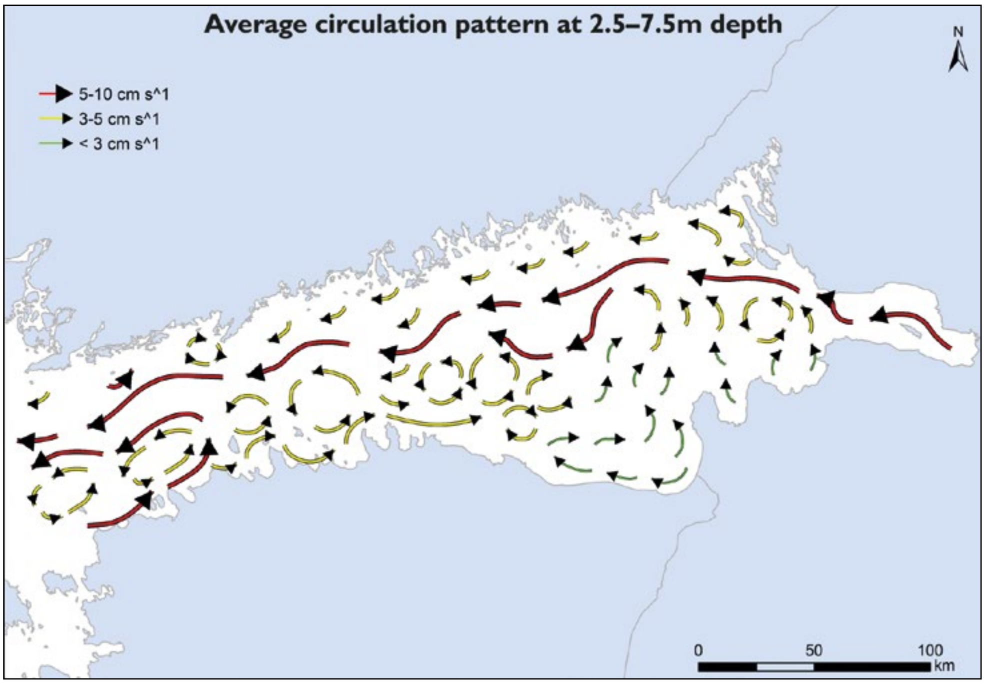

Figure 7. Average circulation pattern at 2.5–7.5 m depth in the GOF. Arrows show the flow direction and the colours denote current velocity (cm/s). Source: Andrejev et al. (2004a).Graph: Marco Nurmi.

the cyclonic, i.e., counter-clockwise general circulation of the GOF but also noted the remarkable variability around the average current field.

The bottom line is that the mean circulation is a statistical property rather than a constant feature. This is often forgotten and the cyclonic pattern inappropriately treated as a permanent feature, such as the Gulf Stream. In fact, the instantaneous currents almost totally mask the long-term mean circulation. Although there is a residual flow in the southern GOF towards the east and another in the northern GOF towards the west, the instantaneous current can be even the opposite. Even an anti-cyclonic gyre may exist in the eastern GOF in certain years (Soomere et al. 2011).

Substances released to the GOF may spread widely around the GOF from their discharge point during several months of time. The knowledge on the circulation patterns in the GOF is essential for assessing the impacts of, e.g., land-based loads and accidents in the oil transportation.

There is a manifold of mesoscale features on top of the general current pattern, as expected for flows with a small internal Rossby radius (Andrejev et al. 2004a). The circulation pattern contain numerous relatively persistent eddies with a typical size exceeding the internal Rossby radius that are probably steered to some extent by complex bathymetry. The Neva Bay and the Shallow Water Area of the eastern GOF possess a persistent and strongly meandering westward / north-westward current pattern evidently supported by the voluminous runoff from the River Neva.

In short, as important as this general concept is for the understanding of the current pattern of the GOF, there are seasonal differences in current stability, and in general, the stability is not as strong as is typically thought (Andrejev et al. 2004a).

Water exchange

The estuarine dynamics of the GOF is mainly governed by a balance between the fresh water flow and the advection from the Northern Gotland Basin (Fig. 8). Strongly anisotropic wind forcing may at times play an important role in the water exchange (Soomere and Keevallik 2003). Strong south-west winds work against the standard estuarine circulation by pushing large amounts of fresher surface water back into the GOF. The excess volume of water increases the hydrostatic pressure in the GOF and may lead to gradual export of the salt wedge in the bottom layer of the GOF (Elken et al. 2003). A major consequence of this reversal of estuarine transport is the weakening of stratification at the entrance to the GOF, accompanied by intensified vertical mixing

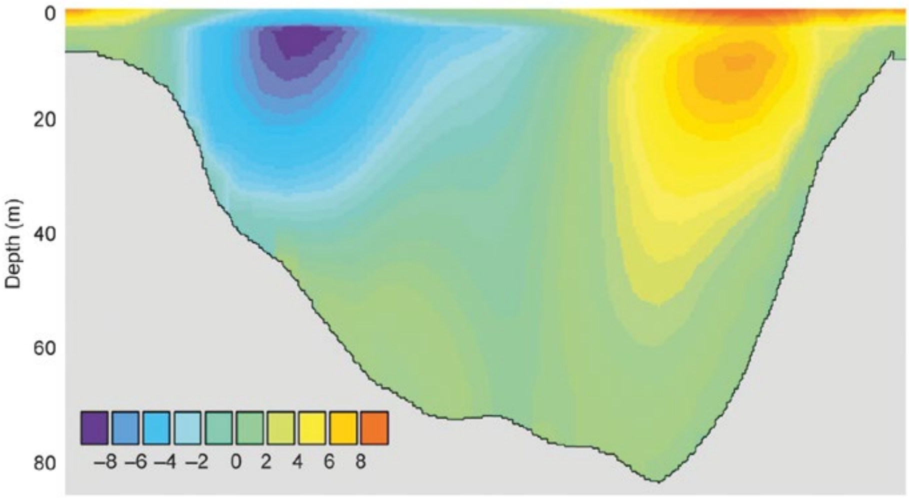

Figure 8. Simulated five-year mean of inflow (positive) and outflow (negative) current speed (cm/s) at the entrance of the GOF (Hanko–Osmussaar line). Finland is on the left and Estonia on the right. Source: Andrejev et al. (2004a).

Rossby radius

The internal Rossby radius of deformation gives the horizontal length scale of mesoscale dynamics in the sea. It is important in defining the required spatial resolution of observations and numerical models. The radius is roughly around 10 km in the Gotland Basin and 1.5 to 5 km in the GOF (Fennel et al. 1991, Alenius et al. 2003, Osinski et al. 2010). In the studies within the frame of the Gulf of Finland Year 2014, the length of the radius seemed to be quite well related to the depth of the area. Thus, the radius was 3 to 6 km in the deeper southern part of the GOF and < 3 km in the shallower northern part of the GOF.

In the GOF, there is often a pronounced secondary halocline in the deepest 5 m of the water column, depending on the water depth and the advection of water masses. Such a thin layer of more saline water affects water stratification, and hence, the near-bottom oxygen condition in the area, for instance. To clarify the role of this phenomenon to the determination of the radius, standard CTD profiles measured down to about 5 m above the bottom were compared to profiles that were extended right down to the bottom with a separate CTD (Figs. 9 and 10).

The complete profiles obtained larger radius – some hundreds of meters – than did those that were extrapolated to the bottom. For fully understanding the dynamics of the GOF, it is thus important to extend the CTD-profiles down to the bottom in the areas where a thin near-bottom layer of higher salinity is expected to occur.

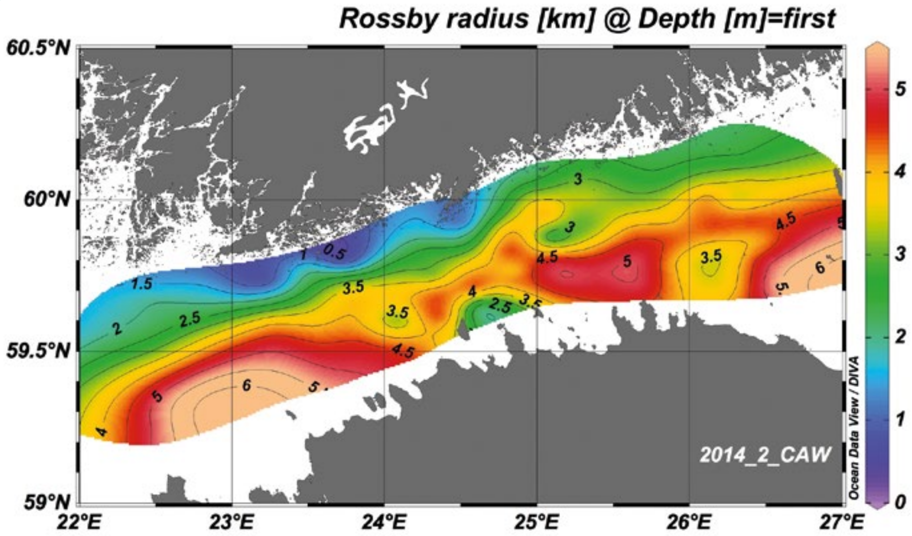

Figure 9.
First internal Rossby radius of deformation in the western GOF in the autumn 2014 calculated from CTD-profiles at the stations < 100 m deep.
The profiles were extended down to the bottom.
Source: Finnish Meteorological Institute.

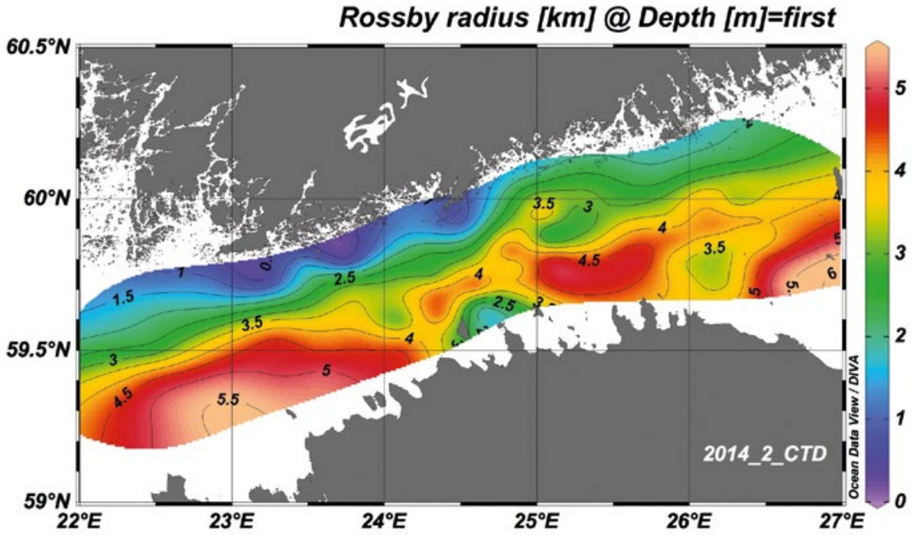

Figure 10.
The same as in Fig. 8 but for CTD-profiles that were extended down to about 5 m above the bottom.
Source: Finnish Meteorological Institute.

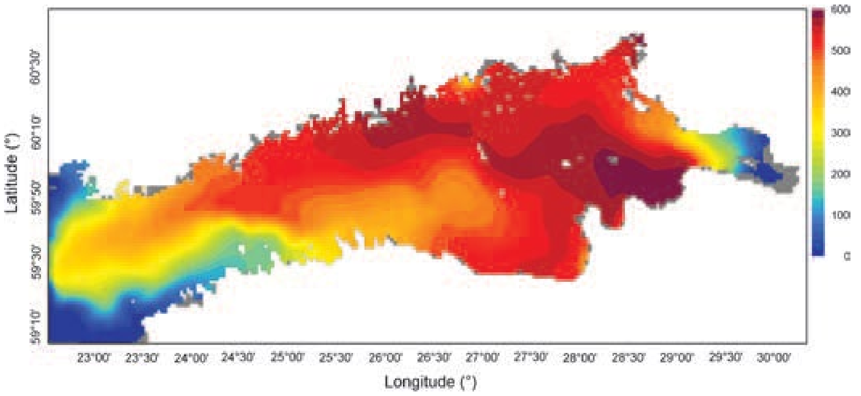

Figure 11. Water age in the GOF in days. Source: Andrejev et al. (2004b).

(Elken et al. 2006). Its practical consequences for the functioning of the deep-water ecosystem are not yet fully understood.

The GOF has a positive fresh water balance. The net outflow of 130 km^3/year was already reported by Witting (1910). Andrejev et al. (2004b) took into account relatively persistent mesoscale features (local jets, synoptic eddies, inertial oscillations) that induce comparatively short-term transport of water across the entrance line of the GOF, and came up with the net outflow of 119 km^3/year in 1987–1992. This is close to the total river runoff to the GOF.

If we define the age of a water particle as the time elapsed since the particle leaves the sea surface (Deleersnijder et al. 2001), the oldest water (about 8.3 years) is evidently located at the bottom of the GOF (Meier 2005). However, the water age in the GOF with respect to water exchange with the Northern Gotland Basin is at most only two years (Fig. 11), emphasizing an intense interaction between these two sub-basins of the BS.

Upwellings

Episodic upwellings are often the most noticeable of the mesoscale phenomena in the GOF (Myrberg and Andrejev 2003, Lehmann et al. 2012). By definition, upwelling represents penetration of denser, cooler waters richer in nutrients towards the sea surface. It not only affects dramatically the water-column stratification, but also redistributes nutrients and other substances both horizontally and vertically (Fig. 12).

Upwellings present horizontal length scales from some kilometers to some tens of kilometers across the GOF (Lips et al. 2014). They may extend to 100 km alongshore (Gidhagen 1987, Lips et al. 2009), and their major effects are observed in a 5 to 20 km wide coastal zone (Lehmann et al. 2002, 2012, Myrberg and Andrejev 2003, Lehmann and Myrberg 2008, Myrberg et al. 2010).

In the GOF, upwelling events are predominantly of coastal type and based on Ekman transport, resulting from horizontal divergence of wind-driven motions in the surface layer. The winds along the GOF cause upwelling in either of the coasts and downwelling on the opposite coast depending on the wind direction. Westerly winds cause upwelling on the northern coast and easterly winds on the southern coast (Fig. 13). The coupled upwelling / downwelling events introduce mesoscale upwelling filaments and eddies that cause advection between onshore and offshore areas (Zhurbas et al. 2008). This feature is more pronounced in the western and middle GOF than in the eastern part (Laanemets et al. 2011).

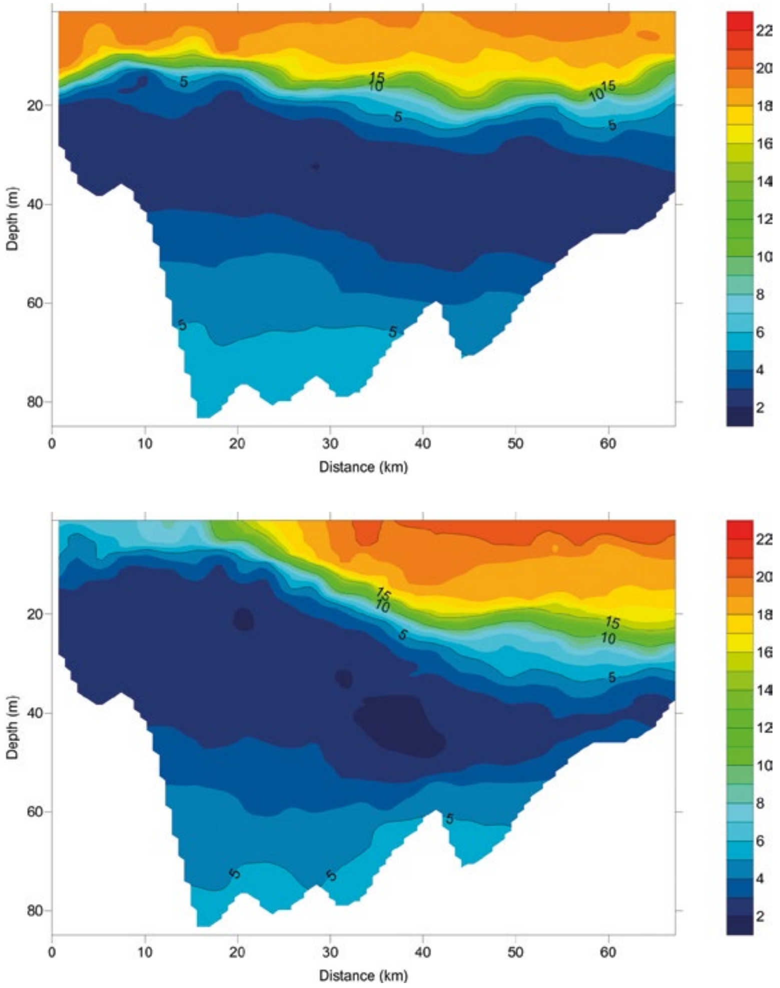

Figure 12.
Measured temperature (°C) cross-section in the GOF in the summer 2006 (Estonia on the left side, Finland on the right side).
A: stratification is normal off the Estonian coast on the 11th of July.
B: pronounced upwelling appearing in this region on the 8th of August.
Source: Lips et al. (2009).

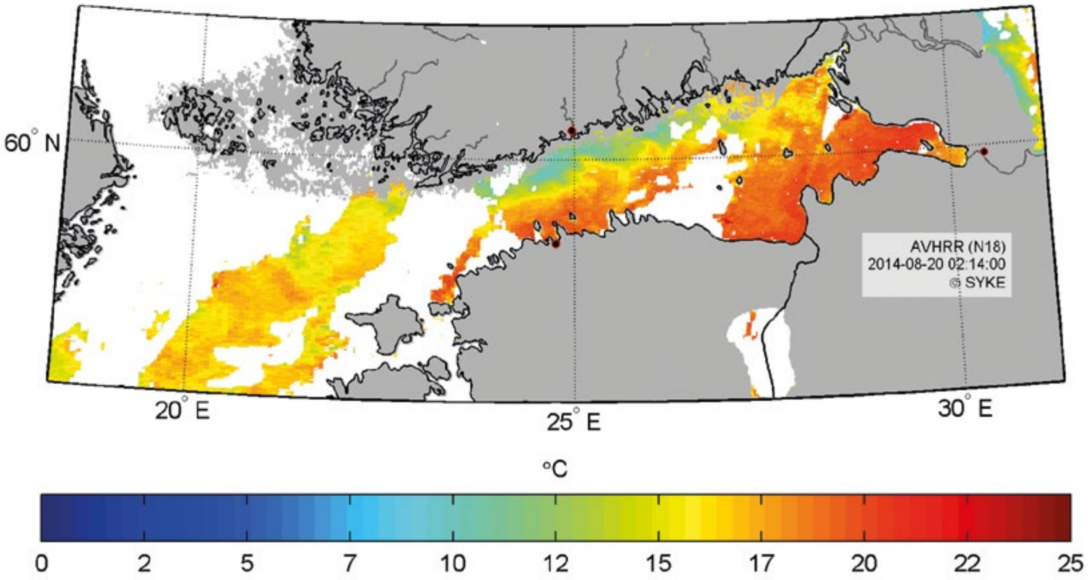

Figure 13. Temperature in the surface layer of the GOF on the 20th of August, 2014. An upwelling in the northern seaboard is clearly visible. Whenever the surface water temperature is > 20 °C, the runoff waters of large rivers, such as the River Neva in this case, may be colder than the sea water. Source: NOAA-18 / AVHRR. Graphics: SYKE.

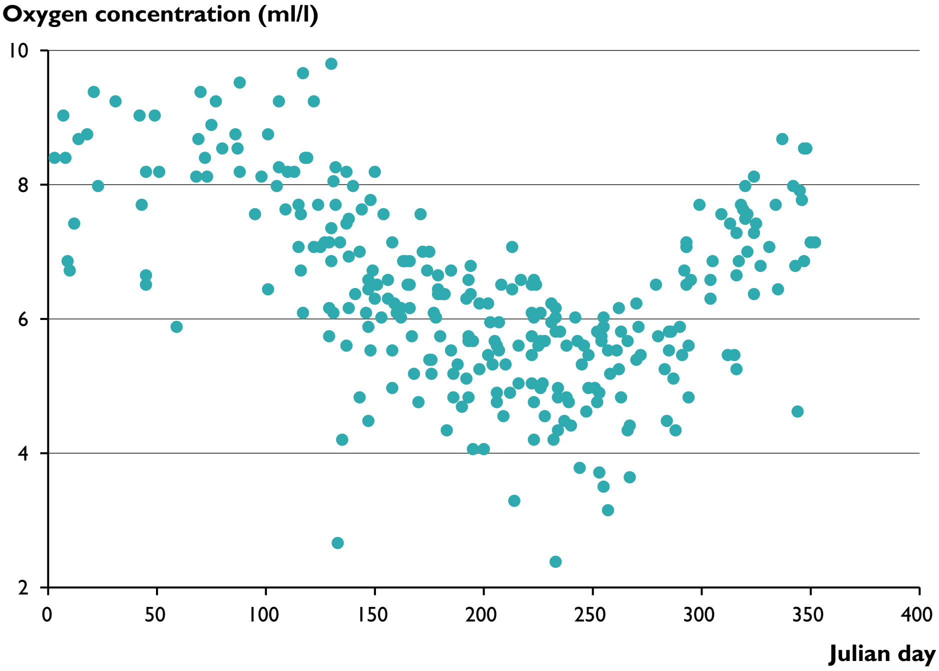

Figure 14. Oxygen content as a function of julian day at 46 m at UUS-10A off Helsinki. Source: SYKE database.

In the GOF, upwelling is typically triggered by alongshore winds with a duration of about 60 hours (Haapala 1994). Its lifetime spans from several days to several weeks. At the Finnish coast, upwelling occurs as frequently as 15 to 30 % of the time (Lehmann et al. 2012). During the summer, when the surface water is at its warmest, upwelling may result in a decrease of up to 10 °C in local surface water temperature.

Deep-water oxygen condition

The expanse of the hypoxic bottom layer is a hydrographic feature that strongly affects the functioning and environmental condition of the GOF. In the areas where seasonal overturning reaches the bottom, the oxygen content renews twice a year. In the summer, temperature-driven stratification hinders vertical mixing effectively and the deep-water oxygen condition is mainly relying on advection processes. As a result, the deep-water oxygen content is typically lower in the summer than in the winter (Fig. 14).

In the deep areas of the western and middle GOF, halocline, if existing, forms another obstacle for vertical mixing. The deep bottoms beneath the halocline rely on the oxygen storage brought by advection from the Northern Gotland Basin. At times, the incoming waters are highly saline and poor in oxygen. The oxygen content in the deep water has indeed clear salinity dependence (Fig. 15).

The oxygen-poor waters penetrate to the GOF and extend eastwards and northwards to areas that are deep enough. Poor oxygen condition may remain for an extended period if the wintertime collapse of stratification does not occur (Liblik et al. 2013). Elken et al. (2014) suggest that such collapses of stratification have recently become more frequent. As a result of the recurrent episodic inflows and collapse events the temporal variation in the deep-water oxygen content is pronounced. Salinity presents temporal variation that is more or less a mirror image to the one of oxygen (Fig. 16).

Because the northern part of the GOF is shallower, the near-bottom oxygen conditions are generally better there than in the deeper southern part. That was observed also in 2014; the oxygen-poor waters originating from the Northern Gotland Basin entered deep into the middle GOF. Consequently, the waters of the GOF below

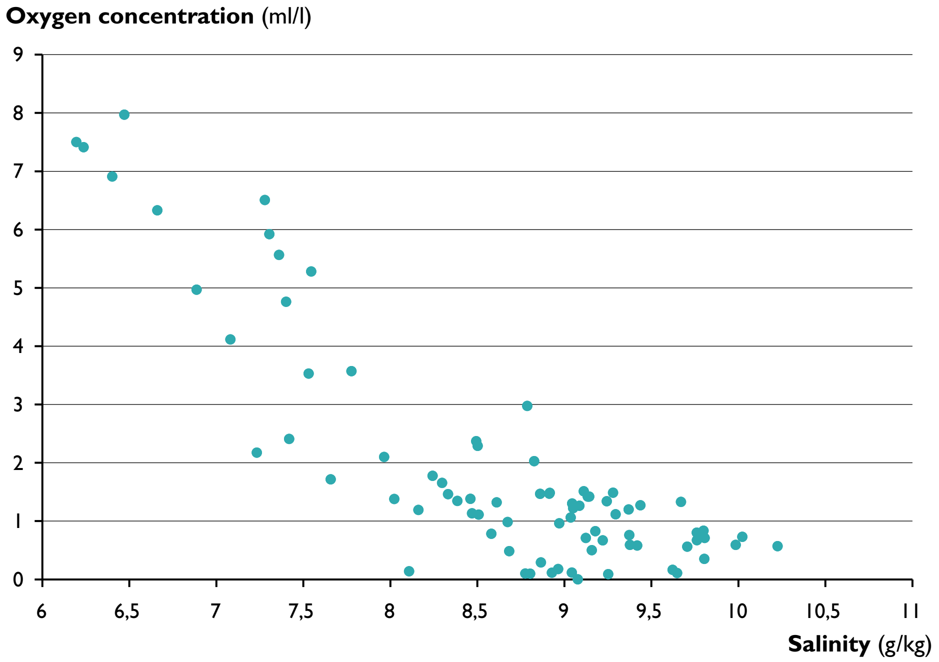

Figure 15. Oxygen content as a function of salinity at 90 m at LL7 in the halfway between Helsinki and Tallinn. Source: SYKE database.

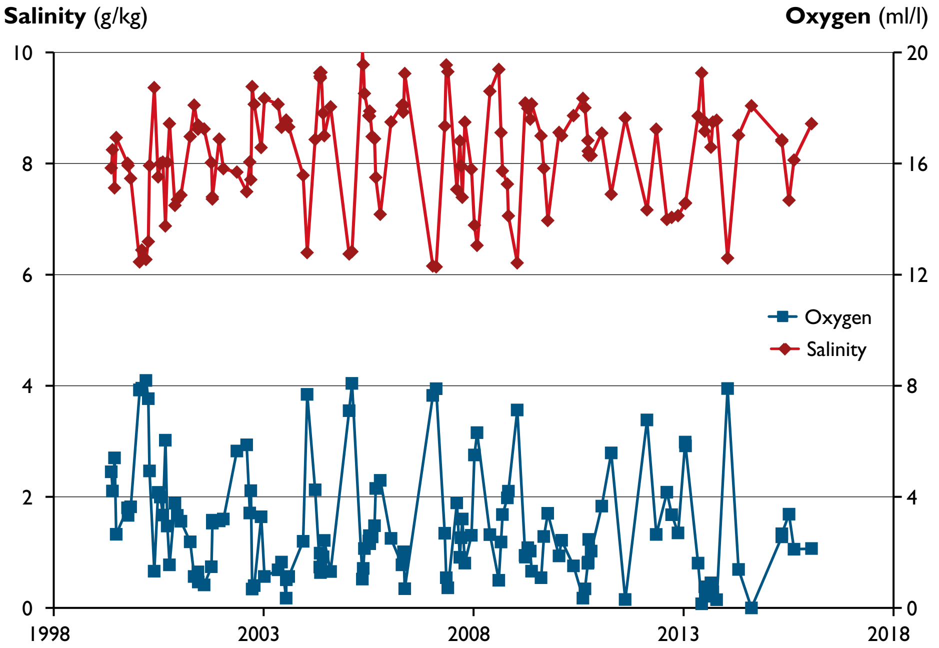

Figure 16. Salinity (red) and oxygen (blue) as a function of time at 70 m depth at LL7 in the halfway between Helsinki and Tallinn. Source: SYKE database.

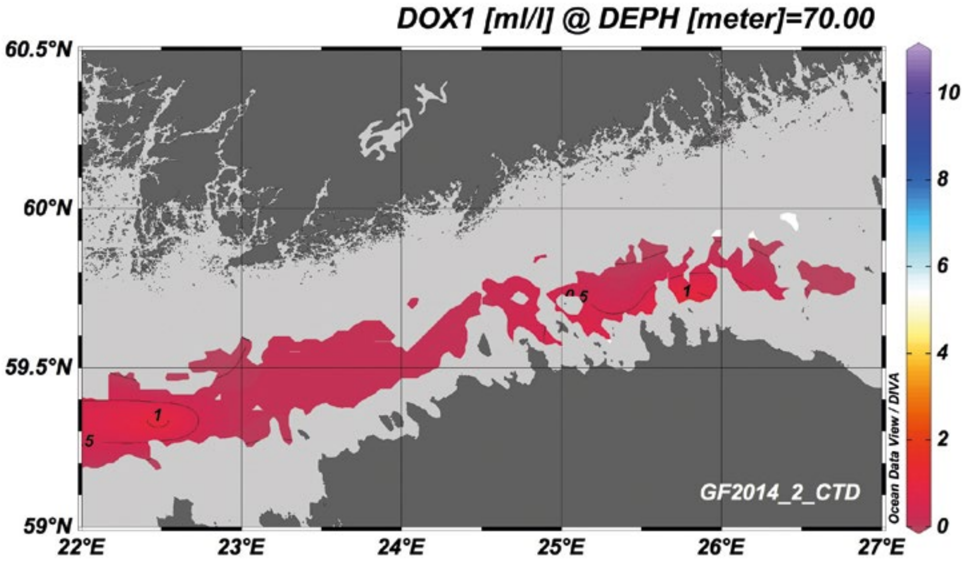

Figure 17. Oxygen content in the deep-water of the western and middle GOF in the autumn 2014. Source: Finnish Meteorological Institute.

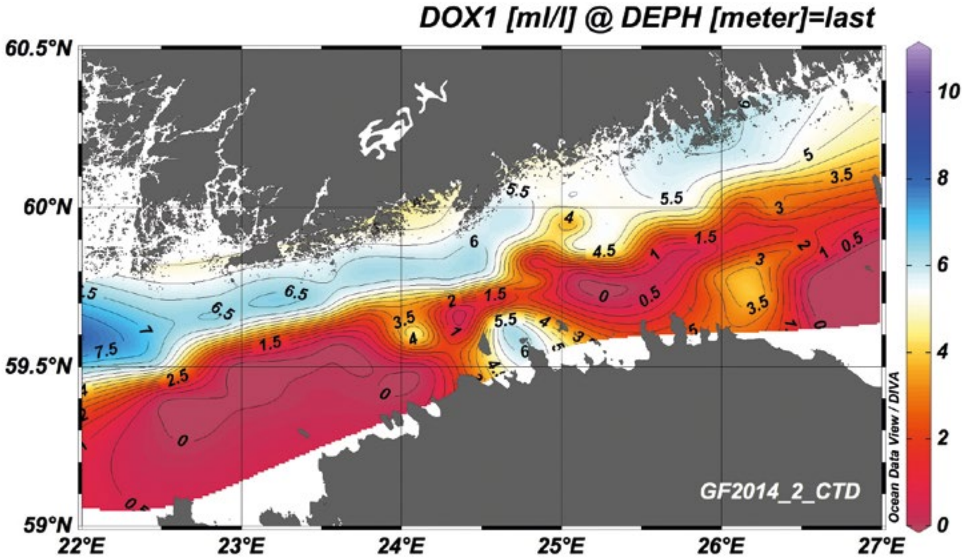

Figure 18. Near bottom oxygen content in the western GOF in the autumn 2014. Note that the bottom depth is different at each station and the oxygen content is determined at 5 m above the bottom at each station. Source: Finnish Meteorological Institute.

the 70 m depth were hypoxic or anoxic from the spring to the autumn, while in the shallower areas the conditions were normoxic (Figs. 17 and 18).

In the western part of the GOF, there are areas where the highly saline and typically oxygen-poor bottom water layer is rather thin simply due to the water depth. The thickness of this layer is often < 5 m. Such areas may be found anywhere where the bottom depth is 30–75 m. High-frequency observations should be extended near to the bottom, i.e., at least down to 1–2 m above the sea floor, which is not possible using current monitoring techniques. We thus suggest that the scientific community would find a routine-operating way to probe the near-bottom layer.

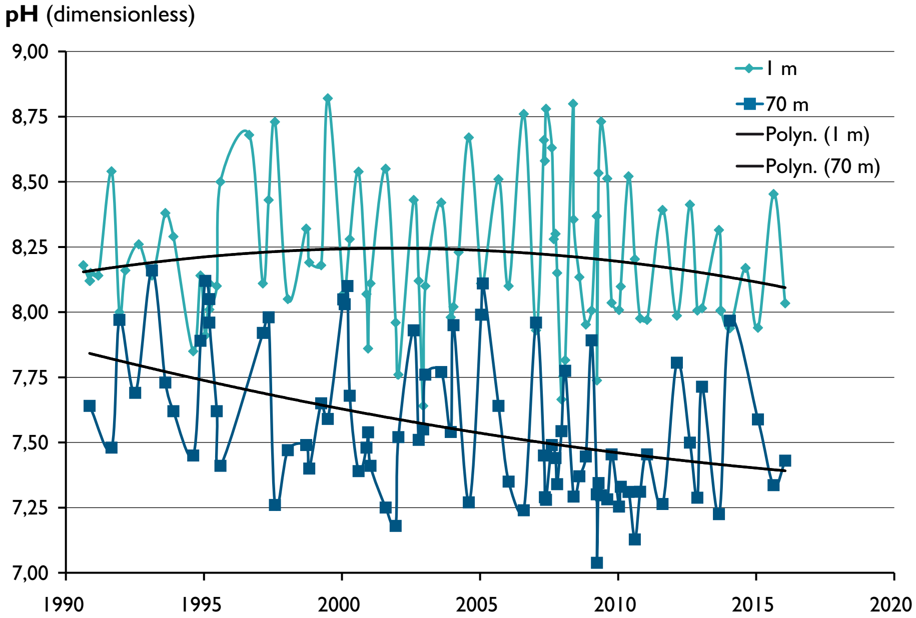

Figure 19. pH at 1 m and 70 m depths at LL7 in the halfway between Helsinki and Tallinn as a function of time. The non-linear fits are embedded to reveal trends. Source: SYKE database.

pH

Ocean acidification is the reduction of seawater's pH due to an increasing partial pressure of atmospheric CO_2. The surface pH in the World Ocean has decreased from 8.25 to 8.14 between 1751 and 1994 (Jacobson 2005). In the current World Ocean, pH is decreasing at a rate of 0.0017 to 0.0026 units/year with the highest rates in high latitudes (Lauvset et al. 2015 and references therein). Scenario modeling suggests that acidification in the BS may cause up to three times increase in acidity (reduction of 0.2 to 0.4 pH units) by the year 2100 (Havenhand 2012).

In the GOF, the seasonal variation dominates the pH pattern (Fig. 19). The difference in the pH level between the summer and the winter has grown since 1990, and is currently about 0.7 units. Superimposed to the seasonal fluctuation, there is also fluctuation in the time scale of 5–10 years, which obscures the detection of any trend for the surface. In the deep layer of the GOF, however, an obvious reduction in pH took place in 1990–2010. The average reduction rate at the time period was as high as 0.024 units/year. Based on that rate, the above-mentioned reduction of 0.2 to 0.4 units would take place much sooner than by the year 2100. The trend in the deep water, however, levelled out after 2010. Furthermore, this decrease reflects not so much the atmospheric CO_2 trend, but rather, worsened ventilation of the deep waters due to strengthened stratification.

Conclusions

The hydrographic features of the GOF are very variable both in time and space. They depend largely on the weather of the Baltic area and the condition of the Gotland Basin. Between the Gulf of Finland Years 1996 and 2014, there were no notable trends in these parameters to note.

The hydrography and hydrodynamics play on rather small scales in the GOF. The resolution of both observations and numerical models should therefore be high enough in order to properly address the key processes. High-frequency monitoring at certain representative stations is elementary, and campaigns collecting data with high spatial resolution add to this basic structure. A monitoring programme that covers only the centerline of the western and middle GOF is clearly not sufficient to assess the state of the GOF.

The GOF is an integral part of the BS. The openness of the GOF to the Gotland Basin is one of its key dynamical features, and its dynamics cannot be understood without taking into account the Gotland Basin. The interplay between the two basins play a major role in the nutrient dynamics of the GOF. In the worst case scenario, having extensive anoxic bottoms and receiving a constant flow of nutrients from the Northern Gotland Basin, the nutrient dynamics of the western and middle GOF is largely governed by processes taking place outside the catchment of the GOF. Thus, we need more research on the following topics:

- Dynamic reasoning behind the large variation in the haline stratification of the GOF, reflecting to variations in the bottom oxygen condition and internal phosphorus loading

- Examination on the current dynamics and water exchange processes between the GOF and the Gotland Basin, combining modelling, autonomous devices, and research vessel based measurements. New information of mass, salt, heat, and nutrient fluxes between the basins is needed.

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GEOLOGY AND GEODIVERSITY

Chapter coordination: Aarno Kotilainen, Geological Survey of Finland

Topography and bedrock

Aarno Kotilainen[1], Anu Kaskela[1], Oleg Korneev[2], Daria Ryabchuk[3], Alexander Rybalko[2], Sten Suuroja[4], Henry Vallius[1], Kai Myrberg[5], Pekka Alenius[6]

[1]Geological Survey of Finland
[2]Federal State Unitary Research and Production Enterprise for Marine Exploration (SEVMORGEO)
[3]A.P. Karpinsky Russian Geological Research Institute (VSEGEI)
[4]Geological Survey of Estonia
[5]Finnish Environment Institute
[6]Finnish Meteorological Institute

The Gulf of Finland (GOF) is a northeastern elongated sub-basin of the Baltic Sea (BS). It is a direct continuation of the Gotland Basin without any sills, and becomes gradually shallower towards its tip (Fig. 1). The GOF is a depression in the bedrock topography that formed along the contact between the crystalline basement and the sedimentary rock cover.

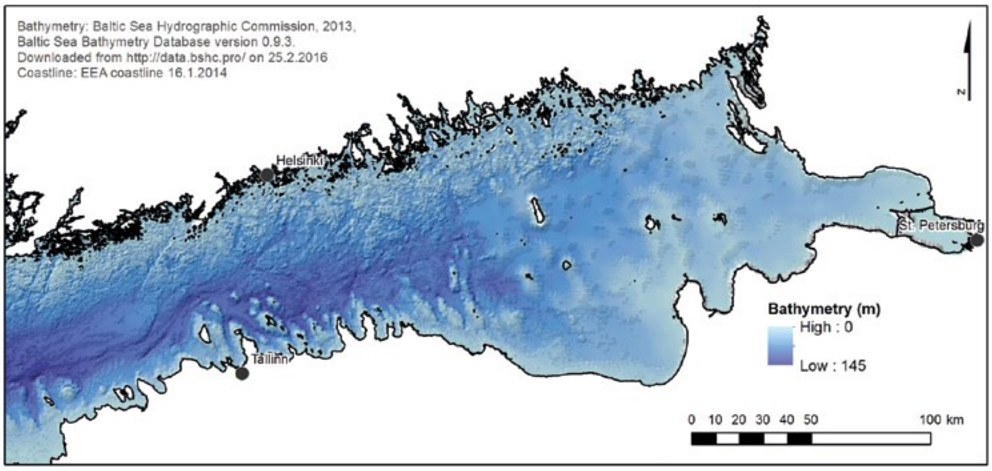

Figure 1. Bathymetry data overlain on top of the hillshade data reflect the topography of the GOF. Source: Baltic Sea Hydrographic Commission.

Photo: Riku Lumiaro.

Crystalline bedrock is exposed in the northern GOF and covered by younger sedimentary rocks in the southern part (Koistinen et al. 2001). The northern slope is gentle with a general dip of the basement planation surface to the south, while the southern slope is steeper and represents the submarine continuation of the North Estonian Klint (Puura et al. 1996, Spiridonov et al. 1997).

Crystalline basement rocks result in a complex and fragmented seafloor in contrast to sedimentary rocks, and lead to high geodiversity and potentially to elevated biodiversity.

The average depth of the GOF is 37 m. The deepest areas (80–100 m) are located in the western and southern parts of the GOF. The central part west of 28 °E is quite deep (> 60 m) and has uninterrupted deep-water connection with the Northern Gotland Basin regardless of the complicated shape of deeper areas. The maximum depth in the Paldiski Deep (the deep is located off the cape where the City of Paldiski lies) is 123 m (Leppäranta and Myrberg 2009). There is a 138-m deep located north of the Osmusaar Island, and west of the Paldiski deep. Here erosional, striated, and grooved surface is located within the foreklint area in the transitional zone between crystalline basement and sedimentary rocks to the south. Local deep basins can be found in the easterly parts, too (e.g., a 90-m deep Paskamonttu in the Finnish waters close to the Gogland Island), and underwater canyons appear as well.

The seabed topography of the GOF is one of the most fragmented in the BS. The seafloor is covered by geomorphic features like plains (25 %), basins (33 %), valleys and holes (10 %), and elevations (32 %, Kaskela et al. 2012). The present topography and bathymetry of the GOF is a result of crystalline and sedimentary bedrock morphology as mentioned, but glacial activity has had its impact, and glacio-isostatic land uplift (i.e., rise of land masses that were depressed by the ice sheet during the last glacial period) still has its impact. Modern sedimentation and erosion processes are there, too. However, the main features of topography are of pre-glacial origin.

Tour around the GOF

The coastal and seafloor topography of the northern GOF is more fragmented and patchy than that of the southern part where sedimentary rocks smooth the topography. The Finnish coast is a typical example of a skären-type coast (Fig. 2). Its stable crystalline bedrock is virtually insensitive to the wave action (Granö and Roto 1989). As this area has a very limited amount of finer material, the bathymetry is governed by the character of crystalline bedrock. The inner coastal area is shallow (depth 10–20 m), has an extremely irregular coastline and rugged bathymetry, and contains extensive archipelagos.

Contrasting the irregularity and mosaic-like of the northern coastline, the southern and eastern coastlines are relatively straight with only few fairly large islands (Fig. 2). The Gogland Island is a landmark in the middle GOF between Kotka and Narva, and the Tjuters Island is located south-east of it. The Moschny Island and the Seskar Island are located further in the east, and the Kotlin Island in the tip of the GOF defines – along with the Flood Protection Facility of St. Petersburg – the outer reach of the Neva Bay. Travelling further counterclock-wise towards the Vyborg Bay we will meet the Berezovy Islands. The boundary between the crystalline bedrock and younger sedimentary rocks as factors shaping the landscape can be observed in this coastal area.

Although the Estonian coast hosts several bays cut deeply into the mainland, on a smaller scale its appearance is quite smooth and regular. Especially the large islands and the peninsula near Tallinn have an important effect on the hydrographic conditions in the middle GOF, because they steer the eastward flowing currents and thus form mesoscale eddies in this part of the GOF. This wave-dominated coast (Soomere and Healy 2011) is typically characterized by, from a local point of view, almost straight sections with a rather steep and regular slope. The islands consist mostly of till, except Osmussaar that has a limestone core, ground by the Pleistocene ice sheet into gentle shapes. An exception is the Neugrund area at the entrance to the GOF; the steep underwater cliffs which have been created by a massive asteroid hit. The south-west coastline of the GOF contains extensive shallow areas with sedimentary seabed occurring north and east of Hiiumaa.

Between 28 and 29 °E there is a transition zone with gradually decreasing width and depth of the GOF. It is situated between the area frequently impacted by the Gotland Basin and the area where estuarine effects predominate, and is sometimes called the Seskar Basin. It plays an essential role in the transport of water and substances (sediments and nutrients) between the domain governed by the river discharge and the rest of the GOF. Due to a combination of massive discharge of fluvial sediment from the eastern GOF and the waters deep enough to prevent re-suspension by surface waves, this intense deposition area acts as a buffer preventing the spreading of various substances further to the west.

The GOF gets gradually shallower until at about 29 °E the mean depth crosses the 20-m limit. The area to the east is called the Shallow Water Area of the eastern GOF. East of the Kotlin Island and St. Petersburg Flood Protection Facility there is the Neva Bay, a 22-km long and 15-km wide tip of the GOF. It is very shallow, with a mean depth < 5 m, except the dredged waterway “Marine Canal” to St. Petersburg.

Figure 2. The coasts formed by the crystalline bedrock (above) and younger sedimentary rocks (below) differ quite much in their topography. Photos: Riku Lumiaro.

Geodiversity

Anu Kaskela1), Aarno Kotilainen1), Oleg Korneev2), Daria Ryabchuk3), Alexander Rybalko2), Sten Suuroja4), Henry Vallius1)

1) Geological Survey of Finland
2) Federal State Unitary Research and Production Enterprise for Marine Exploration (SEVMORGEO)
3) A.P. Karpinsky Russian Geological Research Institute (VSEGEI)
4) Geological Survey of Estonia

Environmental diversity consists of biological and geological elements. Biodiversity is an established definition for biological diversity, that is, the variety of organisms present in an ecosystem, but geodiversity (i.e., geological diversity) is a less familiar concept. It can be described as the variety in elements of geology – such as rocks, minerals, fossils, and soils – and the natural landforms and processes that shape them through geological time. In marine realm, it relates to fragmentation and patchiness of the physical environment on the seafloor. Geologic features provide habitats and shelter; variable seafloor environments thus support potential biodiversity hotspots (Fig. 3).

The seafloor environment of the GOF is very diverse at the BS scale (Kaskela et al. 2012). Especially the northern seaboard of the GOF stands out. There, fracture and weakness zones of an ancient crystalline divide bedrock into the blocks. Fragmentation creates a labyrinthine archipelago that is evident on a map. The labyrinthine landscape with elevations and depressions appears underwater as well. In the southern part of the GOF, the crystalline bedrock is covered by younger sedimentary rocks that smooth the topography and fragmentation. This difference in the landscape can easily be seen when comparing fragmented archipelago of the Finnish coast to a straighter Estonian coastline and high limestone cliffs (Fig. 2).

As described earlier, the seafloor within the GOF consists of different types of sediments. The majority of the sediments have been deposited during or after the latest

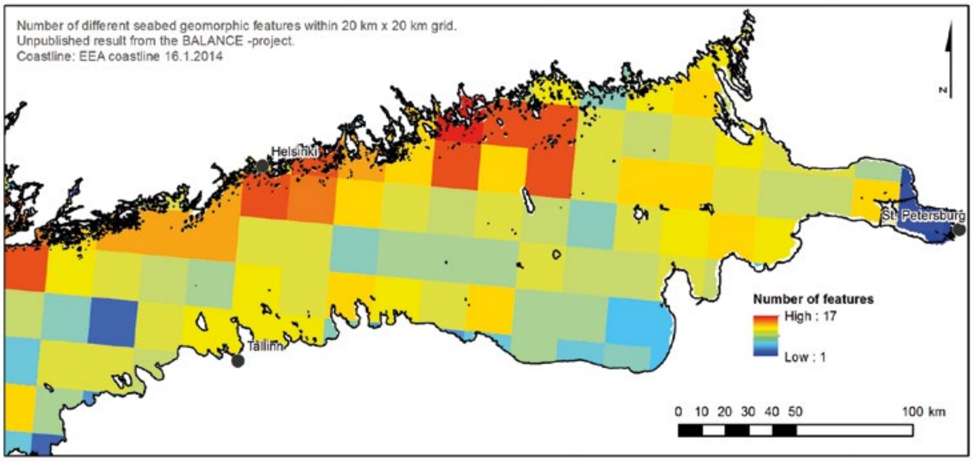

Figure 3. Geodiversity index map over the GOF's seafloor based on geomorphological variability. Geomorphologically variable environment on the seafloor leads to patchy sediment distribution and supports heterogeneous habitats. Source: BALANCE –project (unpubl.).

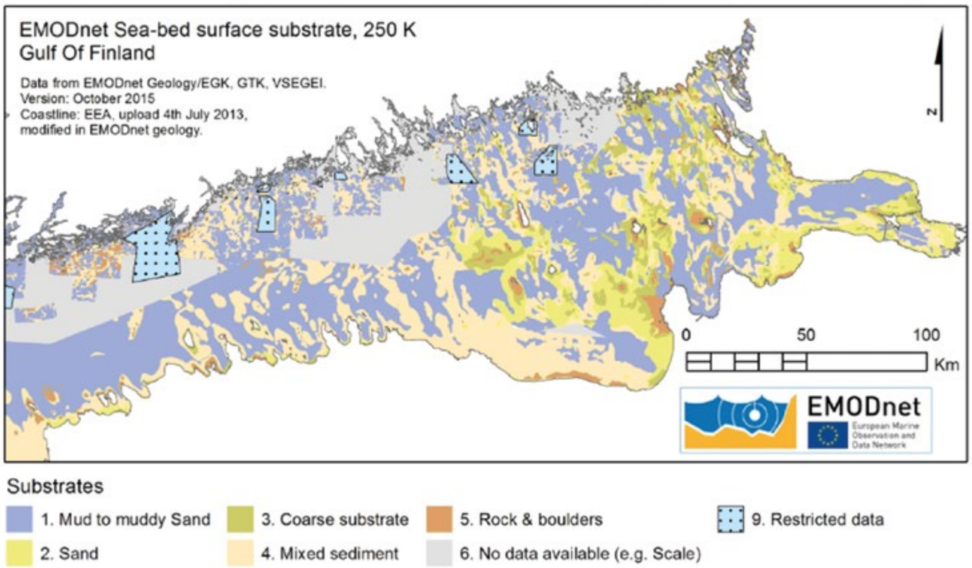

Figure 4. Seabed substrate map over the GOF. Source: EMODnet.

glaciation. The typical sediment stratigraphy for the area reflects the sedimentation history. These sediments consist of i) glacial sediments/substrates, such as glaciofluvial material, ice-rafted erratic boulders, and glacial varved clays and silts, and ii) post-glacial sediments that have been deposited during various limnic and brackish-water phases of the BS. Affected by a range of abiotic and biotic factors, seafloor can be composed of different type of substrates of different ages from glacial till to recent mud.

The spatial distribution of different substrate types on the GOF seafloor is very patchy (Fig. 4). Erosion, transportation, and accumulation bottoms vary spatially but also temporally (Winterhalter et al. 1981, Al-Hamdani et al. 2007). Large sedimentation basins are located primarily in the central part of the GOF and a variety of smaller seabed features occur in coastal areas. At present, 34 % of the seafloor of the GOF can be regarded as a sediment (soft sediment) accumulation area (Kaskela et al. 2012). These accumulative sediments contain also the majority of harmful substances at the seafloor. The most recent changes in accumulation take place in the areas subject to pronounced anthropogenic activity, such as in the Neva Bay.

Sand formations and moraines are found in places throughout the GOF and form pronounced geomorphological units. The eskers have often submarine extensions. Some bedrock outcrops occur, too, being generally relatively rare (3 %) but clustered in the Finnish coastal area (Kaskela et al. 2012). In the eastern GOF, in the rapakivi granite area, the boulder-rich seabed characterizes the area. In addition, different types of depressions, such as canyons and basins, occur in the GOF and its coastal areas. Also the pockmarks, which are craters in the seabed formed by the expulsion of gas and/or fluids from the sediment, occur in the GOF.

In Russia, the term "geodiversity of marine environment" is interpreted as the zonality of facies, i.e., the bottom types based on sedimentation processes. Processes of sedimentation create three main groups of facies: accumulative and sedimentogenic; erosional or destructive; and intermedial or transit. The characteristics of the facies depend on the local hydrodynamics and bottom relief. The zonality of facies serves as a basis for making of geoecological charts, and facies situations determine the bottom sediment formation.

Neugrund

Neugrund meteorite impact crater is located 10 km west of the Osmussaar Island (Fig. 5). The structure formed in the Early Cambrian time, about 535 million years ago, and it is the best-preserved offshore impact structure in the world. The crystalline basement rocks are uplifted on the crater rim walls up to the depth of 20 m below the surface whereas the normal depth for basement rocks in these surroundings is 150 m. The crater was buried shortly after the impact with deposits and was partially re-exposed by erosion during the Pliocene (5.3–2.6 million years ago). An 80-m deep erosional canyon exposes impressive cliffs between the crater rim wall, formed of crystalline rocks and filling sedimentary rocks.

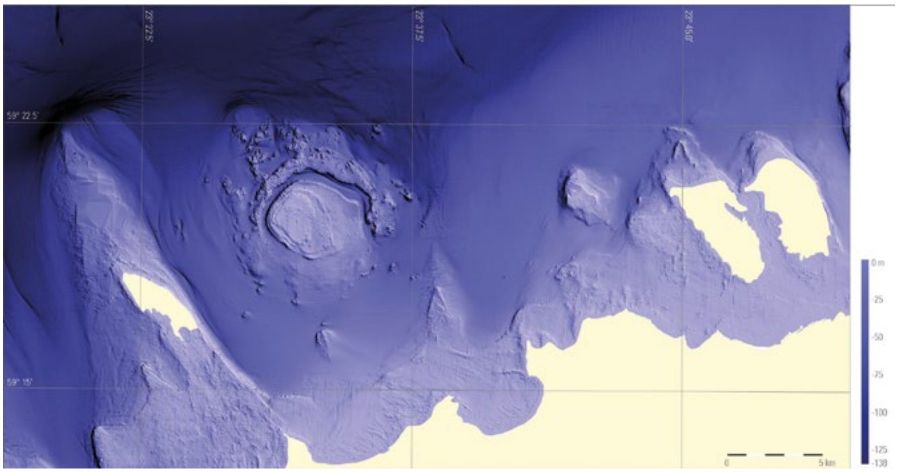

Figure 5. Seabed shaded relief map of Neugrund meteorite impact crater at the entrance to the GOF. Source: Estonian Maritime Administration.

Geodiversity in the Russian waters

Oleg Korneev[1], Alexander Rybalko[1], Daria Ryabchuk[2], Vladimir Zhamoida[2], Andrey Grigoriev[2], Alexander Sergeev[2], A Evdokimenko[2]

[1] Federal State Unitary Research and Production Enterprise for Marine Exploration (SEVMORGEO)
[2] A.P. Karpinsky Russian Geological Research Institute (VSEGEI)

Geodiversity of bottom sediments is shaped by local distribution of various sedimentation factors and is favored by a partitioned bottom relief. A mixture of various sedimentation factors supports a heterogeneous distribution of benthos. The description of geodiversity is crucial for understanding the spatial distributions of the benthic fauna and the bottom-inhabiting fishes.

A granulometric composition of the bottom substrate – an alternation of boulders, sands, and silts – has a profound influence on the distribution of the benthic fauna. The distribution of these benthic landscape types depends substantially on the distribution of the accumulation and erosion zones. The Russian part of the GOF consists of areas having a mosaic of sedimentation zones leading to a high range of geodiversity. The borders between the distinctive zones can be very sharp because of the absence of modern bottom sediments.

Anthropogenic impact brings along changes to geodiversity. In contrast to biodiversity, this impact leads to a more diverse general picture thanks to the appearance of technogenic facies. These appear in the bottom of all port construction areas, and areas near to the Flood Protection Facility of St. Petersburg. In these areas of intense bottom dredging natural sedimentation processes are altered. At the underwater dumping grounds, in turn, the composition of the sediment has been subject to a remarkable change.

Accumulation zones

Zones of stable accumulation

Areas where nepheloid (i.e., the layer of water above the seafloor that contains significant amounts of suspended sediment) accumulation occurs occupy > 50 % of the bottom surface of the eastern GOF (Fig. 6). These areas occur mostly in depressions where clayey or silty-clayey mud is the main seabed substrate type. The zones of clay-like deposits are thus an ensemble of depressions stretching from the Kotlin Island to the Gogland Island where the depth gradually increases from 20–30 m in the east to 60–70 m in the west. Geodynamical elevations separate these depressions. A typical thickness of Holocene deposits is 30–40 m.

- The sedimentation basins with the > 10 m-thick nepheloid layer are situated west of the Shepelevsky Cape in the Shallow Water Area.
- The next sedimentation basin, the Seskar basin, has its western border by a series of glacial ridges extending from the Luga Bay to the west of the Berezovy Islands. The zone of nepheloid accumulation, restricted by a vendian klint, locates to the south from the Shepelevsky Cape to the Moshny Island.

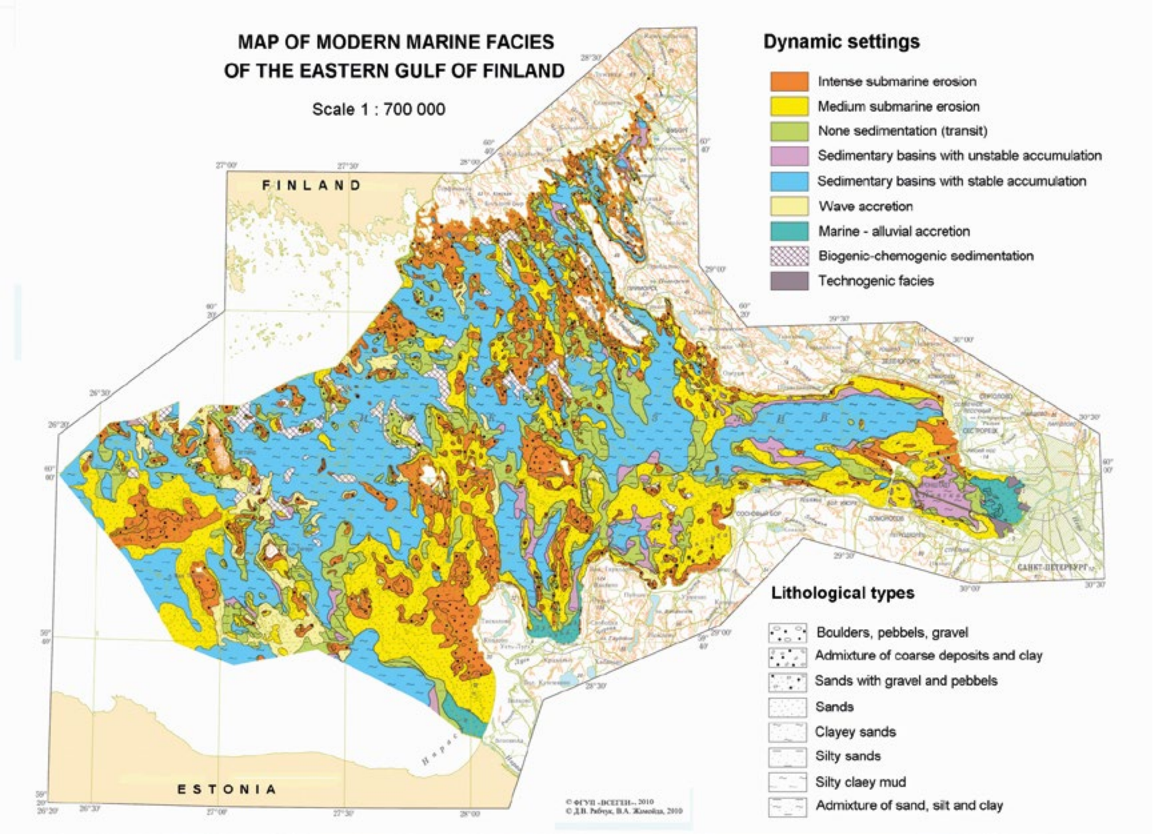

Figure 6. Map of geological diversity of the Russian part of the GOF. Source: VSEGEI (2010).

- The next sedimentation basin is called the Interislands. It is situated north of the Seskar Island and the Moshny Island, and extends to the coast of the Vyborg Bay. The western ridge is limited by a complex of marginal glacial deposits of Nevan stage, elongated from the Kurgalsky peninsula through the Moshny Island and the Maly Island up to the Karelian Isthmus. The basin is characterized by marine clay deposits of variable thickness (1 to 15 m) that have been formed by slow near-bottom currents.
- The deepest sedimentation basin is located near the Gogland Island between the above-mentioned glacier ridge and the rising complex of the Tuters Island / the Gogland Island. The ferro-manganese (Fe-Mn) concretions are found in this basin and its margins, and in the context of some elevated bottom reliefs (Fig. 7).

Sedimentation basins are small but have a thick layer of accumulated nepheloid sediments. This is typical for the bays in the southern seaboard of the GOF, such as the Koporye Bay, the Luga Bay, and the Narva Bay. In these areas, the influence of riverine suspended solids is also typical.

Zones of occasional accumulation

Areas of occasional nepheloid accumulation are located either in the vicinity of a depression with active sedimentation or in the shallow water areas of the Neva Bay where accumulation of silts starts from a water depth of 2–3 m. The accumulation of siltyclay sediments in the Neva Bay, forming to a depth of 5 m, are of major interest; the Neva Bay is an unstable and young sedimentation basin with a very thin layer of Holocene sediments.

Figure 7.
An agglomeration of Fe-Mn concretions on the seafloor. To scale, an adult crustacean *Saduria entomon* at the forefront makes its way through the jungle of concretions. Photo: A. Sergeev, I. Neevin. Source: VSEGEI (2013).

Sedimentation zones impacted by water movements

Areas of wave erosion exist down to the depth of 5 m (down to 10 m in the open GOF). These are typical for coastal zones, and are composed of fine-grained or medium-grained well-sorted sands. The majority of coastal zones of the Russian part of the GOF are so-called "starved coasts" with a narrow underwater coastal slope. Accumulative sites along the coasts are relatively rare and can be found in the tips of bays. Wide wave sedimentation fields are situated along the coasts of the Narva Bay, and from time to time, these can be found in the Koporye Bay. These fields form a wide arch on the coast of the Resort District of St. Petersburg. The morphogenetical zonality of the shores varies from accumulative to erosion. Outcrops of starved structures alternate with sands of various grain sizes, and only on the accumulative sites of the coast all underwater slopes are covered by sand.

Current-formed sedimentary units cover only small areas. Some narrow depressions are related to these. There, erosion by near-bottom currents is the main factor for the formation of the relief and bottom sediments. The principal type of the bottom deposit there is medium- and coarse-grained sand. Such deposits are found near the Nerva Island; they are distinctive for the zones of a solid bed contact, such as glacier ridges and nepheloid deposits. The current-formed deposits are developed near to the northern part of the Flood Protection Facility of St. Petersburg as well.

Sedimentary units impacted by fluvial flow are confined to the river mouths. These sedimentary types, composed of the sand brought by the river's flow, are finally formed by wave action, e.g., in the Luga Bay. In the Neva Bay, the role of these is not as significant because of a small amount of sand drift; sands in the Neva Bay are mainly relict (i.e., sediments that were originally deposited under different environmental conditions than those occurring today).

Erosion zones

Zones of intensive erosion occur in the depth of 0–10 m. These zones are typically found on positive forms of the relief. These sedimentary units are composed of boulders-pebble and sandy-gravel materials.

Zones of an intensive wash-out are also typical for shallow coastal areas (depth of 0–5 m) where they are represented by the alternation of spots of boulders-pebble and sandy-gravel deposits. Differing from above-mentioned erosion zones, the near-coastal sedimentary types are dynamic due to wave conditions, and they are able to change their shape and location. The examples of such sedimentary units are the shallow coastal waters of the Vyborg Bay and the Kurgalsky peninsula, and the coastal area of the Koporye Bay.

Transit zones

In the transit zone, the current velocity is too low for the bottom material to get washed out, but too high for a nepheloid-type of accumulation. As a result, the suspended matter passes through the transit area towards the sedimentation basins. Thus, sediments (silty sand with gravel) are not in accord with a real hydrodynamical regime and exceed the hydraulic size.

Transit zones are found in clay sands and sandy mix sediments below the 10 m depth where the impact of waving is practically absent. However, transit types are also linked to the parts of medium-intensive wash-out zones. In that part, a sandy perluvial is developed upon the glacier-lake and early-Holocene lacustrine sediments with a layer thickness of 5 to 15 cm, which prevents a wash-out of the underlying sediments.

Narrow fields of spheroidal Fe-Mn concretions are also found with the same deposits. Flat and disk-shaped concretions form fields on the areas of elevated relief (15–20 m), where both modern terrigenous sedimentation and wash-out processes are absent, i.e., the environmental conditions are stable. The main acting hydrodynamical factor in these zones is a variable and weak near-bottom current. The sedimentary units are widely distributed, creating bottom mosaics. This is typical to marine basins in glaciated areas.

Fe-Mn concretions in the Vyborg Bay

The intensity of anthropogenic impact on the marine underwater landscapes, and the regeneration process of Fe-Mn concretions were studied in the area of concretions' underwater mining in the Vyborg Bay in 2006-2008 (Fig. 8). A continuous Fe-Mn concretion layer was preserved only on the undisturbed remnants of the bottom surface.

The 1-m deep trenches left by a mining vessel had markedly changed the local sedimentation conditions. A former slow or almost non-existent sedimentation in these trenches was replaced by an accumulation of silty-clayey mud. The sedimentation rate was abnormally high: up to 1 to 1.5 cm / year. Spheroidal concretions up to 1 cm in diameter and their debris were rare, and whenever found, they were mainly buried by a sediment layer of a depth of 5 to 10 cm. The lack of micro-concretions and a smoothed surface of these buried spheroidal concretions indicated that concretions did not grow at that time, but rather, dissolved.

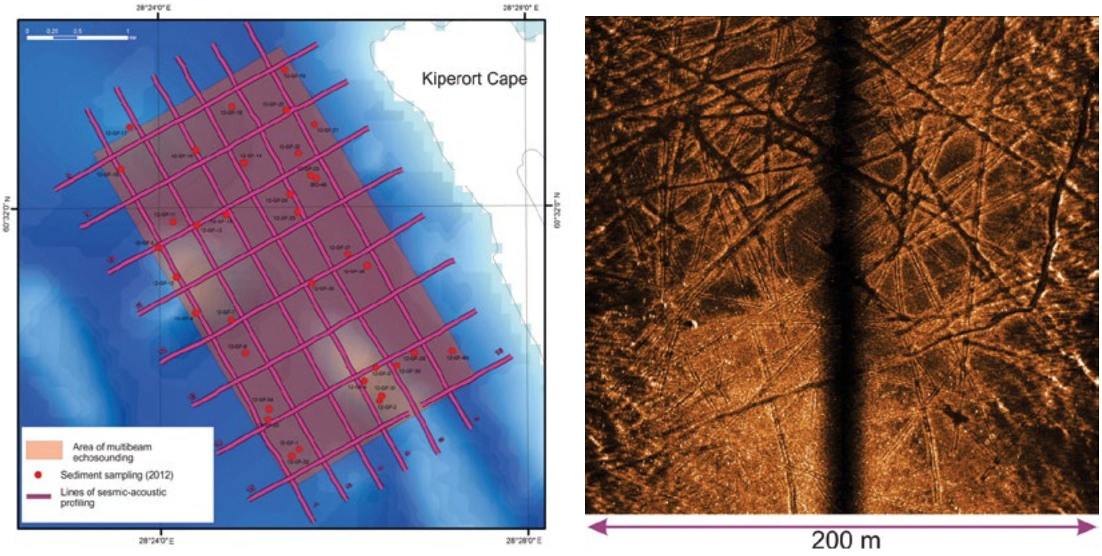

Figure 8. The area of Fe-Mn concretion extraction (left), and 1-m deep trenches left by a mining vessel (right). Source: VSEGEI (2013).

The geochemical structure of concretions sampled within the area was violated probably as a result of a selective removal of elements from the dissolving concretions. Thus, the concretions that remained after the mining, experienced a change in the sedimentation conditions, and became a secondary source of contamination for the bottom sediment. It is not possible to predict whether these concretions continue to dissolve or, perhaps, start to form again before the trenches are filled and the sedimentation equilibrium is restored to the state before the mining.

Concretions sampled within different areas of the GOF are characterized by specific distribution of different forms of chemical elements. Here, concretions were mostly characterized by oxides and hydroxides of Fe and Mn. Occurrence of water-soluble and adsorbed forms of elements, as well as forms related to bitumen organic component, were limited.

Trace metals in the sediment

Henry Vallius[1], *Aarno Kotilainen*[1], *Sten Suuroja*[2]

[1] *Geological Survey of Finland*
[2] *Geological Survey of Estonia*

The GOF has received a considerable load of anthropogenic harmful substances during the past decades. There are also natural inputs of, e.g., heavy metals entering the GOF, being controlled by the geochemistry of the local bedrock (Vallius 2009). As a result, elevated concentrations of harmful substances are recorded in seabed sediments (HELCOM 2010, Borg and Jonsson 1996).

Heavy metal input into the GOF began to increase in the 1950's due to the post-war industrialization. The input peaked from the 1960's to the 1970's, and started to decline in the mid-1980's (Vallius 2014). Despite this decreasing trend, there are still areas where cadmium (Cd) and mercury (Hg) concentrations in the seabed sediments are still relatively high (Vallius 2014).

Cadmium

Cd is one of the main contaminants in the GOF sediments; so far the highest concentrations have been observed in the eastern GOF in the early 1990's (Vallius and Leivuori 1999, 2003, HELCOM 2010). Recent sediment studies reveal that the Cd peak surface anomaly is located more in the west than earlier, indicating probably a westward transport/movement of the most contaminated material (Fig. 9).

In the present hydrographical conditions, Cd is suggested to move further west than earlier from its source in the River Neva area. The St. Petersburg Flood Protection Facility was thought to hinder the movement of matter from the Neva Bay into the GOF, but the new deep shipping channels seem to act as a gateway for particulate matter and harmful substances (Vallius 2012).

The overall Cd concentration has recently declined in the GOF sediments (Fig. 10). In the western GOF, the concentrations are below toxic levels. In the middle GOF, concentrations are elevated (up to 5 to 6 mg/kg in the subsurface sediments). In the eastern GOF, the concentrations are intermediate (Vallius 2014). The bottom sediments of the St. Petersburg port are an exception; the concentrations reach their highest level there (> 30 mg/kg).

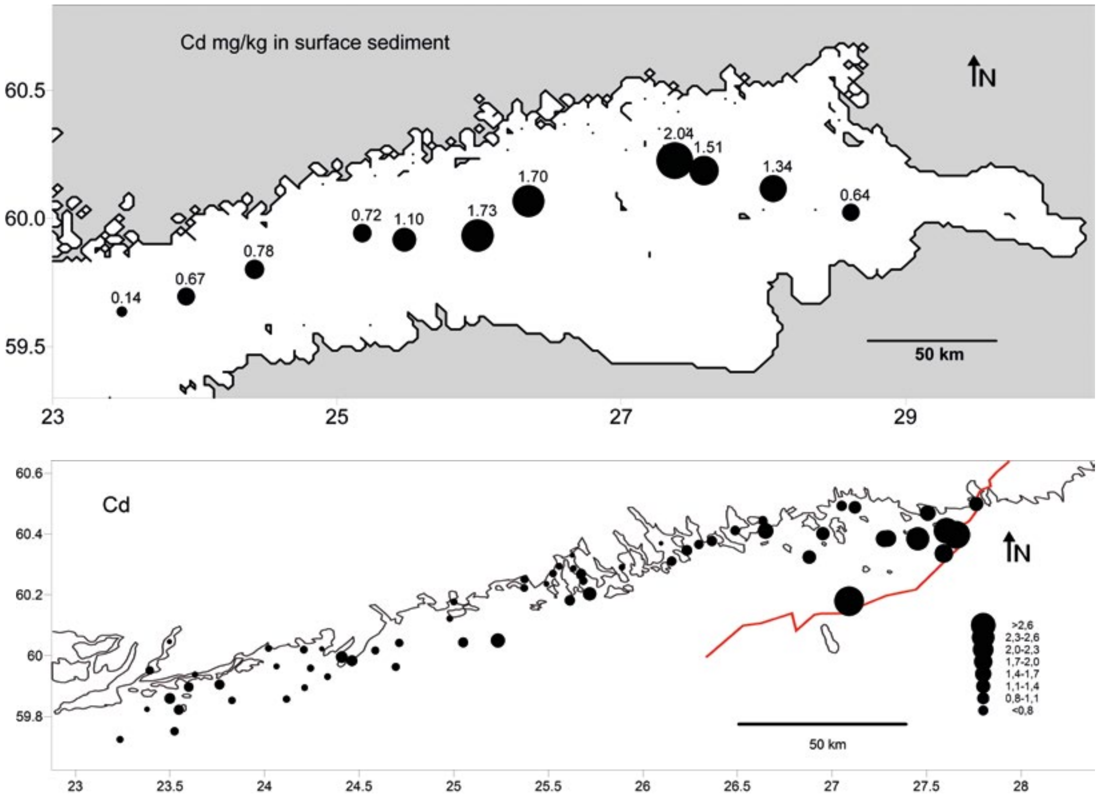

Figure 9. Cd concentrations (mg/kg) in the surface (0 to 1 cm) sediments of the GOF. Source: Vallius (2012) and Vallius (2009).

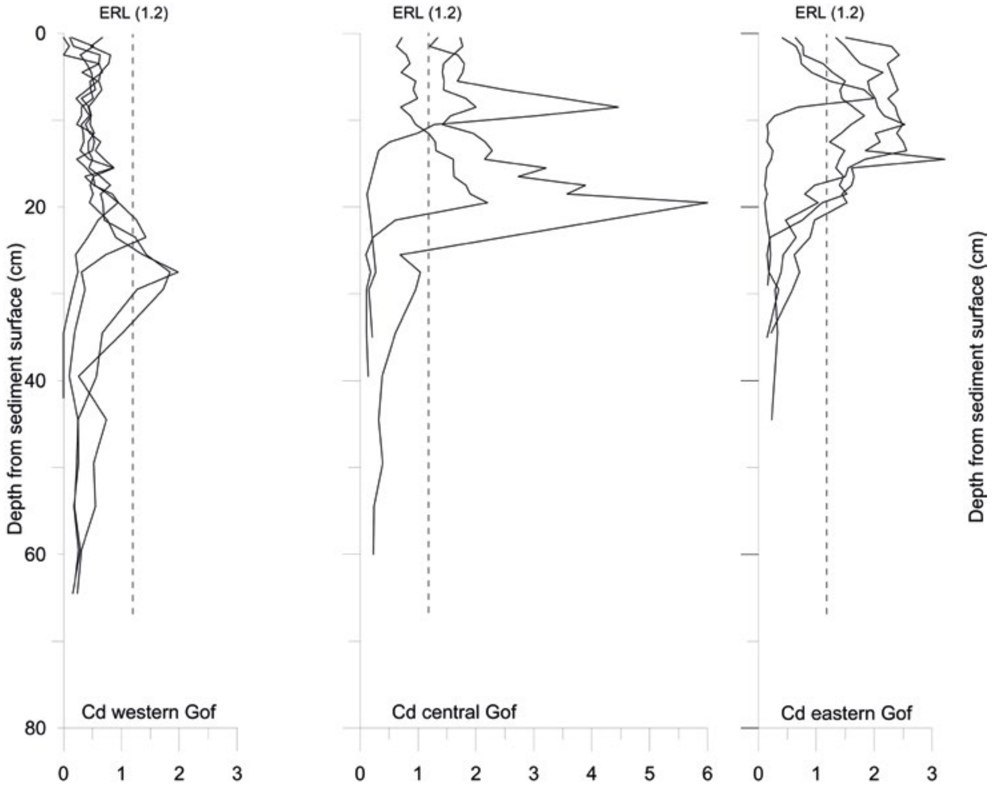

Figure 10. Cd concentrations (mg/kg dw) in the sediments of the western, middle, and eastern GOF. Lower toxicity limit (effects range-low, ERL) is indicated as a dotted line after Long et al. (1995). Source: Vallius (2014).

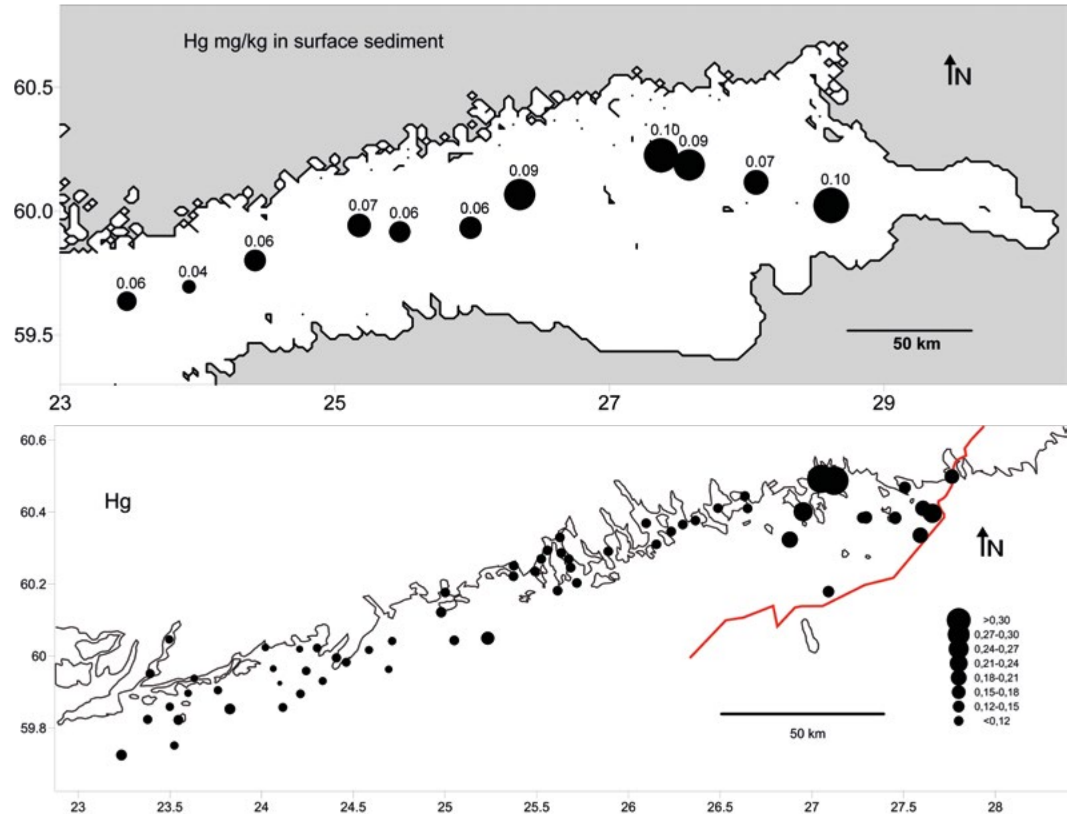

Figure 11. Hg concentrations (mg/kg) in the surface (0 to 1 cm) sediments of the GOF. Source: Vallius (2009, 2012).

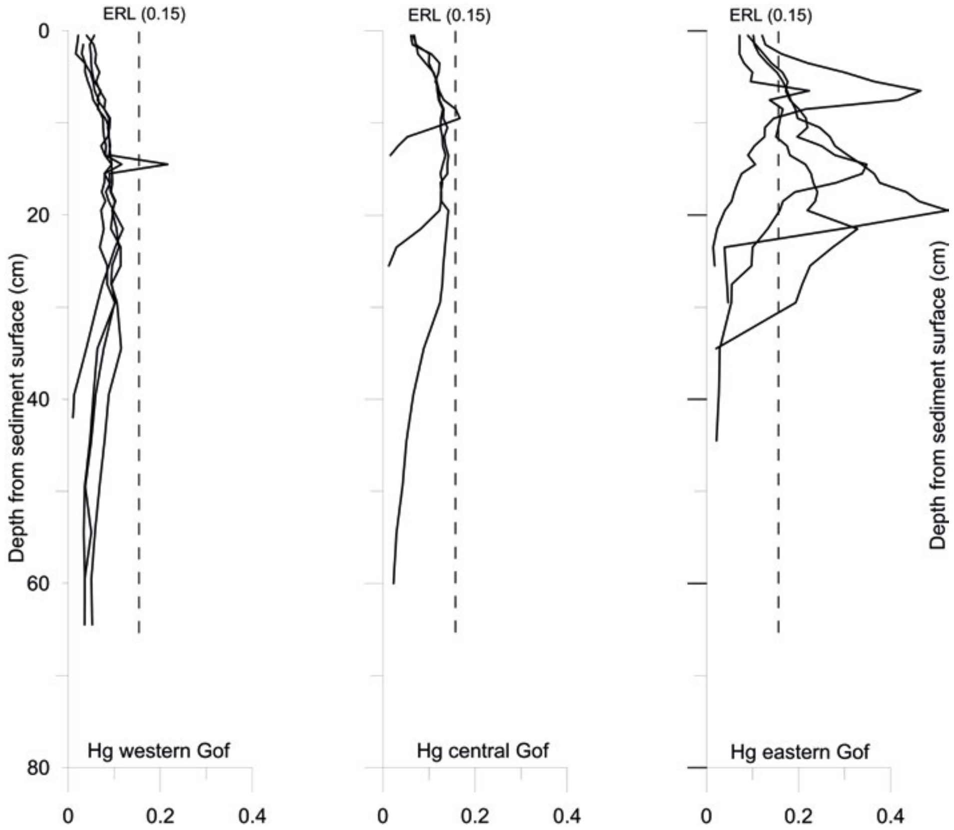

Figure 12. Hg concentrations (mg/kg dw) in the sediments of the western, middle, and eastern GOF. Lower toxicity limit (effects range-low, ERL) is indicated as a dotted line after Long et al. (1995). Source: Vallius (2014).

Mercury

The highest Hg concentrations in the seabed sediments are found in the eastern part of the GOF, and lowest in the western part (Fig. 11, Vallius 2014). Hg is a significant contaminant of the seabed especially off the River Kymijoki's outlets. The main contamination took place decades ago – in the 1950's and the 1960's – by the industry on the upper reaches of the river, but the contaminated sediments are still a source of the Hg for the GOF. Sites near the Finnish – Russian border also show slightly higher concentrations of Hg compared to the western GOF, suggesting for another source of the Hg in the east (Vallius 2009).

Hg concentrations in the GOF sediments have decreased over the past decades. They seem to have stabilized at relatively low albeit slightly elevated present-day levels (Fig. 12), and no longer warrant concern in terms of their toxicity. In the eastern GOF, sediments having Hg concentrations up to 0.2 to 0.5 mg/kg are covered by only few cm thick surface sediment layers (Vallius 2014).

Zinc

Alike Cd and Hg, also zinc (Zn) is a major contaminant of the GOF. The highest concentrations of Zn have been observed in the middle and eastern GOF for reasons still unknown (Fig. 13). Its concentration has recently decreased quite substantially from rather high levels in the 1990's (Vallius 2012), but is still on a too high level with respect to its toxicity (Fig. 14).

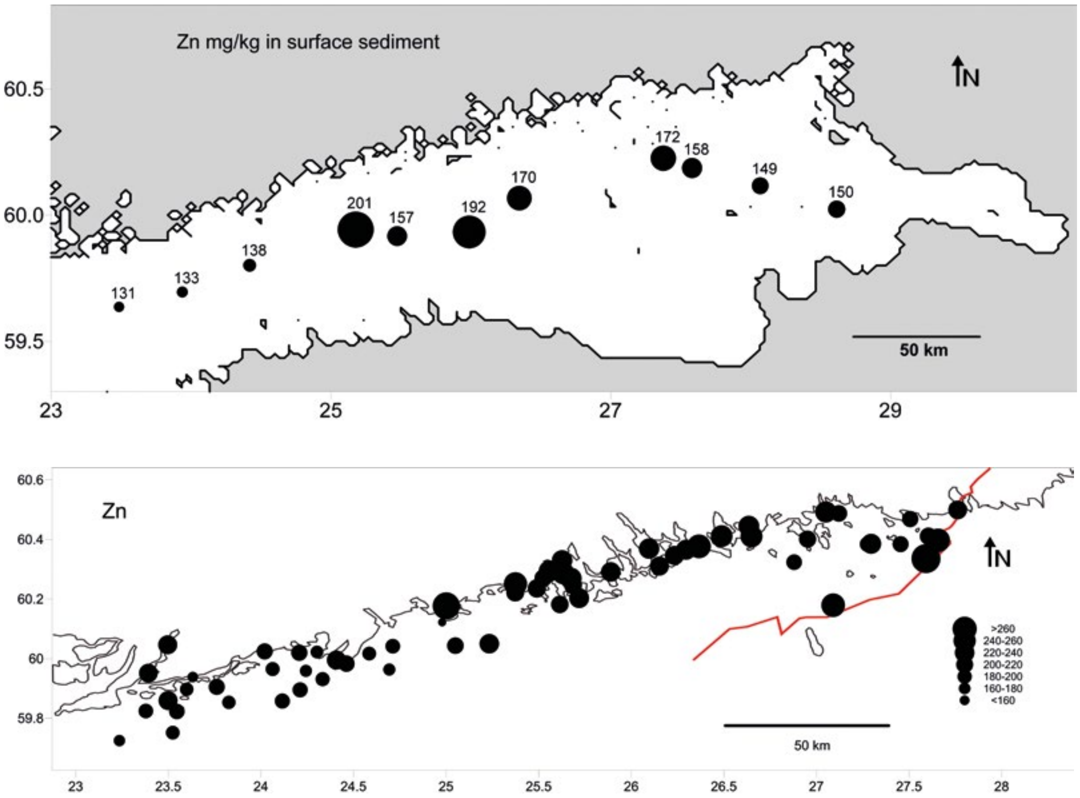

Figure 13. Zinc (Zn) concentrations (mg/kg) in surface (0 to 1 cm) sediments of the GOF. Source: Vallius (2009, 2012).

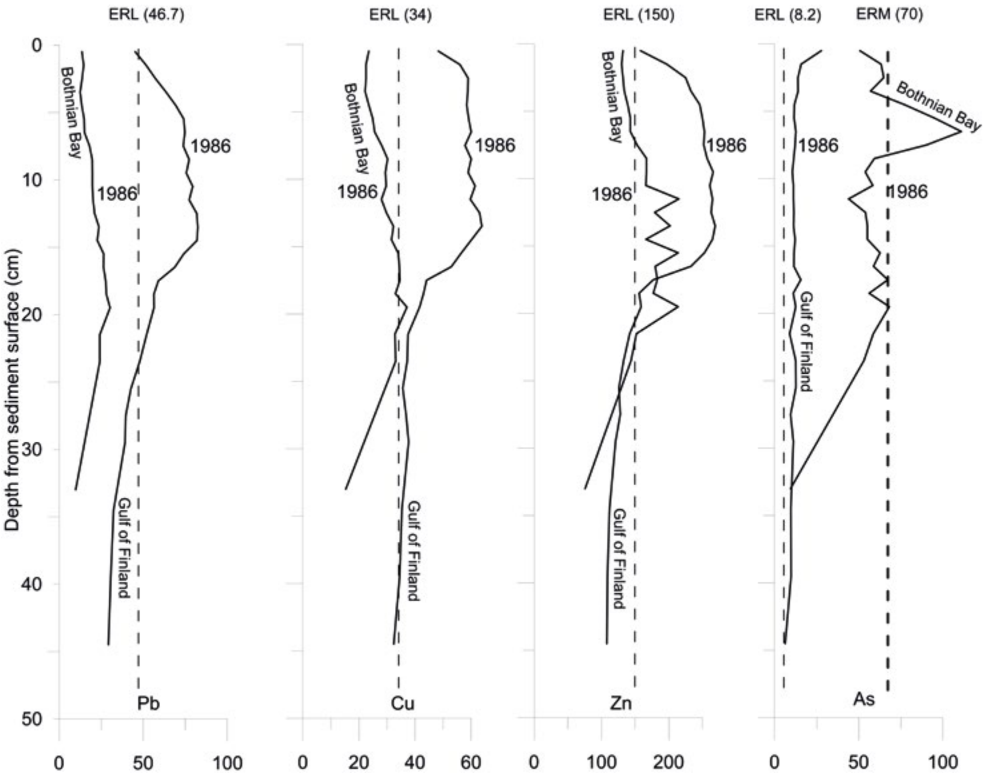

Figure 14. Pb, Cu, Zn, and arsenic (As) concentrations (mg/kg dw) in the sediments of the Bothnian Bay and the eastern GOF. Lower toxicity limit (effects range-low, ERL) and middle range toxicity limit (effects range-middle, ERM) are indicated as dotted lines after Long et al. (1995). Source: Vallius (2014).

Alike Zn, also lead (Pb) and copper (Cu) used to be present in the surface sediments in too high concentrations, but also those have decreased during the past decades (Vallius 2014). Especially Pb seems to have stabilized to almost satisfactory concentration levels. The Estonian project “Assessment for ecosystem based management of marine environment on the basis of sea bottom and sediments of the Gulf of Finland” (SedGOF) studied the uppermost three cm of the sediments in the southern GOF. They reported that the contents of Cd, Pb, and Zn are not higher there than in the deeper part of the sediment.

Geological processes in the eastern GOF

Daria Ryabchuk, Vladimir Zhamoida, Mikhail Spiridonov, Andrey Grigoriev, Alexander Sergeev,
Olga Kovaleva, Igor Neevin
A.P. Karpinsky Russian Geological Research Institute (VSEGEI)

Geological hazard processes can threaten human life, lead to essential damage for property, and affect significantly the normal development of biota (Fleischauer 2006). These processes are caused by natural endogenic and exogenic driving forces, or generated by anthropogenic activities. An interaction of geological processes and intense anthropogenic activities – such as hydro-engineering structures, harbors, oil and gas pipelines, land reclamation – is potentially hazardous for the densely-populated coastal areas in the GOF. The European Spatial Planning Observation Network (ESPON) requested an assessment of spatial patterns and territorial trends of hazards and risks (Schmidt-Thomé 2006). This mapping of potential geological hazards in the Russian sector of the GOF is the first step towards the integrated coastal zone management and coastal risk prevention.

The natural hazards are divided into two groups: unfavorable ones and catastrophic ones that threaten human life. As a rule, the catastrophic events are unpredicted and very intense, such as meteorite impacts, earthquakes, volcanic eruptions, tsunamis, landslides, mud flows, avalanches, hurricanes, and floods (Harkina 2000). An important feature of the hazards is their cause-and-effect character; earthquakes can provoke landslides and tsunamis, and surges and floods accelerate coastal erosion.

Endogenic processes

The potential hazard of endogenic processes in the eastern GOF is questionable, although some probable seismic zones were distinguished within the GOF and adjacent areas by Assinovskaya and Novozhilova (2002). These zones are traced from the territory of Finland through the Russian part of the GOF to its coastal zone. Recent intensification of construction work (including skyscraper projects) in St. Petersburg, where the upper part of geological sequence is represented by the Quaternary deposits with unfavorable geotechnic properties, makes tectonic problems very topical. The other aspect of geological risk assessment is radon emission along tectonic faults (Dvernitsky 2007).

Pockmarks

Pockmarks are crater-like structures at the seabed. They are formed by expulsions of gas or fluids from the sediment. Their average diameter is in the range of 10 to 20 m, and the depth relative to surroundings can reach 1 m. Their morphology indicates their status (relict, not active, active), and the pulsating character of the fluid emission (Figs. 15 and 16).

Pockmarks located within the areas of Holocene silty-clayey sedimentation in the middle GOF are formed by gas seepage due to active decomposition of organic matter by microbiological processes. In the Kopora Bay, pockmarks were found in the area where the Holocene mud thickness does not exceed 40 cm, excluding the possibility of their formation as a result of recent biogenic gas seepage. They are possibly associated with groundwater discharge from the Vendian aquifer system. Alternatively, there is some spatial correlation between the pockmark fields and the distribution of tectonic faults and rock fracturing zones.

The concentrations of chemical elements sampled inside the pockmarks are only slightly higher than their background values; the average ratio between the former and the latter varies in the range of 1.05 to 2.15.

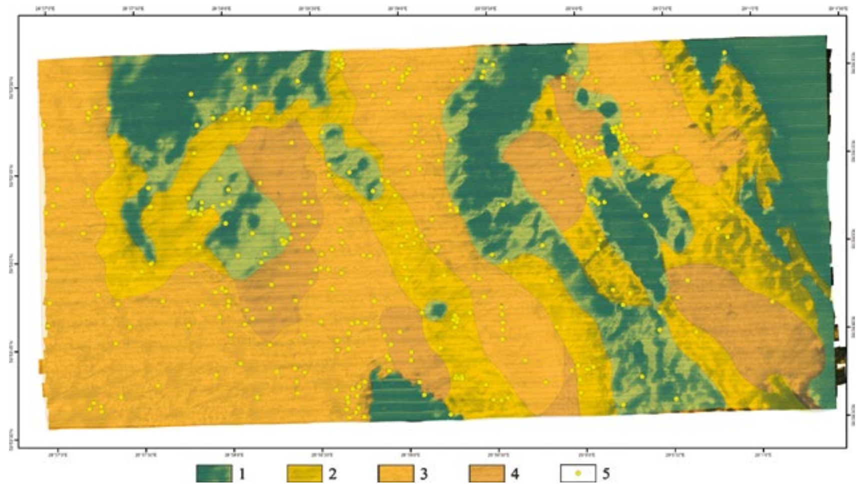

Figure 15. The area of pockmarks in the Kopora Bay with multibeam echo sounding and side-scan sonar. Source: Zhamoida et al. (2015).

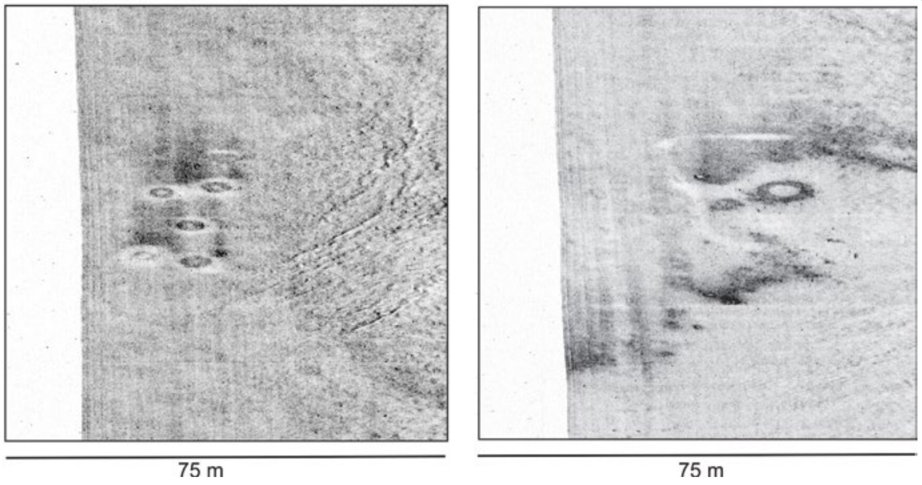

Figure 16. Side-scan sonar images of pockmarks in the Kopora Bay. Small active pockmarks (5 m in diameter, left), and a large active pockmark (14 m in diameter, right). Source: Zhamoida et al. (2015).

Exogenic processes

Exogenic processes pose a true hazard potential onto the coastal zone of the eastern GOF. The probability for a process to occur is caused by an interaction of various factors which can be divided as: i) permanent factors during the term of forecast, such as geological structure and relief, ii) slowly changing factors, such as modern tectonic movements and stable hydro-dynamic regimes, and iii) rapidly changing factors, such as storm events and hurricanes (Krupoderov 1994, Sheko and Krupoderov 1994, Osipov and Shoigu 2002).

The most intense process is coastal erosion (Fig. 17). The length of the shoreline of the Russian part of the GOF is about 520 km. These coasts have not been considered to have active litho- and morphodynamics but recent study has revealed that they suffer heavily from erosion. Over 40 % of these coasts are seasonally eroded, and it is difficult to distinguish between the areas of intense erosion and stable parts of the coast. Coastal erosion reclaims territories and destructs buildings, roads, and communications.

The geological and geomorphological factors determine the long-term coastal zone development. The key factor for the coastal erosion is the composition and properties of the local coastal deposits. The coasts consist mostly of easily erodible Quaternary deposits (clays and sands), augmented by boulder belts formed as a result of glacial till erosion. Moreover, some small-scale features – such as submarine terrace erosion and erosion runnels – play an important role in the erosion process.

The most extreme erosion events occur when a long-lasting storm from the west or south-west hits the coast during a period of high water level in the autumn or

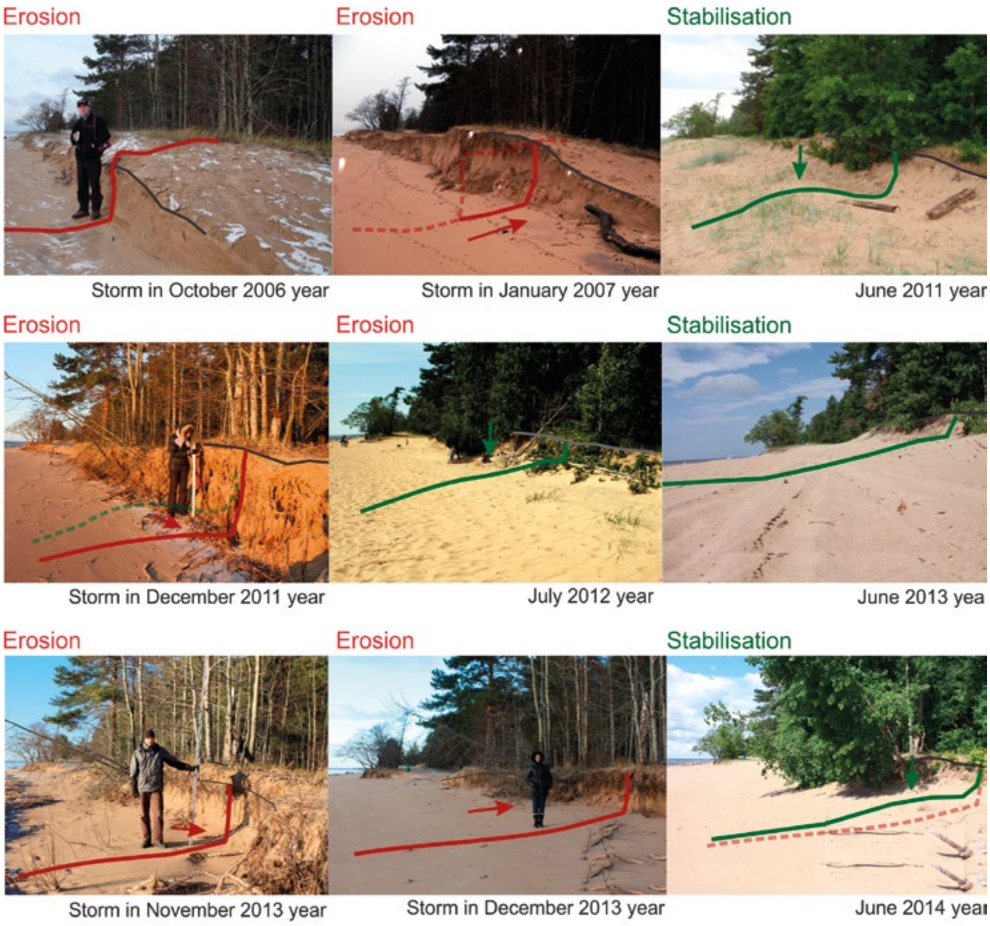

Figure 17. An alternation of erosion events and coastal dune stabilizations in the Komarovo beach in 2006–2014. Source: VSEGEI (2014).

Figure 18. The Serovo village as an example. A: a coastal retreat due to erosion will be 53 m until the year 2100 for the current climate scenario; B: coastal retreats due to erosion will be 50 and 75 m for the optimistic (green color) and the pessimistic (red color) scenarios, respectively. Source: Ryabchuk et al. (2015).

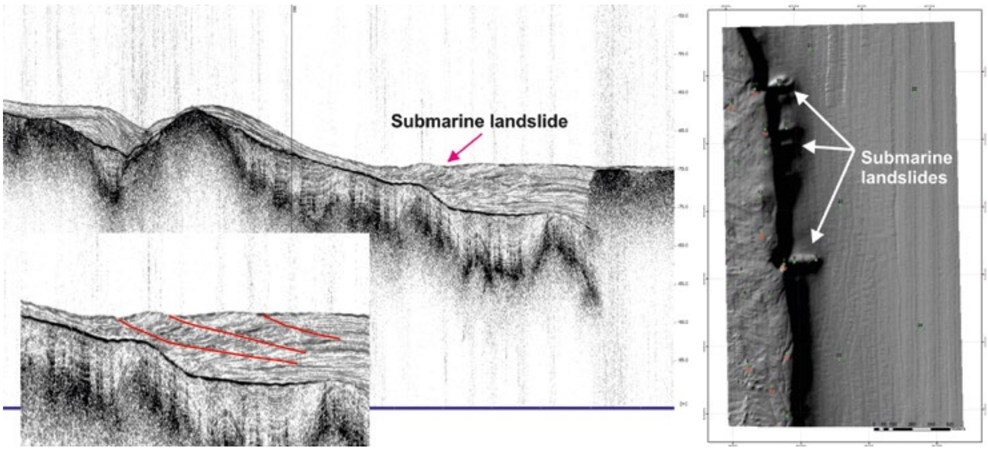

Figure 19. Submarine landslide in the slope of the Kurgalsky Reef: an acoustic profile and a multibeam shadow relief. Source: VSEGEI (2014).

winter when the sea ice is still absent. The frequency of occurrence of such combination has evidently increased since 2004 especially due to late freezing (Ryabchuk et al. 2011). During the most recent decade, extreme erosion events occurred during autumn – winter seasons of 2006–2007, 2011–2012, and 2013–2014.

One of the most vulnerable parts of the eastern GOF is the Kurortny (Resort) District. Without an effective adaptation strategy for the coastal erosion, including the realization of the coastal protection measures and the marine spatial planning, the coast in the District may retreat by 50 m, and a total area of eroded territories would be 2.8 km^2 (Fig. 18). This was an optimistic climate change scenario. According to a pessimistic scenario, the coast may retreat by 200 m in some areas, and the area of eroded territories would reach 4.6 km^2.

The coastal landslides in the eastern GOF are observed locally between the Flotsky Cape and the Peschany Cape, and in the vicinity of the Lebyazhye village where the coastal cliffs reach heights of 25 to 30 m. Submarine landslides occur within relatively steep slopes of the glacial till ridges (Fig. 19).

Sediment pollution cannot be classified as a geological hazard potential as such but it should be taken into account in any risk assessment related to the hydro-engineering activities that alter the natural sedimentation processes. Mud in the depositional basins is a collector of hazardous substances, and thus, we have something like a hidden bomb in the sediments of the BS. In the eastern GOF, an extended and prolonged seafloor anoxia within local coastal depositional basins can worsen the environmental problems by accelerating the release of metals and nutrients from the sediments (Kotilainen et al. 2007). In the Russian part of the GOF, the Neva Bay is the most polluted area (Spiridonov et al. 2004, Ryabchuk et al. in press).

The exogenic geological activity in the seafloor in the Russian part of the GOF and its coastal zone has recently increased. Yet the present level of knowledge of the coastal zone processes in this area is only moderate. This is especially true for the combination of the different factors controlling these hazard potentials.

Constructions in the Neva Bay

Leontina Sukhacheva[1]*, Marina Orlova*[2]*, Daria Ryabchuk*[3]*, Vladimir Zhamoida*[3]

[1] *Research Institute of Remote Sensing Data for Geology (NIIKAM)*
[2] *St. Petersburg Research Centre, Russian Academy of Sciences*
[3] *A.P. Karpinsky Russian Geological Research Institute (VSEGEI)*

The Neva Bay is the easternmost and shallowest part of the GOF. The Flood Protection Facility of St. Petersburg separated it from the rest of the GOF in the 1980's, and it is practically an anthropogenic lagoon.

The distribution of light in the water is important for the development of planktonic, phytobenthic, and macrozoobenthic communities. The underwater optical condition in the Neva Bay has recently been subject to a pronounced anthropogenic impact caused by dredging and dumping activities as part of the projects including land reclamation and reconstruction of shipping infrastructures. These activities have led to an intense bottom sediment disturbance and redistribution of hazardous substances previously buried in the sediments (Pitulko 2014, Spiridonov et al. 2014). The consequent increase of the suspended matter concentration in the water column affects negatively the success of planktonic and benthic communities in the Neva Bay (Maksimov 2014).

Anthropogenic impact on the Neva Bay and its coasts started along the foundation of St. Petersburg in 1703. Construction of the city was accompanied by uplifting of the swampy territories close to the average water level, and by rearranging of the natural river network. As the water depth within the most part the Neva Bay is only about 2 m, and St. Petersburg's harbor is located in the easternmost part of the bay, dredging of the ship channels has been carried out on a constant basis. In 1885, the "Marine Canal" – the marine fairway to St. Petersburg – was constructed. The water depth in the channel is

Nord Stream gas pipeline

Mika Raateoja
Finnish Environment Institute

Nord Stream AG installed an underwater gas pipeline from Vyborg, Russia, to Greifswald, Germany, in 2010–2012. Notable construction work at the seafloor preceded the installation of the line. There was no preconception how the construction and operation of the pipeline would affect the benthic environment in the topographically heterogeneous middle GOF. The key environmental question to be addressed was whether the structures laid on the seafloor would restrict/redirect the near-bottom currents that are essential in delivering oxygen into the area. The monitoring campaign carried out found that the alterations in the near-bottom current pattern did not markedly interfere with the deep oxygen condition. On the contrary, the large-scale hydrodynamic processes in the study area produced natural variation in the oxygen condition large enough to override any impact of the pipeline.

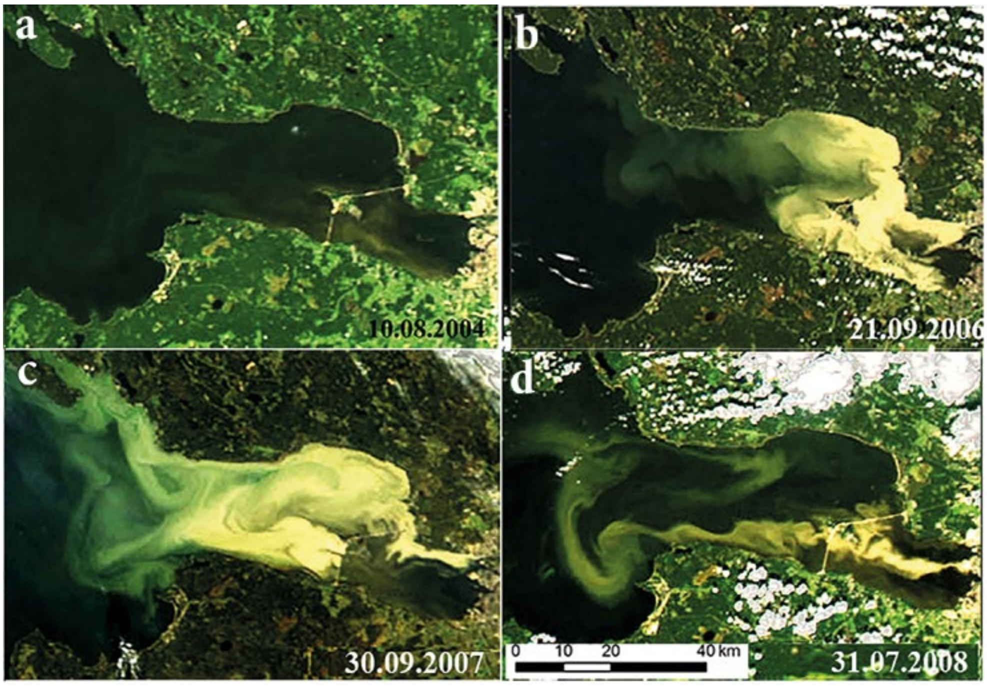

Figure 20. Timeline of hydro-technical works in the Neva Bay. A: the time before the beginning of the works included in the St. Petersburg harbor Marine Facade project (Period 1). B: intensive dredging with sediment dumping into underwater pits (Period 2). C: intensive dumping along the northern coastline. D: dredging in the area of the new terminal (Period 3). Source: Sukhacheva and Orlova (2014).

14 m. In the 20th century, St. Petersburg became a metropolis, having a highly-developed industrial and transport infrastructure, including several ports. This development caused an enormous increase in the anthropogenic load into the GOF. The construction of the Flood Protection Facility started in 1979. The construction work was postponed in the 1990's due to an ecological risk assessment work, resumed in the late 2000's, and the Facility has been operational since 2011.

The hydro-engineering works carried out for land reclamation in the Neva Bay in the late 1980's – the early 1990's increased suspended matter concentration in the upper water layers of the Neva Bay. The highest level observed was 200 mg/l that was ten times the natural level. As a result, accumulative processes of silty-clay material became more active. The hydro-engineering works were stopped in 1993 and the suspended matter concentration gradually decreased, and eventually in 1998 reached levels that were 3 to 4 times less than in the early 1990's. Sedimentation conditions in the bay changed again.

A new phase started in 2006. In the eastern part of the Bay, near the Vasilievsky Island, 477 hectares of new territory for the St. Petersburg passenger harbor was reclaimed using sand-dredging technology. For deepening of ship channel up to 14 m for larger vessels, the bottom sediments of clayey material were dredged, moved, and damped into the previous sand extraction locations in the bay. As a result of dredging and dumping processes, the concentration of suspended matter in the water was extremely high in 2007. The area under the effect of suspended material extended all the way to the Vyborg Bay.

Following continuous satellite monitoring data from 2003 until 2012, three major periods could be identified when drastic changes took place in the optical conditions of the Neva Bay and adjacent areas (Fig. 20).

As a result of hydro-technical activities in the Neva Bay, a clayey layer up to 3 cm thick had formed on the sandy surface of the near-shore bottom in 2007–2008. At the same time, the concentration of fine particles in the beach sands of the Resort District increased by 5 to 7 %. Sedimentation system of the eastern GOF was significantly disturbed. A study

Figure 21. The Eastern GOF in the 24th of November, 2007, and again six weeks later. Fine fraction of suspended sediments keeps waterborne for a relatively long time (up to two months) after dredging and dumping are finished. Source: Sukhacheva & Orlova (2014).

Figure 22. Impact of the works related to the construction of Bronka: a view over the area. A: before hydro-technical works started (20th April, 2014), B: at the time of hydro-technical works (7th July, 2014). Source: Sukhacheva and Orlova (2014).

carried out in 2011–2013 showed that the system is very slowly reversing back to more natural state (Fig. 21).

Among the recent examples of an anthropogenic impact on the Neva Bay and adjacent areas, there is an on-going construction of a multi-functional maritime shipping complex "Bronka", started in 2010. Hydraulic engineering works has been carried out in the southwestern part of the bay. In this case, water stratification and upwelling events often re-directed the water masses transporting suspended sediment material from the southern to northern coast of the eastern GOF (Fig. 22). Significant changes in the abiotic characteristics of the Neva Bay (e.g. bottom relief, surface sediment types, sedimentation rates, geochemistry, hydro-optical and chemical properties of the near-bottom water) lead to dramatic changes in the benthic communities.

Geological processes of the southern GOF

Sten Suuroja

Geological Survey of Estonia

Geological hazards in the Estonian coast of the GOF are mainly related to coastal erosion and landslides. Landslides up to 200 m in width have occurred along the coastline of north-east Estonia (Fig. 23). The uppermost part of the sediment that lies on the water-saturated Cambrian blue clay surface slides down the Klint escarpment during extensive rainfalls or the period of snow melt.

The southern shoreline of the GOF is multipartite with peninsulas and bays. The erosion is predominant on the top of peninsulas and accumulation is common on the tips of the bays. The shoreline retreats on the average by 0.4 m per year in Klint cliffs where Ordovician and Cambrian siliciclastic rocks are eroded during the storms (Fig. 24).

Figure 23. The largest landslide on the southern shoreline of the GOF. A 150 m cliff section in width of the 25-m high Pakri cliff fell down in spring 2008 due the erosion of the Cambrian sandstone on the cliff's foot. Photo: Sten Suuroja.

Figure 24. The erosion of the Kakumäe Cliff in Tallinn City area. The boulder located at the shoreline in 1998 (left). Nowadays the shoreline is retreated about 8 m from the boulder (right). Photos: Tõnis Saadre, Sten Suuroja.

Conclusions

The seafloor topography of the GOF is very diverse in the BS scale. Especially the northern coast of the GOF stands out. Here, bedrock fracture and weakness zones of an ancient crystalline divide bedrock into the blocks. In the southern part of the GOF the crystalline bedrock is covered by younger sedimentary rocks, smoothing the topography and fragmentation. Topographically variable seafloor environment leads to patchy sediment distribution and supports heterogeneous habitats.

The seafloor is covered by varying geomorphic features, such as plains, basins, valleys, holes, and elevations. Other features such as canyons, pockmarks, and Fe-Mn concretion fields occur, too. At present, approximately 34 % of the seafloor of the GOF can be regarded as a sediment (soft sediment) accumulation area.

The bottoms over large areas in the GOF suffer from a severe anthropogenic pressure. In the Neva Bay, the intensive bottom dredging increases the sedimentation rate and leads to an accumulation of contaminated silts. The original composition of the bottom material is lost at the underwater dumping sites.

The elevated concentrations of harmful substances, such as heavy metals, are recorded in seabed sediments. The concentrations of heavy metals have generally declined over the last decades. In some areas, however, concentrations of Cd, Hg, and Zn in the surface sediments are still relatively high.

Mapping of potential geological hazards in the Russian sector of the GOF and its coastal zone have revealed geological hazards, such as coastal erosion and landslides. The most intense and potentially hazardous process in the areas characterized by sedimentary rocks is coastal erosion.

Recommendations

Large-scale geodiversity should be acknowledged in benthic habitat mapping and spatial planning of the fragmented seafloor areas.

Seabed areas including high concentrations of harmful substances should also be acknowledged in marine spatial planning.

Mapping of potential geological hazards should be done in the GOF scale.

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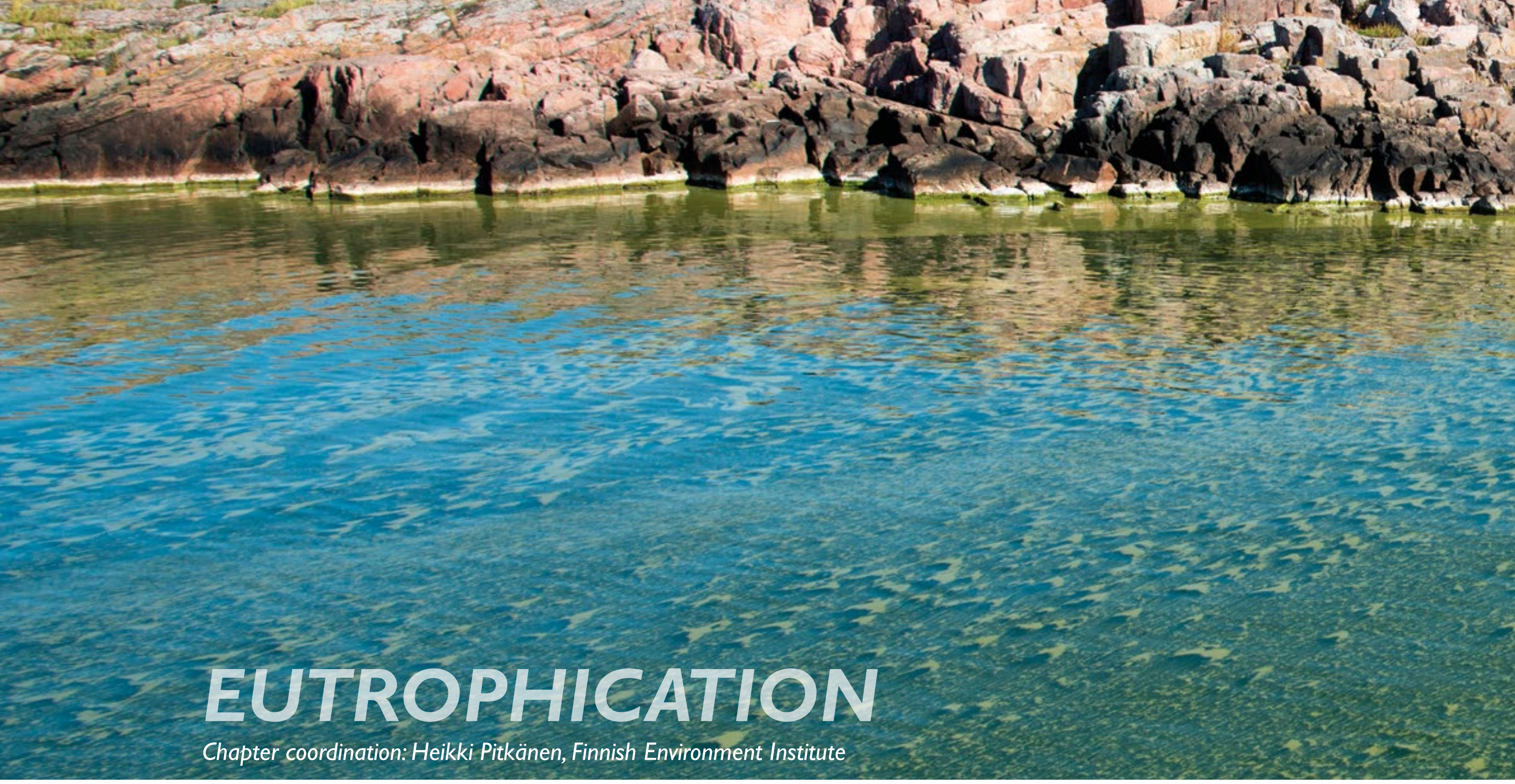


EUTROPHICATION

Chapter coordination: Heikki Pitkänen, Finnish Environment Institute

Viewpoint

Heikki Pitkänen1), Harri Kuosa1), Tatjana Eremina2), Urmas Lips3), Jouni Lehtoranta1), Alexey Maximov4)

1) *Finnish Environment Institute*
2) *Russian State Hydrometeorological University*
3) *Marine Systems Institute, Tallinn University of Technology*
4) *Zoological Institute, Russian Academy of Sciences*

The Gulf of Finland (GOF) is eutrophic both due to natural and anthropogenic reasons. The present state of the GOF is a manifestation of intrinsic hydrographic/hydrodynamic characteristics of the GOF area, and the phosphorus (P) and nitrogen (N) load into the GOF; the land-based nutrient load is higher per unit of surface area than for the most other sub-basins of the Baltic Sea (BS, Pitkänen et al. 2008). In short, the present eutrophication status of the GOF is less than good, and, in most cases, poor or bad (HELCOM 2010, 2014a).

The external loads of both N and P into the GOF decreased by 30 to 40 % in the late 1980's and in the 1990's (Pitkänen et al. 2001, Kiirikki et al. 2003) due to water protection measures and the decrease in agricultural and industrial production in Russia and Estonia at the time of the collapse of the former Soviet Union (Lääne et al. 2002).In recent years, the success stories in the waste water treatment of St. Petersburg and of EuroChem's Phosphorit fertilizer plant by the River Luga (HELCOM 2012b, Atkins International Ltd 2015, SUE Vodokanal of St. Petersburg 2015) have further reduced the external P load.

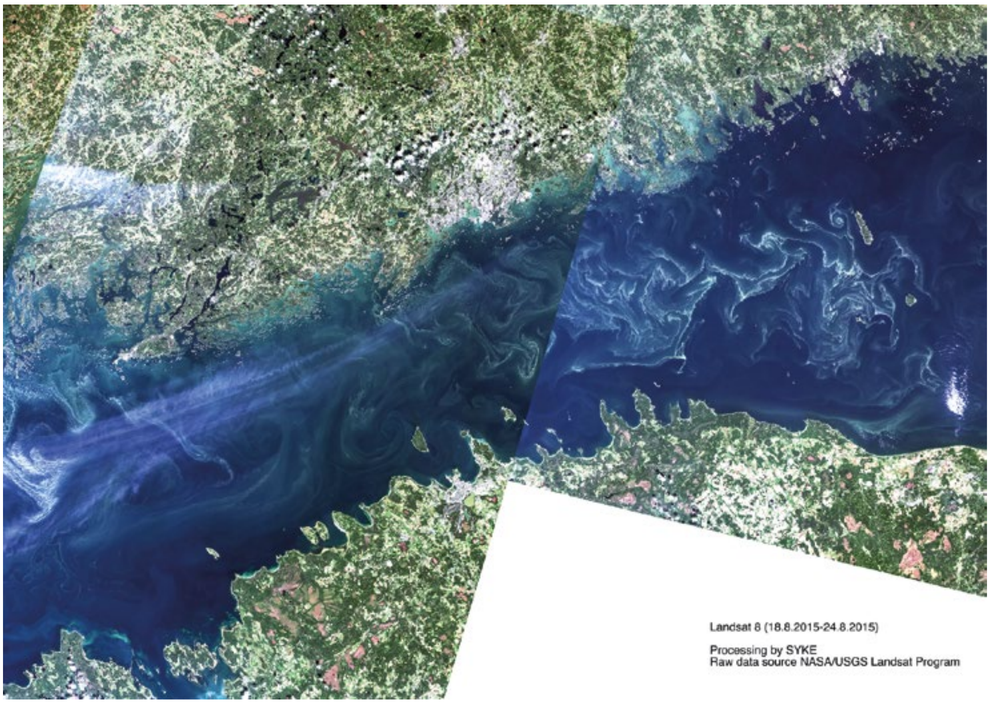
Long-term development of the trophic state of the GOF followed only partly the decreased nutrient load in the late 1980's and the 1990's. The accelerated sediment inorganic P release in hypoxic conditions led to increases in the summertime chlorophyll *a* (Chl *a*) concentrations in the 1990's and the early 2000's, and to an intensified production of the N-fixing cyanobacteria that became an icon of the BS's eutrophication (Kahru et al. 2000, Raateoja et al. 2005). However, springtime phytoplankton biomasses have decreased in the south-western coast of Finland in the GOF, which could be connected to the decreased inorganic N concentrations and decreased loading of N (Raateoja et al. 2005). Similar development probably took place also more widely in the GOF (Pitkänen et al. 2008).


Photo: Riku Lumiaro.

Setting the frames

The water exchange between the GOF and the Northern Gotland Basin has potential to control the trophic status of the GOF. For N, the annual net flux directs clearly out of the GOF, whereas for P, it often directs into the GOF (Savchuk 2005, HELCOM 2009). The input of saline deep water affects the nutrient balance of the GOF also indirectly via strengthening the halocline, and hence, degrading the near-bottom oxygen conditions, and further, controlling the intensity of the benthic nutrient release (Pitkänen et al. 2001).

An intensified benthic nutrient release, a.k.a. internal loading, does not introduce new nutrients in the water-sediment system but circulates already settled nutrients.



Cyanobacterial blooms in the GOF in late-summer 2015. Source: NASA/USGS. Photo: Finnish Environment Institute.

Thus, it is not commensurate to the nutrient load either from the catchment or from the atmosphere. What it does, however, is that it keeps the nutrient content of the water mass on an elevated level, increasing algal production, and partly compensating for the positive effects of the nutrient load reductions.

The climate change will influence eutrophication of the BS to an unknown extent, and it is likely that the impact will vary amongst the sub-basins. Eremina et al. (2012) suggested that the deterioration of the oxygen regime in 1995–2010 was mainly due to large-scale changes of atmospheric processes in the Northern Hemisphere. As the climate change proceeds, greater river runoff in the northern parts of the BS catchment is predicted, which may affect nutrient inputs and eutrophication condition (HELCOM 2013g, Viitasalo et al. 2015). This can significantly alter the external nutrient load.

The present assessment aims at describing and analyzing recent changes in the nutrient load and eutrophication state of GOF, and assessing the roles of the external load and the internal processes in the development of eutrophication of the GOF. Assessing the GOF as just one entity is in many respects an oversimplification. In addition to having differences between its onshore and offshore waters, there are differences between the more marine western part, and the more estuarine eastern part. Additionally, most of the external nutrient loading enters the eastern part. Thus, a credible analysis on the eutrophication of the GOF requires a sub-area division regarding both coastal and open sea waters.

Internal nutrient processes controlling the state of the GOF

Oxic sediments have a good capacity to bind inorganic P, and subsequently, the largest inventory of P in the GOF exists there. Especially the eastern GOF contains a large pool of P (Lehtoranta 1998). A significant part of P is bound to iron (Fe) and organic matter (Lukkari 2008, Lukkari et al. 2009). In good oxygen conditions, Fe maintains its ability to bind P. Furthermore, Fe captures a large part of inorganic P that is mineralized in sediments, and the release of P to the water is small. However, when oxygen conditions are degraded, these P storages can be released to the water through reduction of Fe oxides and mineralization of organic P. The response of the Fe-bound P pool to anoxia happens rather fast, whereas the mineralization of organic P is a slow process (Lukkari 2008), which maintains the high release rate of P into the water for an extended period of anoxia (Ahlgren et al. 2006, Jilbert et al. 2011). The concentrations of P in the stable deep-water layers may increase drastically during anoxic condition. To conclude, the dynamic cycling of P pools between the water and the sediments in variable oxygen conditions determine the amount of the bioavailable P in the water, which affects the ecosystem functions and trophic state of the GOF.

Several processes in the inorganic N cycling are still unresolved and/or poorly quantified in the BS. Nitrogen fixation is a process assumed to be very important in the BS due to the existence of massive late-summer blooms of diazotrophic cyanobacteria. The present estimates of cyanobacterial N fixation rates in the GOF vary largely (Lessin 2014). The modelled annual mean fixation rate for 1997–2006 was the highest in the western GOF, up to 1.8 g/m^2 per year, whereas in the easternmost part it was practically non-existent due to strong P limitation. The annual mean nitrogen fixation rate in the GOF was estimated as 27 000 tonnes of N/year. To compare with the opposite process denitrification that removes N from the aquatic system to the atmosphere, the annual mean denitrification in the GOF has been estimated to range from ≤ 16 000 to 45 000 tonnes of N/year (Tuominen et al. 1998, Jäntti et al. 2011).

Nutrient inputs

Antti Räike(1)*, Seppo Knuuttila*(1)*, Petri Ekholm*(1)*, Sergey Kondratyev*(2)*, Peeter Ennet*(3)*, Reet Ulm*(4)*,*
Natalia Oblomkova(5)

(1) *Finnish Environment Institute*
(2) *Institute of Limnology, Russian Academy of Sciences*
(3) *Estonian Environment Agency*
(4) *Estonian Ministry of the Environment*
(5) *SPb PO "Ecology & Business"*

Nutrients enter the BS mainly via riverine inflow, but also via direct point source load and as atmospheric deposition. The inter-annual variation in the riverine load is high due to the fluctuation in the flow itself; weather conditions affect the annual riverine nutrient load. Estimating this load reliably requires at least monthly nutrient sampling and continuous river flow measurements (HELCOM 2015c). However, these requirements are not met in all the monitored rivers (Table 1). Additionally, some coastal areas and rivers remain unmonitored, which increases the uncertainty of the load estimates.

Table 1. Current state of monitoring of the riverine nutrient load into the GOF. The catchment area of the GOF is nearly 14 times the sea area, leading to a high nutrient input into the GOF related to its area and volume. * the largest rivers (the River Neva, the River Luga, the River Narva) are monitored monthly. N/A = not available. Source: HELCOM (2015d).

	Catchment area (km^2)	**Catchment area monitored** (%)	**Monitoring frequency per year**
Estonia	26 400	72	12
Finland	107 000(1)	90	12–22
Russia	286 000	N/A	4–12*
Total	423 000(2)		

1) 56 200 km^2 of the River Vuoksi catchment discharges to the GOF via Russian territory
2) 3 600 km^2 belongs to the Latvian territory and discharges to the GOF via Russian territory

Two heavy-weight polluters of the GOF. Photo: Juha Laaksonen.

Current nutrient load

The average annual total nitrogen (TOTN) input into the GOF in 2009–2013 was 112 000 tonnes (Table 2). The rivers accounted for 79 % of this, direct point sources 10 %, and the atmospheric deposition 11 %. The corresponding total phosphorus (TOTP) input was 4 270 tonnes (Table 3), of which rivers accounted for 88 % and direct point sources 12 %.

The largest share (61 % of TOTN and 74 % of TOTP) of the inputs came from Russia, although the area-specific inputs (input divided by catchment area) were smaller for Russia than for Estonia or Finland. Russia has the largest area and population in the GOF's catchment, which explains the high total input. On the other hand, the Russian catchment hosts large lakes, such as Lake Ladoga and Lake Onega that both retain nutrients effectively, reducing the area-specific input.

Development in time

Nutrient inputs into the GOF were decreased by 35 % in the late 1980's and the early 1990's (Pitkänen et al. 2001) partly due to the water protection measures and partly due to decreases in agricultural and industrial production at the time of the collapse of the former Soviet Union (Lääne et al. 2002). The changes in total annual nutrient inputs into the GOF were largely governed by the changes in Russian national loads,

Table 2. Annual TOTN input into the GOF. Riverine inputs refer to the years 2009–2013, except for Russia (2012–2013), and point source loads refer to the year 2013, except for Russia (2012–2013). Atmospheric deposition was estimated by the European Monitoring and Evaluation Programme of the Long Range Transboundary Air Pollutants in Europe (EMEP). N/A = not available. Sources: HELCOM (2013d, 2015d), Kondratyev et al. (manuscript).

TOTN	Riverine input 1), 3)	Municipalities	Industry	Aquaculture	Total inputs		Area specific inputs
		tonnes per year				%	kg/km^2
Estonia	13 800	502	51	11	14 400	13	544
Finland	15 200	1 190	239	25	16 700	15	327
Russia[2]	58 700	9 750	N/A	N/A	68 400	61	198
Deposition					12 700	11	
Total	87 700	11 400	290	36	112 000	100	265

1) Russian riverine export also includes transboundary inputs from Finland (the upper catchment of the River Vuoksi, area 56 200 km^2)
2) Russian point source load includes only St. Petersburg, Sosnovy Bor, and Vyborg
3) One third of the export load from the Narva River has been included in the Estonian and two thirds in the Russian load according to relative proportions of the catchment area of this border river

Table 3. Annual TOTP input into the GOF. Riverine inputs refer to the years 2009–2013, except for Russia (2012–2013), and point source loads refer to the year 2013 except for Russia (2012–2013). N/A = not available. Sources: HELCOM (2013d, 2015d), Kondratyev et al. (manuscript).

TOTN	Riverine input 1), 3)	Municipalities	Industry	Aquaculture	Total inputs		Area specific inputs
		tonnes per year				%	kg/km^2
Estonia	405	26	2	1	434	10	16.4
Finland	623	37	20	3	683	16	13.4
Russia[2]	2 620	520	8	N/A	3 150	74	9.1
Total	3 650	583	30	4	4 270	100	10.1

1) Russian riverine export includes also transboundary inputs from Finland (the upper catchment of the River Vuoksi, area 56 200 km^2)
2) Russian point source load includes only St. Petersburg, Sosnovy Bor, and Vyborg
3) One third of the export load from the Narva River has been included in the Estonian and two thirds in the Russian load according to relative proportions of the catchment area of this border river

more specifically by the decreases in the nutrient fluxes from the River Neva and from St. Petersburg.

The riverine flow into the GOF has exceeded the long-term average (3 490 m^3/s) in recent years. Consequently, since 2007, the annual riverine TOTN load has constantly surpassed the 20-year average of 93 000 tonnes/year. In contrast, the riverine TOTP load into the GOF has been lower than the long-term average of 6 000 tonnes/year most of the time since 2007. The explanations for the latter are the improved waste water treatment in St. Petersburg and the measures implemented in the Fosforit fertilizer factory in the River Luga catchment (Atkins International Ltd 2015, SUE Vodokanal of St. Petersburg 2015).

During the last two decades, variations in the riverine flow has largely explained the inter-annual changes in TOTN load (Fig. 1), whereas TOTP load has clearly decreased since 2005, and particularly since 2011, despite the increasing flow pattern. In Finland, the flow-normalized TOTN load from agricultural land has increased in many river basins, while the corresponding TOTP load has decreased from 1985 to 2006 (Ekholm et al. 2015).

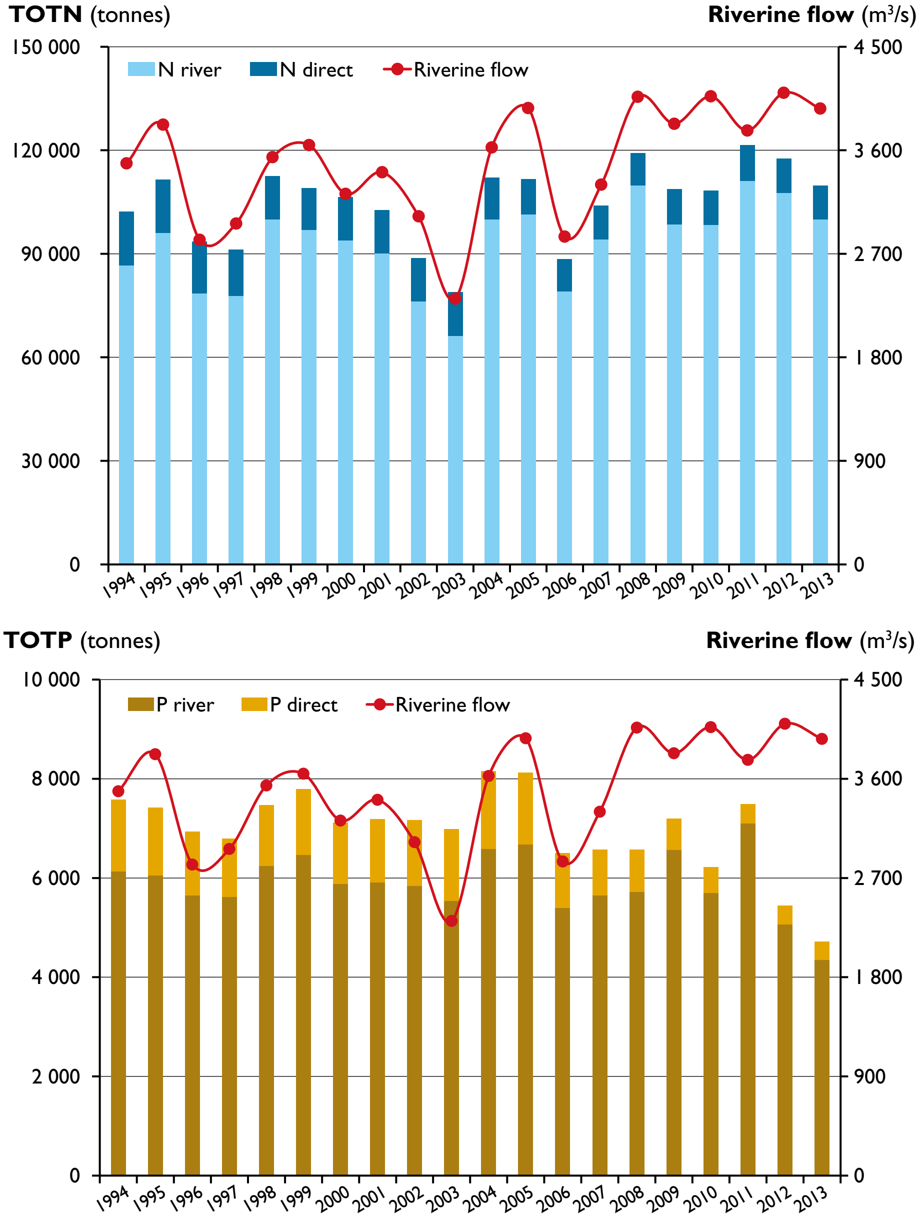


Figure 1. Annual TOTN (above) and TOTP (below) input by direct point source load and riverine load as well as riverine inflow into the GOF in 1994–2013. Source: HELCOM (2015d).

Some readers might notice numerical discrepancies between the tables and the figures for the P inputs in 2012–2013. These are mainly due to various input estimates for the Russian unmonitored areas. The higher estimates in Fig. 1 are based on the data reported to HELCOM/PLC database (HELCOM 2015c), whereas the lower estimates in Table 3, based on the data from the coastal rivers not included in the basic monitoring programme, are from Kondratyev et al. (manuscript).

The removal rates of N and P in waste water treatment plants (WWTP) vary considerably between the cities and the countries around the GOF, but generally, they have improved remarkably during the recent past, especially in St. Petersburg. Also, more people are currently connected to urban waste water collection and treatment systems than at the beginning of the 2000's (HELCOM 2011). The current P removal rate from waste waters is generally on a high level, but several WWTPs still need to upgrade their N removal process.

The development of waste water treatment of St. Petersburg

Prior to 1978 – the year when the Central WWTP became operational – the purification of wastewaters in St. Petersburg was almost non-existent, and practically all waste waters were discharged directly into the GOF or the River Neva. The completion of the Northern WWTP in 1987 and the South-Western WWTP in 2005 substantially reduced the amount of untreated effluent discharged into the GOF. The implementation of chemical P removal at the Central WWTP was completed in 2009. In 2010 and 2011, the same process was realized at the South-Western and the Northern WWTPs. After the completion of the South-Western WWTP in 2005, the city's capacity for treating waste water increased to 85 %. The construction of the Northern Tunnel Collector to the Northern WWTP in October 2013 increased the capacity to 98.5 % (SUE Vodokanal of St. Petersburg 2015).

Since 2004, the decreases in P and N loads have been about 1 800 and 3 900 tonnes/year, respectively (SUE Vodokanal of St. Petersburg 2015). Since the beginning of wastewater treatment in the city in 1978, the P and N loads have decreased by 3 600 (90 %) and 14 000 tonnes/year (60 %), respectively (Fig. 2). Currently, St. Petersburg fully meets the recommendations of HELCOM: concentration of P in the effluent does not exceed 0.5 mg/l.

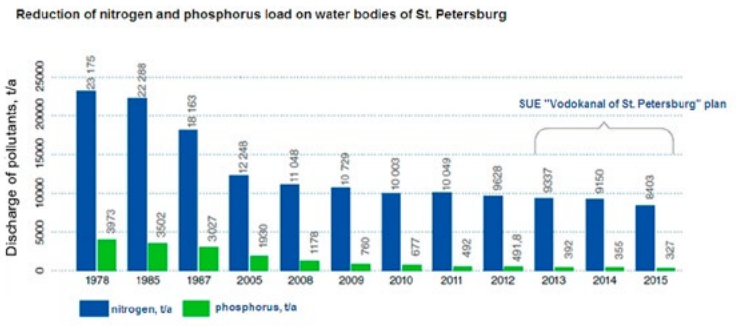


Figure 2. Nutrient load from St. Petersburg into the GOF in 1978–2015. Source: SUE Vodokanal of St. Petersburg (2016).

Nutrients: sources and retention

A part of the land-based nutrient load is retained through sedimentation (P, N) and denitrification (N) in inland waters, and thus does not end up in the sea. By estimating the total inputs to inland waters and how they are transported and/or retained in lakes and rivers allows dividing riverine nutrient inputs into their original sources. This source apportionment of riverine fluxes enables more precise targeting of mitigation measures.

Retention of nutrients is efficient especially in catchments harboring large lakes. In total, 42 % of the N input and 73 % of the P input once discharged to inland waters is retained in lakes and rivers in the GOF drainage basin (Piirmäe et al. 2007). Retention is most efficient in the lake-rich River Neva and River Kymijoki catchments (Stålnacke et al. 2014). In contrast, in the coastal areas, where lakes are typically small, retention is low.

The biggest share of land-based nutrient load originates from diffuse sources, especially from agriculture. In Finland, more than half of the annual P load comes from cultivated fields, even though these fields cover on the average < 10 % of the land area of the catchments. In the Finnish coastal river catchments of the GOF, the share of fields of the land area is ≤ 30 %. Also in Estonia, diffuse sources are responsible for the major part of the total nutrient load.

The division of the riverine nutrient load into individual sources cannot currently be done for the entire GOF area. Few small river basins are regularly monitored in the Russian part of the catchment of the GOF, and there are small unmonitored coastal river basins also in Finland and Estonia. In addition, information on the Russian point source discharges, as well as the monitoring of the non-point loading in the river catchments is largely missing.

Recommendations

Reliable nutrient load estimates require comprehensive monitoring of riverine fluxes and point source discharges. There is still a lot to be done for a basin-wide division of the riverine nutrient load into individual sources.

In order to reliably monitor riverine loads, daily flow measurements and monthly sampling of water quality is needed in those rivers contributing substantially to the national nutrient inputs.

Since there is still a considerable uncertainty in the nutrient inputs into the GOF, both sampling and chemical analyses should be performed with equal and comparable methodology according to HELCOM Guidelines (HELCOM 2015c) in all three countries.

Eutrophication mitigation policies, such as the HELCOM BSAP, tend to rely on total nutrients as indicators of nutrient loading, thus giving an equal weight to all nutrient forms regardless of their bioavailability. A more detailed analysis is needed of different nutrient forms from all relevant sources.

Nutrients in the water

Mika Raateoja[1], Heikki Pitkänen[1], Tatjana Eremina[2], Urmas Lips[3], Tatjana Zagrebina[4], Pirkko Kauppila[1], Seppo Knuuttila[1], Alexandra Ershova[2], Evgenia Lange[2], Andres Jaanus[5], Silvie Lainela[5]

[1] Finnish Environment Institute
[2] Russian State Hydrometeorological University
[3] Marine Systems Institute, Tallinn University of Technology
[4] North-West Interregional Territorial Administration for Hydrometeorology and Environmental Monitoring (Hydromet)
[5] Estonian Marine Institute

Marine primary production happens within the frames set by the physical and chemical environment, and the nutrient inventory is the most direct and easiest metrics for assessing the general trophic status of the sea. More specifically, the safest ground for estimating this status is the dissolved inorganic nutrient stock in the surface layer in the winter. The dissolved inorganic N and P forms (here DIN = NO_2-N+NO_3-N and DIP = PO_4-P) are the preferred nutritional forms for the primary producers. They are also readily accessible in the surface layer – where the large bulk of the primary production takes place – due to regeneration processes and vertical mixing. Moreover, their concentrations are at their peak in the wintertime due to virtually absent primary producers, and due to the relatively low metabolic rates of those inhabiting the water.

The GOF is one of the most eutrophic basins of the BS, and has been that since the pre-industrial times (Savchuk et al. 2008, Gustafsson et al. 2012). Still, the most notable increase in the nutrient stocks has taken place within the past five decades; DIN depository increased in the 1970's and the 1980's, and the DIP depository did that in the 1990's (Fleming-Lehtinen et al. 2008). Partly because of this, and partly boosted by the intensification of the late-summer cyanobacterial blooms around the turn of the millennium (Kahru et al. 2007), the environmental state of the GOF has lately received much attention in the media (Lyytimäki 2012) and amongst the general public and decision-makers. Moreover, its trophic state has for a long time been subject to an extensive scientific effort.

The trophic state of the GOF has been assessed by HELCOM in recurring basis and for 2007–2011 at the latest (HELCOM 2014a). Back then, the ecological status of the GOF with respect to winter nutrient concentrations failed to reach a good level; the average DIN concentration for December–February in 2007–2011 was roughly twice the target level of 3.8 µmol/l for a good status, and the corresponding DIP average was almost 50 % higher than the target level of 0.59 µmol/l. Compared to the earlier assessment period 2003–2007 (HELCOM 2010), the DIN concentrations seem to have increased somewhat. The HELCOM's assessments deal with the entire BS and are obliged to see the GOF as one geographical area, thus missing the intra-regional variation we will describe here.

In this section, we describe the past changes in the trophic status of the GOF using the nutrient regime. We used the GOF2014 dataset, covering the years 1996–2013, supplemented by the 2014–2015 trilateral data. Our conclusions are based on the DIN and DIP data collected in the upper 10 m in the wintertime (December–March). For the Russian waters of the GOF, summertime nutrient data was used because coherent winter data was not available.

An all too common sight in the GOF. Photo: Riku Lumiaro.

Spatial approach

In order to assess the trophic state within the various parts of the GOF, we divided the GOF into regions based on geography and topography (a figure in the chapter GOF2014 dataset). This division was employed also to the Chl *a* section. The regions are as follows:

- Estonian Coast Inner (ECI) represents the inner Estonian coastal area. In spite of being called "Inner", ECI possesses much of the characteristics of the offshore areas: it has a similar salinity range due to the open coastal topography and the typical current pattern of the GOF.
- Estonian Coast Outer (ECO) represents the outer Estonian coastal area. ECO is fully comparable to offshore areas, and includes actually the deepest stations in the GOF.
- Finnish Coast Outer (FCO) represents the transition zone between the Finnish archipelago and the offshore area. The stations are located near to the outer islets, and represent quite well the offshore environment. KYVY-1 is an exception: it is located off the River Kymijoki's outlet and is subject to a considerable riverine impact. In addition to the GOF2014 stations, the station 39A off Helsinki was included in this area.
- Finnish Coast Eastern (FCE) represents the tension zone between the Finnish archipelago and the offshore area east of the Gogland Island. This region is affected by the high river flow and nutrient loading into the easternmost GOF.
- Luga and Koporye Bays (LAKB) represent the southern Russian coastal area east of the Narva Bay. Here, the two bays are handled together.
- Narva Bay (NB) is the shallowest (albeit open coast) region under study within the southern seaboard, and as such is cannot be considered as a true offshore region.

The natural variation and how to deal with it

The GOF is by marine standards a highly dynamic area. This instability of the nutrient regime introduces a challenge to discover any trends in the long-term data. When all the annual observations in a region are concerned, we can see that the variation is at times notable (Fig. 3). For this study, all the water samples for nutrient analyses have been collected within a quite restricted and stable (in a chemical sense) time of season (December–March). Thus, most of the variation stems from the inter-station differences. In practice, this information has to be averaged. Fortunately, the GOF2014 dataset provides a wealth of data which enables pooling of the existing information.

By pooling a number of stations into one mold, even from relatively small areas as the regions used here, we accept to deal with the varying trophic conditions of the stations. Consequently, for trend analyses, all the data within the region had to be normalized in order to exclude the impact of the inter-station differences:

$$\text{Value}_{\text{standardized}}=(\text{Value}_{\text{original}}\text{-stationwise average of Value})\times\text{stationwise sd of Value}^{-1}$$

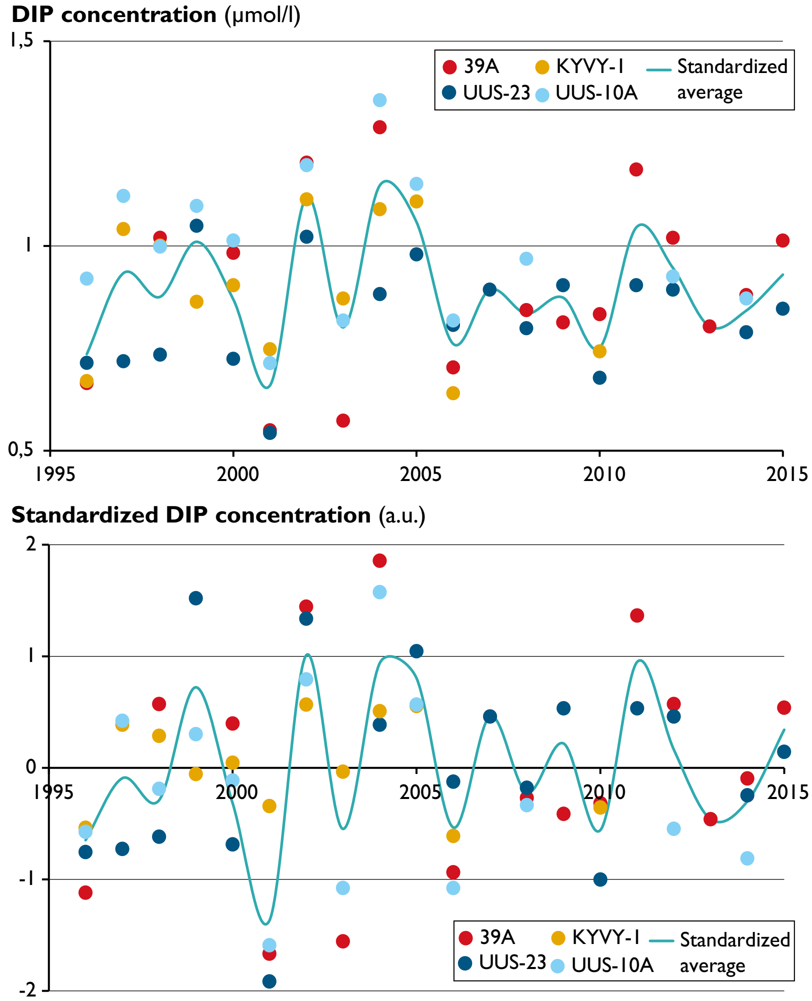


Figure 3. The DIP pattern in FCO as a function of time. Above: the stationwise annual averages with the regional fit. Below: the same except for standardized values. Source: GOF2014 dataset.

- Offshore East (OE) represents the offshore area of the eastern GOF between the Gogland Island and the transect Shepelevsky cape – Flotsky cape, having salinity of about 3.5 g/kg. The inner part of OE, having a western limit along the transect Berezovye - Seskar Islands, is under the impact of the River Neva flow.
- Offshore West (OW) representing the offshore area of the western GOF, having salinity of about 6 g/kg. This region has been divided further into Estonian (OWE) and Finnish (OWF) parts.
- Offshore Middle (OM) represents the offshore area of the middle GOF, having salinity of about 5 g/kg. This region has been divided further into Estonian (OME) and Finnish (OMF) parts.
- Shallow-water area (SWA), which lies between the transect Shepelevsky cape – Flotsky cape and the Kotlin Island (and St. Petersburg Flood Protection Facility), has surface salinity ranging from 0.5 to 2 g/kg.
- II+IIIa and IIIb. These areas are described in a figure in the chapter GOF2014 dataset.

Looking at the entire GOF area, both DIN and DIP concentrations had a general tendency to increase eastwards and towards the coasts (see Annex 1). As an exception, a decreasing P gradient to the east of the Finnish waters has been observed in recent years.

East-West transect: OM and OW. In general, the DIN and DIP concentrations tended to increase towards the east. We arrived in clear west-east gradients: i) from LL12 to LL3A where DIN increased from 6.6 to 10.0 µmol/l and DIP increased from 0.60 to 0.94 µmol/l, and ii) from H1 to F1 where DIN increased from 4.4 to 6.1 µmol/l and DIP increased from 0.59 to 0.79 µmol/l. Particularly for DIP, the steepest gradient occurred between the two westernmost stations; LL12 and H1 are here to represent the western border of the GOF but perhaps could better be categorized into Northern Gotland Basin stations.

East-West transect: FCE and FCO. The eastward increasing pattern in DIN and DIP holds true also for the Finnish outer coastal waters. FCO covers the area from the Hanko peninsula to the coastal area off the River Kymijoki estuary, and FCE covers the eastern part of the Finnish coastal area. The eastward array of stations from UUS-23 to KYVY-11 had increasing tendencies for DIN and DIP (6.7 to 10.2 and 0.83 to 1.11 µmol/l for DIN and DIP, respectively).

East-West transect: ECI and NB. ECI was split up into groups according to the DIP levels; the western group of stations (23A, PW, PE), covering the coast from Osmussaar to Paldiski, had DIP averages ≤ 0.60 µmol/l whereas the eastern group (2, 3, 57A, 18A), situating off Tallinn and in Kolga Bay, had averages > 0.75 µmol/l. Further, the station network in NB had a higher DIP with > 0.80 µmol/l at all but one station. For DIN, a similar tendency was not there. NB had a slightly higher average DIN than had ECI (6.8 and 6.1 µmol/l, respectively), otherwise it seemed that the differences in DIN inside ECI and NB were related to the distance of the coast rather than station's location in the east-west direction.

North-South transect: ECI and ECO. ECI and ECO were located approximately at the same longitudinal interval and thus formed a solid pair for the coast-offshore comparison. As expected, the groups had a moderate difference in the average DIN (6.1 and 5.2 µmol/l, respectively) but not so much difference in the average DIP. More precisely, the Tallinn transect from 19 to 57A had clear increasing trends for DIN and DIP towards the coast (DIN 4.9 to 8.3 µmol/l and DIP 0.63 to 0.77 µmol/l) most probably due to the anthropogenic impact.

East-West transect: OE and SWA. The TOTN concentration increased in the Seskar basin; the western stations in OE (3, 4) had the average of 30 µmol/l while the average increased to 34 and beyond at the station 2 and further east in SWA. The pattern for TOTP was quite the opposite; the values of > 0.50 µmol/l in OE changed to values < 0.50 µmol/l in SWA. Both the TOTN and TOTP values did not exhibit any marked intraregional variation.

Environmental targets

As part of the EU MSFD (EU 2008) implementation, EU (2010) stipulated the criteria for good environmental status (GES) to its marine areas. The definition of Descriptor 5 is that human-induced eutrophication is minimized. The criterion [5.1.] defines GES according to the nutrient levels not causing direct or indirect harmful impact on the marine environment. Consequently, based on mathematical ecosystem models, HELCOM agreed the target values for its eutrophication core indicators "concentration of DIN" and "concentration of DIP" (HELCOM 2013c). For the open GOF, the target values were 3.8 and 0.59 µmol/l for DIN and DIP, respectively (HELCOM 2014a). These indicators were built in the same way as in this assessment except that HELCOM uses the months December – February instead of December – March. We extended the assessment period until the end of March because the vernal bloom period starts in the GOF later than in the southern areas (Raateoja et al. 2011).

We chose to reflect the DIN and DIP trends of three stations in the GOF onto these targets. LL12 is located in the offshore area at the western brink of the GOF, and in this comparison it serves as a baseline, i.e., as the station with the lowest nutrient content. LL7/LL7S in the middle of the GOF has the longest time series available. It represents well the middle GOF. KYVY-11 situates at the brink of the offshore area in the eastern GOF. It has the highest nutrient content in the outer Finnish territorial waters probably due to its location within the westward current field occurring in the northern part of the GOF, and thus, being affected by the high N input from the River Neva. Furthermore, it is affected by effective wintertime vertical mixing bringing deep water P in to the surface layer.

For DIN, LL7/LL7S has not met the GES target level during the study period (Fig. 4), actually not since the mid-1970's. At LL12, the target level has been reached occasionally also since then. KYVY-11 has not met the target level during the monitored period, which was expected as the target represents the offshore area. For DIP, all of the stations have met the GES target at some point of time (Fig. 4). KYVY-11 did this in the late 1960's, and LL7/LL7S has done this occasionally but not after 2001. LL12 meets the target. However, it does not situate in the actual GOF, but immediately outside the entrance to the GOF in the Northern Gotland Basin. If we compared the LL12 dataset to the target values of the Northern Gotland Basin (2.9 and 0.25 µmol/l for DIN and DIP, respectively), it would not reach the targets at any time.

Using the GOF2014 dataset, the long-term station wise inspection tells that the DIP target level was met only at some stations in the offshore western GOF and in the western Estonian coast (Annex 1). The DIN target level was not met at any station. According to the most recent (2014–2015) data, neither the DIP nor the DIN target level was met.

The closest comparison to these targets for the coastal waters in Estonia and Finland comes from the EU WFD (EU 2000). However, these target values are based on the summertime total nutrient quotas, and are thus only noted here. Briefly, for the areas subject to this assessment, the borders between good and moderate environmental status, based on the total nitrogen (TOTN) and total phosphorus (TOTP, µmol/l), were as follows: i) FIN: south-western outer archipelago 21 and 0.58, ii) FIN: outer GOF archipelago 23 and 0.65 (Aroviita et al. 2012), and iii) EST: western GOF coast 18 and 0.70 (Lips 2004, Estonian Ministry of the Environment 2010). None of the stations in FCO or FCE met the Finnish targets, but they were occasionally quite close to those (the stationwise study averages 0.63 to 0.79 µmol/l for TOTP, and 23 to 26 µmol/l for TOTN, data not shown). The same applied for Estonia (the stationwise study averages 0.72 to 0.90 µmol/l for TOTP, and 19 to 22 µmol/l for TOTN, data not shown).

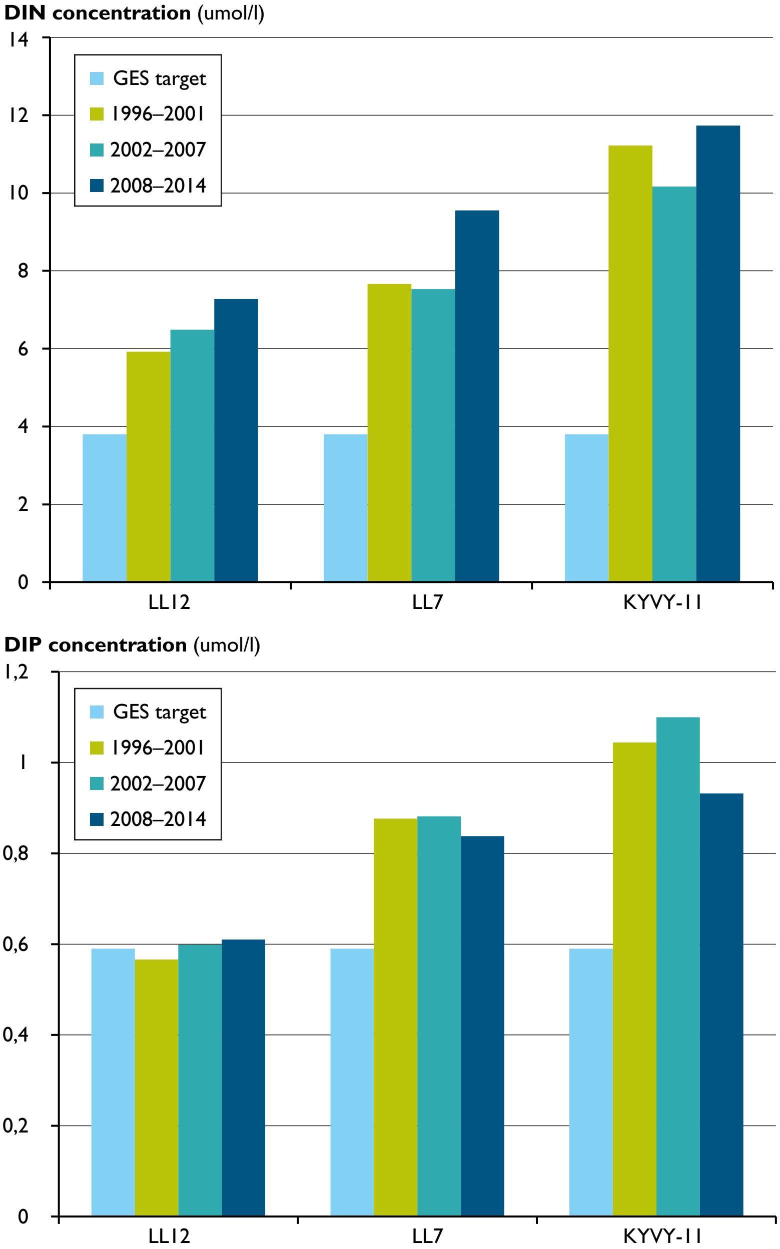


Figure 4. DIN (above) and DIP (below) (μmol/l) as a function of time, and the EU MSFD GES target values at various stations. Source: GOF2014 dataset.

Distribution in time

Fluctuations…

In addition to the P load from the catchment, the internal DIP fluxes affect the DIP inventory of the GOF. The cascade of mechanisms triggered by the deep water intrusions from the Northern Gotland Basin plays a major role in the GOF's nutrient dynamics. It increases the deep water DIP content in the GOF both by bringing DIP from the Northern Gotland Basin, and by creating favorable conditions for enhanced benthic nutrient release. For certain years of extensive hypoxia, this impact on the DIP quota has been estimated to be larger than the one resulting from the land-based load (Pitkänen et al. 2003). We thus expected that the temporal trends of the land-based DIP load into the GOF and the DIP content in the GOF would not escort closely to each other.

The temporal pattern of DIP (and of DIN, too) was characterized by large recurring fluctuations throughout the studied period 1996–2015. The fluctuation was at times so large that it obscured a detection of possible trends. If we accept that this fluctuation was caused by the mechanisms described above, we can state that their effect has not lately settled. At times, the fluctuations were observed to be basin-wide. For instance, the DIP peaks were found in every region in the western and middle GOF in 2004 and 2011. Thus, it is safe to state that the mechanisms behind the accelerated sediment nutrient release affect the entire GOF, typically the deeper areas in the western and middle GOF, but occasionally in the eastern GOF as well.

A glimpse of the past.

The monitoring of the GOF – and the BS in general – was re-defined by HELCOM in 1979 with the introduction of the Baltic Monitoring Programme (BMP). It brought along the monitoring of Chl a on a constant basis and the wintertime monitoring of nutrients. Since those times, the GOF's eutrophication has advanced. If we choose to use LL7/LL7S as a standground for comparison, we can conclude the following:

- DIN concentration increased in the 1980's and decreased somewhat in the 1990's, but have not changed much since then. The temporal variation has lately increased, though (Fig. 5)
- Chl a concentration increased in the 1990's, but subsequently started to decrease at the turn of the millennium
- DIP concentration increased in the late 1990's. Since then, the temporal variation has been pronounced, but it seems that the average level has been quite steady.

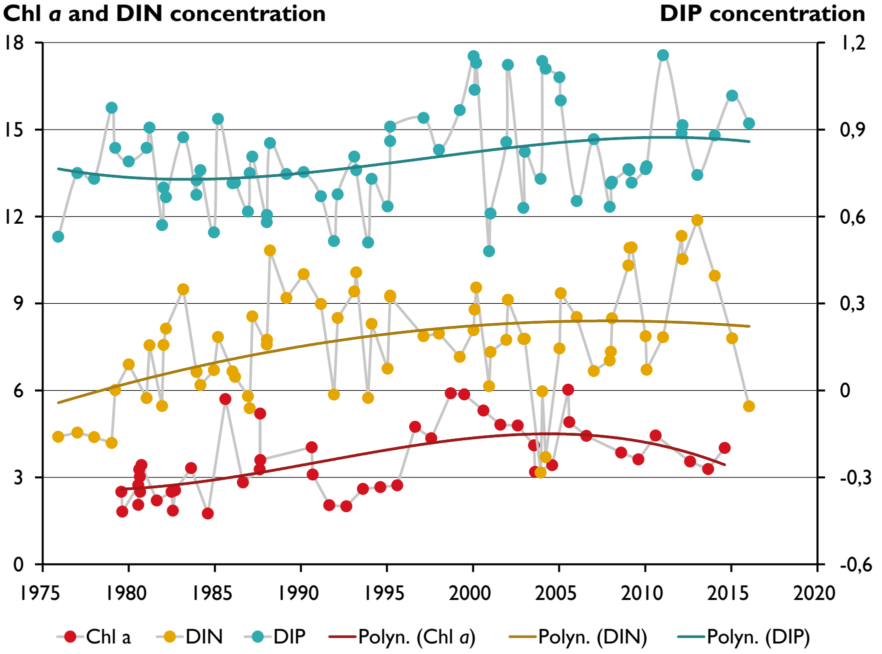


Figure 5. Forty years of maritime monitoring. Timelines of Chl *a*, DIN, and DIP at LL7/LL7S in the offshore middle GOF. DIN and DIP: µmol/l, 0–10 m, December–March. Chl a: µg/l, 0–10 m, June–September. Non-statistical smoothers are embedded to reveal trends. Source: SYKE database.

… and their causes

Apart from the stagnation phase in the 1980's and after the 1993 Major Baltic Inflow, the coverage of the hypoxia in the Gotland Basin has varied only moderately for the past half a century. The expanse of the bottom area covered by hypoxic waters in the early 2000's was roughly at the same level as in the 1970's (Conley et al. 2009, Hansson et al. 2011), and after this it has almost continuously increased until the Major Baltic Inflow in 2014 (Hansson and Andersson 2015). The corresponding temporal variation in the GOF is relatively much larger and varies much quicker (See Fig. 16 in the chapter Gulf of Finland physics). This is a manifestation of the water balance of the GOF. The flow pattern at the entrance of the GOF is described by a typical estuarine one; outflow in the surface layer and inflow in the deep layer (Alenius et al. 1998). Thus, there is a predominant inflow of the Northern Gotland Basin deep water keeping up the deep-water density gradient and consequent bottom oxygen deprivation in the GOF. This inflow may be halted, and sometimes reversed by existing wind pattern in the Baltic area (Elken et al. 2003). As such, the actual amount of nutrients and salt entering the GOF is predominantly dictated by the depth of the halocline in the Northern Gotland Basin. It is of considerable importance for the GOF's deep oxygen and nutrient conditions how large share of the incoming deep waters originate from below the halocline.

Supplemented by the oxygen requirement of the decomposing export production, the baseline flow pattern sustains the oxygen deprivation in the deepest areas in the western and middle GOF. Whenever more prominent deep-water intrusions enter the GOF, the subjected area stretches eastward and covers shallower bottoms. These large intrusions are caused by the existing wind pattern of the Baltic area (Liblik et al. 2013) and occasionally also by Major Baltic Inflows (Eilola et al. 2014). From this angle, the GOF's biggest problem is the existence of the Northern Gotland Basin; the lack of ridge formations between the GOF and this large stratified and anoxic basin leads to an intrinsic characteristic of the GOF to become eutrophic.

Western and middle GOF

For DIP, the offshore areas OM and OW presented a pronounced fluctuation within a two to four year interval (see Annex 2). Actually, we should not draw so much attention to this fluctuation but to the baseline level between the peaks. This level seems to have started to increase in OMF and OWF in the late 2000's. The fluctuations have extended lately, thus adding a component to the new, although faint and still unclarified, increase in the DIP pattern. The Finnish coastal areas FCE and FCO showed also pronounced fluctuation, but here the superimposed trend after the turn of the millennium was to decrease, more clearly in FCE.

The interpretation of the P trends in the OM and OW was found to be dependent on the stations that were used in the study. The sole use of the Finnish stations (OMF, OWF) led to an interpretation described above whereas the sole use of the Estonian stations (OME, OWE) would result in a step-up in the DIP status in the late 2000's. OME and OWE as well as the coastal areas ECI, ECO, and NB had much of a similar kind of a fluctuation pattern to the Finnish areas, which was however damped by the considerable rise in the DIP level between 2009 and 2012. Since 2012, fluctuations seem to have continued although this could not be fully evidenced.

The considerably different behaviour of the Estonian DIP pattern to the Finnish one has some leverage from the Chl *a* results; the southern seaboard was the only area in the GOF that did not show a decreasing Chl *a* pattern since the mid-2000's (see section Chlorophyll *a* and phytoplankton blooms). The considerable changes in the DIP content of the water, at times taking place over relatively short distances between the stations, cannot be fully explained by natural variation (see the conclusions of this section). A closer examination is needed to find solutions to secure that the future trend assessments based on the monitoring data of the GOF are better in line between the countries. This process has already started by Estonian Marine Institute at the time of writing of this assessment.

The DIN pattern in the offshore areas OMF and OWF started to exhibit a fluctuation similar to DIP only in this millennium. OMF and OWF had an increasing trend up to the mid-2000's which seems to have levelled off since then. Whether the decreasing phase starting in 2012–2013 is a first step into a better trophic condition or just a part of another fluctuation is too early to say. Nevertheless, it is the longest decreasing phase observed in this dataset. The Finnish coastal area FCE also showed an increasing trend that levelled off in the mid-2000's. The Estonian regions (OME, OWE, ECI, ECO, NB) presented a step-up in the DIN status in the late 2000's alike DIP.

Eastern GOF

The Russian monitoring program lacks the continuous wintertime monitoring, and we used the summertime monitoring data to describe the trophic state in the Russian territorial waters (for details, see Annex 1 caption).

The nutrient dynamics of the easternmost GOF is shaped by the occasional intrusions of the deep water high in nutrients from the west, and on the other hand, variations in the River Neva flow (Eremina and Karlin 2008, Golubkov and Alimov 2010). The mechanisms that increase the nutrient quota in the deep waters of the western and middle GOF play a role also here; there exists a hydrodynamic cascading effect triggered by the deep water intrusions from the Northern Gotland Basin. The results are similar, too, affecting the DIP condition both by the DIP content of the advected sub-halocline waters and by creating favorable conditions for local enhanced benthic nutrient release (see section Processes controlling P storages). As a difference to the western GOF, the estuarine effect (fluvial advection patterns and related mixing in and at the brink of the Shallow Water Area) has a pronounced role in the extent of the intrusion towards to the tip of the GOF. The effect of the River Neva and St. Petersburg on the GOF nutrient dynamics can be regarded pronounced throughout the Shallow Water Area. This impact is increasingly masked towards deeper areas by the effect of the hydrodynamic cascade shaped by the general current pattern of the GOF.

Alike in the western GOF, the long-term DIP dynamics in its easternmost part demonstrated a large inter-annual fluctuation (see Annex 2). There was a decreasing trend for the surface TOTP in SWA. Also, using deep-water TOTP, we found a decreasing trend in OE (data not shown). It is worth noting that the changes in the deep-water TOTP outside SWA cannot be interpreted to reflect solely the changes in the nutrient load from the catchment. In addition to the decreasing trend for TOTP in SWA, we observed a decreasing phase with every P form in every sub-region of the Russian waters since 2010. Again, whether this phenomenon is evidence of moving to the right direction with regard to eutrophication or the beginning of just another fluctuation is too early to say. Nevertheless, the considerable reductions in the land-based P load taken place in the area especially since 2012 suggest for the former (section Nutrient inputs). Also the invasion of *Marenzelleria arctia* has possibly had a role in this positive development (Maximov et al. 2014).

We found temporary peaks of TOTP/DIP in 2003, 2006, and 2010. In 2003, the flow of the River Neva was abnormally low (Golubkov and Alimov 2010) and the oxygen condition in the middle GOF was poor; oxygen deprivation was observed in the deep basins of the eastern GOF all the way to Moschnyi Island (Hansson et al. 2009). The physical set-up was there to create an intrusion that led to increases in TOTP/DIP throughout the GOF, and consequently, the highest observed TOTP/DIP values in SWA and II+IIIa were observed in that year. Based on these observations, it seems that the hydrodynamical set-up enabled the intrusions to penetrate deep into the eastern GOF; here, low riverine input allows waters from the west to enter the shallow water area, contrasting the idea of a pronounced riverine input to trigger compensational currents.

The long-term TOTN/DIN pattern showed an abrupt increase in every sub-region of the Russian waters in the latter part of the 2000's. Maximov et al. (2014) tackled this issue and explained the increase to take place due the invasion of the non-indigenous polychaete *Marenzelleria arctia* and its bioirrigation and bioturbation activity. This step-up seemed to be only a temporary change in the nutrient regime, as TOTN and DIN levels have lately been decreasing back to levels observed in the early 2000's.

The River Luga case

The Russian data for 2008 delivered to HELCOM-PLC in August 2011 indicated higher TOTP load into the GOF than in previous years. This information, together with the exceptionally high P concentration observed at the mouth of the River Luga during the PRIMER project in the summer 2008 (Finnish Environment Institute 2009) contributed to the suggestion to include the River Luga as a test case in the HELCOM BALTHAZAR project.

Already the first BALTHAZAR sampling in October 2011 revealed previously unidentified source of DIP entering the GOF via the River Luga (HELCOM 2012a). The DIP load was discharged into the river between Kingisepp and the river mouth, and the fertilizer manufacturer Phosphorit in Kingisepp was soon pin-pointed to be the origin of the load.

According to Atkins International Ltd (2015), the additional annual P load caused by the fertilizer plant area has been on the average 1 700 tons in 2008–2011. As much as 90 % of this source consisted of DIP, emphasizing the impact of this source on the functioning of the GOF. To scale, the total waterborne P load into the GOF in 2010 was about 6 200 tonnes (HELCOM 2013d).

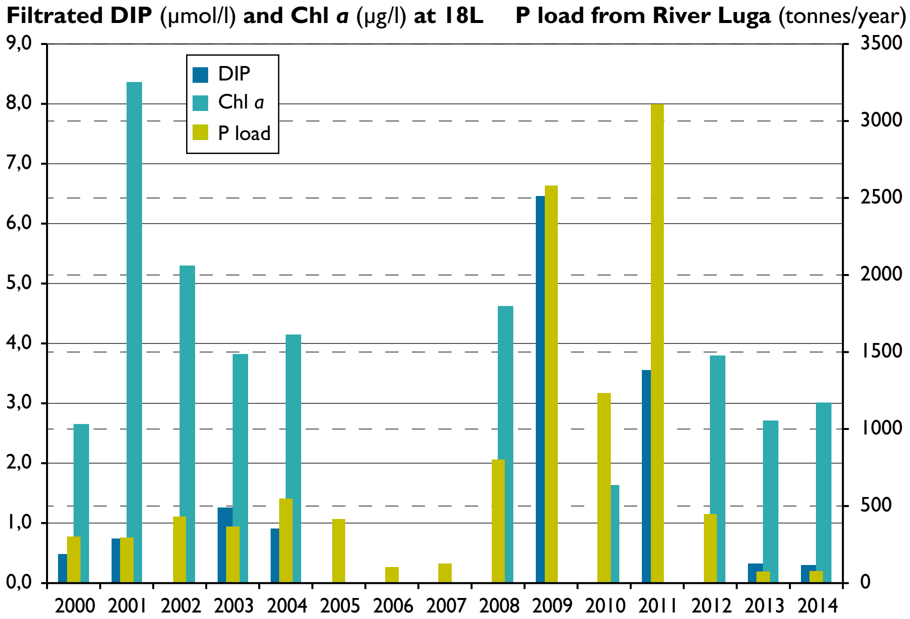


Figure 6. The filtrated surface layer DIP (µmol/l) in October and Chl *a* (µg/l) in August at the station 18L in the Luga Bay as well as the annual P load (tonnes/year) from the River Luga. Source: Hydromet, HELCOM (2012b), Atkins International Ltd (2015).

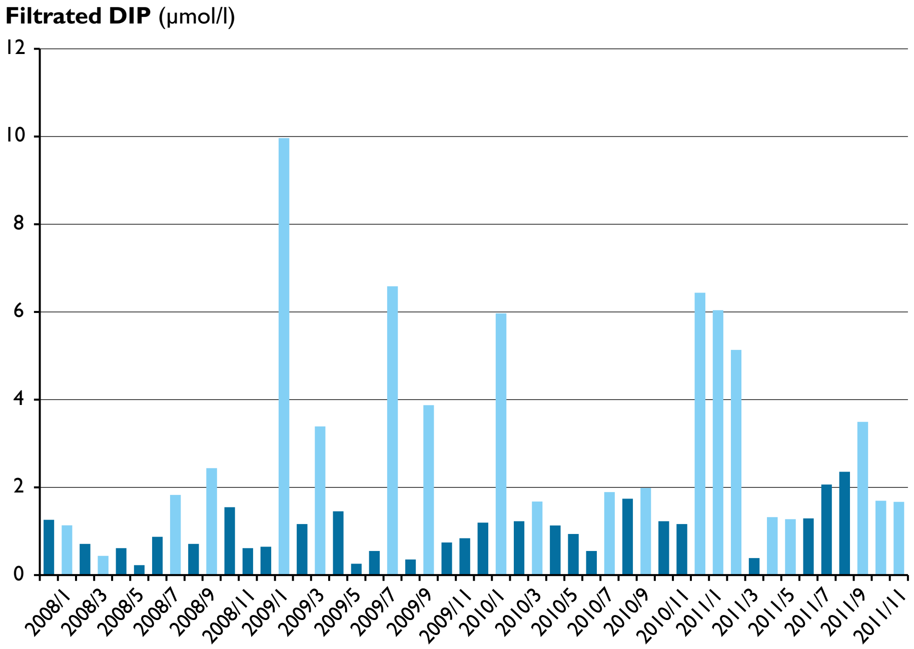


Figure 7. Filtrated DIP (µmol/l) in the River Luga in 2008 to 2010 reflected the episodic DIP discharges from Phosphorit factory area, but not from the phosphogypsum waste stacks. The 2011 data included the loads from the factory area and the stacks. The number string in the x-axis refers to year/month. For clarity of the presentation, the baby-blue bars represent values that are divided by ten, i.e., the highest values were about 100 µmol/l. Source: Hydromet.

According to the GOF2014 dataset, the effect of the elevated DIP load in the Luga Bay could be detected at least between 2009 and 2011 (Fig. 6). At that time, the surface DIP levels at the station 18L were roughly five times the levels at the turn of the millennium. The river monitoring data downstream of Kingisepp shows that the period of high P load commenced in 2008.

The location of the river monitoring station was critical in this case. Two brooks, Gorsky and Verhovsky, brought waters from the factory area. Gorsky, the upstream one, brought waters from the actual factory site while Verhovsky, the downstream one, had its waters predominantly from the phosphogypsum waste stack. The official monitoring station in the River Luga was erroneously reported to had been transferred from the original location between the brooks (48 km upstream from the river mouth) to a location downstream of both of the brooks (41 km upstream) for 2008 to 2011, and moved back to its original location in 2012 (HELCOM 2012b). Actually, the monitoring station was transferred downstream of Verhovsky brook (Pulkovo village) only for testing purposes in 2011.

In 2008–2010, the temporal range of the river DIP concentration was extreme from the levels typical for the GOF to 100 times the typical values (Fig. 7). This highly episodic pattern stems partly from inconsistent sampling procedure but the consistent timing of nutrient pulses (February, April, August, October) suggests that the loads were linked to the factory's process itself. These exceptional concentrations were initially thought being caused by a leakage from the phosphogypsum stack. When BALTHAZAR project initiated a special sampling programme in October – December 2011 at the river mouth in Ust-Luga locating itself downstream of both of the brooks, the range of concentrations was very low (HELCOM 2012b). This as well as monthly monitoring data in 2011 suggests that the leakage from the phosphogypsum waste stack was a more stable source of nutrients than the factory's process waters (Fig. 7).

Initially, the Verhovsky brook was identified to be the major pathway for the nutrient load. In the light of the new information about the sampling point in 2008–2011,

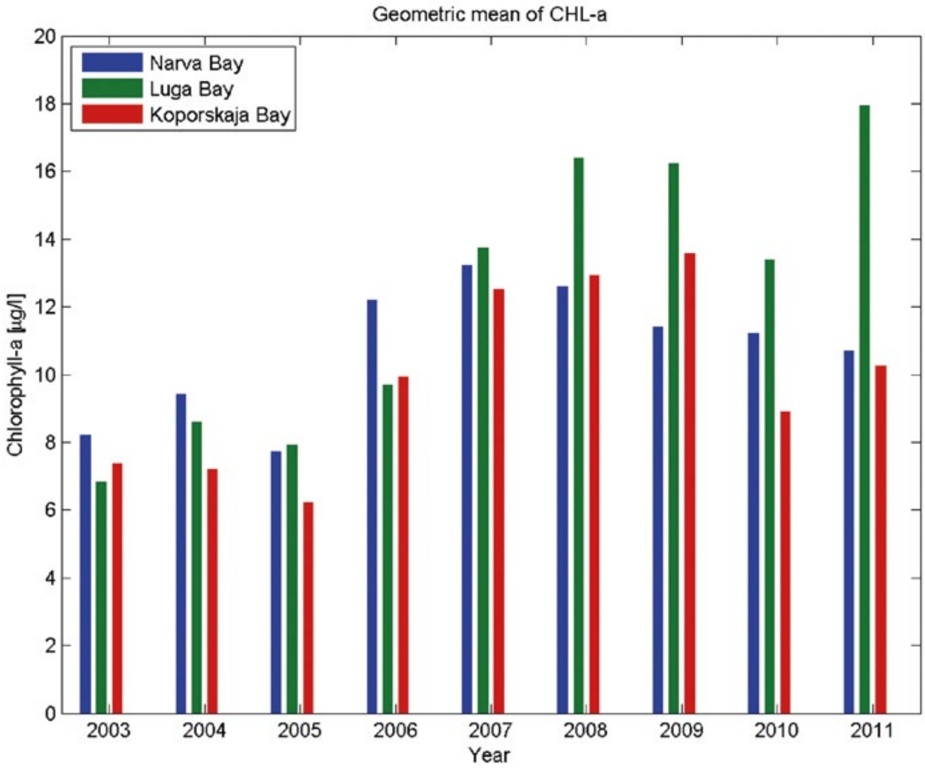


Figure 8. A remote sensing based Chl *a* (µg/l) in July – August as a function of time in the Narva Bay, the Luga Bay, and the Koporye Bay. In 2003 to 2007, all the regions showed increasing trend, while in 2007 to 2011 Luga Bay took a different path to the other regions. The MERIS-satellite data ended up in 2011, not allowing analysis of Chl *a* in the Luga Bay after the load was cut down. Source: ENVISAT / MERIS. Graphics: SYKE.

the mutual importance of the two brooks in terms of delivering the DIP load into the River Luga became evident.

The surface DIN and DIP in the Luga Bay were back again at the previous levels by 2013 (Fig. 6). Actually, the drop in the DIP load from the Verhovsky Brook occurred already in January 2012. After that the TOTP concentration in the River Luga near Ust-Luga dropped to one fourth of the previous level (HELCOM 2012b). This turning point was a manifestation of the actions taken by EuroChem, the owner of Phosphorit, in the early 2012. Nowadays, a storage system consisting of dams and natural reservoirs hold the runoff waters in the factory area, and a waste water treatment facility is in place to precipitate P. The plant's P load is currently at a pre-2008 level (Atkins International Ltd 2015).

The high P load did not reflect in such distinctive increases in phytoplankton biomasses in the Luga Bay area as could be imagined (Figs. 6 and 8). Surely, the Luga Bay stands apart from the nearby coastal areas in 2007–2011; unlike the other areas, it exhibited an increasing Chl *a* trend. Still, the increase in Chl *a* is moderate when scaled to the available nutrients. The River Luga is a considerable large river (average flow of is > 100 m^3/s). As the strongly pulsed P load discharges into the relatively shallow Luga Bay with a short residence time, the river plume carries most of the nutrient load to the offshore area. This way, the Phosphorit's elevated nutrient load was incorporated into the general eastern GOF nutrient inventory. The impacts of this incident and the remedial measures taken are therefore difficult to precisely assess.

Conclusions

The nutrient dynamics for the entire GOF was observed to be shaped by the hydrographical pressure from the Northern Baltic Proper, and for the eastern GOF, also by the River Neva flow pattern. The resulting fluctuation in the temporal DIN and DIP trends frequently obscured the detection of clear temporal trends, even though the conclusions were made focusing not on the fluctuation but the baseline level. The generalizations for the time period since 1996 are presented in Table 4.

To upscale, P levels seem to have decreased in the eastern and northern GOF but increased in the southern GOF. Remembering the estuarine circulation and the current pattern of the GOF, the eastern and northern parts of the GOF are primarily subject to decreased anthropogenic load into the eastern GOF, while the southern part of the GOF is the first to experience more active hydrographic pressure from the Northern Gotland Basin.

There were several cases, however, where the latest two to four years of the study period had decreasing nutrient trends (Annex 2). There is no reason to suspect that the factors currently influencing heavily on the GOF's nutrient dynamics would lose their impact in the future, even though the climate change will reshape those. These factors are: i) the inflow of the Northern Gotland Basin deep water rich in nutrients and poor in oxygen, ii) the sediment DIP depositories subject to biochemical

Table 4. The visually observed trends / level changes for N, P, and Chl *a* as well as the time period when the changes have taken place. Red text: increase, green text: decrease. ECI = Estonian Coast In, ECO = Estonian Coast Out, FCE = Finnish Coast East, FCI = Finnish Coast In, FCO = Finnish Coast Out, LAKB = Luga and Koporye Bays, NB = Narva Bay, OE = Offshore East, OME = Offshore Middle EST, OMF = Offshore Middle FIN, OWE = Offshore West EST, OWF = Offshore West FIN, SWA = Shallow Water Area. * = data under evaluation.

	Nitrogen	**Phosphorus**	**Chlorophyll *a***
Estonian waters (ECI, ECO, NB)	ECI, ECO, NB: late 2000's – early 2010's*	ECI, ECO, NB: late 2000's – early 2010's	ECI: late 1990's – late 2000's
Finnish waters (FCE, FCO)	FCE: mid-1990's – mid-2000's	FCE: mid-2000's – early 2010's	FCE: mid-2000's – early 2010's
Russian waters (II+IIIa, LAKB, SWA)	II+IIIa: mid-2000's – late 2000's SWA: early 2000's – late 2000's SWA: late 2000's – early 2010's	SWA: early 2000's – early 2010's	II+IIIa: mid-2000's – early 2010's LAKB: turn of the millennium – mid-2000's SWA: early 2000's – early 2010's
Western offshore (OWE, OWF)	OWE: late 2000's – early 2010's* OWF: mid-1990's – mid-2000's	OWE: late 2000's – early 2010's	OWE: late 2000's – early 2010's OWF: mid-2000's – early 2010's
Middle offshore (OME, OMF)	OME: late 2000's – early 2010's* OMF: mid-1990's – late 2000's	OME: late 2000's – early 2010's	OME: the mid-1990's – mid-2000's OMF: mid-2000's – early 2010's
Eastern offshore (IIIb, OE)	OE: turn of the millennium – late 2000's OE: late 2000's – early 2010's IIIb: mid-2000's – late 2000's	No trend	IIIb: mid-2000's – early 2010's

processes leading to enhanced benthic DIP release under oxygen deprivation, and iii) the variations in the riverine inflow affecting the nutrient (especially N) balance, particularly in the eastern GOF. Even though the origin of the nutrient stocks laid on the bottom sediments is anthropogenic, the integrated impact of these factors may be called to represent natural DIP variation because the system's functioning is out of our control. Onto this background and disregarding the easternmost GOF, the data simply does not allow interpreting the instances of lately-decreasing nutrient values as starting phases of a lowered trophic level, which is perfectly plausible. A continued rigorous monitoring of the GOF will clarify this in the near future, especially taking into account that the main drop in P loading took place not until in the early 2012.

The Gulf of Finland – not an easy patient

The GOF, as the whole BS, has a tradition of showing resilience to trophic pressures that have been laid upon it (Gustafsson et al. 2012). For instance, a major deterioration of the ecosystem functioning, as a result of eutrophication, was noticed decades after the commencement of the elevated anthropogenic nutrient load. This process works in both ways; the ecosystem shows currently resilience to a gradually decreasing anthropogenic nutrient load. The nutrient load reductions in the GOF's catchment have not resulted in better water quality in such proportions as was initially anticipated, although positive signs have been observed. This resilience has traditionally been explained by the enhanced benthic nutrient release. This assessment brings about more understanding for the mechanisms behind this process; there is a complicated cascade of mechanisms that together produce the release. In fact, only part of the nutrient load that is tradionally considered to be introduced by this release originate from the sediments of the GOF, and the rest comes from the Gotland Basin. To know this is to realize that the trophic state of the GOF can be improved only to a limited extent with the actions taken solely in its catchment. So, the riparian countries should be active in all the fora where the targets and reductions of the nutrient load into the entire BS are discussed.

At first sight, it might be thought that there is little sense to monitor the environment if the products of the programme leave as much to speculate as in this case, especially bearing in mind the recent achievements in the abatement of the point-source load into the GOF from Russia. To better understand the dynamic nature of the GOF, co-operation in the trilateral monitoring activity should be continued and developed, and more efforts must be targeted to understand the processes affecting nutrients fluxes and their consequences.

Practical aspects

We were reminded by the crucial role of high-quality analytical performance as part of the monitoring programme. We observed discrepancies between Estonian and Finnish nutrient monitoring data (Fig. 9). The differences could partly be explained by variations in water masses and biological phases due to somewhat different timing in the winter sampling. However, especially for DIN values before 2010 the systematic differences between the Finnish and Estonian results from the practically same sampling stations were so pronounced that the analytical performance have most likely played a role here. This should be clarified. Most of the Estonian winter DIN values in 1998–2010 are exceptionally low compared with the general winter level of the GOF (HELCOM 2014a). Possible reasons to these low DIN values are under the evaluation by Estonian Marine Institute at the moment.

The integrated monitoring within the GOF area can provide the scientific community with rugged tools for its work. This does not come true if we do not know

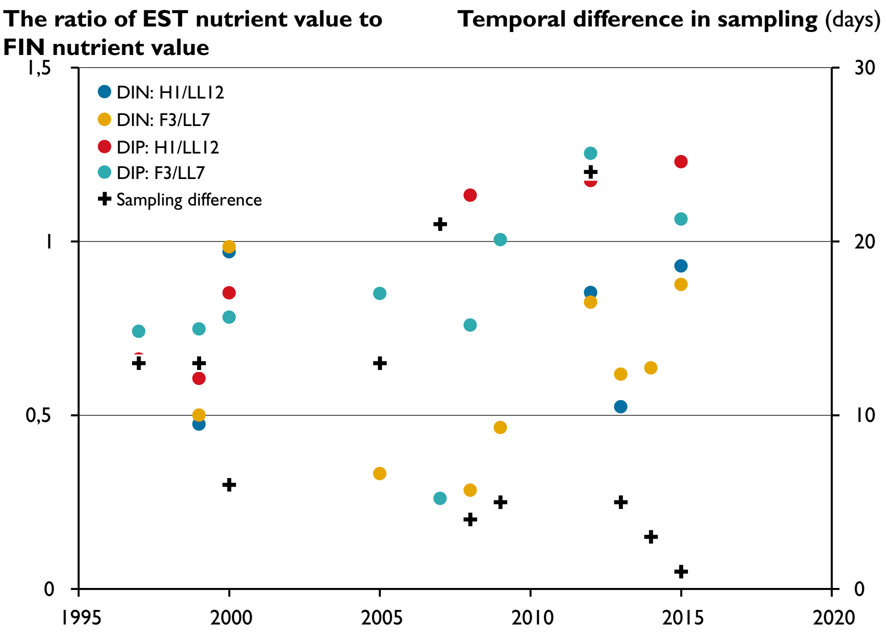


Figure 9. A ratio of Estonian DIN/DIP to Finnish DIN/DIP as a function of time. The stations F3 and H1 are included in the Estonian monitoring program, and LL12 and LL7/LL7S in the Finnish one. In OW, the stations H1 and LL12 are less than two nautical miles apart. In OM, the stations F3 and LL7/LL7S (here just LL7) are less than one nautical mile apart. Reaching unity means that the countries ended up having a similar estimate of the nutrient condition. Only those years were included when the temporal difference between the national samplings was less than a month. For those two years when the temporal difference was > 20 days, the samplings were carried out in the period of the mid-Jan to the mid-Feb. In 2007, the Estonian sampling was carried out later, and in 2012, it was carried out earlier.

precisely what we are measuring. The countries are advised to monitor exactly the same parameters that are sampled and analyzed in the same way with instruments the validation and calibration of which are done in a widely acknowledged manner. No certificate of accreditation can ensure this alone. We recommend the continuation of mutual analytical ring-tests and inter-calibrations to sustain the laboratories' performance in a high level regarding N and P. The baseline for all quality-related aspects in the GOF monitoring is provided by HELCOM (2008, 2016). Further, the countries need to come up with guidelines for sample filtration as part of the DIP and TOTP analytics, and how to measure surface layer Chl *a*. At the moment, there is a variety of Chl *a* approaches: a single sample at 0 m, a series of discrete samples in the upper 10 m, a composite sample stretching from surface to 4 to 10 m, and a composite sample stretching from surface to three times Secchi-depth (see section Chlorophyll *a* and phytoplankton blooms).

ANNEX 1.

The stations in the GOF: N (DIN, 0–10 m, December–March), P (DIP, 0–10 m, December–March), and Chl *a* (0–10 m, June–September) content of the water for the entire study period and for the recent past. The DIN and DIP were calculated to represent the wintertime, not a calendar year. For instance, all the observations from December 1999 to March 2000 form the representative value for the winter 1999–2000, and are presented as the value for the year 2000. Chl *a* values are summertime values and this does not concern those. Exceptions: i) OE and SWA: N as TOTN (0–10 m, June–August), and P as TOTP (0–10 m, June–August), ii) II+IIIa and IIIb: N as DIN (near-bottom, June–August), and P as DIP (filtrated, near-bottom, June–August). Depending on a station, Chl *a* was collected i) as a single sample at 0 m, ii) as a series of discrete samples in the upper 10 m, iii) as a composite sample stretching from surface to 4 to 10 m, or iiii) as a composite sample stretching from surface to three times the Secchi-depth. II+IIIa and IIIb: regional averages are based on visual interpretation of the annual representative figures in the report provided by Tatjana Eremina, Alexandra Ershova, and Evgenia Lange, and the stations listed here cover the Chl *a* condition only in 2014. 39A is not part of the GOF2014 dataset, but used here nonetheless. Obs = number of observations. ** TOTN results not included. Source: GOF2014 dataset, trilateral data 2014–2015, SYKE Marine Research Centre, Russian State Hydrometeorological University.

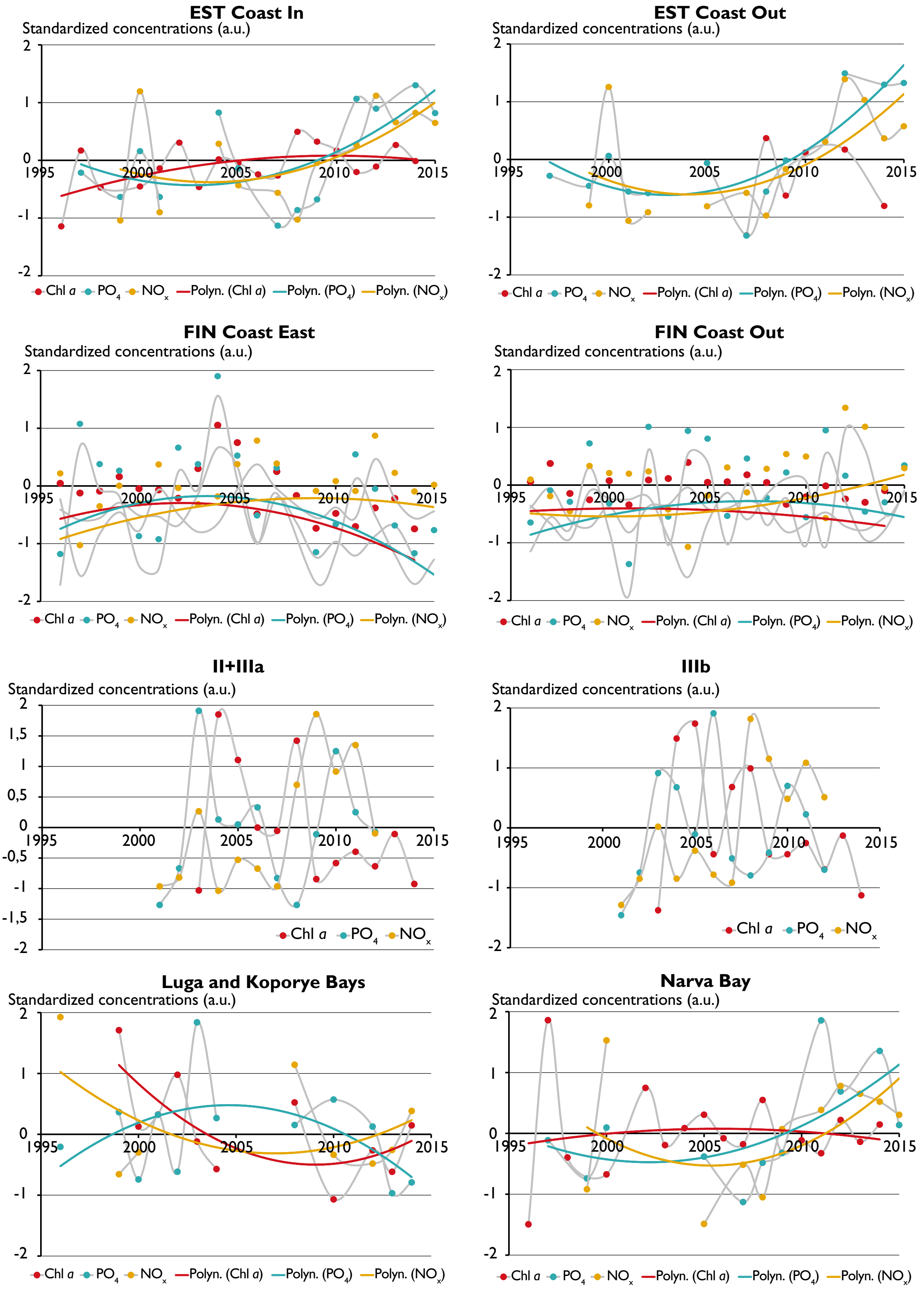
Region / Station	Depth (m)	Surface salinity (g/kg)	**Obs Chl *a***	Mean Chl *a* (µg/l)	**Mean Chl *a* 2013–2014**	**Obs DIN**	Mean DIN (µmol/l)	**Mean DIN 2014–2015**	**Obs DIP**	Mean DIP (µmol/l)	**Mean DIP 2014–2015**
EST Coast In			**339**	**4.4**	**4.9**	**217**	**6.1**	**8.1**	**214**	**0.71**	**1.05**
2	44	5.9	112	4.2	4.5	41	5.8	8.5	44	0.77	1.05
3	40	5.5	58	4.0	4.3	36	5.3	7.8	36	0.82	1.11
PE	21	6.0	19	4.1	3.7	30	5.6	7.4	27	0.60	0.92
18A	46	5.3	10	4.8		33	5.3	6.5	33	0.80	1.24
23A	25	6.1	17	3.1		20	6.3		20	0.51	
57A	10	5.9	104	5.3	6.5	27	8.3	10.7	27	0.77	1.03
PW	24	5.9	19	3.9	5.1	30	6.5	6.7	27	0.55	0.93
EST Coast Out			**38**	**4.2**	**3.0**	**126**	**5.2**	**6.3**	**118**	**0.69**	**1.09**
17	102	5.3	12	4.3	2.6	42	5.4	6.5	39	0.77	1.22
18	96	5.1	12	4.2	3.6	33	5.5	6.9	31	0.70	1.17
19	85	5.9	7	4.4	3.1	30	4.9	6.2	30	0.63	1.01
23	90	6.3	7	3.7	2.9	21	4.7	5.6	18	0.59	0.90
FIN Coast East			**400**	**6.2**	**4.8**	**189**	**12.5**	**10.9**	**189**	**1.13**	**0.92**
KYVY-11	65	4.2	200	5.5	4.2	61	10.2	10.8	61	1.11	0.91
KYVY-8A	48	3.7	200	7.0	5.6	128	13.6	11.2	128	1.14	0.94
FIN Coast Out			**639**	**5.4**	**4.7**	**390**	**8.8**	**8.3**	**395**	**0.90**	**0.87**
39A	42	5.2				46	9.7	9.6	49	0.90	0.92
KYVY-1	28	3.5	175	6.3	6.5	76	13.1		76	0.89	
UUS-10A	53	5.3	268	5.7	6.2	109	8.5	7.9	109	1.04	0.87
UUS-23	60	5.9	196	4.3	3.0	159	6.7	7.1	161	0.83	0.81

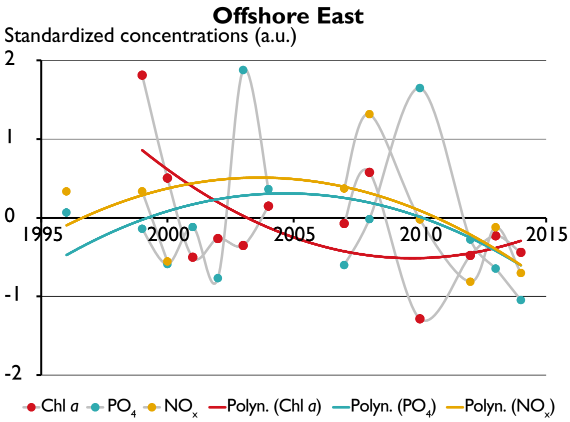
Region / Station	**Depth** (m)	**Surface salinity** (g/kg)	**Obs Chl *a***	**Mean Chl *a*** (µg/l)	**Mean Chl *a* 2013–2014**	**Obs DIN**	**Mean DIN** (µmol/l)	**Mean DIN 2014–2015**	**Obs DIP**	**Mean DIP** (µmol/l)	**Mean DIP 2014–2015**
II+IIIa			**12**	**5.8**	**3.9**	**12**	**6.2**		**12**	**1.67**	
2F	22		11	9.9							
3F	24		10	10.4							
4F	29		10	7.5							
6F	37		10	5.2							
7F	26		5	5.7							
8F	30		7	4.6							
10F	37		6	3.6							
11F	40		4	6.4							
12F	38		5	4							
1K	20		6	3.5							
1F5	27		8	9							
5F5	23		6	3.9							
6F5	15		4	3.3							
2FG	30		6	7.2							
2UGMS	37		8	2.8							
IIIb			**12**	**3.2**	**2.2**	**12**	**7.0**		**12**	**2.63**	
17F	50		10	3.1							
20F	49		8	2.6							
25F	37		5	2.6							
34F	49		6	2.6							
36F	59		7	2.7							
7F5	33		4	3							
9F5	50		7	2.2							
1L	28		9	5.1							
4UGMS	59		10	3.2							
Luga and Koporye Bays			**63**	**4.5**	**3.4**	**54**	**33.0**	**35.0**	**74**	**0.50**	**0.33**
3K	13	3.1	16	4.2	4.3	14	37.8	45.7	19	0.66	0.57
6K	26	3.0	16	4.8	3.5	12	33.2	29.3	17	0.46	0.21
6L	28	3.5	15	5.3	2.9	14	28.8	30.0	19	0.39	0.22
18L	10	3.0	16	3.9	2.9	14	32.4	32.3	19	0.51	0.26
Narva Bay			**283**	**5.1**	**4.9**	**177**	**6.8**	**7.9**	**180**	**0.86**	**1.08**
15	25	4.6	5	3.5		33	6.0	7.3	33	0.78	1.07
38	8	4.4	84	5.4	4.8	25	7.4	8.6	26	0.91	1.09
12C	13	4.6	54	4.4	3.8	35	6.4	8.2	38	0.87	1.09
G	8	4.9	5	3.1		22	7.4	8.2	23	0.88	1.14
N12	38	4.5	45	4.5	6.3	33	6.1	6.9	31	0.84	1.06
N8	13	3.2	90	5.9	5.3	29	7.9	8.4	29	0.89	1.04
Offshore East			**65**	**4.3**	**3.3**	**106**	**31.5**	**26.1**	**146**	**0.56**	**0.20**
2	37	3.0	17	5.5	3.9	30	34.3	28.4	40	0.59	0.14
3	48	3.6	15	4.2	3.1	26	30.0	25.9	36	0.55	0.23
4	61	4.2	16	2.4	2.6	25	30.1	26.2	35	0.55	0.20

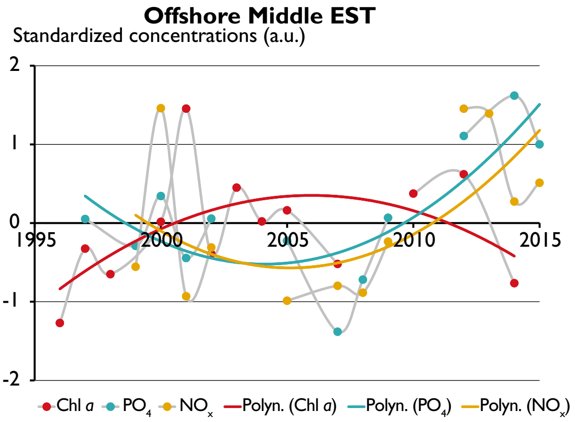
Region / Station	**Depth** (m)	**Surface salinity** (g/kg)	**Obs Chl *a***	**Mean Chl *a*** (µg/l)	**Mean Chl *a* 2013–2014**	**Obs DIN**	**Mean DIN** (µmol/l)	**Mean DIN 2014–2015**	**Obs DIP**	**Mean DIP** (µmol/l)	**Mean DIP 2014–2015**
A	30	3.4	17	5.0	3.5	25	31.3	24.1	35	0.55	0.25
Offshore Middle EST			**66**	**3.9**	**2.9**	**111**	**5.5**	**6.5**	**104**	**0.78**	**1.17**
14	75	5.1	7	3.6	2.9	39	5.5	6.2	37	0.79	1.16
F1	75	4.9	9	3.4	2.8	33	6.1	6.7	30	0.79	1.14
F3	80	5.4	50	4.0	3.0	39	4.9	6.6	37	0.76	1.20
Offshore Middle FIN			**173**	**4.7**	**3.8**	**186**	**8.8**	**8.8**	**203**	**0.90**	**0.93**
LL3A	68	4.8	81	5.0	4.3	54	10.0	9.4	60	0.94	0.92
LL5	70	5.2	13	4.2	3.1	50	8.7	8.2	55	0.91	0.92
LL7/LL7S	100/77	5.3	79	4.6	3.7	82	8.2	8.9	88	0.86	0.95
Offshore West EST			**11**	**3.4**	**3.7**	**21**	**4.4**	**5.2**	**21**	**0.59**	**0.87**
H1	80	6.2	11	3.4	3.7	21	4.4	5.2	21	0.59	0.87
Offshore West FIN			**109**	**4.3**	**3.3**	**122**	**7.2**	**6.4**	**134**	**0.69**	**0.74**
LL12	82	6.2	74	4.3	2.7	61	6.6	6.2	67	0.60	0.64
LL9	69	5.7	35	4.4	3.9	61	7.8	6.6	67	0.77	0.83
Shallow water area			**115**	**8.1**	**4.5**	**129**	**35.4**	**32.6**	**174**	**0.46**	**0.15**
1	29	2.0	16	5.2	2.9	16	33.6	28.4	21	0.47	0.14
19	10	0.5	17	10.4	6.3	22	34.8	34.8	30	0.48	0.20
20	12	0.9	16	8.7	4.3	14	36.4	37.1	19	0.50	0.19
21	14	1.0	17	9.8	3.0	22	34.6	32.8	31	0.43	0.11
22	10 to 20	1.3	16	7.2	5.6	16	34.8	26.6	21	0.49	0.15
24	21	1.5	17	6.6	4.0	17	35.7	34.6	22	0.40	0.14
26	7	0.6	16	8.8	5.1	22	38.0	36.0	30	0.45	0.17
TOTAL			**2325**	**5.3**	**4.3**	**1852**	**7.9****	**7.8****	**1976**	**0.80**	**0.79**

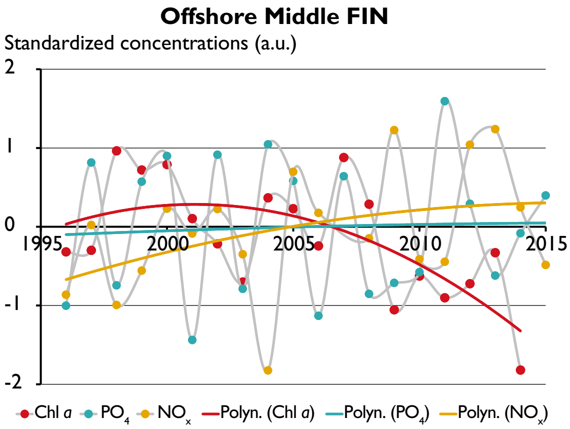
ANNEX 2.

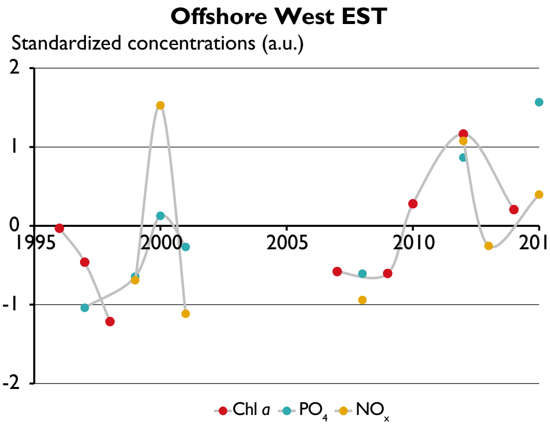
The standardized DIN (= NO_x = NO_2-N + NO_3-N), DIP (= PO4-P), and Chl *a* for the regions as a function of time. For the spatiotemporal definition of the parameters, and exceptions used to assess Russian waters, see Annex 1 caption. Source: GOF2014 dataset, Russian State Hydrometeorological University.

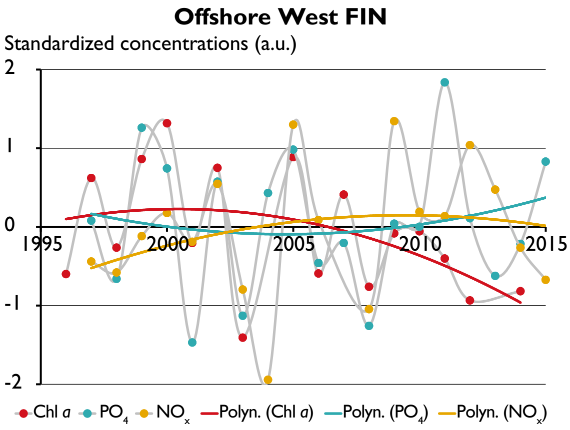


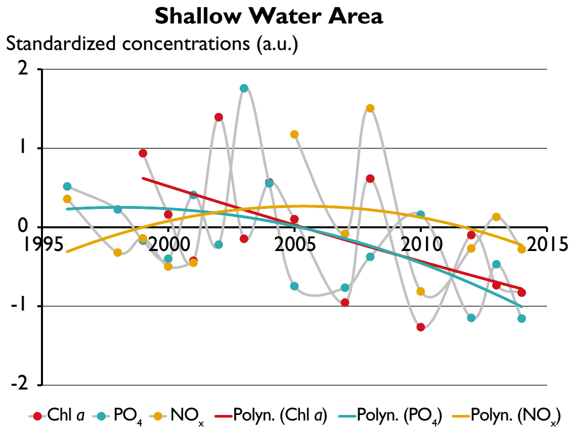

Offshore East
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x
Polyn. (Chl *a*)
Polyn. (PO_4)
Polyn. (NO_x)


Offshore Middle EST
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x
Polyn. (Chl *a*)
Polyn. (PO_4)
Polyn. (NO_x)


Offshore Middle FIN
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x
Polyn. (Chl *a*)
Polyn. (PO_4)
Polyn. (NO_x)


Offshore West EST
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x


Offshore West FIN
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x
Polyn. (Chl *a*)
Polyn. (PO_4)
Polyn. (NO_x)


Shallow Water Area
Standardized concentrations (a.u.)
2
1
0
-1
-2
1995
2000
2005
2010
2015
Chl *a*
PO_4
NO_x
Polyn. (Chl *a*)
Polyn. (PO_4)
Polyn. (NO_x)

Chlorophyll *a* and phytoplankton blooms

Pirkko Kauppila[1)], Tatjana Eremina[2)], Alexandra Ershova[2)], Alexey Maximov[3)] Inga Lips[4)], Urmas Lips[4)], Hanna Alasalmi[1)], Saku Anttila[1)], Jenni Attila[1)], Jan-Erik Bruun[1)], Seppo Kaitala[1)], Kari Kallio[1)], Vesa Keto[1)], Harri Kuosa[1)], Heikki Pitkänen[1)], Evgenia Lange[2)]

1) *Finnish Environment Institute*
2) *Russian State Hydrometeorological University*
3) *Zoological Institute, Russian Academy of Sciences*
4) *Marine Systems Institute, Tallinn University of Technology*

Eutrophication is a major problem in the GOF, manifesting itself, e.g., as elevated phytoplankton biomasses and intensified phytoplankton blooms (e.g., Kahru et al. 2007). Phytoplankton chlorophyll *a* (Chl *a*), a proxy for phytoplankton biomass, is included in the core indicator list of HELCOM and is applied in the environmental assessments of the BS (HELCOM 2009, 2013c, 2014a). Also, the EU Member States are using Chl *a* in the ecological classification of the WFD.

Summertime Chl *a* concentration increased in the GOF in the 1990's and the early 2000's mainly due to strengthened stratification, declined oxygen conditions, and an accelerated benthic nutrient release (Pitkänen et al. 2003). Also, the cyanobacterial accumulations – whose intensity is largely controlled by the excess P after the spring bloom period and summertime upwelling events (Kanoshina et al. 2003, Lips and Lips 2008, Raateoja et al. 2011) – have intensified since the late 1990's (Kahru et al. 2007). In addition to the HELCOM's periodic eutrophication assessments (e.g., HELCOM 2010, 2014a), it is important to make analyses that take into account the sub-regional point of view. This approach is employed here to assess the basin-wide eutrophication status of the GOF and recent changes in it based on Chl *a*.

Here, we present the past changes in the eutrophication of the GOF regarding summertime (June–September) Chl *a* and phytoplankton surface accumulations. Variations

Cyanobacterial blooms can at times invade the sea; M/S Finnmaid on her route Helsinki – Travemünde in 2005. Photo: Finnlines.

in these factors accompany the changes in nutrient concentrations and their ratios; the remineralized nutrient pool affects the summertime Chl *a*, and the excess P pool affects the extent of the cyanobacterial blooms. We averaged a series of discrete Chl *a* samples in the upper 10 m or used the results of composite samples (1–10 m) to follow the principles used for the assessments of HELCOM and EU WFD (EU 2000).

Spatial approach

The regional division used for nutrients – and described in the section Nutrients in the water – was also used here.

The long-term mean Chl *a* concentration in the offshore area ranged between 3 and 5 µg/l, and has lately decreased somewhat (Annex 1 in the section Nutrients in the water). Concentrations higher than this were observed in the northern coastal area (FCE, FCO) and in the easternmost GOF (II+IIIa, SWA). Chl *a* concentration has decreased in all of these regions in the recent past as well. In the innermost bays, the Chl *a* concentrations of 8 to 10 µg/l seem not to be uncommon. The coastal areas having an elevated Chl *a* level are most directly exposed to the anthropogenic nutrient load, which explains observed high values. Considerably higher concentrations would have been met in the inner Finnish coastal area. However, being an exception topographically in the GOF scale, the area was not included in any closer examination.

The remote sensing (RS) based interpretation of Chl *a* provided with a view of Chl *a* in the GOF with a better spatial and temporal resolution than did the view based on water

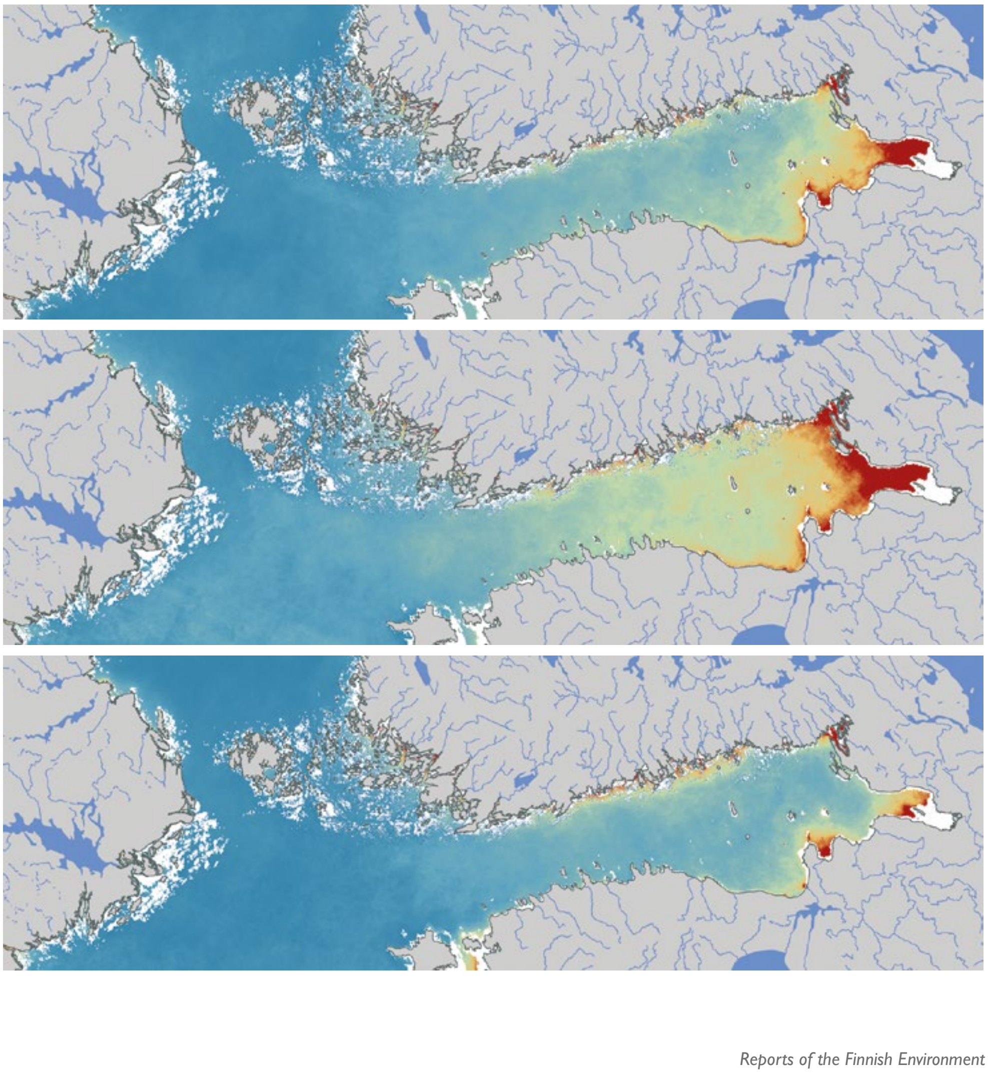


Figure 10. Geometric means of Chl *a* (ChlGM, µg/l) in the GOF in July–August in 2006 (above), 2007 (middle), and 2011 (below). For the RS data, ChlGM was used due to log-normal distribution of Chl *a* observations (Attila et al. manuscript). Source: ENVISAT / MERIS. Image processing: SYKE.

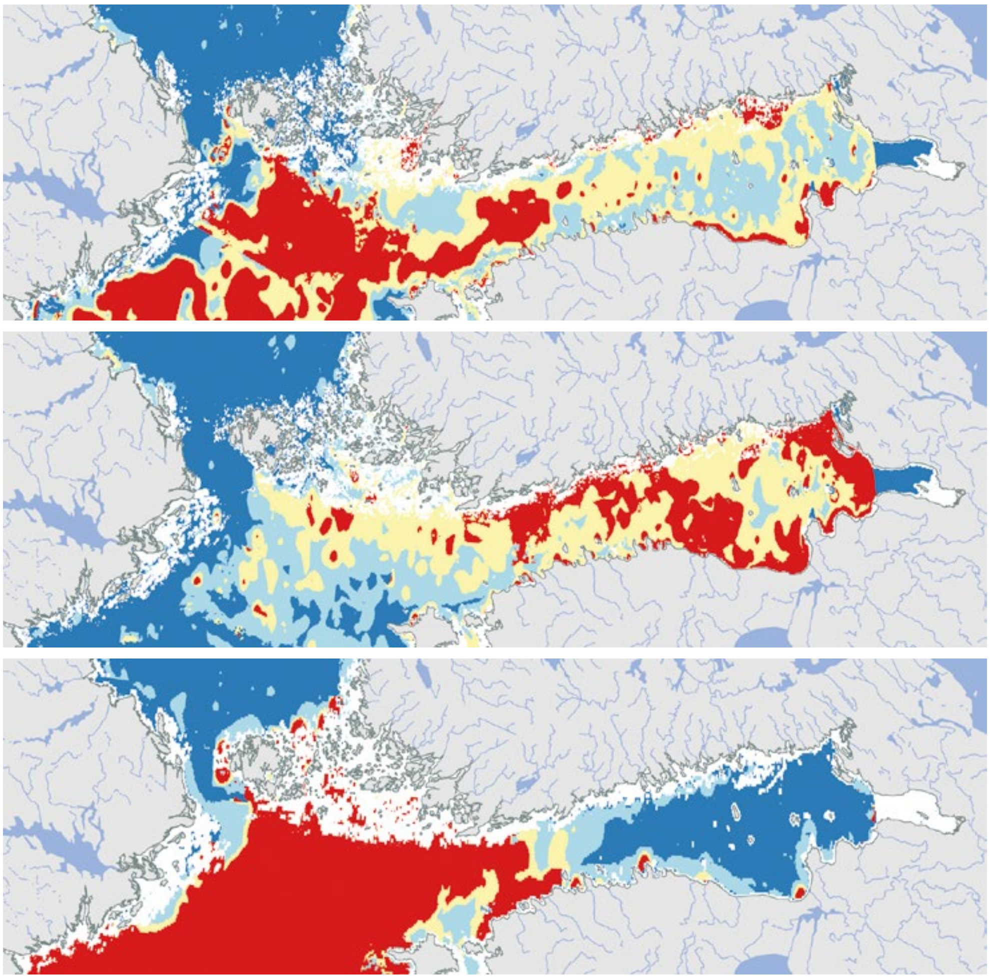


Figure 11. Cyanobacterial surface accumulations in the GOF in July – August in 2005 (above), 2007 (middle), and 2014 (below). Source: ENVISAT / MERIS and AQUA / MODIS. Image processing: SYKE.

samples. Apart from the tip of the GOF where ChlGM was on a high level irrespective of the year, the inter-annual variation in ChlGM was pronounced (Fig. 10). In some years, especially in 2004 and 2007, but also in the other years in the period 2004–2008, ChlGM was on a clearly elevated level in the whole GOF.

The extent and intensity of phytoplankton surface accumulations in the GOF in 2008–2014 varied considerably, too (Fig. 11). The situation was exceptionally good for example in 2010 when surface accumulations were observed only in relatively restricted coastal areas. In turn, extensive surface accumulations were observed in the whole GOF in 2004, 2005, 2007, and 2008. In 2014, the exceptionally strong blooms were concentrated in the westernmost part of the GOF and the Northern Gotland Basin, but practically no blooms were recorded in the middle and the eastern GOF.

Distribution in time

Summertime Chl *a* fluctuations followed to some extent those of DIP. However, the Chl *a* pattern does not have a direct causal relation to the pattern of the wintertime DIP (or DIN), because those nutrient inventories do not directly control the summertime phytoplankton biomasses. The spring bloom period typically exhausts DIN – and most of the DIP – from the surface layer, leaving the remaining DIP to fuel the growth of the N-fixing cyanobacteria (Janssen et al. 2004, Raateoja et al. 2011).

In OM and OW, Chl *a* fluctuated in two to four years intervals excluding the peak phase from the late 1990's to the early 2000's (see Annex 2 in section Nutrients in the water). Since then, Chl *a* has had a predominant decreasing trend. The fluctuation has still been there,

Two approaches to assess Chl *a*

Two approaches were applied to assess Chl *a* in the GOF: interpretation of the RS data and laboratory analyses of water samples (WS). These approaches differ in many ways:

- While the WS approach relies on individual water samples collected at certain stations at certain time of the year, the RS approach typically amounts up to several million individual pixels within the annual assessment period
- Measurement times and the locations of sites are seldom absolutely the same
- The RS approach has its information from the upper two to three meters of the water column, and does not represent the sunlit water layer. During intensive cyanobacteria blooms, it represents even thinner surface water layer

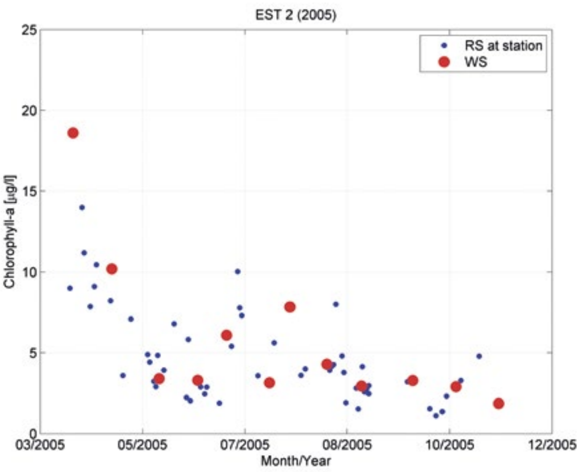


Figure 12.
The RS-based and WS-based Chl *a* (µg/l) as a function of time at station 2 in Estonian coastal waters in 2005. Source: GOF2014 dataset (WS), SYKE (RS).

Despite the demand for consistency, we did not expect the RS and the WS approaches to yield identical outcomes. The overall correspondence between the approaches was nonetheless good (Fig. 12).

The RS data may also be applied as a common metric for evaluating the comparability of Chl *a* results originating from different monitoring programs. A station pair in the eastern GOF – KYVY-11 (FIN) and 3 (RUS) – served as an example. The general patterns of the RS-based Chl *a* were quite similar at the stations, which was expected as the stations are located relatively close to each other (Fig. 13). However, when the WS-based Chl *a* was related to the RS-based Chl *a*, the WS-based Chl *a* was clearly lower at 3 than at KYVY-11. The surface water layer of two times Secchi depth is assumed to correspond to the euphotic layer. In Russia, Chl *a* is sampled in the water layer corresponding three times the Secchi depth (in practice extending to a depth of 10 m), while in the Finnish coastal waters Chl *a* is measured from a composite sample corresponding two times the Secchi depth (generally < 10 m). Chl *a* results were not completely comparable, because the countries estimated the Chl *a* either in the sunlit layer or also partly beneath from it. Primary production does also occur beyond the euphotic layer due to vertical mixing of water, but still, Chl *a* concentration is usually lower beyond the euphotic depth.

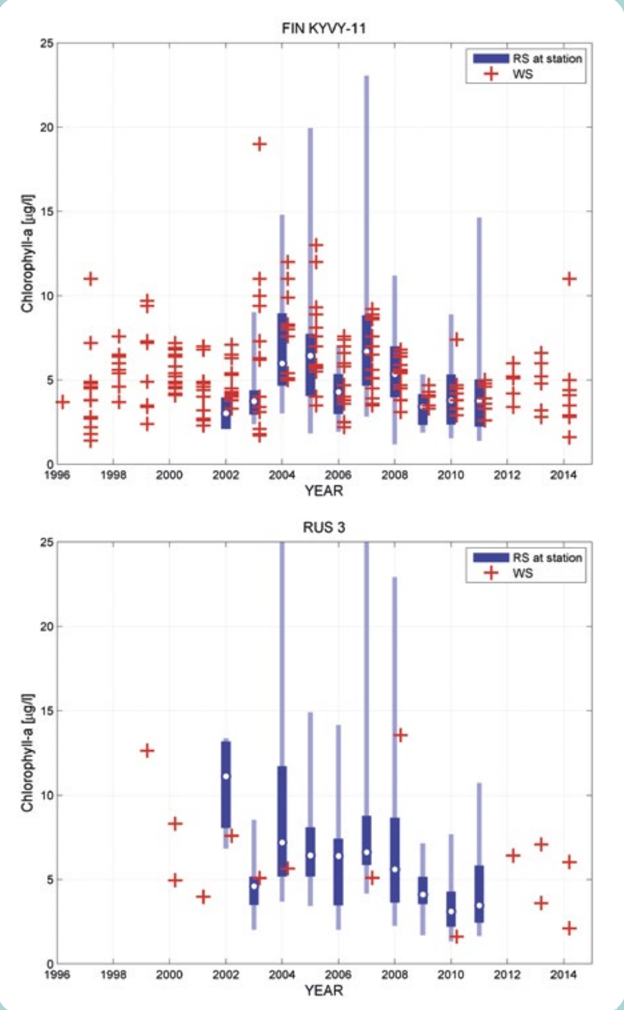


Figure 13.
The RS-based and WS-based Chl *a* (µg/l) at KYVY-11 (above) and at 3 (below) as a function of time in June–September in 1996/1998–2014. As for the RS data, the variation of Chl *a* was presented using boxplots, where the extremes of the thinner parts of the pillar describe the 5th and 95th percentiles and the box marks the of 25th and 75th percentiles. The white dots represent the geometric mean value (ChlGM) during the assessment period. As for the WS data, the results of Chl *a* are indicated by red crosses. Source: GOF2014 dataset (WS) and SYKE (RS).

however. The differences between the Estonian and Finnish monitoring data has been dealt with in the section Nutrients in the water.

In FCO and FCE, Chl *a* fluctuated with intervals partly similar to those observed in OM and OW. Superimposed to this fluctuation, there was a Chl *a* peak there, too. It occurred later than in the offshore area, that is, in the mid-2000's. Since then, Chl *a* has decreased in these regions, likewise on their neighboring offshore areas. The decrease in Chl *a* has been more pronounced in FCE than in FCO.

Chl *a* showed no clear trend in ECO and NB, but a faint increase was there in ECI from the late 1990's – to the late 2000's. Pronounced fluctuation, typical to NB in the late 1990's, levelled out in the 2000's.

In OE and IIIb, the fluctuation was at times pronounced with more stable periods in between. A decreasing trend occurred since the mid-2000's. In the Russian coastal waters (SWA, II+IIIa, LAKB), Chl *a* fluctuated partly with similar intervals as it did in the offshore area. However, the decreasing trend of Chl *a* was observed in all of those regions since the early 2000's.

To generalize, Chl *a* has decreased somewhat in the offshore waters and clearer in the Finnish coastal waters and the eastern GOF, while no trend was observed in the Estonian waters. In some years, such as in 2004, the fluctuation of Chl *a* was basin-wide, similar to DIP. The Chl *a* trends could not be related to the trends of the wintertime DIN, as expected. Nevertheless, the observed decrease in Chl *a* was probably connected with the simultaneous decreases in wintertime DIP taken place in the Finnish coastal waters and in SWA.

Environmental targets

The EU WFD (EU 2000) aims to maintain surface waters at least in the good environmental status (GES), or restore them where necessary to that level by 2015. The EU MSFD (EU 2008) integrates all pressures and impacts with the purpose of achieving the GES by 2021. In the open GOF, the Chl *a* targets are based on the criteria determined by HELCOM (EU 2010, HELCOM 2013a), whereas in the Estonian and Finnish coastal waters, the criteria have been established nationally to comply with the WFD requirements (Lips 2004, Aroviita et al. 2012). We used data from June–September for all sub-regions and assessed Chl *a* for six-year periods since 1996 (Fig. 14).

Regarding the open GOF, the Chl *a* target (2 µg/l) has not been achieved (Annex 1 in the section Nutrients in the water). In the OW and OM, the level of Chl *a* has decreased since 1996, but the periodic average values of 3.8 and 4.0 µg/l for 2008–2014 were still clearly elevated compared with the target value. However, considering long-term trends, the individual summertime values of Chl *a* could occasionally be below the target at LL12 in OW.

As for Estonia, ECI and NB correspond with the national coastal WFD types, whereas ECO represents offshore waters. In NB and ECI, the periodic average values of Chl *a* have increased since the late 1990's reaching the levels of 5.1 and 4.8 µg/l, respectively. In ECO, the average Chl *a* of 3.8 µg/l in 2008–2014 was also elevated, although in some summers Chl *a* appeared to be below the target. Thus, the targets (2.7, 3.7, and 2.0 µg/l, respectively) have not been achieved in any of the Estonian sub-regions.

In FCO and FCE, the recent levels of Chl *a*, 4.9 and 4.6 µg/l, are elevated compared to the targets of 2.3 µg/l and 2.5 µg/l, respectively. At KYVY-11 in FCE, the periodic average Chl *a* has dropped from 5.6 µg/l in 1996–2001 to 4.6 µg/l in 2009–2014, but the summertime values of Chl *a* revealed large variation.

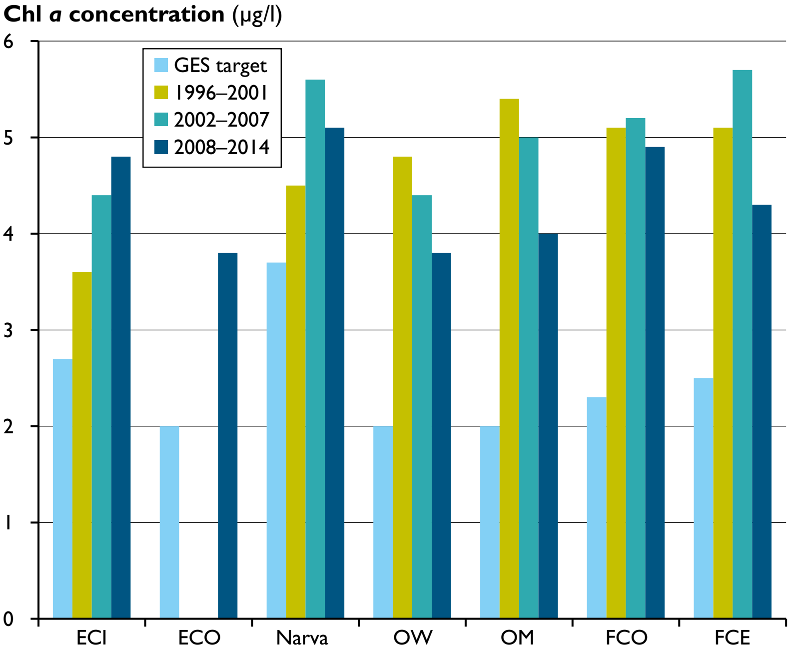


Figure 14. Chl *a* (µg/l) as a function of time, and EU WFD and EU MSFD GES target values in various regions. Source: GOF2014 dataset.

Phytoplankton bloom indices

Few indicators describe phytoplankton blooms properly. Spatiotemporally comprehensive RS data and high-frequency ship-of-opportunity (SOOP) data enable the development of proper indicators. One of those is the Spring Bloom Index, which is built on Chl *a*, and based on RS and SOOP (Fleming and Kaitala 2006). Additionally, a multi-metric RS-based index is on its way to integrate information of the intensity and spatio-temporal occurrence of the cyanobacterial blooms (Anttila et al. manuscript).

The Spring Bloom Index estimates the total biomass of phytoplankton by integrating the time series data on Chl *a* based on the duration, strength, and the timing of the peak of the spring bloom period (Fleming and Kaitala 2006, Platt and Sathyendranath 2008, Verliin et al. 2014). The results of the index, produced by using both SOOP data and RS data, were consistent with each other and revealed large inter-annual variation. Based on the index, springtime eutrophication status in the western GOF has not changed significantly in 1992–2014 (Fig. 15).

Cyanobacteria are mainly responsible for the summertime phytoplankton peaks in the GOF. The Cyanobacterial Surface Accumulation (CSA) index, based on RS data, describes probabilities for cyanobacteria to form surface accumulations (Anttila et al. manuscript). The method integrates information about the length of phytoplankton surface accumulation period and the bloom intensity into a seasonal index value. The value responds negatively to increasing eutrophication, i.e., low values indicate increased eutrophication and vice versa. Target conditions are derived using independent RS-based time series on phytoplankton surface accumulations in the BS following the approach presented by Kahru and Elmgren (2014). Based on the index, the target has not been met in the offshore GOF and the summertime algal situation in the 2000's seemed to be especially bad in 2004 and 2007 (Fig. 16). The latter is also evident considering the maps of phytoplankton blooms.

M/S Finnmaid belongs to the SOOP-fleet of the BS. Photo: Finnlines.

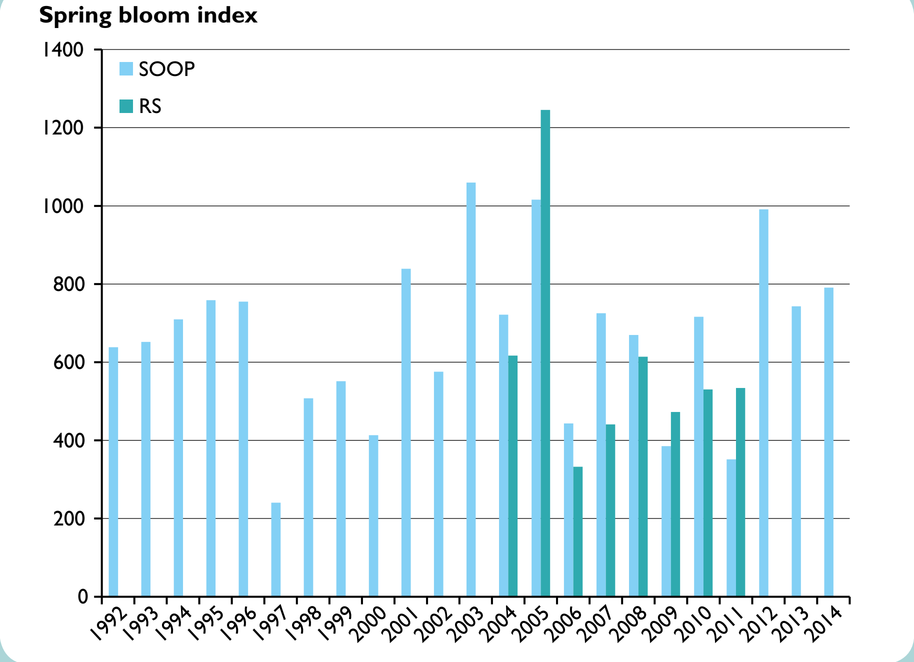


Figure 15. The Spring Bloom Index (a.u.) as a function of time defined for the western and middle offshore GOF using both Alg@line SOOP data collected on board Silja Serenade cruising on-route Helsinki–Stockholm in 1992–2014 and RS data in 2004–2011.

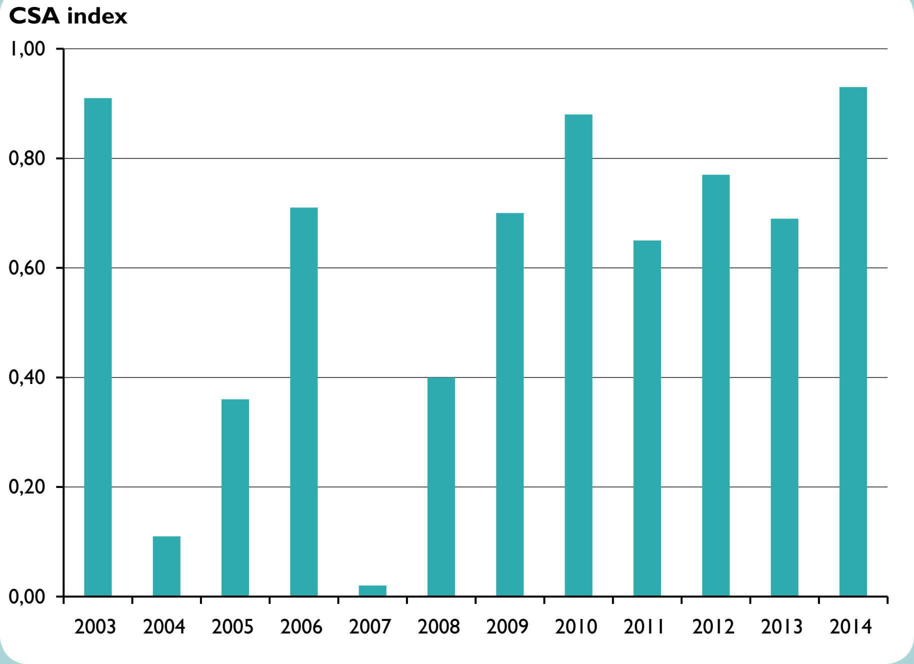


Figure 16. The CSA-index as a function of time determined for the offshore GOF.

Patterns and their reasoning

In many parts of the GOF, the increase in Chl *a* concentration observed in the late 1990's and the early 2000's turned to a decrease after the mid-2000's. The decrease in Chl *a* in the water after the mid-2000's coincided with the average decrease in the water's P storage since 2004. Variations in the deep water storage of P in the GOF is controlled by inputs originating from the Northern Gotland Basin together with local benthic inputs, which, in turn, are reflected in strong variations in the wintertime inorganic P in surface water (see section Processes controlling P storages).

These deep water P storages are mixed throughout the water column during the autumn and winter, and thus, fuel the primary production of the following summer. For example at KYVY-11 in the easternmost Finnish waters, the excess P in surface water layer in the winter is clearly related to the variation in DIP near the bottom during the previous summer (Fig. 17). This excess P, or at least the part that remains in the water after the spring bloom, will be available for the summertime algal growth.

In the easternmost GOF, the reduction of anthropogenic P loading, together with the decreased deep water storage of P after the mid-2000's, is a notable cause behind the observed decreasing trend of Chl *a*. Especially in SWA, the average decrease of Chl *a* in recent years is most probably related to the improvements in the waste water treatment of St. Petersburg since 2005. Both reduction in the anthropogenic P loading and reduced sediment release tend to increase the ambient DIN/DIP ratio, and thus, makes the room smaller for the cyanobacteria to form mass occurrences. Coastal monitoring results from the Finnish intensive stations suggest clear decreases in phytoplankton biomass after the mid-2000's, which have been largely due to decline in cyanobacterial abundances (Lehtinen et al. 2015).

According to Maximov et al. (2014, 2015), *Marenzelleria*-induced changes in nutrient cycling contributed to the increase in the DIN/DIP ratio, thus mitigating the surface accumulations of nitrogen-fixing cyanobacteria as well. Intense dredging works in the Neva Bay in 2006–2007 (Marine Facade construction) and in 2014–15 (Bronka harbor construction) have probably played a local role for decreasing Chl *a* level in those years through increased turbidity, but could not extensively affect the long-term trends.

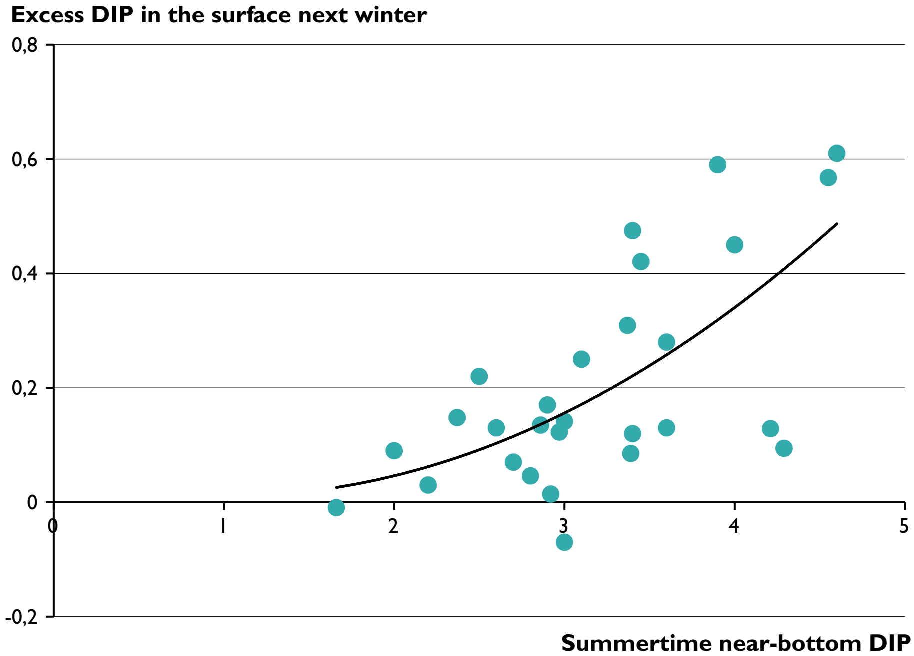


Figure 17. The excess DIP (µmol/l) in the surface layer in the winter as a function of the near-bottom DIP (µmol/l) in the previous summer at KYVY-11. Source: SYKE database.

The dichotomy in Chl *a* trends – an increase followed by a decrease – did not concern Estonian coastal waters where Chl *a* fluctuations have levelled out since the mid-1990's without any trend. The peak in 1997 coincided with the basin-wide and prolonged phytoplankton surface accumulations in the GOF (Rantajärvi 1998). This phenomenon was related to an accelerated benthic P release during the extensive oxygen deficit in the summer of 1996, which boosted the accumulations next summer (Pitkänen et al. 2003). In the late 1990's, the strong fluctuation in Chl *a* most probably masked a slightly increasing trend.

In 1996–2014, the summertime Chl *a* and phytoplankton surface accumulations revealed strong spatiotemporal variability. The hydrodynamical pressure from the Northern Gotland Basin reflected in temporal fluctuations of Chl *a* level via fluctuations in the nutrient pools. The fluctuations are a manifestation of the episodic internal processes related to this pressure; benthic release of nutrients, and deep-water influx of nutrients from the Northern Gotland Basin (e.g., Lehtoranta 2003, Pitkänen et al. 2003). Regardless of the pronounced variation, the results of the summertime Chl *a* and phytoplankton surface accumulations were largely consistent with each other; the extensive bloom events followed the peaks in the summertime Chl *a*.

Conclusions

In many parts of the GOF, Chl *a* concentration increased in the late 1990's and the early 2000's mainly due to strengthening of salinity stratification (Kahru et al. 2000, Pitkänen et al. 2003) and the resulting enhanced benthic release of P. This development levelled out in the early 2000's and turned to a decrease. Especially in offshore waters (OW, OM) and the Finnish coastal waters (FCE), the decrease could be connected to a decrease in the deep water P storages. In the eastern GOF, and especially in SWA, reductions in the land-based P loading, too, have led to decreases in Chl *a* concentration. The overall decrease in Chl *a* level has not so far been marked enough for reaching the target for GES in any parts of the GOF. The observed changes are generalized in the conclusion of the section Nutrients in the water.

Considering the wealth of the Chl *a* data, we conclude that its spatiotemporal coverage was relatively good if all the data sources used for this report, namely conventional water quality monitoring, RS, and SOOP are included. As a whole, inclusion of the RS data to the assessment improves reliability and representativeness of the results. In some parts of the GOF, validation of the RS data was now limited due to the low frequency of water sample measurements. Therefore, it is important to take the validation requirements of the RS data into account whenever monitoring programs are planned. In the near future, the RS data available for the monitoring of the GOF will increase through European Space Agency's Sentinel Program.

At present, the SOOP systems provide with information on water quality collected onboard the merchant ships commuting within a triangle of Tallinn – Stockholm – Helsinki in the Northern Gotland Basin and in the western GOF. The conventional monitoring, the validation of RS products, and the assessment work of the GOF would all benefit if the SOOP approach could be extended to stretch throughout the GOF with a regular route to St. Petersburg.

The HELCOM countries have made effort to ensure comparability of the results by agreeing on the guidelines for the sampling and analysis methods of Chl *a* to be used under the HELCOM COMBINE monitoring (HELCOM 2016). We suggest that this work should continue; differences in the sampling and determination methods between the countries made the comparison with the Chl *a* data challenging. We recommend the HELCOM countries to perform extra intercalibration exercises for Chl *a* analytics.

Processes controlling P storages

Jouni Lehtoranta1), Kim Dahlbo1), Mika Raateoja1), Pirkko Kauppila1), Oleg Savchuk2), Harri Kuosa1), Antti Räike1), Heikki Pitkänen1)

1) Finnish Environment Institute
2) Baltic Nest Institute, University of Stockholm

Phosphorus from the outside

The P load from the catchment increases the P storages in the water and in the sediments of the recipient system. In the system, a variety of biotic and abiotic processes regulate this entered P quota: uptake and chemical binding, settling on the seafloor, and after settling, release back to water or removal through burial.

The GOF belongs to those BS sub-basins having the highest P load per surface area and water volume (Savchuk 2005). The River Neva discharges into the tip of the GOF and dominates the freshwater input. The catchment of the River Neva includes the lake-rich sub-catchments of the River Vuoksi, Lake Onega, and Lake Ladoga. A major part of these sub-catchments consists of forests and peatlands with a high natural retention capacity of P, and therefore constitutes a limited background input of P into the GOF. The major anthropogenic sources of P into the GOF have been large cities and agriculture. The overall point source load of P started to decrease in the 1980's. Since 2005, the P load has decreased by about 3 000 tonnes/year, mostly due to improvements in the waste water treatment efficiency of St. Petersburg and the management of the P load from the Phosphorit fertilizer factory area in 2012 (see sections Nutrient inputs and Nutrients in the Water). Despite the drastic decreases in the point-source P load from the late 1980's to the early 1990's, the P concentration

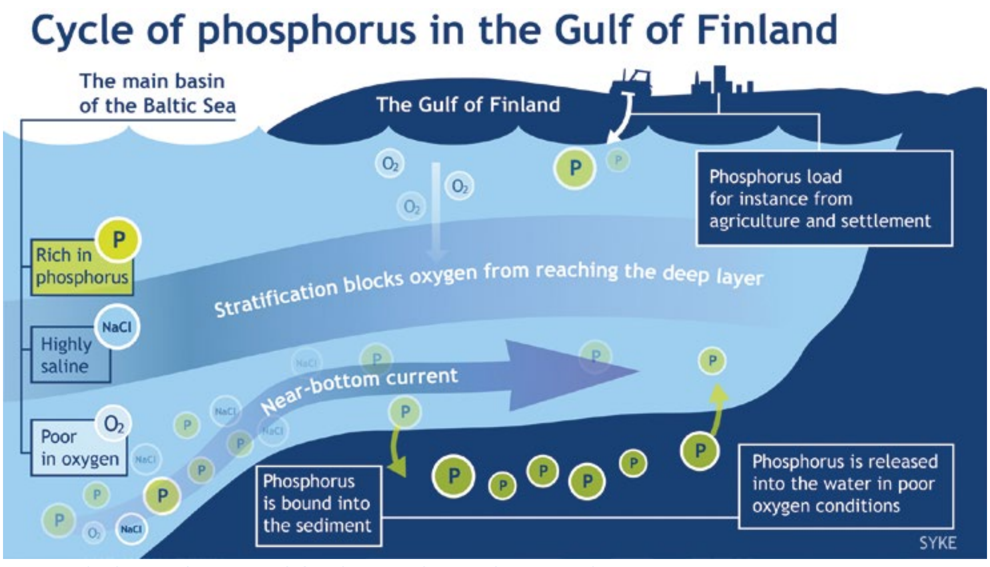


Figure 18. Cycle of P in the GOF. Source: SYKE. Graphics: SYKE & Kaskas Media.

in the water has varied markedly without a clear decreasing trend (Savchuk 2000, Pitkänen et al. 2001).

In this chapter, we describe the internal factors which affect the amount of P in the water (Fig. 18). We will point out that in the scale of the whole GOF, the large variation observed in the P pool is mainly driven by the internal factors obscuring the effect of the realized reductions in the land-based P load.

Phosphorus from the inside

The lack of sill formations between the Northern Gotland Basin and the GOF creates a dynamic boundary-system having an ability to exchange large volumes of water at the entrance to the GOF. This reflects in a significant exchange of P between the basins (Savchuk 2005). The positive fresh water balance of the GOF created by the voluminous freshwater input suggests that there is a net export of P out of the GOF. However, the deep water inflow contains much higher concentrations of P than does the outflowing surface water, and therefore there is an average net import of P into the GOF (Savchuk 2005). Especially, the salt water inflows from the Northern Gotland Basin degrade the oxygen conditions and challenge the ability of the benthic system to retain P in the sediments in the GOF. The bottom sediment of the GOF has generally a good capacity to capture P (Lehtoranta et al. 1997, Lukkari et al. 2008), and the sediment may act as a site for burial of P originating either from the catchment or from the Northern Gotland Basin.

However, the ability of the GOF to retain P varies temporally. Regarding the whole GOF, especially the deep water intrusions play a significant role; the inflowing water is poor in oxygen and rich in P (Fig. 18). The density difference between the surface waters and the deep waters hinders the vertical mixing of water, and hence, the vertical transport of oxygen. Thus, oxygen deprivation is immediate or is rapidly formed in the near-bottom water layers after the intrusion. Then, the P bound to bottom sediments has chances for leaking back to the water. In short, an intrusion increases the storage of P in the water column directly by transporting P with the inflowing water and indirectly by creating the favorable condition for the local benthic release of P.

To conclude, the hydrodynamical alterations in the boundary accompanied with the large pools of redox-sensitive Fe bound and organic P in the sediments of the GOF have together the potential to significantly re-shape the storage of P in the entire water volume of the GOF (Lukkari 2008).

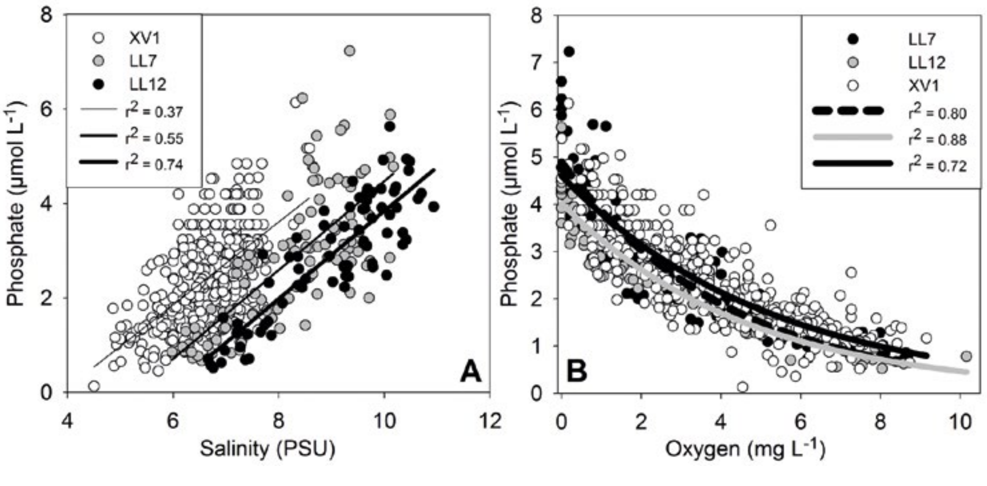


Figure 19. DIP as a function of salinity and oxygen concentration at stations along the west-east gradient of the GOF. XV1 = KYVY-11. For station locations, see a figure in the chapter GOF2014 dataset. Source: Lehtoranta et al. (manuscript).

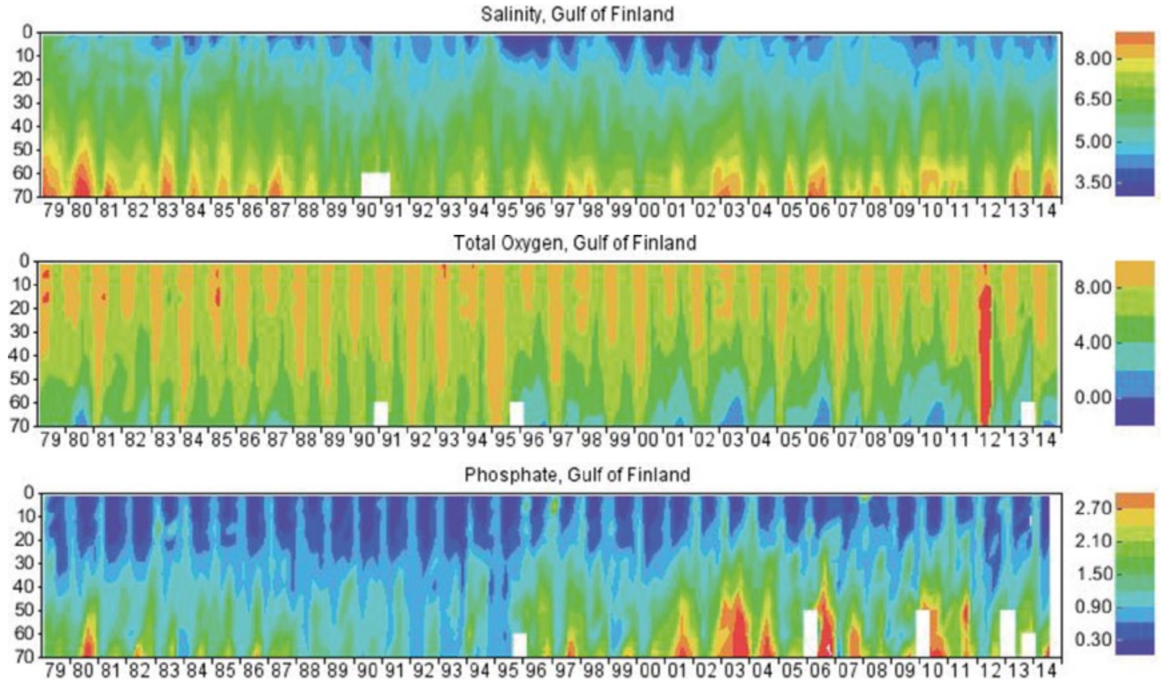


Figure 20. Variation in salinity (g/kg, above), oxygen (ml/l, middle) and phosphate (µmol/l, below) at LL7. Source: Lehtoranta et al. (manuscript).

Salinity, oxygen, and phosphorus describing water movements

In the near-bottom waters of the western and middle GOF, the variations in salinity and oxygen are accompanied with large changes in the P concentration (Figs. 19 and 20). A notable turn took place in the 2000's when the deep-water P was clearly elevated. The general pattern is evident: whenever salinity goes down, then oxygen goes up and phosphate goes down, and vice versa.

The vertical mixing intensity of water gradually increases towards the shallower waters in the east. This can be observed already when we arrive at the middle GOF, as indicated by the inter-annual variation in the concentration of oxygen with few exceptions (Fig. 20). It is notable that the lower salinity value in the eastern GOF results in as high P concentrations as in the more saline bottom water in the west (Fig. 19).

The changes in hydrodynamics and the P pattern coincide in large areas, and the deep salt water belt has the potential to reach the shallow eastern GOF – and has done that occasionally. Thus, the basin-scale alterations in hydrodynamics have at times a basin-scale impact on the benthic processes.

It is not possible to reveal the origins of P – i.e., in what proportions P originates from the Northern Gotland Basin or from the sediments of the GOF – by the sole comparison of salinity and P, because the salt water intrusion has a potential to cause anoxia and trigger local benthic P release (Lehtoranta 2003). However, the larger variation in the relationship of P and salinity at KYVY-11 than at LL7 suggests a greater role of local benthic release in the eastern GOF than in the western part (Fig. 19, Pitkänen et al. 2001).

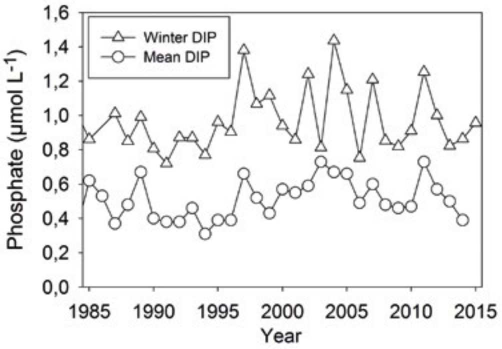


Figure 21. Mean concentration of DIP as a function of time in the entire water volume compared to the winter DIP in surface water at XVI. Note the clear DIP increase in the 1990's and in the early 2000's. Source: Lehtoranta et al. (manuscript).

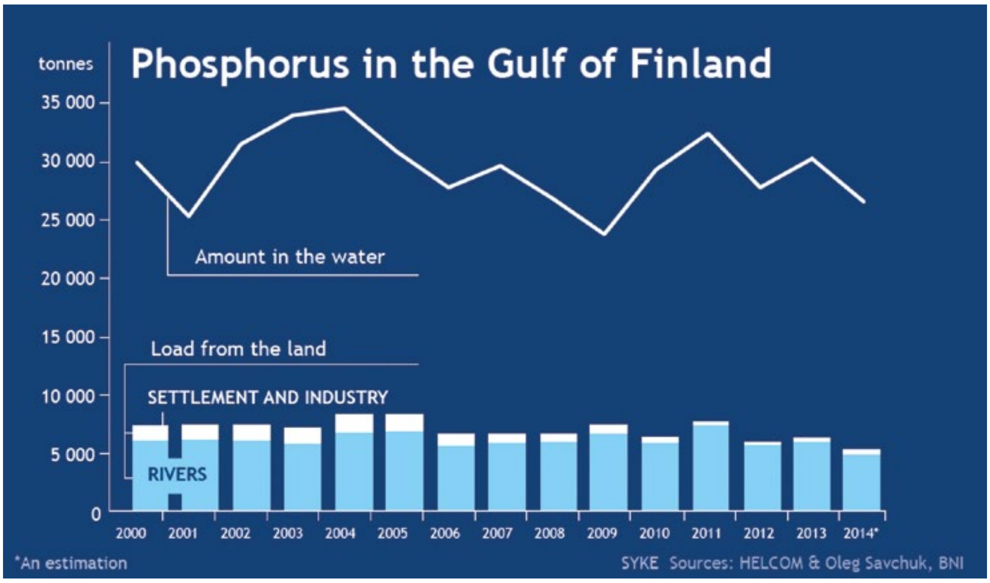


Figure 22. Timelines of the annual storage of TOTP in the water of the GOF and the annual TOTP load into the GOF. The inter-annual anomalies – i.e., how much the annual values differ from each other – since the turn of the millennium: for P load, average 700, and maximum 1 700 tonnes; for P storage, average 3 400, and maximum 5 500 tonnes. Note: the loads in 2012–2013 used in the preparation of this figure are somewhat higher than the values according to the latest knowledge. Correct numbers are to be found in the section Nutrient inputs. Source: SYKE, Oleg Savchuk, HELCOM (2013d). Graphics: SYKE & Kaskas Media.

Variation in the P storage

The highest concentrations of P in the surface water are observed in the winter when P accumulated to the deep-waters is transported to the surface. In the spring, the spring bloom exports large amounts of P to the bottom sediments (Heiskanen and Leppänen 1995), and the remaining reserve will be incorporated into organic material during the summer or maintained in the deep water layers. The annual mean concentration of P is thus lower than the concentration in the winter (Fig. 21).

The mean annual storage of P in the water of the GOF has varied from 24 000 to 35 000 tonnes since the turn of the millennium (Fig. 22). The inter-annual variations in this storage and in the annual P load into the GOF do not match; the fluctuation in the load does not explain the vast changes in the storage. Also, the correlation between the load and the storage is insignificant. Thus, the variation has to be linked to internal dynamics. The system receives at times large amounts of P from the Northern Gotland Basin and cycles it in the GOF between the sediment and water. The P storage may also decrease significantly by being exported out of the GOF or being trapped in the sediments.

Conclusions

The large inter-annual variation in the P content of water cannot be explained by the changes in the annual P load into the GOF. Rather, the content is affected by the water intrusions rich in P and by benthic processing of P, both phenomena being partly linked to the short-term regional climatic variation, i.e., wind and air pressure patterns. The changes in such internal dynamics lead to a highly variable nutrient condition, which affect the trophic status of the GOF. The internal processes pumping P between the Northern Gotland Basin and the GOF, and between the sediment and the water, have the potential to largely mask the effect of the land-based load reductions.

The large P reductions carried out in the catchment will ultimately decrease the amount of P cycling in the water-sediment system. Furthermore, the realized nutrient reductions have already had significant positive effects in the coastal regions in the easternmost GOF. Considering that the recovery through nutrient reductions will be a long-term process, there is a need for continuing the measures at the catchment targeted to mitigate the nutrient load. At the same time, we need research and feasibility studies on technical and bio-manipulation methods which may improve in their part the environmental status of the GOF.

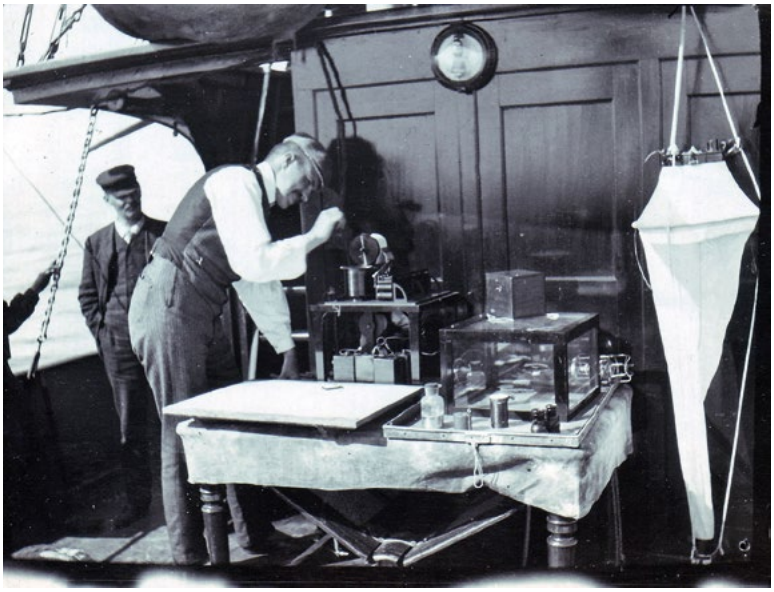
Are modeled scenarios supported by observations?

Heikki Pitkänen, Kim Dahlbo
Finnish Environment Institute

Modelling has been a widely used tool in the BS area to produce quantitative scenarios on the impacts of load reductions for action plans aimed at counteracting eutrophication. According to HELCOM's BSAP – based on model simulations by Savchuk et al. (2012) – reaching the good ecological status (GES) would require total reductions of 3 900 tonnes of P/year and 11 900 tonnes of N/year by the three countries combined, as compared with the normalized averaged inputs for 1997–2003 (7 500 tonnes of P/year and 116 000 tonnes of N/year; HELCOM 2007a, 2013f).

For the GOF, most of the published scenarios, based on physical-biogeochemical simulation modelling suggest that extensive and even basin-wide decreases in the trophic state are possible with strong enough cuts in the external nutrient load (Kiirikki et. al 2003, Pitkänen et al. 2007, Wulff et al. 2007, Savchuk and Wulff 2009, Vanhatalo et al. 2012, HELCOM 2013f).

The land-based load into the western GOF is on a relatively low level and further reductions in it would in practice affect only the state of coastal waters (Kiirikki et al. 2003, Pitkänen et al. 2007). The improvement in the state of the open western GOF would take place slower than in the eastern part because the load reductions in the east do not affect immediately the western GOF. Additionally, the western GOF is strongly dependent on the state of the Northern Gotland Basin, which will recover much more slowly than the GOF (Savchuk and Wulff 2007, Wulff et al. 2007).



Field sampling shows a longer history than modelling. Photo: Finnish Institute of Marine Research.

The implemented measures in the municipal waste water treatment of St. Petersburg since 2004 have decreased the total external P load into the GOF by 20–25 % (SUE Vodokanal of St. Petersburg 2015). According to modelling estimates, these reductions should have been able to lower the basin-wide trophic state, especially the amounts of N-fixing cyanobacteria (Kiirikki et al. 2003, Pitkänen et al. 2007). On the other hand, the modelling results of Savchuk et al. (2009) suggest that even substantial nutrient reductions from St. Petersburg would clearly affect only the innermost part of the Neva Estuary.

The summertime trophic state has improved – i.e., water quality has developed favourably – almost all over the GOF during the recent decade. The decrease in Chl *a* concentration has been strongest in the Neva Estuary, but it can be observed also elsewhere in eastern GOF, in the middle and western offshore, and in the outer coastal waters of Finland (section Chlorophyll *a* and phytoplankton blooms). Decreases in phytoplankton biomass have been observed in the outer Finnish coastal waters after the mid-2000's as well, largely due to a decrease in the cyanobacterial abundance (Lehtinen et al. 2015).

Deep water input from the Northern Gotland Basin, related hydrographic features of the GOF, and consequent deep-water oxygen conditions together frequently override the external load in the control of P storages of the GOF (Lehtoranta et al. manuscript). Despite a strong inter-annual variation driven by the internal processes, a decrease in the annual P inventory has occurred since the early 2000's (see section Nutrients in the water). It is obvious that this decrease largely explains the simultaneous decreases in the Chl *a* and in the cyanobacterial biomass in the GOF.

Modelling scenarios and monitoring results together give support to the conclusion that the trophic state of GOF will improve in case the BSAP and the targets of the national Programs of Measures are implemented. Reaching the GES in the whole GOF is not, however, possible without strong nutrient load reductions into the Gotland Basin, which is a prominent source of nutrients for the GOF (Savchuk and Wulff 2009). Even if we someday managed to reach the GES in the offshore GOF it would probably take at least several decades.

As a summary, water physics controls the P variations in the western and the middle GOF. In the open eastern GOF, the same applies, only complemented by the effects due to a strongly decreased land-based P load. The effect of the reduced load will most likely spread westwards in the future, although periods of unfavorable physical conditions will cause occasional drawbacks in the trophic state.

What explains the P variations in the GOF?

There has been a decreasing P trend in the inner Neva Estuary since the early 2000's (section Nutrients in the water), which coincides with the improvements in the management of the municipal waste waters of St. Petersburg after 2004. Also, the deep-water P storage – being controlled by hydrographic conditions of the GOF – shows an average, although irregular, decrease since the mid-2000's (Fig. 23). In the offshore north-east GOF, a weak long-term decreasing trend in the wintertime DIP in the surface waters can be observed as well, which probably is a result of a decrease in both the external load and the internal storage.

Before its management in the winter 2012, the P load from the Fosforit fertilizer plant area into the River Luga has been, at least in 2009–2011, so large (section Nutrients in the water) that the total P load into the eastern GOF might have even increased in those years, despite the decreased load from St. Petersburg. Thus, only the years 2012–2015 represent the period of a clearly lowered P load (section Nutrient inputs). This relatively short period provides no solid basis for drawing any certain conclusions about the spatiotemporal extent of the effects of the decreased P load on the state of the open eastern GOF, let alone the entire GOF. Nonetheless, results of the 2014 and 2015 winter monitoring cruises demonstrate that a wintertime surface flow from the Neva Estuary may affect the P condition over large areas in the eastern GOF and the easternmost Finnish waters (Fig. 24).

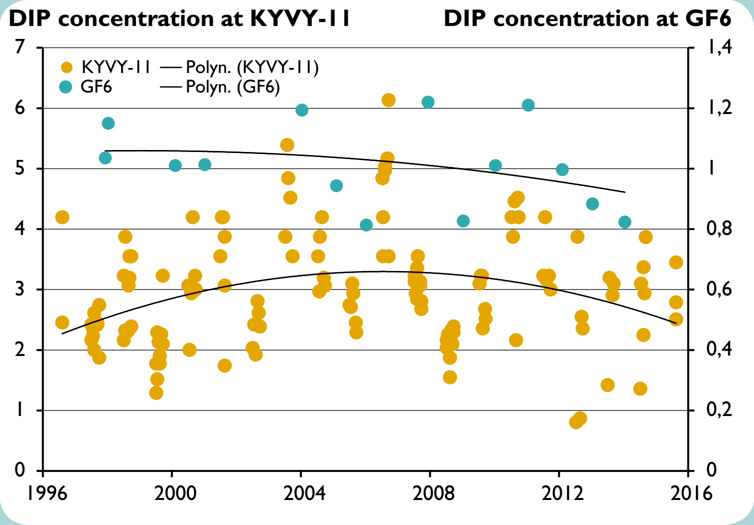


Figure 23. DIP concentration (µmol/l) as a function of time: deep water (50–70 m) in the summer at KYVY-11 (= XVI) and surface in the winter at GF6 in the north-eastern GOF. Polynomial fit is embedded to reveal the trend. Source: SYKE database.

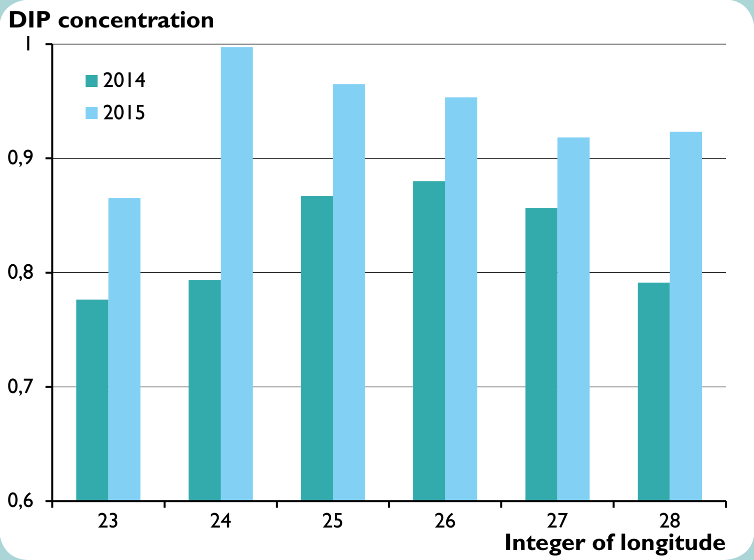


Figure 24. Calculated DIP concentration (µmol/l) at the surface water of the GOF in January 2014 and 2015 as a function of longitude, based on monitoring stations in the Finnish and Russian waters. Source: GOF2014 dataset.

Eastern GOF under the climate change

Vladimir Ryabchenko[1)]*, Alexey Isaev*[2)]

[1)] *St. Petersburg Branch of the Institute of Oceanology, Russian Academy of Sciences*
[2)] *Russian State Hydrometeorological University*

Future changes in the DIN and DIP patterns of the eastern GOF were modelled by the St. Petersburg Eutrophication Model (SPBEM) according to various climate change and nutrient loads scenarios (Eremina et al. 2014, Ryabchenko et al. 2016). Future climatic changes were calculated for the period 1961–2099 with the A1B scenario of greenhouse gas emissions and global socio-economic development; the future world of very rapid economic growth, global population that peaks in the mid-century and declines thereafter, the rapid introduction of new technologies, and a balanced use of all energy sources (Meier et al. 2011).

Future changes in nutrient loads into the GOF were considered according to two scenarios:

- the reference (REF), using modern atmospheric deposition and concentrations in rivers (Eilola et al. 2009). Here, N deposition and concentrations of nutrients and organic matter in rivers were assumed to be constant as of 2007, equaling their average values in 1995–2002 (data according to Gustafsson et al. 2011)

- the Baltic Sea Action Plan (BSAP), using reduced concentrations of nutrients in the rivers recalculated using target loads for the GOF (HELCOM 2007b) and a 50 % reduction in the atmospheric deposition. Here, concentrations of nutrients in the rivers and the atmospheric deposition decrease linearly between 2007 and 2020 from modern to future values. As of 2020, these characteristics were assumed to be constant

Because no nutrient data was available for 1961, data for 1990–1995 were used instead to set the initial 3-D winter nutrient distribution in the BS and the GOF (retrieved from the Baltic Environment Database of Stockholm University) The BALTSEM model (Savchuk et al. 2012) was used to recalculate the nutrient content for 1961, and the initial nutrient distribution was obtained by scaling the 1990–1995 fields by the ratio of the winter total nutrient content in 1961 to that in 1990–1995. River and atmospheric loads for 1961–2006 were obtained from the Baltic Environment Database. For the 1960's, the data of 1970 were used.

SPBEM was subjected to calibration and validation for the GOF, including the Russian waters for the ice-free period from May to November–December (Neelov et al. 2003, Savchuk et al. 2009, Isaev 2010). Additionally, SPBEM was validated along with three other eco-hydrodynamic models (Eilola et al. 2011, Skogen et al. 2014) for the period 2001–2005, and by Ryabchenko et al. (2016) for 1971–2000. The validation dataset concerned mainly the BS, but there were stations in the GOF, too.

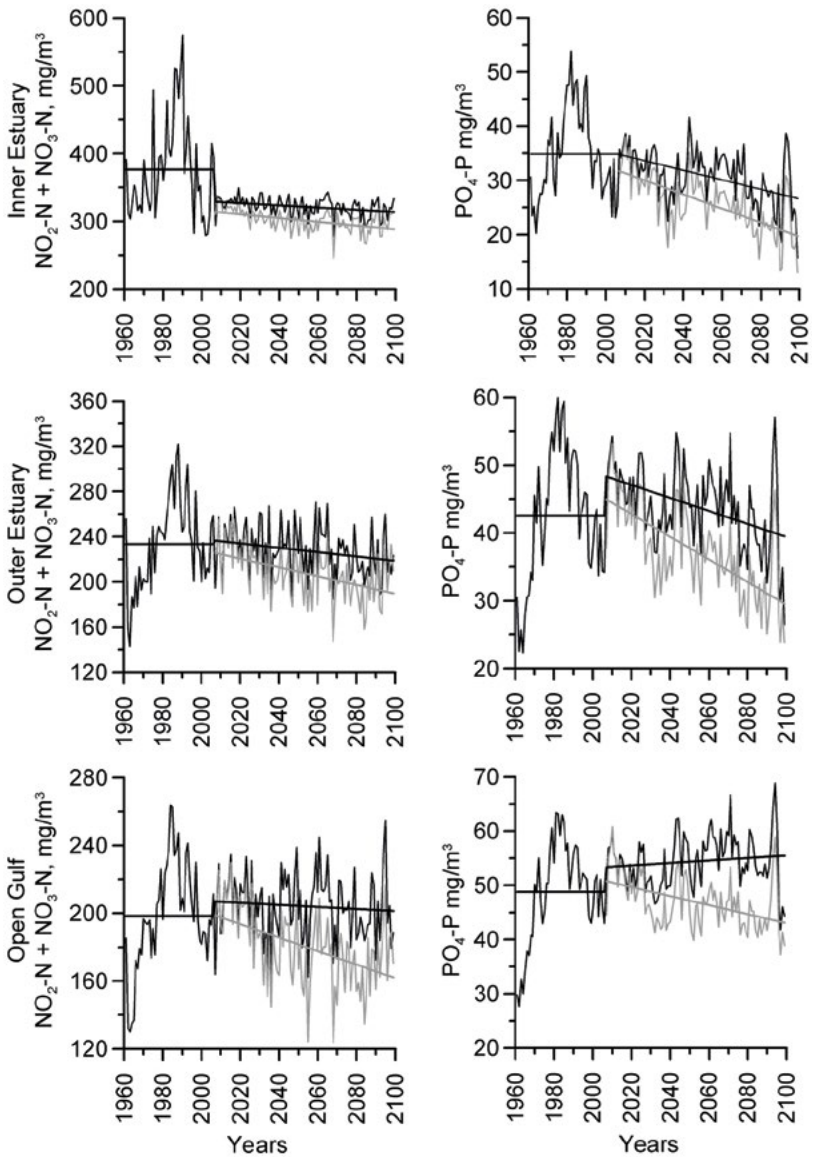


Figure 25.
The modeled interannual variability of winter depth-averaged concentrations of nutrients in 1961–2006 and future climate according to REF (black lines) and BSAP (grey lines) scenarios. Straight lines: average concentration for the current period (1961–2006) and a linear trend in the future (2007–2099).

All three subareas – the inner Neva estuary, the outer Neva estuary and the offshore GOF – were characterized by an increase in nutrient concentrations (winter, depth-averaged) in 1961–1985 and a decrease in 1986–2006 (Fig. 25). For the latter period, the modelling results are in line with the observed changes in the nutrient load via the River Neva and from St. Petersburg (see section Nutrient inputs).

The A1B scenario suggests that the future climatic changes in the eastern GOF area will lead to increased surface water temperature and increased riverine inflow. Increased riverine inflow will reduce the salinity throughout the water column due to the almost complete vertical mixing during the autumn-winter period. Changes in the deep layer salinity will be greater than that in the surface layer, causing weakened salinity stratification. The weakened stratification would result in a rise of the bottom water oxygen concentration, which hinders the release of P and N from the sediments, and nutrient stocks in the water will decrease.

The BSAP scenario, if realized, will lead to a pronounced decrease in the DIN and DIP concentrations in all the sub-ares by the end of the 21st century, in comparison to what the REF scenario suggests. Compared with present (the early 2000's) eutrophication state of the GOF, the BSAP scenario would lead to lower eutrophication state in the Neva estuary and to a lesser extent also in the offshore eastern GOF, whereas the REF scenario would not.

Nutrient load: targets and required reductions

Seppo Knuuttila1), Sergey Kondratyev2), Urmas Lips3), Petri Ekholm1)

1) Finnish Environment Institute
2) Institute of Limnology, Russian Academy of Sciences
3) Marine Systems Institute, Tallinn University of Technology

BSAP, MAI, and CART

In 2007, the HELCOM's contracting parties adopted a nutrient reduction scheme as part of the HELCOM Baltic Sea Action Plan (BSAP). The scheme is a regional approach to share the burden of the nutrient reductions in order to place the BS in a state unaffected by eutrophication (HELCOM 2007b). The provisional nutrient reduction scheme of the BSAP was reviewed and revised in the 2013 Copenhagen ministerial meeting. Based on a more complete dataset, an improved modeling approach, and the revised harmonized eutrophication status targets, the country allocated reduction targets (CART) for the GOF were provided (HELCOM 2013b, Table 5).

During the 2013 ministerial meeting, HELCOM countries decided that the actions to reduce the nutrient inputs should be included in the national implementation programs, the river basin management plans (RBMP), and the Programs of Measures by 2016, and to be in place by 2020.

Recently, HELCOM has prepared an assessment for a progress towards the CARTs covering data up to 2012 (Table 5). The assessment is based on nutrient input data submitted by the contracting parties to the HELCOM's Pollution Load Compilation (PLC) water database and to the European Monitoring and Evaluation Programme (EMEP, HELCOM 2015a).

Table 5. The CARTs, MAIs, and missing reductions for TOTN and TOTP (tonnes/year). CART=country allocated reduction target, MAI = maximum allowable input. Source: HELCOM (2013b).

	TOTN			**TOTP**		
	CART	MAI	Missing reductions to fulfill MAI	CART	MAI	Missing reductions to fulfill MAI
Estonia	1 419	11 265	1 840	268	236	234
Finland1)	2 603	20 653	1 989	364	322	354
Russia2)	7 879	65 522	10 061	3 277	2 892	2 291

1) Finland's own view is that CART for TOTN is fulfilled and that the remaining reduction target for TOTP is 227 tonnes when reductions in nutrient inputs to the Archipelago Sea, the Bothnian Sea, and the Bothnian Bay have been accounted for, in proportion to the effect on a neighboring basin (Laamanen 2016).

2) According to the more recent and relevant data (Knuuttila et al. manuscript, Kondratyev et al. manuscript) the remaining reduction targets for Russia are considerably lower, about 250 tonnes of P and 8000 tonnes of N

Buffer strips are an integral part of environmentally friendly agricultural practice. Photo: Riku Lumiaro.

Implementation of national action plans

Estonia

According to the information submitted to HELCOM, detailed estimates of the reduction of annual Estonian nutrient inputs to the BS and its sub-basins, as a result of implementation of the EU WFD, are lacking. However, the targets are in accordance with the HELCOM BSAP – to reduce the annual P load by 268 tonnes and the N load by 1 419 tonnes (sum of both water and air) in comparison to the load in 1997–2003.

Main measures are described in the RBMP for 2016–2021:

- Reduction of the nutrient load from point sources. This concerns municipal wastewater treatment plants (WWTPs) in settlements with > 2 000 people as well as smaller settlements and industrial WWTPs. Both enhancement of purification as well as administrative (analysis of permit requirements and inspection) measures are planned.
- Reduction of the nutrient load from agriculture; both from land cultivation and from livestock. Concrete measures are related for instance to manure handling, consulting, and agricultural support system.
- Reduction of the diffuse nutrient load by creating areas for nutrient retention, including bonds or stripes with vegetation between streams and agricultural fields. An analysis of the nutrient load from storm waters is planned, and measures will be suggested to reduce direct load to streams and rivers.

Additional measures in the Estonian Marine Strategy's Program of Measures to achieve or maintain the GES in the Estonian marine area and to reach the established environmental targets are:

- Promotion of the use of liquefied natural gas (LNG) as ship fuel
- Additional reduction of nutrient, hazardous substance, and litter inflows from stormwater directly to the sea.

Estonia has also committed to provide appropriate port reception facilities for wastewater intake from cruise ships in ports to reduce dumping of untreated wastewater directly into marine waters.

Industrial installations rarely have much aesthetic value, but their loads into the surrounding waters are easier to manage as compared to agriculture. Photo: Riku Lumiaro.

Finland

The overall reduction targets into the Finnish coastal waters in accordance with the EU WFD's RBMP are higher for both P and N loads than the reduction requirements set out in the BSAP for the offshore BS. The sole exception compared with the BSAP is the P target for the GOF. The reduction requirements for the GOF are at least 170 tonnes of P and 3 000 tonnes of N/year (Table 6).

Implementation of the current measures will make progress towards the agreed reduction targets for the nutrient load into the coastal waters of the GOF. However, it is hardly realistic to expect that the required load reductions will be achieved by 2020, which is the prerequisite of achieving the GES. Even if all the existing measures would be fully implemented, only one third of the reduction target of the WFD's RBMPs would be achieved. Therefore, several additional new measures have been included in the national implementation plan of the EU MSFD in order to get closer to the GES. According to preliminary estimates, those new measures could reduce about 50 tonnes of the P load and about 500 tonnes of the N load in the catchment area of the GOF by the year 2020. Even if these new measures are fully implemented, the overall reduction targets of the WFD's RBMPs will not yet be fulfilled. However, as a result of the implementation of the EU WFD and new measures, the N target in the BSAP will be nearly fulfilled, but the P reduction target will still fall about 140 tonnes short (Tables 5 and 6).

Reducing nutrient load from agriculture is problematic, slow, inefficient, and costly (HELCOM 2014a). Admittedly, designing and implementing effective agri-environmental management actions is challenging, because one has to tackle spatiotemporal heterogeneity in farming practices and natural conditions, inertia in soil processes, and policy and governance problems.

In Finland, the most important effort to cut down the agricultural nutrient load falls under the agri-environmental scheme of the EU Rural Development Programme. More than 90 % of the farmers have participated in the scheme since 1995, and committed, for example, to adjust fertilizing and promote winter plant cover of fields according to the conditions of the scheme. A recent study on the effectiveness of the scheme showed that the agricultural P load into the GOF shows a slight decreasing

Table 6. P and N load reduction targets for the GOF, and expected sector-wise and total reductions (tonnes/year) when the measures in accordance with the RBMPs of the EU WFD (EU 2000) and additional new measures according to national implementation plan of the EU MSFD (EU 2008) are realized. The reference period is 2006–2011 and the target year for the good ecological status (GES) for the coastal waters is 2020 according to the EU MSFD. Nutrient reduction targets were estimated on the basis of physical-chemical classification included in the classification of the ecological status of coastal waters. Source: Laamanen (2016).

	Reduction target	**Sum of WFD and new measures***	**Expected reductions when measures in accordance with the WFD are implemented**					**New measures**
			Agriculture	**Foresty**	**Scattered dwellings**	**Point source loading**	**Storm waters**	**Sum***
Phosphorus	170	110	38	1	12	6	**	55
Nitrogen	3000	1575	262	8	24	771	**	505

**Rounded by 5*
***Not estimated*

trend, whereas the N load first increased but has taken a slight path downwards in the period 2007–2012 (Rankinen et al. 2014, 2016).

Efficient reduction of the agricultural nutrient load calls for measures that can be applied to large field areas, yet preferably targeted to those parcels and practices that produce the highest load. Although the agri-environmental scheme in Finland sets maximum allowed fertilization levels for various crops and soil types, a further adjustment of fertilizer use is possible without compromising plant yields (Lemola et al. 2013). The agricultural P load could be reduced by about 10 % in 20 years by fertilizing according to plant requirements (allowing 95 % yield maximum). In many regions, the P in manure would suffice for years to come without any need for commercial fertilizers, assuming that manure can be transported to the fields in need of P addition (Ylivainio et al. 2014). There is a strong national impetus to enhance the recycling of the manure-based nutrients in the spirit of a circular economy, but so far this recycling has not been efficient due to technical, economic, and regulatory hindrances.

Fertilizing according to plant needs results in gradual lowering of the soil's P content, and, more importantly, the content of P readily available for aquatic primary production. Due to the legacy P content that has built up in the soils during the recent decades, the soil P status and the P losses from there have been decreasing slowly. For the transition period, the P load can be reduced by novel methods, such as amending the chemical condition of the soil by gypsum or structure lime additions. Gypsum has a potential to halve the P losses from the soil during about four years after spreading (Ekholm et al. 2012). Increasing vegetation cover in the winter, e.g., by reduced tillage, is a widely used method, which decreases P and N losses rapidly, but may increase the losses of dissolved P. In addition to above agri-environmental measures, it is crucial that soil quality is maintained and improved so that soil is less sensitive to erosion and allows efficient crop production, and hence, high nutrient uptake by plants. For example, liming of low pH soils and maintaining subsurface drainage systems have been neglected due to an increasing area of leased fields.

Central WWTP of St. Petersburg. Photo: John Nurminen Foundation.

Russia

In Russia, the official strategy for reducing the load on the GOF, the standards of an allowable impact (Normativi Dopustimogo Vozdeistviya, NDV), and the scheme of a complex use and protection of water bodies (Schema Komplexnogo Ispolzovaniya i Ohrani Vodnih Objectov, SKIOVO) are currently being developed under the guidance of the Ministry of Natural Resources and Environment of Russian Federation (Ministry of Natural Resources and Environment of the Russian Federation 2007a, 2007b). When the programme is officially approved, expected nutrient load reductions will be legally binding. For the time being, however, this information is not available. Development of NDV and SKIOVO implies certain difficulties associated with the lack of data necessary for calculations. Currently, there are no regional, officially approved maximum allowable concentrations for TOTP and TOTN for Russian inland waters. Since 2010, reporting obligations for point source loads have not included TOTP.

In 2011, the Russian government adopted the Federal Target Program "Development of water management complex of the Russian Federation in 2012–2020." During the implementation of the program, the project "Scientific-based proposal for the establishment of the nutrient load on the Gulf of Finland from Russia and determining the load requirements of the HELCOM Copenhagen Ministerial Declaration" is planned to be carried out. Thus, in the future, calculated values of the maximum allowable load, corresponding to the recommendations of the BSAP, can be used in the development of SKIOVO.

Russia has not yet fulfilled the HELCOM requirements for annual reporting of PLC data (HELCOM 2015b), which hinders the assessment of Russian sector-wise load reductions and the remaining reduction potential. According to Swedish Environmental Protection Agency (2015) the main gaps are: i) loads from point sources are not given for single loading sources, but only in aggregated form or not at all, ii) not all obligatory parameters are measured in monitored rivers, and iii) loading for unmonitored areas is not reported. In periodical reporting carried out every six years, Russia has reported discharges from a number of coastal and inland point sources and the total riverine inputs, but no source apportionment of nutrient sources in the river catchments has been performed. Therefore, the gaps in the Russian data have been filled in by using expert judgment, e.g., in the background document for the 2013 Copenhagen ministerial meeting (HELCOM 2013f).

Although Russia regularly reports some single point sources (e.g., St. Petersburg), the reporting has not covered coastal point sources comprehensively. The reporting of loads from unmonitored areas, and the delivery of sufficient data from point and diffuse sources, and other necessary information for source apportionment should be arranged in time for the compilation of PLC-6 (Swedish Environmental Protection Agency 2015).

Results of international co-operation projects

Since 2007, several international joint projects have studied sources and amounts of the nutrient load in the catchment area of the GOF in the North-West Russia. The objective of the PRIMER project was the identification of major nutrient load sources in the catchments of the GOF and the River Neva (Lehtoranta et al. 2009). Even though the report states that some of large livestock farms in the North-West Russia form a potential risk of nutrient leakage into the GOF, the reduction potential in the nutrient load was estimated to be largest in several small municipalities.

The project indicated that the average P removal efficiency was only about 20 % in the WWTPs of 41 municipalities in the study area. The estimated P load of 580 tonnes/year could be reduced by about 500 tonnes/year, assuming that HELCOM's recommendations could be fulfilled. Regarding reductions of the N load, the implementation of HELCOM's recommendations for the WWTPs of small towns of the North-West Russia could mean a reduction of 1000 to 1500 tonnes/year. In this respect, the most important area of action would be the catchments of the tributaries of the River Neva. The heavy anthropogenic pressure on those rivers (especially the River Slavianka, the River Ohta, the River Tosno, and the River Izhora) was recently showed by the BASE project as well (HELCOM 2014b). During the recent decade, measures to improve waste water treatment efficiency have been launched in several municipalities, but so far the project has been completed only in Sosnovyi Bor and Gatchina.

The HELCOM BALTHAZAR Project aimed to promote the protection of the BS from hazardous waste and the agricultural nutrient load in Russia by improving the management and by building capacity within the environmental monitoring body for producing information for HELCOM PLC (HELCOM 2012c).

Sampling in one of the case study sites of the project, the River Luga, revealed a significant source of P to the GOF entering the river near the town of Kingisepp. The case has been dealt in detail in the section Nutrients in the water. The measures implemented by EuroChem, the owner of the fertilizer factory Phosphorit, within a couple of months after the identification of the release were – from the viewpoint of both ecology and cost-benefit estimation – an efficient and quick way to decrease the P load from the factory to the GOF.

Widespread progress has not taken place in mitigating emissions from industrial animal production in the North-West Russia. Since the worst emission sites were first time identified in 2009, measures to curb emissions have been so far taken only in one poultry factory, Udarnik, in the Karelian Isthmus (John Nurminen Foundation 2015).

Conclusions

Estonia

Main measures are described in the RBMPs for 2016–2021. The programme includes constructional, administrative, educational/consulting, and investigational measures. The following main groups of measures are applied:

- Reduction of the nutrient load from municipal and industrial WWTPs.
- Reduction of the nutrient load from agriculture both from cultivation of land and from livestock.
- Reduction of diffusive nutrient load by creating areas for nutrient retention.
- Analysis of the loads from stormwaters is planned.

Finland

The EU MSFD's Programme of Measures does not include any measures concerning municipal waste waters, but it emphasizes the importance of full implementation of measures in accordance with the EU WFD in order to achieve the best possible reduction efficiency. The N removal efficiency should be increased to at least 70 % in all those treatment plants south of the Quark that have population equivalent of > 10 000 and discharge into the coastal waters. Furthermore, it should be improved to 90 % on larger treatment plants, which discharge into coastal waters, whenever this is technically and economically feasible. Most of the achievable N reduction in the point source load can be gained through improvements in the municipal WWTPs (Table 6).

For reaching the goals of the EU MSFD's Programme of Measures for fish farming, it is important to develop farms having a lower nutrient load, e.g., by using closed circulation concept. The imported feed raw material should be replaced by the BS fish, and preferably, by the use of plant-based raw materials grown in the BS region. This measure could theoretically reduce the nutrient load into the GOF and the Archipelago Sea by > 20 tonnes of P/year and > 180 tonnes of N/year.

Finland continues to participate in negotiations in HELCOM and in the IMO regarding decision to designate the BS as another nitrogen oxide emission control area (NECA). According to estimates, the BS as NECA has potential to reduce the annual N input to the whole BS by about 7 000 tonnes over 30 years, meaning about 75 % reduction compared to the current level (HELCOM 2013b).

To reduce the agricultural P load, it is recommended to adjust the agri-environmental support scheme so that the maximum allowed fertilizer levels would be based on plant requirements. Manure instead of commercial fertilizers should be used when feasible, and technology and governance of manure recycling should be promoted. Fertilizing according to plant needs would reduce the P load into the GOF and the Archipelago Sea by about 28 and 33 tonnes/year, respectively, in 20 years. Gypsum amendment would immediately reduce the P load into the GOF and the Archipelago Sea by some 50 and 100 tonnes/year, respectively. Gypsum should be spread every fourth to fifth year. For gypsum amendment to gain popularity, it should be better incorporated into the agri-environmental support scheme.

Russia

During the last decade, the decrease in the P load from St. Petersburg equals about 1 800 tonnes/year and in N load about 3 100 tonnes/year (SUE Vodokanal of St. Petersburg 2016). Since the beginning of wastewater treatment in the city in 1978, the P load has decreased by 3 600 tonnes/year (90 %) and N load by 14 000 tonnes/year (60 %).

In the case of the Luga Bay, the average decrease in the P load from Fosforit was estimated to be about 1 700 tonnes/year (compared between 2008–2011 and 2012; Atkins International ltd 2015). Knuuttila et al. (manuscript) estimated the corresponding decrease to be 2 800 tonnes/year. They compared the years 2011 and 2012, because the monitoring station in the River Luga located itself downstream the whole factory area only in 2011. This was not the case in 2008–2010.

Several joint projects have studied sources and amounts of the nutrient load in the catchment area of the GOF in the North-West Russia. Currently, the biggest reduction potential in the nutrient load is estimated to be found in several small municipalities in the surroundings of St. Petersburg. Curbing emissions from some hot spot industrial size livestock farms in the North-West Russia would be important as well.

The HELCOM PLC-5 project indicated that further improvements are needed to obtain reliable point source data from Russia. Therefore, discharges from all relevant point sources should be monitored, reported, and stored in the HELCOM's database. The individual point sources should be reported separately by the category (municipal WWTPs, industrial plants, fish farming units).

Large-scale livestock production has increased rapidly in the North-West Russia. However, no monitoring data on nutrient losses from these installations is available, except the data gathered during above mentioned joint projects. As most of the hot spot farms are located in the unmonitored catchments the risk of nutrient transport into the GOF cannot be estimated. Priority should be given for establishing proper monitoring programs, also compatible with PLC guidelines, in these catchments.

Cost efficient protection of the Gulf of Finland

Markku Ollikainen
University of Helsinki, Department of Economics and management

The main polluting sectors in the GOF are agriculture, municipal and industrial point sources, and scattered housing. This chapter discusses measures that are available to reduce nutrient loads as well as associated costs and policy packages to achieve the HELCOM's BSAP targets for the GOF.

Polluters and abatement measures

For water policies targeting each sector, it is important to make the distinction between point sources and non-point sources. Point source loads enter the waterways from a definite point and are thus easy to measure. Furthermore, they can be reduced by applying technical measures leading to high abatement rates (often 90 % and beyond). Municipal waste water treatment plants (WWTPs) represent a special case of point sources: they have been specifically designed to abate biological oxygen demand and nutrients from sewage water, and can cover their abatement costs by charging households. For industrial point sources, nutrient loads represent a side effect of the production, and end product price should cover abatement costs.

Agricultural non-point source pollution enters the waterways as diffuse load from fields. Without a costly experiment it is next to impossible to say how much a particular field parcel pollutes water. Agricultural loads depend on the stochastic weather conditions, especially precipitation, and many other factors, such as soil erosion. Despite the fact that there are many measures available to reduce loads, at the moment none of them is especially efficient in doing it: even achieving a 30 % load reduction may be challenging for agriculture. Key measures in agriculture include environmentally friendly cultivation methods, reduced fertilization, establishing buffer strips between waterways and fields, and building wetlands.

As a polluting sector, scattered housing is in between point sources and non-point sources. So far policy for scattered housing has focused predominantly on sanitation aspects but nutrient loads have gradually received an increasing role. Modern micro-sewage systems reduce both N and P at the site, only they are expensive. The distance to waterways, retention, and many other issues ultimately determine how much scattered housing ultimately pollutes the waterways and the GOF.

Costs of reducing nutrients

Cost-efficiency requires that nutrient reduction requirements are allocated between sectors so that the marginal costs from abating the last unit are equal. Therefore, one has to compare abatement costs between the sectors. There is little information about

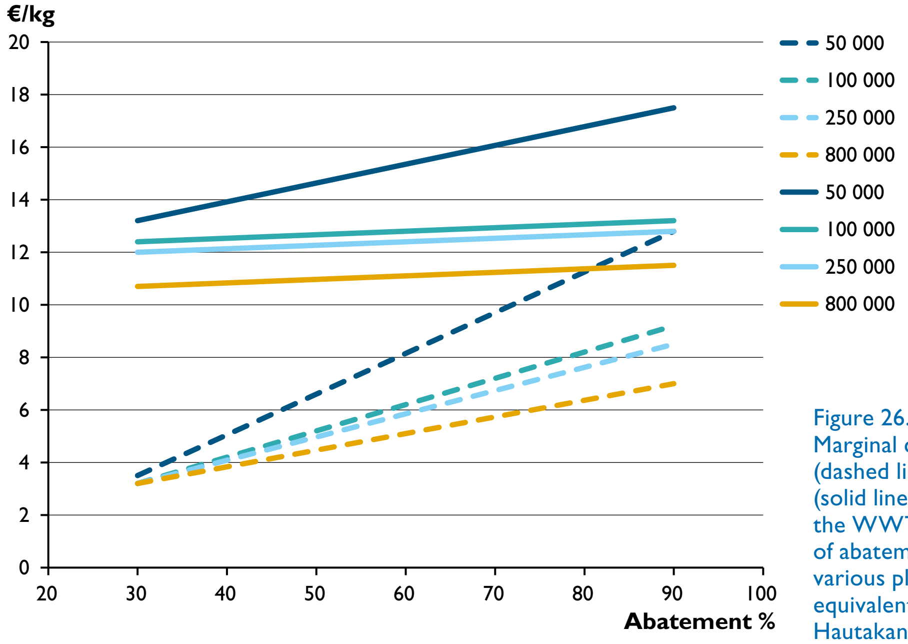


Figure 26.
Marginal costs of N (dashed lines) and P (solid lines) removal in the WWTPs as a function of abatement % with various plant sizes (person equivalent). Source: Hautakangas et al. (2014).

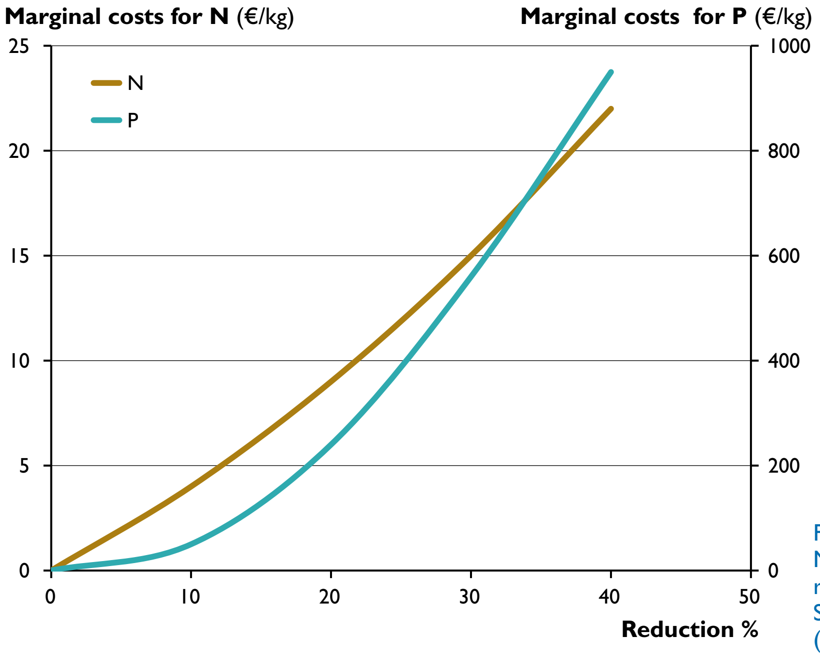


Figure 27.
Marginal costs of N and P reduction in agriculture. Source: Hautakangas et al. (2014).

abatement costs with regard to industrial point sources, but we know more about the costs related to the WWTPs, agriculture, and scattered housing.

The marginal costs of N abatement in the WWTPs are rather low: even at a high 90 % abatement rate they range between 7 and 13 €/kg depending on the plant size (Hautakangas et al. (2014), Fig. 26). Removal of N requires expensive but long-lasting initial investment. Hence, access to capital for the investment is required to improve abatement. In contrast to N, P abatement does not require high investment. Marginal costs of P range between 11 and 18 €/kg depending on the size of the plant. Abatement potential in the WWTPs will be discussed later.

The abatement costs in agriculture depend on whether the focus is on N or P abatement (Fig. 27). Reducing the N load by 10 to 30 % is relatively cheap: marginal costs range from 5 to 15 €/kg in a farm land in the GOF region (Ollikainen et al. 2012). Agricultural P loads consist of particulate P in eroded material and dissolved reactive P in runoff waters. Reducing the latter in the short run is next to impossible using current means. Therefore, abating P becomes quickly very expensive. Actually, the marginal costs are low only for the first 10 %, and after that they increase rapidly; reducing 30 % of the P load entails a marginal cost of 600 €/kg.

There is not systematic research data on abatement costs in scattered housing. Based on casuistic observations, the investment costs of abatement systems in Finland range from 3 000 to 10 000 € per household, the average being roughly 7 500 €. Current Finnish requirements entail 30 % of N and 70 % of P removal at the site. Using zero interest rate, the marginal cost of P removal in scattered housing (a four person family) is about 340 €/kg at the site, and much higher than this when measured with respect to loads entering the GOF.

Cost-efficient policy package

The cost estimates will be developed for measures and abatement intensities that are regarded feasible in the short run. The knowledge on loads and abatement possibilities is best for the WWTPs, as Hautakangas et al. (2014) provide new estimates on nutrient reductions obtainable for better abatement (Table 7).

Data in Table 7 provides the starting point of the analysis in Table 8, where the figures are adjusted slightly downwards, because the very recent investments have increased abatement rates (see the section Nutrient load: targets and required reductions). Investing in increased abatement in the WWTPs is the most feasible abatement measure in the short run, while reducing especially P loads in agriculture takes time under the currently used measures.

The current N removal rate of Estonia is rather low ranging between 30 and 50 % (Hautakangas et al. 2014). A notable exception is the WWTP in Tallinn, which abates N with > 80 % (Tallinna Vesi 2016). Implementing the EU's Urban Waste Water Directive (EU 1991) at 80 % reduction level reduces N loads by about 700 tonnes at the annual cost of 7 M€. Increasing P removal up to 95 % would cost 2.6 M€. For the remaining reduction (1 140 tonnes of N and 64 tonnes of P) one must look at measures in agriculture and other polluting sectors. Note that increasing abatement of N to technically feasible 90 % in the Estonian WWTPs would result in 1 100 tonnes reduction with the cost of 11.8 M€. Given that P fertilization in Estonia was low for a couple of decades resulting in a low soil P status, achieving P reduction in agriculture will take time and needs targeted policies.

The policy challenge is quite different for Finland. By implementing the EU's Urban Waste Water Directive, Finland has already achieved the N target, although possibilities for reducing further N loads exist. For instance, the increase of N abatement rate to 85 % in the coastal WWTPs would reduce N loads in the Archipelago Sea and in the GOF by 800 tonnes, which would cost 8.8 M€ annually. The removal of P in the WWTPs is currently > 96 %, so the reduction potential has been practically exhausted. Thus, the

Table 7. Nutrient abatement potential (tonnes) in Estonia, Finland, and Russia. Source: Hautakangas et al. (2014).

	N abatement			**P abatement**		
	70 %	80 %	90 %	80 %	90 %	95 %
Estonia	580	870	1300	100	150	190
Finland	3 900	5 400	7 300	0	0	4
Russia	2 500	5 000	7 600	400	800	1 000
Total	6 980	11 270	16 200	500	950	1 194

P reduction should be achieved in other sectors. Achieving the 227 tonnes reduction in agriculture using extensively current means would lead to marginal costs of 48 €/kg and the total cost of 53 M€. Even then, the outcome would be uncertain thanks to stochastic weather conditions (Ollikainen et al. 2012). The cost estimate reported in Table 8 is based on a new method, using gypsum to fix P on fields, as discussed in the section Nutrient load: targets and required reductions. The use of gypsum is predicted to yield about 30 % reduction of P loads from clay soils. By current estimates – and in case load reductions into the Archipelago Sea will be accepted as part of the reductions into the GOF – Finland could reduce the P load into the Archipelago Sea by 100 tonnes and into the GOF by 70 tonnes with the annual cost of 15 M€. The remaining reduction of 84 / 57 tonnes should be covered by other means and sectors.

Russia has a substantial reduction requirement for N. By increasing N removal up to 80 % in St. Petersburg and in the smaller WWTPs, Russia can cover as much as 4 000 tonnes with the costs of 35 M€. If the removal rate is increased up to 90 %, this would result in the abatement of 6 000 tonnes with annual cost of 61 M€. It is good news that even after the huge reductions taken place in the P load of St. Petersburg, Russia still has potential to achieve up to the reduction of 500 tonnes by improving P removal in smaller WWTPs with the annual cost of 8 M€ (see the section Nutrient load: targets and required reductions). Perhaps actions in scattered housing and industrial point sources may provide this reduction with a cheaper price tag. Missing data on costs prevents, unfortunately, a closer cost comparison.

All in all, our analysis shows that Estonia, Finland, and Russia can achieve most of the remaining reductions in the GOF with rather low costs in the near future. Estonia and Russia can do this by investing in the WWTPs. Most importantly, by using the full-cost principle, these investments would be financed by the consumers without any need for the government budget money. Finland can achieve the target by introducing the new method of gypsum to agriculture. If the costs of gypsum can be incorporated in the Finnish Agri-Environmental Program, this would not increase the need for the government budget money. To achieve a full 100 % reduction will, however, take time and targeted policies in agriculture, scattered housing, and industrial point sources.

Table 8. HELCOM's estimates of the remaining country-based reduction needs (tonnes, Svendsen et al. 2015, labeled with *) and updated estimates of the remaining loads for Russia and Finland (tonnes), and estimated short run abatement possibilities (tonnes) and associated costs. The first two columns recapitulate previously presented estimates for the remaining reduction requirements. The next two columns present the estimate of reduction possibilities in each country in the short run, reflecting the current reduction potential in agriculture for Finland and in the WWTPs for Estonia and Russia. The last two columns deliver rough estimates of the annual costs of achieving plausible reduction in nutrient loads. Source: the section Nutrient load: targets and required reductions, Kondratyev et al. (manuscript), Laamanen (2016).

	Remaining reduction target		**Short-run reduction possibilities**		**Cost estimates (M€) of short-run reduction**	
	N	P	N	P	N	P
Estonia	1 840*	234*	700	170	7	3
Finland	1 989* / 0	354* / 227	800 1)/ 0	170 1)	9 / 0	15
Russia	10 061* / 8 111	2 291* / 251	4 000	540	35	8
In total	13 890* / 9 951	2 879* / 712	5 870	960	51	26

1) Reductions into the Archipelago Sea have been totally (1:1) calculated for the benefit of the GOF

Conclusions for the chapter

Compiled by Heikki Pitkänen from the main results and conclusions of the sections.

The GOF is sensitive to eutrophication due to salinity stratification and the unrestricted connection with the Northern Gotland Basin, which enables the oxygen-poor and nutrient-rich deep waters to penetrate into the GOF. Although the land-based nutrient load into the GOF has decreased by 40–50 % since the late 1980's, the summertime trophic state of the offshore waters is presently poorer than 30 years ago. The previous large drop in the N load during the 1990's resulted in decreases in the N concentrations and the springtime algal biomasses. However, at the same time P concentrations started to increase as a result of an increased input of saline deep water rich in P from the Northern Gotland basin, leading to deprived oxygen conditions and the consequent enhanced benthic release of P.

During the recent past, the external loading of P into the eastern GOF has decreased strongly. At the moment, the effects are evident in the easternmost GOF but elsewhere they are largely masked by internal processes that are under control of influxes from the Northern Gotland Basin. The trophic state has improved in most parts of the GOF and especially in the east, but the main factor behind the development is generally more favorable climatic and physical conditions in recent years than about a decade ago.

One may be frustrated to note that the major achievements in the abatement of the point-source load into the GOF have not left such a notable fingerprint in the ambient nutrient levels as was once foreseen. The fingerprint is already there; the gradual decrease in the point-source load into the GOF since the mid-2000's has been so notable that its effect cannot simply vanish (see section Nutrient inputs). For the time being, this effect is almost, but not completely, overrun by the above-mentioned internal processes. We should also remember that the major land-based reductions in the nutrient load into the GOF – in their current extent – have taken place only since 2012, not so long ago. Although the nutrient load reductions in St. Petersburg started to have their impact in 2005, the elevated P load from the Phosphorit factory, entering the GOF via the River Luga in 2008–2011, partly compensated for the reductions achieved in St. Petersburg. A logical conclusion is that the more time passes after the major reductions in the anthropogenic load into the GOF, the more likely these successes will reflect in the trophic state of the GOF. To accelerate this development requires further lowering the anthropogenic nutrient load into the GOF and into the Gotland Basin.

The development in coming years will largely depend on physical conditions. In case no large-scale deep-water influx into the GOF occurs, the beneficial effects of the decreased land-based load will clearly emerge in larger areas outside the easternmost GOF. Most likely there will be both good and bad years with respect to physical conditions, which then will reflect in the state of GOF. However, returning back to the trophic state that the GOF had about a decade ago is unlikely because of the strongly reduced land-based P load.

According to HELCOM's most recent assessment (HELCOM 2015b), Finland and Russia should further decrease their common P load by about 2 900 and N load by about 14 000 tonnes/year (compared with the loads of 1997–2003) to reach targets of the BSAP. If the Russian load is updated to correspond the most recent data, the remaining reduction targets for the GOF would go down by about 2 000 tonnes/year of both P and N. Finland's view on the remaining loads would decrease the national targets by about 130 tonnes/year of P and 2 000 tonnes/year of N (Laamanen 2016). Although in these cases a considerable part of especially the P target would have been reached, reducing the whole remaining nutrient loads is still challenging. In order to reach the GES or some state even close to that in the GOF, the BSAP-based reductions should be implemented also for the Gotland Basin; the state of the former is decisively dependent on the state of the latter. Also in this case, reaching the GES in the GOF would take at least several decades.

Recommendations

Nutrient load

The implementation of nutrient emission reductions specified in the HELCOM's BSAP is a necessity, and so is the realization of the EU-stipulated Programmes of Measures in Estonia and Finland and Water Protection Programmes in Russia.

Reduction of the nutrient load from municipal waste waters continues to be important. WWTPs should be able to remove 70 % of N present in waste water from urban areas with > 10 000 residents, and 90 % in the case of larger cities whenever this is economically and technically feasible. In the North-West Russia, special emphasis should be paid to waste water management of small towns and to enhanced P removal.

In agriculture, the use of fertilizers should not exceed the nutrient requirements of the crop. Recycling of nutrients (use of manure as fertiliser), as well as studies on new technical practices to decrease nutrient load (e.g., gypsum treatment of fields) should be developed.

The N emissions from shipping should be reduced, for example, by increasing the use of LNG as ship fuel. In the annual meeting in March 2016, HELCOM countries and EU agreed on a roadmap to submit to the International Maritime Organization (IMO) a proposal for designating the BS as another nitrogen oxide emission control area (NECA).

Monitoring and research

The monitoring of the GOF should be continued and developed in a close co-operation between the three countries in the frames of HELCOM and EU MSFD. Results of the monitoring should be reported regularly under the GOF trilateral cooperation.

The conventional ship-based monitoring is expensive, but its results form the basis for state evaluations and protection programmes. A more closely integrated trilateral monitoring programme of the GOF is needed within the frames stipulated by EU and HELCOM.

In Russia, monitoring of the nutrient loads should be developed so that all relevant sources also in the river catchments are monitored, and source apportionment of the nutrient load entering the GOF is possible.

R/V Aranda with Super A1 ice class does not really need additional manpower to maneuver through the ice. Photo: Ilkka Lastumäki.

The trophic baselines cannot currently be determined in the Russian territorial waters on a routine basis. The realization of routine wintertime sampling programme is crucial for a truly holistic nutrient-based eutrophication assessment of the GOF. This should be realized by conventional monitoring in the first place, as unattended monitoring is hardly manageable during the icy conditions.

The conventional monitoring is a necessity, which can be replaced with no other approach. Autonomous platforms – earth observation, buoys, drifters, and flow-through systems – can however supplement this monitoring with spatiotemporally high-frequency data and fill the blank spaces left in the monitoring scheme. The riparian countries of the GOF have already a long tradition and profound expertise in the monitoring automation. The introduction of the ship-of-opportunity line visiting St. Petersburg at constant intervals would be valuable for gaining a better insight into the trophic state of the eastern GOF.

The GOF2014 project managed to bring about fluent data exchange amongst the trilateral community. At the time of publication of this assessment, the GOF2014 dataset has been supplemented with the 2014 trilateral data, and the 2015 data was being processed. We suggest that for the time being this dataset will be kept up to date for providing additional data for the trilateral community, HELCOM, and uses stemming from EU WFD and MSFD.

Special emphasis should be given to the use of fully comparable methodology and quality assurance in analytical work. We suggest that special trilateral attention should be paid to technical and quality aspects of the monitoring.

The exchange of water and nutrients with the BS and the internal nutrient processes play an important role in the overall trophic state of the GOF. The magnitude and dynamics of these processes should be subject to a special research and assessment effort. This would provide important new knowledge for the future environmental target-setting. Pronounced fluctuation continues to be present in the long-term nutrient datasets, which poses challenges to trend analysis, as well as to the use of these results in marine research. Any advances in the combination of meteorological, hydrodynamic, chemical, and biological monitoring should be met by more closely integrated trilateral work.

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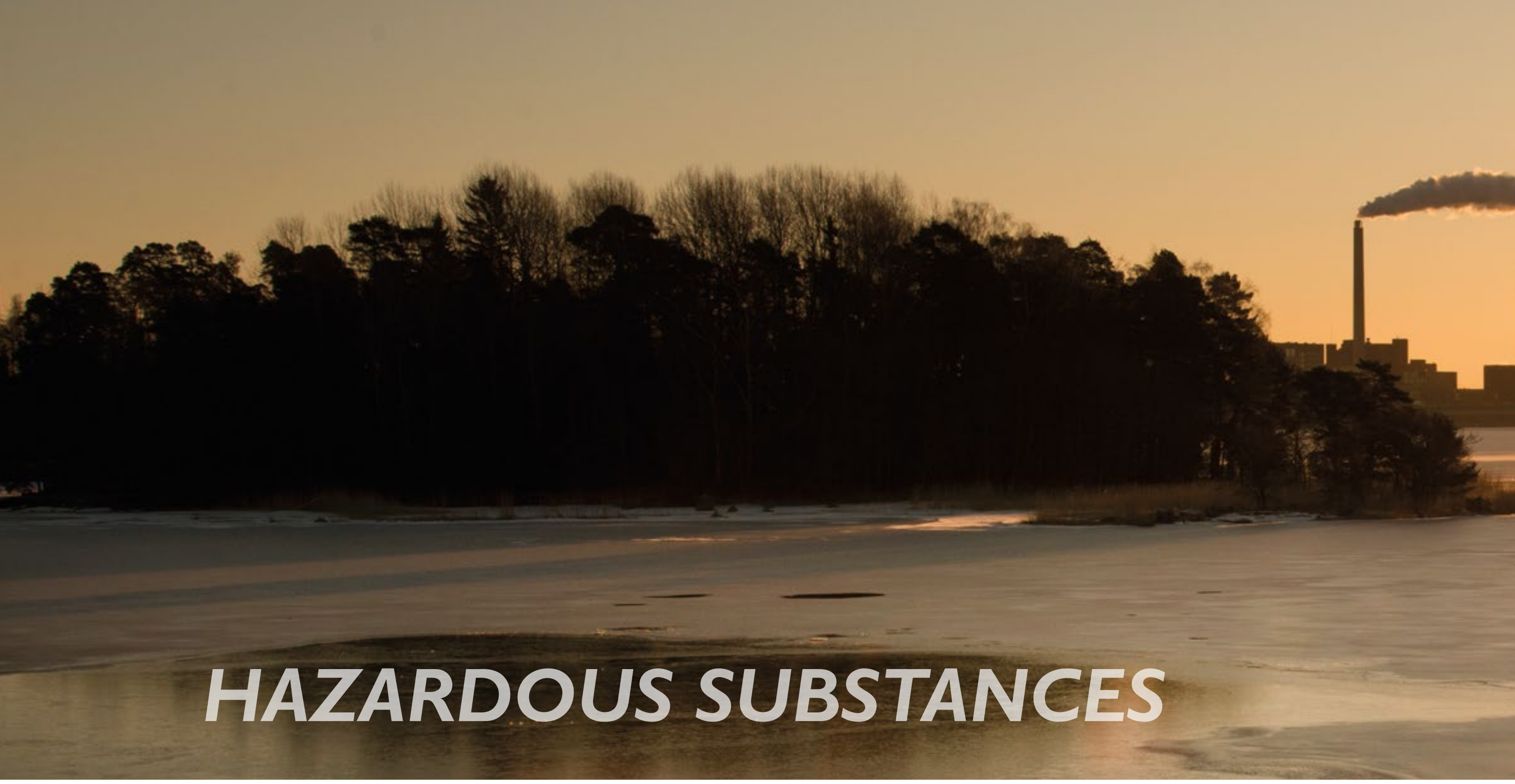


HAZARDOUS SUBSTANCES

Hazardous substances

Jaakko Mannio[1], Kari Lehtonen[1], Kirsten Jørgensen[1], Harri Kankaanpää[1], Oleg Korneev[2], Jukka Mehtonen[1], Ott Roots[3], Henry Vallius[4], Pekka Vuorinen[5], Lauri Äystö[1], Natalia Fedorova[2], Marja Keinänen[5], Tiit Lukki[6], Oksana Lyachenko[7], Alexander Rybalko[2], Simo Salo[1], Sara Söderström[1], Raisa Turja[1], Zoya Zhakovskaja[8]

[1] Finnish Environment Institute
[2] Federal State Unitary Research and Production Enterprise for Marine Exploration
[3] Estonian Environmental Research Centre Ltd.
[4] Geological Survey of Finland
[5] Natural Resources Institute Finland
[6] University of Tallinn
[7] State Research Institute of Lakes and Rivers Fishery
[8] Scientific Research Center for Ecological Safety, Russian Academy of Sciences

Viewpoint

Awareness of problems concerning hazardous substances and their effects in the Gulf of Finland (GOF) ecosystem has again increased after being somewhat overshadowed for a while by issues related to eutrophication. Although the manufacturing and use of many classical hazardous substances, such as various organochlorine compounds, is presently restricted or completely banned, they remain widely present in the marine environment. Meanwhile, new types of contaminants are emerging. More than 13 000 registered chemicals are currently in use within the EU and Russia, and new ones are continuously being adopted. The emerging and not yet regularly monitored contaminants in the marine environment include new surface-active compounds and flame retardants, various pharmaceuticals, hormones, and personal care products.

Hazardous substances can have various negative effects on marine biota, and also to avian and terrestrial consumers along the food web, including humans. Many of the substances that are of anthropogenic origin are highly persistent, bioaccumulative, and toxic (the so-called PBT substances). Global environmental legislation has improved the situation with regard to many contaminants, and decreased their concentrations in water, biota, and sediments of the GOF during the most recent decades. However, in many cases the concentrations of these compounds are still above acceptable levels, and in some areas, considerably high.

Photo: Riku Lumiaro.

Although monitoring of hazardous substances and their effects in the GOF has slightly improved lately, especially due to the implementation of EU MSFD (EU 2008), there is still need for major improvement. For example, no harmonized datasets between Estonia, Finland, and Russia exist; the data is sporadic and partly unavailable.

The Gulf of Finland – a sensitive sea area

The GOF catchment area is relatively densely populated, bringing along various sources of chemical pollution. Industrial and municipal waste waters as well as extensive maritime traffic and numerous large harbours contribute to the pollution burden of the GOF. The natural environment of the GOF is highly susceptible to pollution due to its poor water exchange, shallowness, and large catchment area.

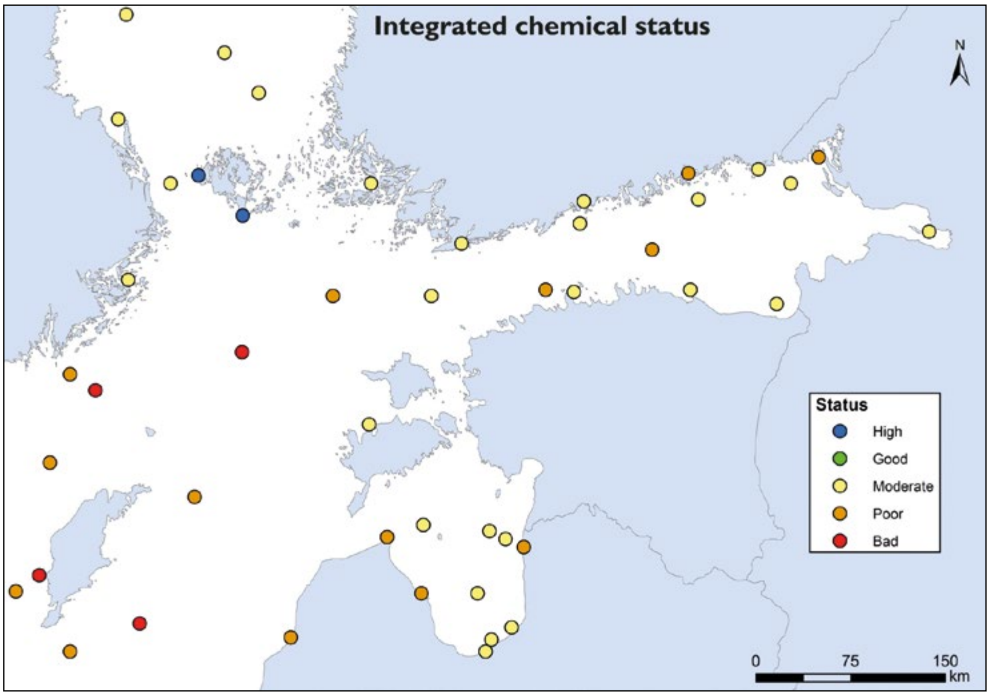


Figure 1. According to the latest comprehensive state estimate of HELCOM, the BS, including the GOF, is substantially affected by chemical pollution. It is to note that the indicators for hazardous substances are not yet considered as reliable as those developed for, e.g., eutrophication. Source: HELCOM (2010). Graph: Marco Nurmi.

Being a brackish water ecosystem it is also species-poor compared to freshwater and truly marine environments. As in the northern parts of the Baltic Sea (BS) in general, the cold conditions during the winter and spring slow down the degradation processes of chemicals and thus their removal from the system.

The BS is one of the most polluted sea areas globally (Verta et al. 2007). In the latest hazardous substances assessment by HELCOM, the GOF stands among the areas classified as "disturbed by hazardous substances" and among those having the environmental status of poor or bad (Fig. 1). Considering the size of the GOF area the number of data points is low; the result of the assessment cannot be considered highly reliable.

With its irregular coastline and recurrent severe ice conditions during the winter, the GOF is particularly vulnerable to accidental oil discharges. Until now the largest oil spills in the GOF have been caused by ship accidents. However, small discharges occur frequently, and harbour activities result in constant low-scale hydrocarbon pollution. Due to the increasing oil transportation and other maritime traffic in the BS, and in particular in the GOF, the risk of a major oil accident has grown despite of enhanced safety systems for traffic monitoring and control. In a case of a major oil spill, widespread and long lasting damage to the ecosystem of the GOF is to be expected (see chapter Maritime traffic and its safety).

Sources

Hazardous chemicals can be introduced to the marine environment deliberately, or they can be naturally produced or accidentally formed as by-products in different industrial processes, such as in the burning of organic material. They can be released into the environment during the entire life cycle of the product, including disposal and recycling. They are emitted or discharged into the environment from various sources (industry, agriculture, traffic, and households) and transported to the sea mainly via rivers or air. Atmospheric emissions from distant sources are an increasingly important source of various substances that are deposited onto the sea surface and thereafter dispersed in different compartments of the marine environment (HELCOM 2010). Hazardous substances are also produced via biological processes by harmful phytoplankton species (phycotoxins) and within sediments (hydrogen sulphide). More recently, the role of urban wastewaters have been acknowledged as a major point source of pollution; wastewater treatment plants (WWTP) act as a gateway for various contaminants, including perfluorinated substances, pharmaceuticals, nanoparticles, and microlitter. Therefore, concentrations of these substances are usually much higher in the coastal zone close to discharge sites than in the offshore area.

Sources of hazardous substances directly from consumers are multiple and include detergents, solvents, glues, biocides, lubricants, and pigments. In addition, electronic equipment, furniture, and other interior and textile items contain various surface treatment agents and flame retardants. Long-lived products containing hazardous substances can be considered as a stock that slowly releases contaminants into the environment.

Finnish emission inventories according to the EU WFD provide the best information about the emissions of nickel (Ni), cadmium (Cd), mercury (Hg), and lead (Pb) into surface waters. Regarding these trace metals, the industry is still a more important source than municipal WWTPs. Overall, point source emissions from both of these sources are greater to coastal than to inland waters. On the other hand, airborne deposition is a much more significant source (or pathway) of Cd, Hg, and Pb into the drainage basin than either of the point sources mentioned above.

Oil refining industry is typically located in the shoreline areas. Photo: Riku Lumiaro.

Sources of hazardous substances from maritime traffic include wastewater discharges from cruisers, illegal oil and bilge water discharges, as well as ship-based emissions.

Sources of hazardous substances already present in the GOF environment include hot spots of contaminated sediments as a legacy of discharges in the past. Substances from these hot spots may spread through resuspension, which can be caused by natural turbulence, propeller propulsion effects along navigation routes and harbours, and via dredging and deposition of sediments. Also previously dumped or sunken materials, such as warfare agents / munitions and shipwrecks, may leak hazardous compounds as corrosion progresses. Since maritime constructions (pipelines, cables, wind power, tunnels, bridges, harbours, recreation areas) are foreseen to proliferate in the coming years, the buried contaminated sediments may pose an increasing threat to the marine ecosystem of the GOF.

Substances

Concentrations of organochlorine compounds in fish and seabirds have clearly decreased from the highest levels recorded in the 1970's (Jörundsdottir et al. 2006, Pikkarainen and Parmanne 2006, Szlinder-Richert et al. 2008), although this decreasing trend in fish has levelled off since the 1990's (Kiviranta et al. 2003, Bignert et al. 2008). Sediment records of the GOF show a marked decrease in the concentrations of dioxins and furans after the cessation of the production of chlorophenols and the use of chlorine bleaching in pulp production (Isosaari et al. 2002). Still, the maximum allowable concentrations of dioxins and dioxin-like PCBs for human consumption set by EU (EU 2011) are exceeded in some fish species (Hallikainen et al. 2011). Organochlorine concentrations in organisms inhabiting the BS have been monitored already for some decades. Dioxins have been analyzed only periodically, and more recently by using archived samples, too (Miller et al. 2013, Airaksinen et al. 2014). In Finland, they are now part of the national EU MSFD monitoring programme.

The state of the BS as a whole has improved with respect to recently restricted chemicals (e.g., penta-BDEs; HELCOM 2010), but the use of substances now emerging

Table 1. Selected hazardous, persistent, and bioaccumulative substances affecting chemical status of the GOF. Source: Mannio et al. (2015).

Compound	Main use and restrictions	Main discharge sources into surface waters	Other observations
Organotin compounds (tributyltin TBT, triphenyltin TPhT)	Prohibited in 2010 By 2012 antifouling removal / overpainting required	Previously used as antifouling paints of ships and yachts, and as an anti-slime agent for industrial pipelines Current sources are wood items brought from outside the EU	Previous discharges have polluted the sediments in harbors, dockyards, and shiplanes TBT-containing antifouling paints have been replaced with copper-based substances Present discharges to surface waters are minor
Brominated flame retardants (polybrominated diphenyl ethers: penta-BDE, okta-BDE, deka-BDE, Hexabromocyclododecane HBCDD)	Penta-BDE and okta-BDE were prohibited in 2004 Deka-BDE is still permitted in specific purposes Occur currently in electronics and textiles (BDEs)	Atmospheric fallout (BDEs) Construction and dismantling of houses, and manufacturing of insulation sheet styrofoams (HBCDD)	Penta-BDE and deka-BDE discharges to surface waters are relatively small
Perfluorinated surfactants (perfluorooctane sulfonate PFOS, perfluorooctanoic acid PFOA)	Prohibited in textile and paper coatings in 2008 Prohibited in fire extinguishing foams in 2011 Currently used in metal coatings	Atmospheric fallout and municipal WWTPs PFAS compounds from used firefighting foams can contribute still via storm waters	
Dioxins (polychlorinated dibenzo-p-dioxin PCDD, dibenzofuran PCDF)	An unwanted by-product in combustions processes Originated from chlorobleaching of pulp and manufacturing of chlorophenol as well as from various other industrial processes	Effluent discharges are small compared to atmospheric emissions and fallout	Mainly long-distance atmospheric fallout and emissions from energy production The sediments outside the River Kymijoki are polluted by the pulp bleaching and manufacturing of chlorophenol. Dioxin levels are also globally high
Mercury	Amalgam Restricted use in products (e.g., energy saving bulbs)	Effluent discharges are small compared to atmospheric emissions and fallout from coal burning and metal industry Chloralkali and woodworking industries, municipal waste waters Occurs also as a impurities in metal production	Riverine loads to the sea originate mainly from atmospheric fallout Silvicultural land use increases the discharge loads to waters

in the environment, such as pharmaceuticals and hormones, has grown during the recent years. This concerns also some of the substitutes of banned brominated flame retardants (Schlabach et al. 2011) and perfluorinated compounds (Scheringer et al. 2014). The presence of brominated flame retardants has been reported in several recent studies (Isosaari et al. 2006, Roots et al. 2009, Stephansen et al. 2012, Vuorinen et al. 2012, Zacs et al. 2013, Airaksinen et al. 2015). Although organotin compounds are banned or strictly regulated they reside in subsurface sediments from where dredging and currents effectively spread and transfer them mainly as attached to suspended matter. Concentrations of organotins can be substantially high in sediments close to harbours, and studies on benthic biota show that these substances can be spread quite far away from hot spot areas (Lehtonen et al. unpubl., BONUS+ BEAST project). Polyaromatic hydrocarbons (PAHs) are distributed mainly in sediments and biota, and occur in these matrices to a varying extent depending on location and season. Except for the monitoring of oil concentrations in seawater there is no systematic PAH monitoring in the GOF.

Eleven substances or substance groups of concern are listed in the HELCOM BSAP. The international BaltActHaz (2010) and COHIBA projects (2012) studied their distribution and emissions within the BS catchment. Some of the substances are still in use, while others have been totally banned, or their use has been partially restricted (Table 1).

Bans and the fulfillment of emission reduction targets for certain restricted chemicals are commonly evaluated based on available data on their use, emissions, and trends of occurrence in the environment. However, for many compounds there is not enough information to reliably assess the emission loads. For the GOF, information about many organochlorine compounds and trace metals, such as Cd and Hg, has been available since the late 1970's. Since the late 2000's, information has been available also about brominated flame retardants, perfluoroalkyl surfactants, and organotins. However, serious knowledge gaps still exist concerning contaminants formed in combustion processes, the recently adopted organocopper compounds, pharmaceuticals, microplastics, and nanomaterials.

Organochlorines

The name dioxin refers to polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF) compounds. They consist of 210 congeners of which 17 are highly toxic and persistent in the environment. Some of the polychlorinated biphenyls (PCB) are called dioxin-like (dl-PCB) because they resemble dioxins with respect to molecular structure and effects.

PCDD/Fs (=PCDD+PCDF) have never been produced intentionally but instead they are formed as by-products of industrial processes, and especially of those where incomplete combustion occurs. Also waste incineration and pulp bleaching are the origins of these compounds (HELCOM 2010). Currently, PCDD/Fs generally enter the GOF via atmospheric deposition (Agrell et al. 2001, MONET 2006, Roots et al. 2010, Roots et al. 2015), by riverine input (Agrell et al. 2001), and via various point sources. Offshore and coastal sediments are considered to be the final sink of the majority of these substances. Thus, vertical sediment profiles are crucial in determining past changes in the loads of hazardous substances (Isosaari et al. 2002, Verta et al. 2007, Erm et al. 2014).

In sediments

The River Kymijoki is a major source of dioxins to the BS. Production of chlorophenols in the 1940's and 1950's and the operation of pulp and paper mills in the 1970's and 1980's taken place in its catchment have polluted the sediments of both the river itself and its estuary with PCDD/Fs (Salo et al. 2008). A total volume of contaminated river sediments is estimated to reach 5 x 106 m^3 and hot spots with extremely high concentrations of PCDD/Fs (up to 292 000 µg/kg ww) have been detected downstream next to the pollution source (HELCOM 2010). In the GOF, the highest concentrations of PCDD/Fs were encountered in the middle part around the River Kymijoki estuary (Isosaari et al. 2002).

The decline in the emissions of PCBs into the GOF has improved the state of surface sediments in the River Kymijoki estuary (Verta et al. 2007, HELCOM 2010, Fig. 2). Despite of this, the recently measured concentrations in accumulation bottoms (about 20 ng/kg) are still high compared to background levels.

There is further evidence of declining concentrations of PCDD/Fs and PCBs in the GOF (Isosaari et al. 2002, Verta et al. 2007). Sediment cores collected at reference locations in the GOF in 1999 showed PCDD/F concentrations of 430 to 2 860 ng/kg dw in the surface layers and 570 to 9 160 ng/kg dw in layers dating back to 1970–1982. For a comparison, a similar sampling campaign in the River Kymijoki estuary and the sea area off Kotka revealed PCDD/F concentrations of 4 290 to 52 900 ng/kg dw in the surface layers, and 9 510 to 101 000 ng/kg dw in layers dating back to 1959–1980. The latter values were at least 10-fold compared to reference conditions. Also, concentrations of PCDD/F and dl-PCBs in the bottom sediments of the Estonian coastal area, sampled in 2010, were much lower in the upper parts of the sediment compared to the deeper layers (Erm et al. 2014). Apparently, stringent regulative actions concerning dioxin-producing processes and the ban on the use of PCBs have served their purpose well.

Apart from the River Kymijoki and its estuary, the most notable source of dioxins to the GOF nowadays is believed to be atmospheric deposition, mostly caused by energy production (HELCOM 2010). Overall, the annual deposition of dioxins to the BS has decreased about 60 % in 1990–2007 (Gusev et al. 2007, 2009b).

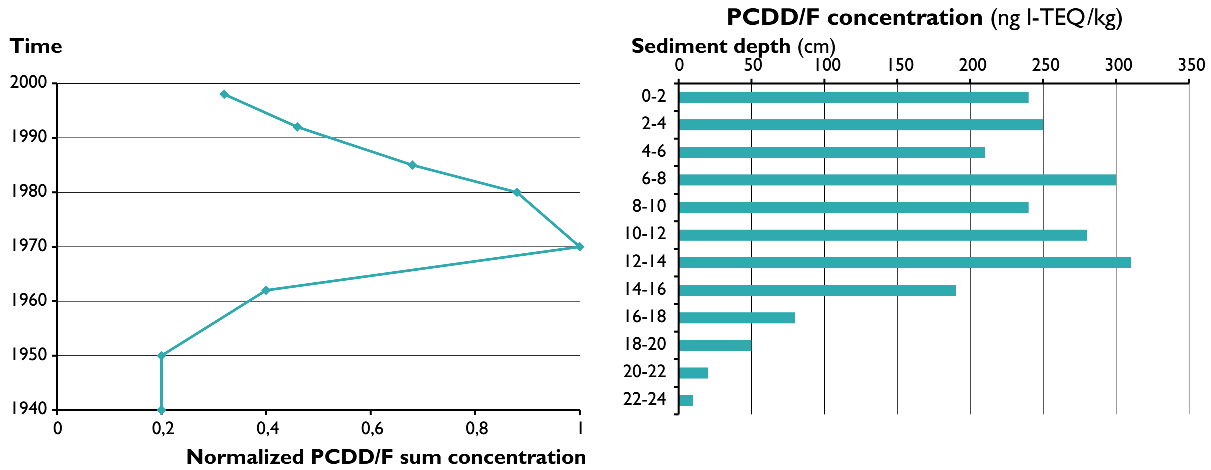


Figure 2. Two examples of declining PCDD/F stratification in soft sediment deposits in the GOF. Left: concentration (summed and normalized to unity) in the sediment surface as a function of time at station LL3A in the offshore middle GOF. Right: concentration (ng I-TEQ/kg) as a function of sediment depth in the Ahvenkoskenselkä area in the western fringe of the River Kymijoki estuary. The surface sediment represents the condition in 2003. Toxic equivalency factor (TEF) expresses the toxicity of dioxins, furans, and PCBs in terms of the most toxic form of dioxin: 2,3,7,8-TCDD. The toxicity of a mixture of dioxins and dioxin-like compounds can be expressed as the toxic equivalency (TEQ) defined by the World Health Organization (WHO). The WHO-TEQ value is a single value resulting from the product of the concentration and the individual TEF values of each congener (Van Der Berg et al. 2006). Source: Isosaari et al. (2002), Verta et al. (2007).

PCDD/F congeners were determined from surface sediments of the River Neva (including St. Petersburg area) and from the Russian part of the GOF in 2011–2012. The concentrations of total PCDD/Fs and WHO-TEQ values ranged from < 0.05 to 219 and from 0.0 to 16 ng/kg dw, respectively. The highest values of PCDD/Fs were measured in the city area. Levels of PCDD/F in these sediments were considerably lower in comparison with reported data from other areas of the BS. An overwhelming majority of the samples analyzed did not exceed the threshold effect level (TELfish 0.85 ng/kg, calculated with TEFs for fish) recommended by HELCOM. PCDF was predominant in these PCDD/Fs profiles, most likely originating from combustion sources in association with human activities.

In biota

Concentrations of PCDDs and PCBs in sprat, herring, and salmon caught in the GOF have been recorded to be higher than in fish caught in other areas of the BS (Vuorinen et al. 2012).

In a Finnish survey covering edible fish species, concentrations of PCDD/Fs and dl-PCBs exceeded the maximum allowable level for human consumption (6.5 pg WHO-TEQ$_{PCDD/F+PCB}$/g ww, EU 2011) in herring, salmon, sea trout, lamprey, and flounder caught in Hanko and Kotka areas (Hallikainen et al. 2011). More recently, concentrations of PCDD/Fs in two-year-old Baltic herring, an age-group not generally used for human consumption, in Hanko and Kotka areas were observed to be 0.39 ± 0.04 and 0.26 ± 0.01 pg WHO-TEQ/g ww, respectively (Finnish EU MSFD data 2015). However, the limit values for fish feed (1.25 pg WHO-TEQ$_{PCDD/F}$/g and 4.5 pg WHO-TEQ$_{PCDD/F+PCB}$/g, EU 2006) adjusted for fresh fish were exceeded even in one-year-old sprat and herring, and consequently, the respective limit values for human consumption were exceeded in salmon caught in the GOF (Vuorinen et al. 2012). Because the EU limit values for both dioxins and dioxins plus dl-PCBs were exceeded in all age groups of sprat and herring, such fish should not be used as feed in aquaculture without refinement.

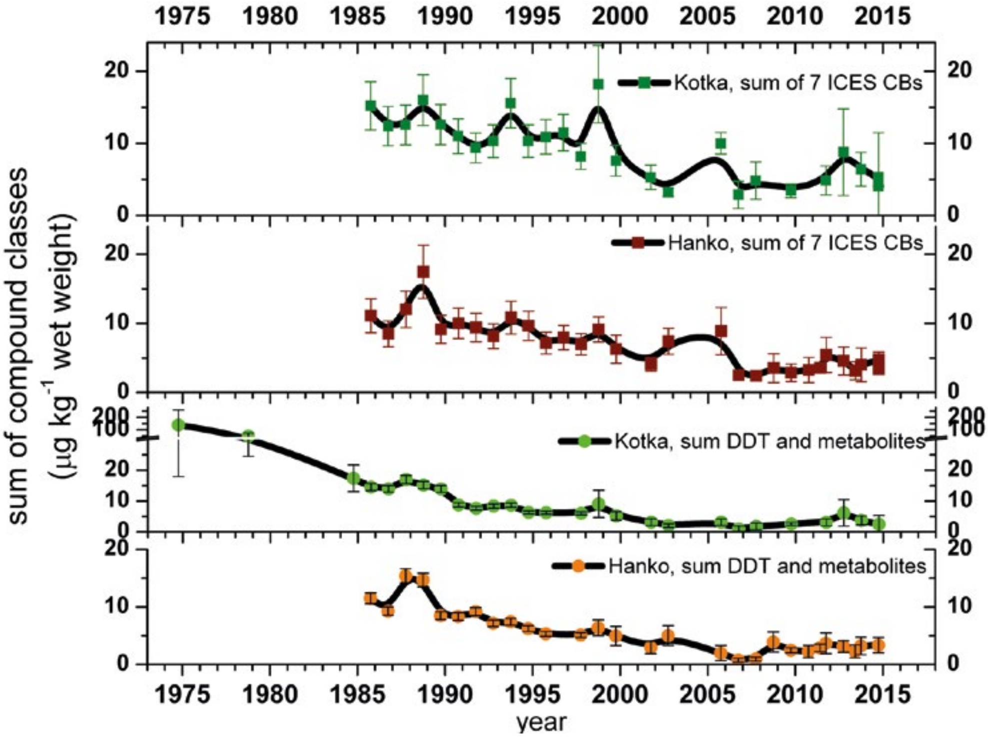


Figure 3. Concentrations of the sums of seven PCB congeners, and DDT and its metabolites (µg/kg ww) as a function of time in 2-year-old Baltic herring in the western (Hanko) and middle part of the GOF (Kotka). Error bars depict either analytical precision (1974–1995) or heterogeneity of the herring sample population (1996–2014). Source: SYKE database. Graph: Harri Kankaanpää.

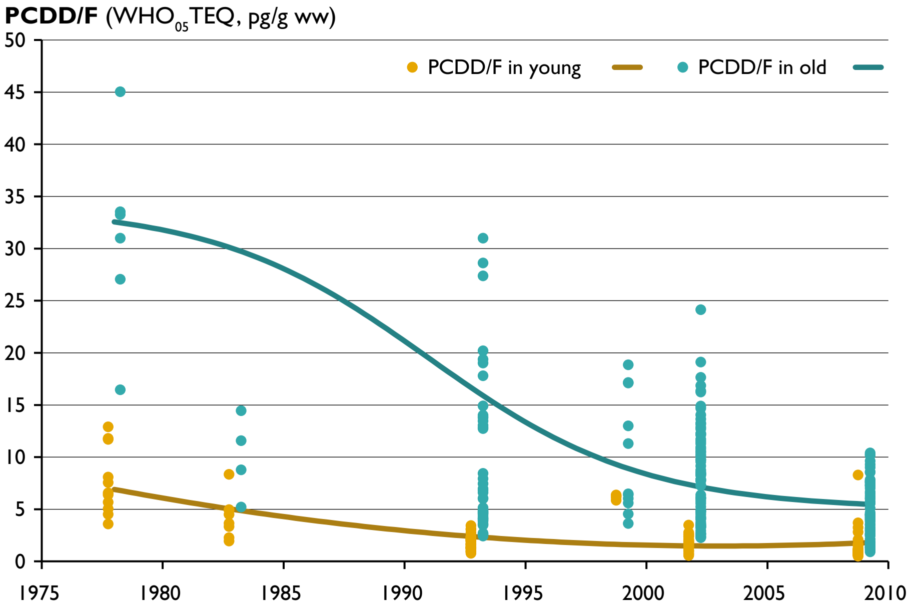


Figure 4. PCDD/F (WHO05 TEQ, pg/g ww) as a function of time in young (< 5 years) and old (≥ 5 years) Baltic herring from the Finnish coastal area (not only the GOF). The sampling for all fish was made at the same time, the observations of young and old herrings were separated temporally from each other for presentation purposes. Source: Airaksinen et al. (2014).

Conclusively, the concentrations of PCDD/Fs and PCBs in fish caught in the GOF have declined. The declining long-term trends in PCBs (given as the sum of seven PCB congeners 28, 52, 101, 118, 138, 153, and 180, as outlined by the ICES) was observed in 2-year-old herring from Hanko and Kotka areas (Finnish monitoring data). Even though there was a declining trend in PCB concentrations from the mid-1980's to 2005 no clear trend can be seen afterwards (Fig. 3).

Further evidence of the overall decline in concentrations of PCBs and dioxins is the decrease by 37 to 62 % observed in herring and sprat from the mid-1990's to 2003–2004 (Vuorinen et al. 2012). The same tendency was reported from all Finnish coastal areas (Airaksinen et al. 2014) with PCDD decreasing in both young (< 5 years) and old (≥ 5 years) herrings with a markedly steeper decline in the old ones (Fig. 4).

PCBs in caged (i.e., on-site transplantation for a fixed time period) mussels (*Mytilus trossulus*) have been studied in various coastal areas of Finland (Turja et al. 2013, 2015, Lehtonen et al. in press). In the GOF, PCB concentrations in a tissue of the mussels caged along a coastal-open sea gradient from the city of Porvoo were two to six times (14.5 to 33.5 ng/g dw) those recorded prior to the caging, depending on a distance from the shore and the nearby Kilpilahti oil terminal (Turja et al. 2013). Markedly lower PCB concentrations were recorded in the mussels transplanted close to the Viikinmäki WWTP discharge site off Helsinki; the highest values (2.0 ng/g dw) were observed close to the efflux pipe opening, and the values decreased with an increasing distance from the source (Turja et al. 2015).

A literature survey was conducted on available data on PCDD/Fs, PCB, DDT, polybrominated diphenyl ethers, and WHO-TEQs for PCDD/Fs and PCB in fish from the GOF. Sample material was not fully comparable because the sampled fishes were of different age and there were differences in the analysis methods and reporting. Concentrations of organohalogens increase with the age of fish (Roots et al. 2009, Vuorinen et al. 2002, 2012). Therefore, time trends should be compiled from samples of fish of the same age, only this time all the reported results were included in the statistical analyses (Table 2). Based on this survey there seemed to be only a small decrease in total WHO-TEQ concentrations in the GOF in 1994–2009 (data not shown).

Table 2. Concentrations of organohalogens in fish caught in the eastern and western GOF. * = the difference between the eastern and the western part is statistically significant ($p < 0.05$, one-way ANOVA). Source: Vuorinen et al. (manuscript).

Species	**IndPCB** (ng/g)		**PCDD/F** (pg/g)		**WHO-TEQ$_{PCDD/F}$** (pg/g)		**WHO-TEQ$_{PCB+PCDD/F}$** (pg/g)		**PBDE** (ng/g)	
	West	East	West	East	West	East	West	East	West	East
Bream	21.7	48.4			*0.71	*1.74	2.56	7.22	0.48	1.12
Burbot	*1.2	*4.1			*0.11	*0.49	*0.21	*0.78	0.08	0.13
Flounder	*16.7	*45.3			*1.0	*9.5	*3.2	*15.8	0.44	0.72
Herring	12.7	18.9			1.88	2.64	4.20	5.94	0.73	2.43
Perch	12.4	17.5			0.8	1.53	2.14	3.34	0.44	0.56
Pike-perch	9.9	11.5			*0.31	*0.79	1.16	1.8	0.29	0.36
Salmon	44.7	76.8			4.62	7.53	15.0	16.0	2.98	4.90
Sea trout			*12.8	*27.1					2.09	2.25
Sprat	9.6	10.9			1.27	2.15	2.72	2.76	0.89	0.89
Whitefish	*8.3	*25.4			0.83	3.71	1.78	6.95	0.26	0.58

This is in agreement with the recent report of Airaksinen et al. (2014) on PCDD/Fs and PCB concentrations recorded in herring collected in Finnish coastal areas during the recent years. The maximum allowable concentration of total WHO-TEQ is exceeded in all the salmon samples and in some of the herring samples. The concentrations of WHO-TEQ$_{PCDD/F+PCB}$ in salmon are approximately three times the concentration measured in its prey. Depending on the prey species even higher biomagnification factors for salmon caught from the GOF have been reported (Vuorinen et al. 2012).

For the more stationary species, such as bream, burbot, flounder, pike-perch, whitefish, and sea trout, the concentrations of dioxins and PCBs measured in the eastern GOF were two to nine times those in the western GOF (Table 2). Again, the historical load of the River Kymijoki is the apparent reason for the regional differences (Salo et al. 2008). As expected, such differences between the eastern and western GOF were not found in pelagic migratory fish species (herring, sprat, and salmon).

Brominated compounds

Brominated compounds have been used extensively for decreasing the flammability of materials, i.e., as flame retardants. Among these, polybrominated diphenyl ethers (PBDEs) are the most commonly used substances in various plastics, textiles, and electronics. Penta-BDEs and octa-BDEs are lower brominated products, while deca-BDEs are fully brominated. Since 2004, the use of penta-BDEs and octa-BDEs has been banned in the EU but they can still be found, e.g., in imported goods. The use of deca-BDEs is currently permitted but is likely to be banned in the near future. PBDEs do not occur naturally in the environment; all PBDEs originate from human activity. They spread to the environment from waste sites or the production and use of flame-protected materials. Current PBDE emissions into the GOF come from waste, industrial point sources, and fire extinguishing waters (the use of firefighting foams). Another important source is atmospheric deposition (Lilja et al. 2009).

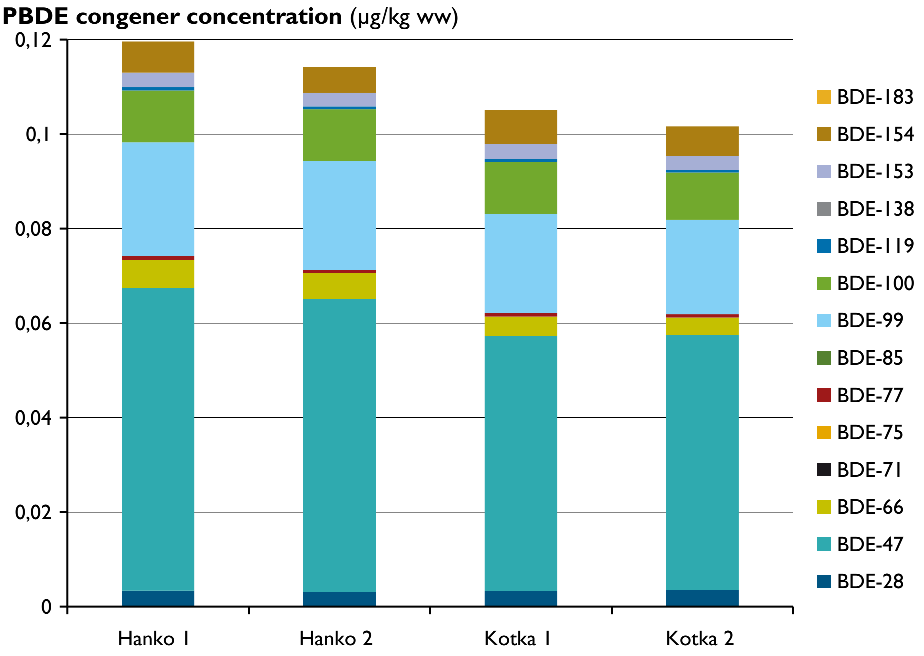


Figure 5. The dominant PBDE congeners (9 detected of 15 congeners analysed, µg/kg ww) in pelagic herring in Hanko and Kotka areas in 2014. Note: Sample Hanko 1 contained also BDE-209 at 0.68 µg/kg ww and was omitted from the graph for clarity. Source: Finnish EU MSFD data.

In fish

In the GOF, the highest concentrations of PBDEs have been determined from salmon, herring, and sea trout (Airaksinen et al. 2015). In the samples collected from Kotka and Hanko areas in the Finnish coast, the concentrations in herring were 0.0 to 1.2 µg/kg ww, and in salmon and sea trout 2.0 to 4.2 µg/kg ww. Similar levels have been observed in the southern BS (Zlinder-Richert et al. 2010). Indeed, the concentrations of PBDEs in sprat, herring, and salmon in the GOF do not differ much of those determined in the other areas of the BS (Vuorinen et al. 2012). According to the Finnish EU MSFD monitoring data from 2014, the concentrations of PBDEs (excluding BDE-209) in herring in the Hanko and Kotka areas were 0.3 to 0.8 and 0.10 to 0.11 µg/kg ww, respectively (Fig. 5). BDE congeners 47, 99, and 100 are the dominant congeners in both perch and herring caught in these areas.

Most of the PBDE congeners in herring collected from Estonian coastal waters in 2006–2010 were observed in concentrations < 1.0 µg/kg ww (Roots et al. 2008, 2009, 2010). The measured concentrations varied according to the region and the age of fish. Alike in Finnish waters, the most commonly observed BDE congeners were 47, 99, and 100. In yet another study, PBDEs were determined from the muscle tissue of herring and perch near the town of Sillamäe, and from flounder and herring in a coastal area of Estonia in the western GOF. The twelve PBDEs measured in this study were mostly under the limit of quantification (LOQ) with only congener 47 being measurable with the method applied (Lilja et al. 2009). Furthermore, PBDEs were analysed from perch liver in eight Estonian coastal areas during a state inventory in 2011 according to the Priority Substance Directive, and all the results obtained were under the LOQ (5 µg/kg ww of liver tissue).

In fish, the revised environmental quality standard (EQS) for PBDE is extremely low (0.0065 µg/kg ww). However, the European Food Safety Authority (EFSA) has not set any threshold value for PBDE concentrations in food.

For local species, such as perch in this case, the existing data shows a wider variability in PBDE concentrations, ranging from 0.2 to 3.3 µg/kg. The highest value measured was recorded from fish sampled in the Vanhankaupunginlahti Bay in Helsinki (Fig. 6). It is probable that there are similar local hot spot areas also in other urban estuaries in the GOF that the so far scarce monitoring has not been able to reveal.

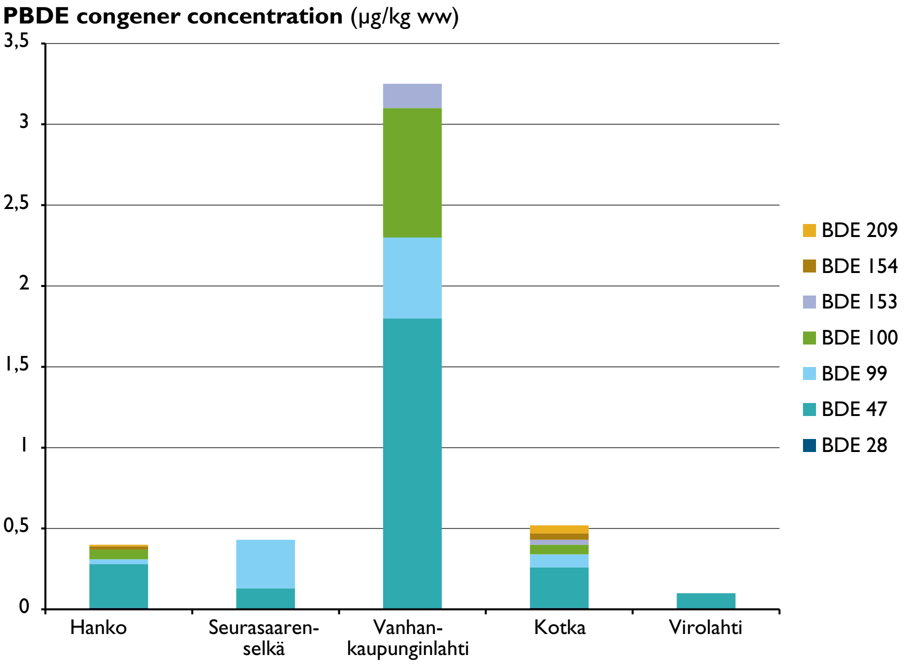


Figure 6.
PBDE (7 most abundant congeners) in perch (µg/kg ww) along the Finnish coast of the GOF in 2009–2012. Seurasaarenselkä and Vanhankaupunginlahti are inner bays in the Helsinki coastal area. Source: Airaksinen et al. (2014), SYKE database.

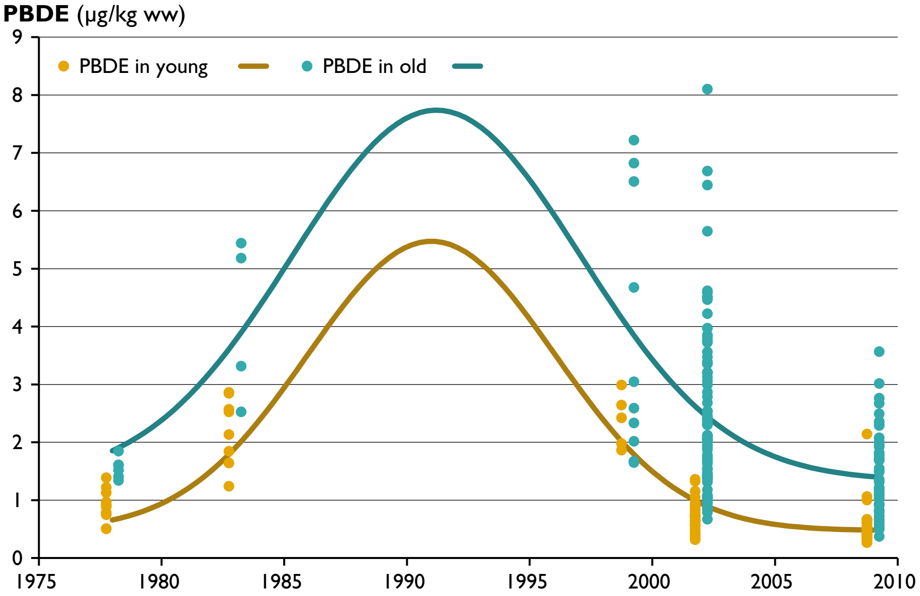


Figure 7.
Concentrations of PBDEs (µg/kg ww) as a function of time in young (< 5 years) and old (≥ 5 years) herring from the Finnish coastal area. The sampling for all fish was made at the same time, the observations of young and old herrings were separated temporally from each other for presentation purposes.Source: Airaksinen et al. (2014).

No long-term data set of PBDEs in fish is available from the GOF. In other areas of the BS, monitoring of herring in the Bothnian Sea and the Western Gotland Basin show a significant decreasing trend in BDE-47 concentration in 1999–2009 (Bignert et al. 2011).

Similar to organochlorine compounds, the concentrations of PBDEs increase with fish age (Fig. 7, Airaksinen et al. 2014); this has been observed in sprat and herring, and especially in salmon because of biomagnification.

Hexabromocyclododecane (HBCDD) is a flame retardant used in polysterene-based insulation products in buildings and construction industry, and in electronic equipment and furniture textiles. HBCDD can be released to the environment during the entire life-cycle of the product. It is mainly distributed to the environment via rivers and atmospheric deposition. Data of HBCDD in fish from the GOF is very scarce. Even less data exists on substances which have recently substituted PBDE and HBCDD as flame retardants (Schlabach et al. 2011).

Of the HBCDD congeners, α-HBCDD appeared to be most abundant in herring with concentrations of 0.07 to 0.15 µg/kg ww in the Hanko region in 2014. Congeners β-HBCDD and γ-HBCDD were not detected. No HBCDDs were detected in Kotka area in 2014 (Finnish MSFD monitoring data 2015). Low HBCDD concentrations (< 0.01 to 0.10 µg/kg ww) were observed in perch in inland lakes (Finnish WFD monitoring data 2015). All these results are very low compared to the upcoming EQS for HBCDD (167 µg/kg ww).

Perfluoroalkyl substances

Perfluoroalkyl substances (PFAS) are a group of substances that have been manufactured for several decades and applied in industrial processes and commercial products, such as water/stain proofing agents and firefighting foams. These substances are extremely persistent and stable in the environment. A substance in the PFAS group currently raising the largest concern is perfluoro-octane sulphonate (PFOS), which bioaccumulates. It is known to cause hormonal imbalance and malfunctions especially in the liver, kidneys, and other protein-rich tissues. Its toxic effects include liver enlargement, loss of weight, immunotoxicity, and developmental disturbances (HELCOM 2010). The EQS for PFOS is 9.1 µg/kg ww. In the GOF, PFOS has been detected in some fish species, while in other parts of the BS, seals and predatory birds have shown alarmingly high concentrations.

The concentrations of PFOS in fish collected in the coastal areas of Hanko and Kotka ranged from 1.70 to 52.1 µg/kg ww in liver and 0.3 to 6.7 µg/kg ww in muscle (HELCOM 2010, Hallikainen et al. 2011). In the Vanhankaupunginlahti Bay in Helsinki, concentrations reaching 211 µg/kg ww in liver and 38.9 µg/kg ww in muscle were recorded for perch (Koponen et al. 2015), thus greatly exceeding the EQS. Disregarding this one hot spot site the concentrations are relatively similar to those measured in fish from other parts of the BS (HELCOM 2010). More recently, concentrations of PFAS in 2-year-old herring (muscle) caught in the offshore areas off Kotka and Hanko in 2014 were 0.49 and 0.60 µg/kg ww, respectively (Finnish MSFD monitoring data).

According to the scarce data available, concentrations of PFOS in fish do not seem to vary much within the GOF. However, all the hot spots in the area are not known. Additionally, only little about transformation and behaviour of these substances is currently known (Houde et al. 2006). Thus, the above results should only be taken as indicative when assessing the risk they pose to the GOF ecosystem.

Trace metals

Trace metals – a.k.a. heavy metals – occur naturally in the environment, but their concentrations vary greatly according to the geological characteristics of the region. Some trace metals, such as Hg, Cd, and Pb, are toxic to biota even at low concentrations. Trace metals are released to the environment mainly from mines, metal smelters, coal-fired power plants, and fertilizer industry. The main sources of Cd to the GOF are point sources and riverine runoff, whereas Hg and Pb originate principally from atmospheric emissions (Gusev 2009a, Knuuttila 2009).

In sediments

In order to examine possible temporal changes in the trace metal load on the seafloor, offshore sediments of the GOF were investigated during the GOF2014 project at five locations identical to those studied during the previous Gulf of Finland Year 1996 (Vallius et al. manuscript). Results show that the loads have decreased substantially. A decrease of 20 to 60 % in concentration was measured for the most important metals Hg and Cd,

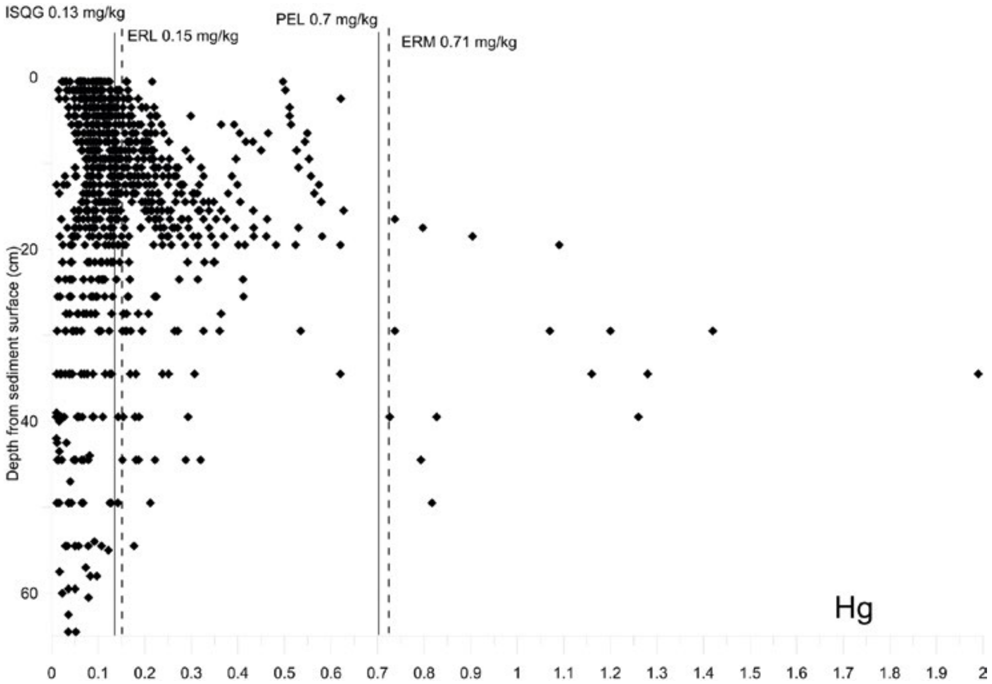


Figure 8. Hg concentrations (mg/kg dw) as a function of sediment depth in 23 sediment cores in the GOF with sediment quality guidelines indicated. ISQG = interim sediment quality guideline, PEL = probable effect level, ERL = effects range-low, ERM = effects range-medium (Long et al. 1995). Source: Vallius (2015a).

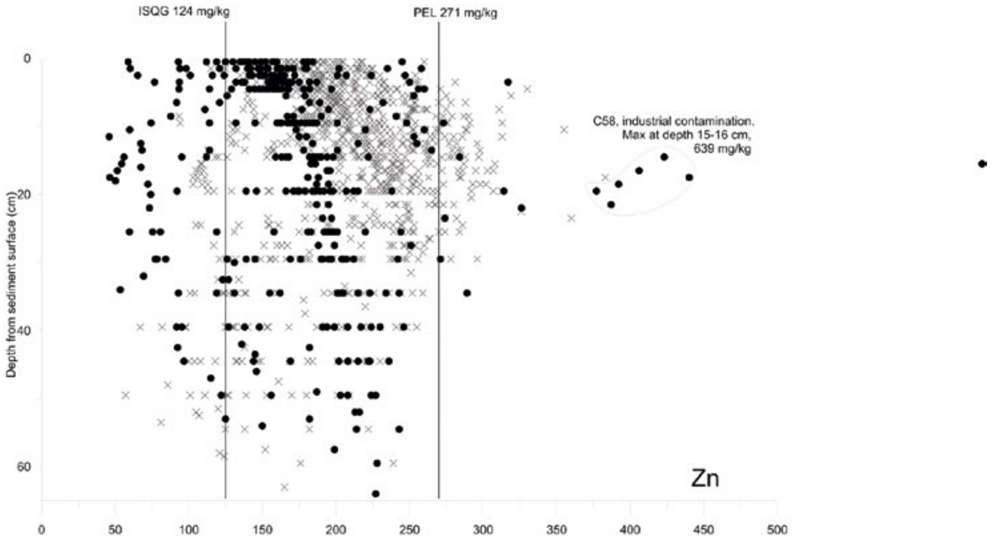


Figure 9. Zn concentrations (mg/kg dw) as a function of sediment depth in 56 sediment cores in the GOF with sediment quality guidelines indicated. Abbreviations as in Fig. 10. Data from the western GOF is printed with black dots and data from the eastern GOF with crosses. Source: Vallius (2015a).

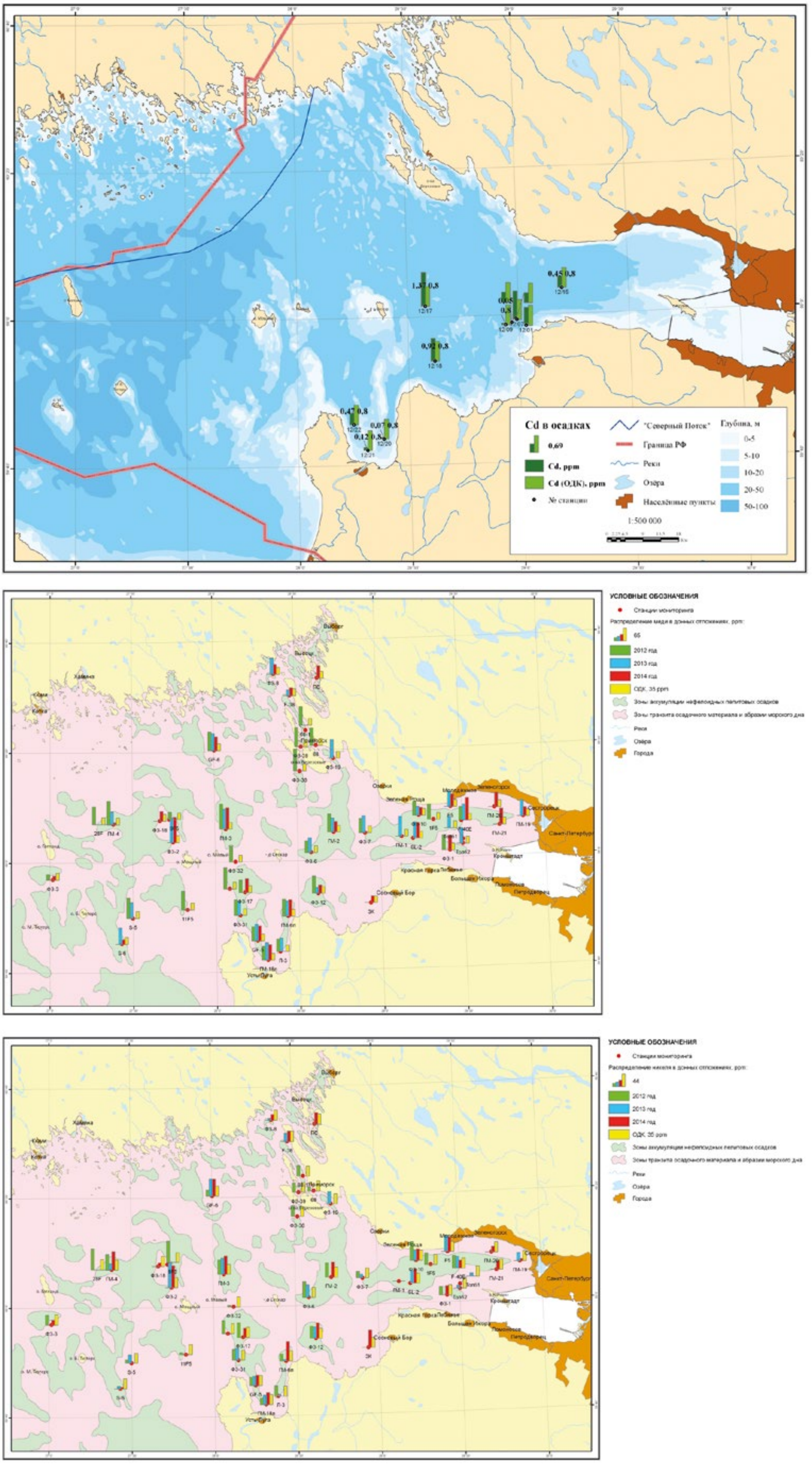


Figure 10. Distribution of Cd (above), Cu (middle), and Ni (below) as ppm (parts per million) in the bottom sediments of the eastern GOF in 2012–2014. The approximate permissible concentration is shown as a light green bar for Cd, and as a yellow bar for Cu and Ni. Source: Rybalko et al. (2015).

Table 3. Trace metal and dioxin levels (dw) in the sediments at four stations in the GOF in June 2010. Source: BaltActHaz project.

Station	**Depth**	**longitude (E)**	**Cd**	**Cu**	**Pb**	**Zn**	**Hg**	**OCDD**	**OCDF**	**1234678 HpCDD**	**1234678 HpCDF**
	m	decimal degrees	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	ng/g	ng/g	ng/g	ng/g
9	66	24.2	0.489	46.3	48.6	313	0.082	88	220	25	170
10	74	24.8	0.505	34.8	33.4	180	0.078	50	160	15	140
11	67	26.4	0.766	33.4	29.4	136	0.200	88	640	30	640
12	85	25.7	1.18	47.3	47	221	0.115	69	540	23	470
Target			1.00	100	50	200	0.5				

and somewhat lower percentages than this for arsenic (As), cobalt (Co), chromium (Cr), and Pb. An increase of 5 to 25 % was observed for copper (Cu) and zinc (Zn) in general, but both of these elements showed a decrease at the easternmost station.

The surface sediments of the GOF can be considered in general to be currently cleaner than two decades ago (Vallius et al. manuscript); recent statistical studies observed slightly more contaminated layers beneath the sediment surface than found today in the surface (Vallius 2015a, 2015b). Typically, half or more of the subsamples exceeded the lower reference levels along a transect through the middle part of the GOF, depending on the element, but only few exceeded the upper reference level (probable effect level PEL). Zn exceeded the upper reference level in about 50 cases, thus being the trace metal of greatest concern, especially since high concentrations were found in the sediment layers that represented the sediment surface as recently as in 2007–2009. Hg was observed to exceed the upper reference level deeper in the sediment, at depths of ≥ 20 cm. In another study, the highest Hg values were observed at sediment depths > 25 cm and the highest Zn values at depths of about 15 cm (Figs. 8 and 9). After dividing the data into the western and eastern GOF, a few subsamples exceeded the PEL for As and Cd, 20 subsamples for Hg, and 50 for Zn in the eastern area (Vallius 2015b). The western subsamples did not usually exceed the PEL except for one site in the Pohjanpitäjänlahti Bay (south-west coast of Finland), associated to industrial contamination.

Conclusively, the trends of trace metal deposition in the GOF area, as well as the quality of the surface sediments there, can be considered as satisfactory except what comes to the trends and levels of Zn.

Of the three GOF countries, only Russia carries out sediment quality monitoring for trace metals. Russia has the maximum allowable concentration of 0.69 mg/kg dw for Cd. This level is exceeded only occasionally in Russian waters (Fig. 10). For Cu, the corresponding concentration is 0.35 mg/kg dw. Based on a sampling programme carried out in 2012–2014, this value was exceeded virtually everywhere in Russian waters with the highest concentrations being three times the maximum allowed (Fig. 10). For Ni, the corresponding concentration is also 0.35 mg/kg dw; based on the same sampling programme this value represents a quite typical concentration of Ni in the sediments collected in the area (Fig. 10).

Trace metal and dioxin levels in the sediments in the Estonian part of the GOF were investigated in 2010 (Erm et al. 2014, Table 3). Furthermore, the concentration of trace metals and several persistent organic pollutants in the GOF sediments were studied in 2010–2011 under the BaltActHaz project (Roots and Nõmmsalu 2011a, 2011b, Roots and Roose 2013).

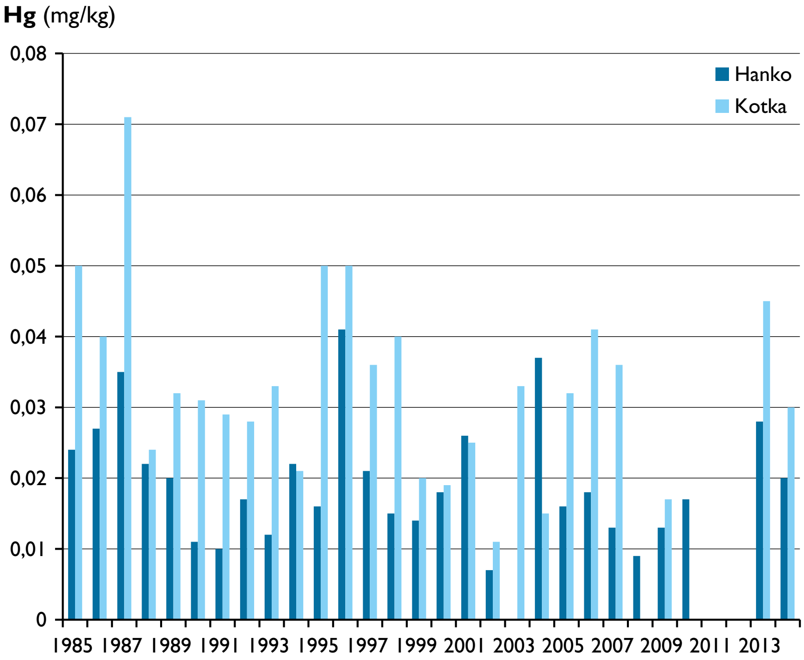


Figure 11. Hg (mg/kg ww) in herring muscle as a function of time in the Hanko and Kotka areas. The concentrations remain constantly lower than the Finnish environmental quality standard (EQS) of 0.20 mg/kg ww. Source: SYKE monitoring data.

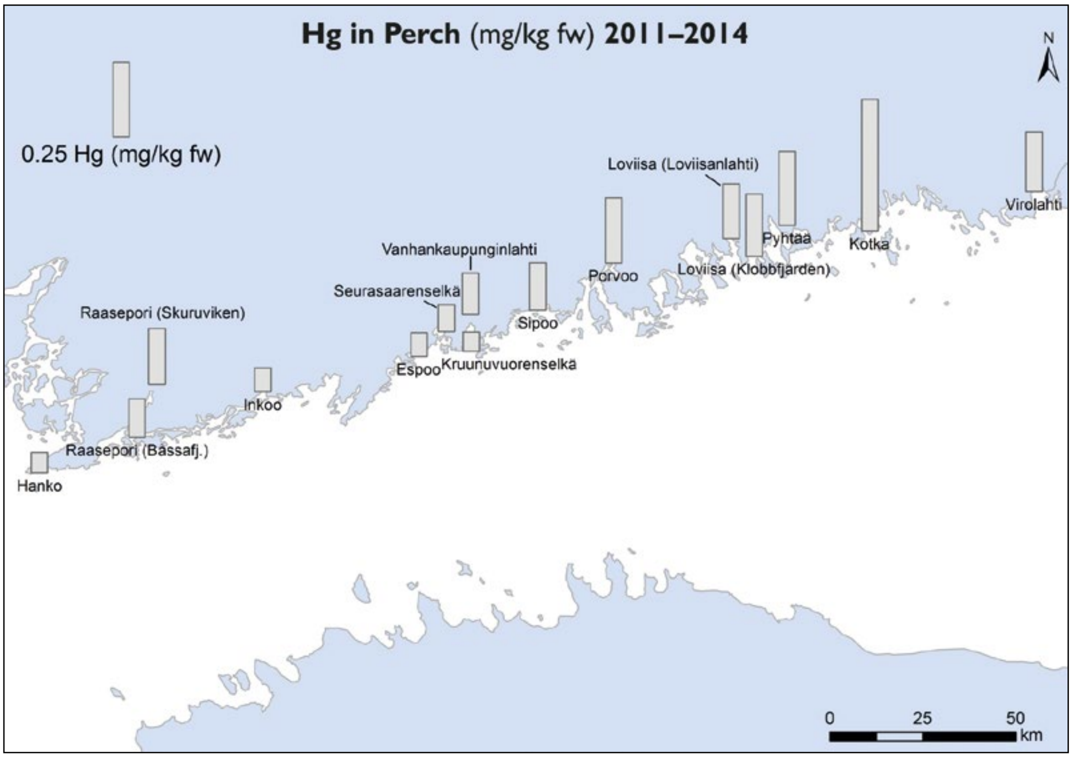


Figure 12. Hg (mg/kg ww) in perch from the Finnish coastal area of the GOF in 2011–2014. Source: SYKE database. Graph: Marco Nurmi.

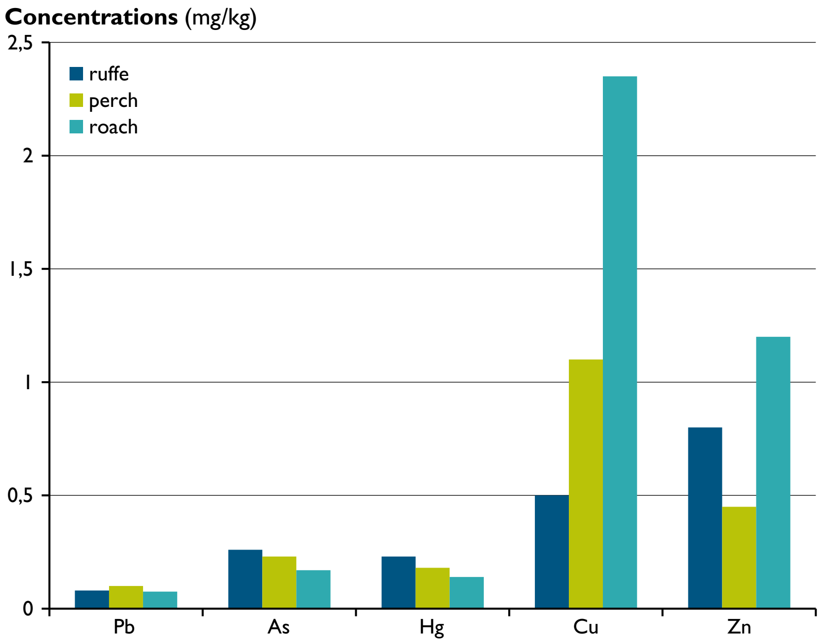


Figure 13. Average concentrations (mg/kg ww) of trace metals in fish muscle from the Neva Bay in 2013. Note: Zn concentrations have been divided by 10. Source: Liashenko OA, Svetashova ES, Ekimova SB / Berg State Research Institute on Lake and River Fisheries.

In fish

The EU limit for Hg in human food has been set at 0.5 mg/kg ww for most fish species. Hg concentrations measured from fish muscle caught in the GOF have remained below this level (HELCOM 2010). Temporal trends in Hg concentrations in herring muscle from the Hanko and Kotka areas show a slight decrease in 1995–2014 (Fig. 11). The concentrations are higher in Kotka, being in line with the trend observed in perch that shows an increase towards the east (Fig. 12). Hg concentration in perch in the eastern part of the Finnish coast exceeds the EQS value of 0.20 mg/kg ww and is roughly ten times that in herring.

Also, recent data on trace metal concentrations in fish is available from the Russian part of the GOF (Fig. 13). However, no long term data is available from this area.

Cd accumulates in liver and its concentration level in fish liver in the GOF is well above the natural background level of 0.026 mg/kg ww (HELCOM 2010). The concentration is, however, much lower in blue mussels and fish muscle. Since fish liver and mussels from the GOF are not usually consumed by humans, the high levels do not pose a direct risk to humans but, of course, do that to the marine ecosystem. Compared to Hg, Cd has a different distribution pattern; Cd seems to spread around over larger sea areas, whereas Hg shows more local anomalies close to the point sources (HELCOM 2010).

Organotin compounds

Organotins (OT) comprise mono-, di-, tri-, and tetrabutyltin as well as triphenyltin compounds. Tributyltin (TBT) is considered to be the most hazardous of them all with triphenyltin (TPhT) showing similar toxicity. OT compounds are extremely harmful to benthic organisms, such as bivalve molluscs and gastropod snails. Endocrine disruption effects, such as imposex and intersex in gastropods, are detected at very low TBT concentrations.

OTs have been used since the 1960's primarily in antifouling paints on ships and smaller vessels, and in a smaller scale as heat and light stabilizers in PVC products, antifungal agents, and wood preservatives. The use of TBT in antifouling paints was first banned in the EU in large vessels in 1991 and globally by the International Maritime Organization (IMO) in 2010. OTs tend to adsorb easily onto suspended matter, and by this way are deposited into the sediment. Therefore, high levels of TBT are still found especially in the sediments of ports, shipyards, and shipping lanes. They are easily resuspended in the water phase along with the sediments due to wave action caused by, e.g., maritime traffic, storms, underwater construction, and dredging. It is unclear how effectively OTs dissolve from the sediment back to the water. However, the main route of TBT uptake by biota is presumably by direct ingestion of TBT-containing particles.

OTs were studied in salmon, perch, pike-perch, and burbot in Hanko, Helsinki (Vanhankaupunginlahti Bay), and Kotka areas in the GOF in 2009 – 2010. In the samples from Hanko and Kotka, the concentrations of OTs in the muscle tissue varied from 3.65 to 50.3 µg/kg ww with the most common OTs detected being TPhT and TBT. Compared to a study made a few years earlier the concentrations had decreased slightly in both of these areas. In individual perch samples from the Vanhankaupunginlahti Bay, however, the concentrations of OTs were up to 384 µg/kg ww in the muscle tissue and 1 100 µg/kg ww in the liver, with no reductions compared to the levels observed in the previous study by Hallikainen et al. (2011). The main OT sources for this hot spot area are most likely the adjacent ports. Accumulation of OTs in fish liver compared to the muscle tissue indicates active metabolic removal of these compounds. From a human exposure point of view the OT concentrations in fish muscle in the GOF were relatively low (Airaksinen et al. 2010). Concentrations of OTs in perch are higher in port areas and outside them than in the GOF in general (Fig. 14). There is no long-term monitoring of OT compounds in fish.

The OT concentrations in the sediment surface are lower than those measured in the 1980's and the 1990's (Fig. 15). This is most likely caused by the combined effect of degradation and/or dissolution of the settled TBT, and sedimentation of less-polluted material.

Antifouling paints introduce OT-compounds into the marine ecosystem. Photo: Riku Lumiaro.

In benthic organisms, total butyltin concentrations in the infaunal Baltic clam *Macoma balthica* collected in different coastal areas of the GOF (outside harbour hot spots) ranged from 13 to 128 ng Sn/g dw, the share of TBT being 31 to 83 % (Lehtonen et al. unpubl.).

In Russia, no official analytical method for TBT determination is in use, and few laboratories have TBT analytics in their area of expertise. However, applying the available methods, high levels of TBT chloride have been measured in the sediments of the easternmost GOF, with the highest level (6 000 µg/kg dw) registered along the main St. Petersburg shipping route near Krasnaya Gorka (Khoroshko et al. 2012). In a more comprehensive study targeted on TBT and related OT compounds during the HELCOM project BALTHAZAR, OTs were found both in water and sediments of the River Neva and the Neva Bay (Table 4). It is noteworthy that TBT was not a major OT in low or moderately polluted sediments, and only in the most contaminated sediment in the Tolbukhin Island area it comprised about 85 % of the total OT pollution.

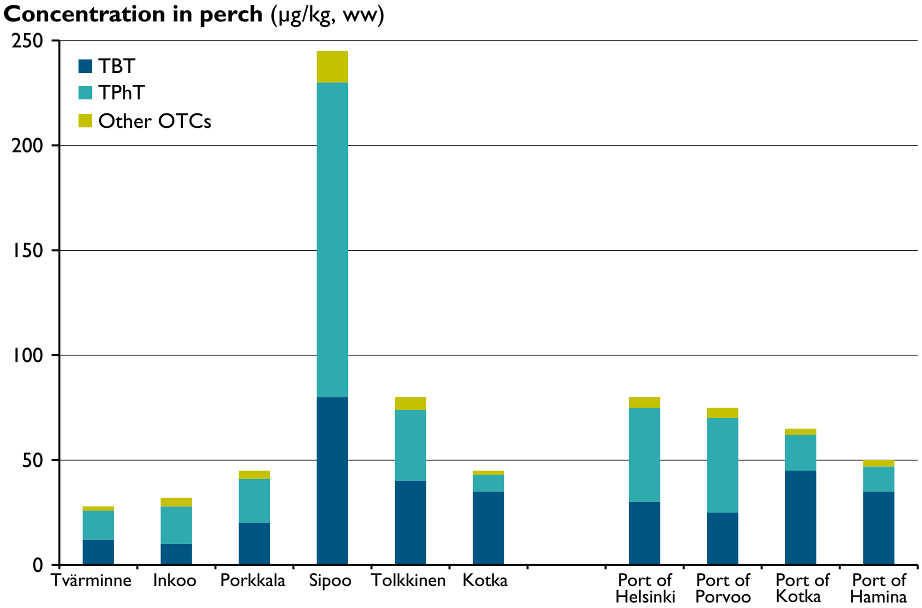


Figure 14.
OT compounds (µg/kg ww) in perch in the Finnish coast in 2005–2007. There is always a marked share of TPhT along TBT in perch muscle. In the left: coastal areas, in the right: ports. Source: Rantakokko et al. (2010).

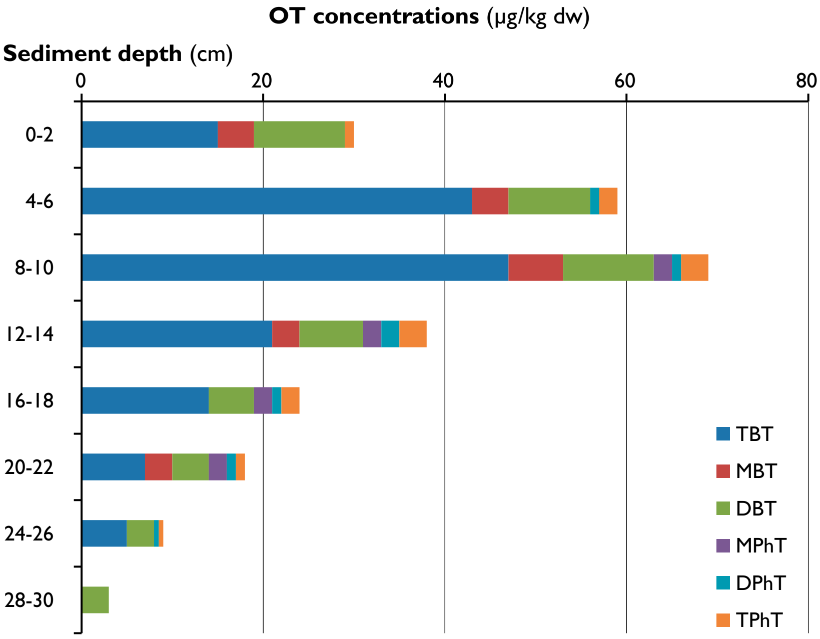


Figure 15.
OT concentrations (µg/kg dw) as a function of sediment depth in an accumulation area off the town of Loviisa in the Finnish coast.
TBT=tributyltin,
MBT=monobutyltin,
DBT=dibutyltin,
MPhT=monophenyltin,
DPhT=diphenyltin,
TPhT=triphenyltin.
Source: Hallikainen et al. (2008).

Table 4. OTs in the River Neva water, in surface sediments in the Neva Bay, and in the WWTP waters of St. Petersburg. MBT = monobutyltin, DBT = dibutyltin, TBT = tributyltin, TPhT = triphenyltin. Source: BALTHAZAR project.

			MBT	DBT	TBT	TPhT
River Neva water	near Slavyanka	ug/L	< 0.01	0.63	1.44	6.41
	near Sapernyi	ug/L	< 0.01	0.97	1.39	1.67
Surface sediments in the Neva Bay	Tolbukhin island	ug/g	3.71	1.62	33.6	0.14
	Strelna	ug/g	0.15	1.25	0.04	0.11
	Port	ug/g	0.32	2.02	0.34	0.06
	Utkina Zavod	ug/g	0.38	9.51	0.15	0.17
	Elagin bridge	ug/g	0.05	0.22	< 0.01	0.07
	Golovin bridge	ug/g	< 0.01	0.57	< 0.01	0.04
	Duderhof	ug/g	< 0.01	0.23	< 0.01	0.05
	Neva near Ostrovki	ug/g	0.06	1.71	< 0.01	0.04
	Ohta river mouth	ug/g	0.04	0.09	< 0.01	0.09
St. Petersburg's WWTP waters	Influent	ug/L	2.09	2.21	< 0.01	1.33
	Effluent	ug/L	0.74	0.42	< 0.01	0.98

Regarding the effluent waters of the St. Petersburg's WWTPs, OTs were detected only in one out of three plants studied (Table 4), indicating a local pollution source.

However, the data on OTs in the Russian part of the GOF has to be treated with caution, since the ISO 17353:2004 analyzing method was employed with certain limitations. In many cases the measured concentrations in the water exceeded the EU AA-EQS of 0.0002 µg/l, and also the Russian maximum allowable concentration (MAC) of 0.01 µg/l. The methods used do not allow the detection of OTs below the former concentration. Information of OTs in biota in the Russian part of the GOF is not available.

St. Petersburg is one of the largest sea ports in the BS region. There are also other large ports in the Russian part of the GOF, including Luga, Vyborg, Primorsk, Vysotsk, and Kronstadt. As maritime traffic is a major source of OT compounds, monitoring of the Russian part is important. Currently, a monitoring program for OTs does not exist and most of the available data needs verification. Conclusively, the available data is not sufficient for drawing any reliable conclusion on the state of OTs in the Russian part of the GOF.

Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are carcinogenic substances that originate from pyrolytic and petrogenic sources but can also be formed in natural processes. PAHs detected in the marine environment are most likely of anthropogenic origin, coming from crude oil and its products, and from incomplete combustion. Aliphatic and aromatic hydrocarbons occur naturally in mineral oils and also in refined oil products. Synthetic oils have a considerably lower concentration of aromatic and polyaromatic compounds compared to refined or crude oils. Major sources of PAHs include emissions from both maritime and terrestrial traffic.

Increased maritime traffic has resulted in frequent oil spills in the BS but their number and volume have decreased in the recent past (HELCOM 2014a). Currently, illegal oil spills are actively monitored using airplane and satellite surveillance by most of the states surrounding the GOF.

Illegal oil spills are easier to detect during the ice season. Photo: Riku Lumiaro.

Many of the PAHs are highly toxic and can cause harmful effects in organisms, including fish. However, fish are able to degrade and excrete many of the PAHs (Tuvikene 1995). Importantly, the intermediary products of PAH compounds are often more toxic than the parent compound itself. As metabolites of PAHs are excreted in the bile of fish, exposure to PAHs can be monitored by measuring their concentrations in the bile (Vuontisjärvi et al. 2004, Vuorinen et al. 2006). The common PAH metabolite, 1-hydroxypyrene, is commonly detected in the bile of several BS fish species, and elevated concentrations have been detected especially in bottom living species (Vuontisjärvi et al. 2004). Highly elevated levels of 1-hydroxypyrene were detected in bile of perch caught in the GOF in the vicinity of an oil refinery (Vuorinen et al. 2003).

In Finland, the former HELCOM and current EU MSFD monitoring of oil in seawater relies on the use of fluorometric analysis of seawater extracts, and originates from an early protocol devised by the International Oceanographic Committee (IOC). This analytical approach yields the concentration of total dissolved and dispersed fractions of oil (or better, oil-derived fluorescent molecules), reflecting the concentrations of PAHs present in seawater. The IOC environmental quality concentration threshold for contaminated seawater, 1.0 µg/l of total oil, has been set as the Finnish EQS in the EU MSFD monitoring. Even though this limit value is occasionally exceeded nowadays, the general trend in concentrations of total dissolved oil has been to decrease, reflecting the overall improvement of the state of BS regarding hydrocarbons (Fig. 16).

In the Russian part of the GOF, total hydrocarbons are regularly monitored in the near-bottom waters and the sediments. There are differences in sampling and analytical methodologies between Russia (infrared spectroscopy of near-bottom water) and Finland (UV/VIS fluorescence spectroscopy of subsurface water), and therefore the results (Fig. 17) are not fully comparable. Since the start of the hydrocarbon mapping in 2007, higher concentrations have been found in sediments located in some main sedimentation areas, and in anthropogenically impacted coastal areas, possibly due to the construction of new harbours.

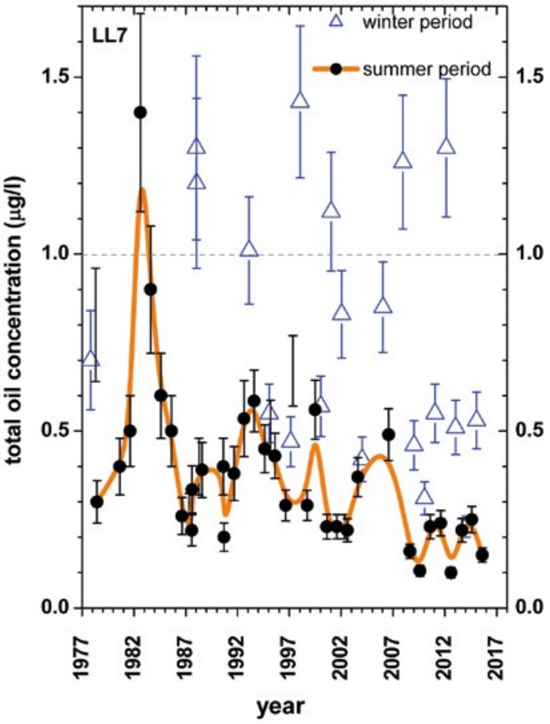
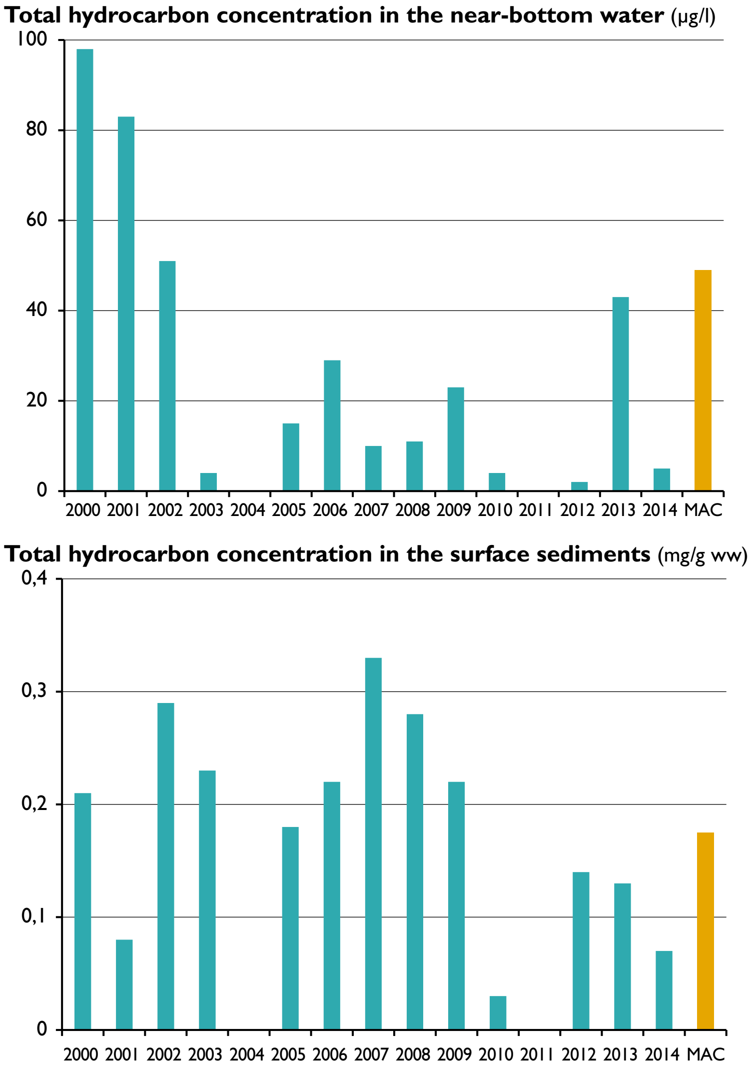


Figure 16.
Total oil concentration (µg/l) in the GOF surface water over the past four decades, exemplified by data obtained at station LL7 (middle part of the GOF). The wintertime total oil concentration typically fluctuates considerably, which may partly relate to the natural patchiness of emissions caused by maritime traffic. The dashed line denotes the IOC EQS limit. Source: Finnish monitoring programme. Graph: Harri Kankaanpää.


Total hydrocarbon concentration in the near-bottom water (µg/l)

Total hydrocarbon concentration in the surface sediments (mg/g ww)

Figure 17.
Total hydrocarbon concentration as a function of time in the Russian part of the GOF in 2000–2014. Upper: in the near-bottom water (µg/l). Lower: in the surface sediments (mg/g ww). The red bar represents the maximum allowable concentration (MAC) set by Russia. Source: Rybalko et al. (2015).

Pharmaceuticals

During the past decade, human and veterinary consumption of various types of pharmaceuticals was finally recognized as a highly relevant environmental issue in spite of the fact that their use and subsequent release in the environment has been continuous for a long time. While data on their sources and occurrence in the environment are accumulating, knowledge about their environmental fate and effects on the ecosystem is still scarce.

Pharmaceuticals are released into the environment from various sources, including WWTPs (sewage effluent waters and sludge), incorrect pharmaceutical waste treatment, veterinary medication, industrial sources, direct consumer use, and atmospheric fallout. Releases from pharmaceutical industry are often reported to be negligible in the Western World, but actual evidence to back up this claim is scarce. Currently, there are no regulations for the monitoring of pharmaceuticals in the aquatic environment, nor there are any threshold values for treated wastewaters (HELCOM 2010).

Pharmaceuticals are designed to have biological effects even at low concentrations, making them potentially harmful to non-target organisms. As an example, hormones and hormone-like substances, such as 17α-ethinylestradiol (EE2) and 17β-estradiol, can interfere with the normal functioning of the endocrine system associated with reproduction. They may alter the behaviour of aquatic organisms at environmentally realistic concentrations. Mating of sand goby, an abundant fish species in coastal waters of the GOF, was found to be disturbed during exposure to < 10 ng/l of EE2 (Saaristo et al. 2009a, 2009b, 2010a, 2010b). Also other pharmaceuticals than hormones can have behavioural impacts; the anxiolytic drug oxazepam was shown to affect the behaviour of perch by increasing their activity and feeding rate, and reducing sociality (Brodin et al. 2013). These types of effects can manifest at the population level as a reduced number of offspring.

Little is known of the development of microbial resistance to antibiotics in aquatic ecosystems. However, antibiotics and their resistance genes have been found in the sediments at fish farming locations in the Turku archipelago (Muziasari et al. 2014).

Rivers in the BS drainage area have been shown to contain up to µg/l -scale concentrations of certain pharmaceuticals, including carbamazepine and metoprolol (IVL database 2013, Äystö et al. 2015). Data on pharmaceuticals in the GOF is scarce since only a minority of a few studies so far conducted on the topic in the BS area has been carried out in the GOF. One of these studies was carried out in the sewage system of St. Petersburg, with the following results:

- Concentration of the common anti-inflammatory drug diclofenac in the effluent varied from 355 ng/l in the summer 2013 to 550 ng/l in the winter 2014. The upper limit for the daily release of diclofenac was estimated to be 1.1 kg, making the annual load about 400 kg. It is estimated that 5 ng of this pharmaceutical flows into the GOF per one litre of the River Neva water (HELCOM 2014b).
- Concentration of EE2 in the effluent water was < 0.004 ng/l, not exceeding the EQS of 0.007 ng/l. The annual amount of EE2 introduced to the sewage system was estimated not to exceed 315 g.
- Concentration of the naturally-produced human estrogen E1 in the effluent remained below the detection limit of 10 ng/l, and the estimated concentration in the water flowing to the GOF would thus not exceed 0.1 ng/l. The annual load of E1 was estimated to be about 40 kg.
- Other natural estrogens such as E2 or E3 were not detected in the influent or effluent samples.

Table 5. Concentrations of pharmaceuticals in passive samplers (type POCIS) at mussel caging sites at varying distances from the Viikinmäki WWTP discharge site. The compounds detected belong to anti-inflammatory drugs (diclofenac, ibuprofen, ketoprofen, and naproxen), beta blockers (acebutolol, bisoprolol and metoprolol), antidepressants (venlafaxine), and antiepileptic drugs (carbamazepine). The values are given as ng/sampler. nd=not detected. Source: Turja et al. (2015).

Pharmaceutical	0.8 km	1.1 km	4.0 km
Diclofenac	25 ± 8	33 ± 1	nd
Ibuprofen	12 ± 1	nd	nd
Ketoprofen	20 ± 9	nd	nd
Naproxen	39 ± 10	12 ± 3	nd
Metoprolol	40 ± 6	25 ± 4	8 ± 2
Bisoprolol	39 ± 3	19 ± 4	5 ± 1
Acebutolol	8 ± 1	4 ± 1	nd
Venlafaxine	25 ± 5	14 ± 2	nd
Carbamazepine	232 ± 15	232 ± 7	147 ± 5

Table 6. Levels (ng/l) of pharmaceuticals in the waters of some rivers discharging into the GOF compared to maximum and average concentrations observed in rivers in the EU area. Results have been obtained within the framework of the international project “EU Wide Monitoring Survey of Polar Persistent Pollutants in European River Waters”. Source: Loos et al. (2009).

Substance	River Emajõgi	River Purtse	River Narva	River Vantaa	Maximum content in EU rivers	Average content in EU rivers
Ibuprofen	6	< 1	3	< 1	31 323	395
Diclofenac	3	1	2	< 1	247	17
Bentazone	2	< 1	1	< 1	250	14
Benzotriazole	13	< 1	< 1	30	7 997	495
Caffeine	22	22	15	74	39 813	963
Carbamazepine	15	< 1	3	11	11 561	248
Methyl-benzo-triazole	< 1	90	< 1	60	19 396	617

Accumulation of pharmaceuticals and possible biological effects caused by exposure to WWTP effluents were investigated using passive samplers and mussels (*Mytilus trossulus*) in the vicinity of the Viikinmäki WWTP discharge site off Helsinki using the caging approach (Turja et al. 2015). Two cages were deployed for one month in the vicinity of the WWTP discharge site and one at a reference site. Increased antioxidant defence system responses, genotoxicity, and lysosomal responses were observed in the mussels close to the discharge site. For most of the detected pharmaceutical compounds the concentrations were higher closer to the discharge site (Table 5).

In 2008, a pan-European project dealing with pharmaceuticals in the rivers was carried out, and three rivers from Estonia and one from Finland discharging to the GOF were included (Table 6). The results show that concentrations of pharmaceutical substances in these rivers appeared to be clearly lower than in European rivers in general.

Radioactive compounds

Radioactive substances can be man-made or of natural origin. The man-made substances pose a greater risk to humans and wildlife than the naturally occurring ones (HELCOM 2010). Their main source to the BS is the Chernobyl disaster in 1986. Another prominent source is the large-scale nuclear weapon testing carried out in the 1950's – the 1980's (Fig. 18). The share of the currently operating nuclear power plants to radioactivity is negligible. Due to the Chernobyl fallout, the most dominant man-made radionuclide found in the BS is cesium-137 (^{137}Cs, Fig. 19). The estimated input of ^{137}Cs from Chernobyl to the BS was 4 700 × 10^{12} Bq. To scale, the post-Chernobyl discharge to the BS is estimated to equal 300 × 10^{12} Bq (Leppänen et al. 2012).

Studies show that radioactive pollution originating from man-made sources into the BS is clearly declining but still remains very conspicuous. The target for radioactivity in the BS has been set at the pre-Chernobyl level of 14.6 Bq/m^3 which will be reached at some point between 2020 and 2030 (Leppänen et al. 2012).

Concentrations of radioactive substances in biota regularly correlates with those observed in the sea water and the sediment. In the Finnish coastal areas, ^{137}Cs accumulates more efficiently in predatory fish. Consequently, the highest levels of radioactivity have been recorded in pike and cod. Radioactivity in herring has declined since 1986 (Fig. 20), slightly more steeply in the GOF than in the Bothnian Sea. The reason for this difference is the better water exchange between the GOF and the Gotland Basin than between the Bothnian Sea and the Gotland Basin.

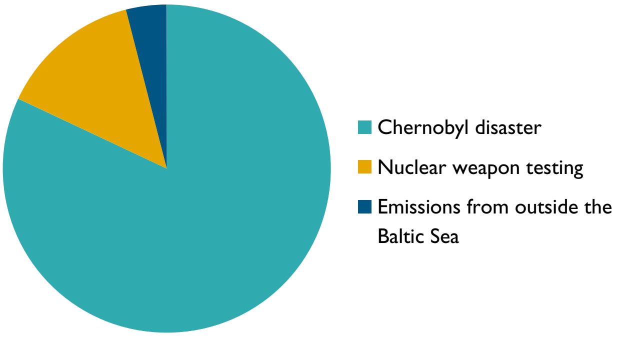


Figure 18. Main sources of radioactivity in the BS. Source: HELCOM (2009).

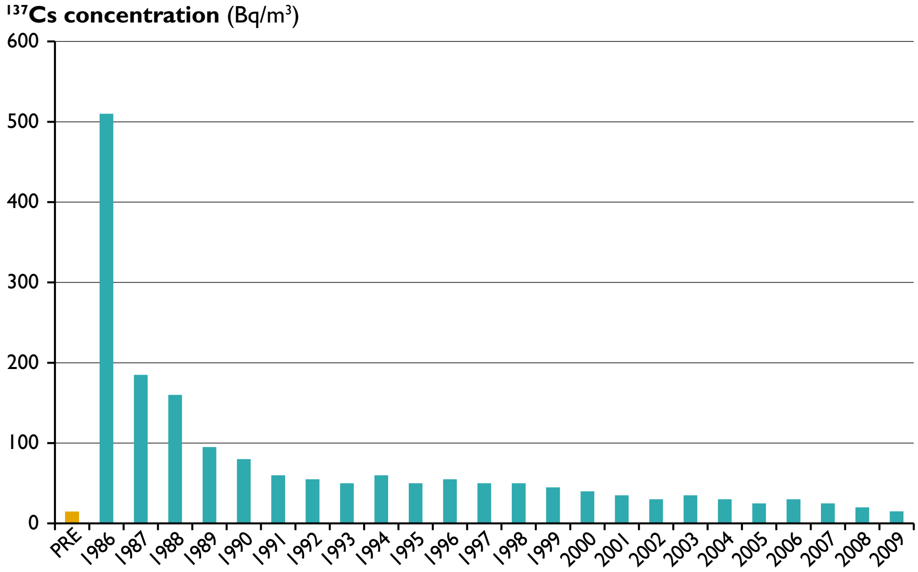


Figure 19. ^{137}Cs in seawater in the GOF as a function of time. The half-life of ^{137}Cs is 30.2 years. PRE = pre-Chernobyl activity concentration (1984–1985 average). Source: HELCOM (2009).

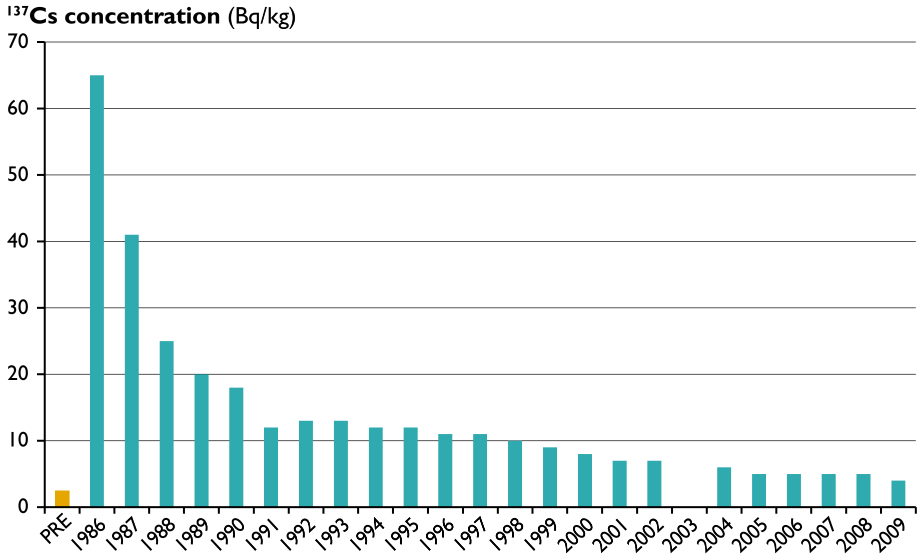


Fig. 20. ^{137}Cs in herring in the GOF as a function of time. PRE = pre-Chernobyl activity concentration (1984–1985 average). Source: HELCOM (2009).

A large fraction of the Chernobyl-derived radioactivity resides in soft sediment deposits. Coinciding with the atmospheric trajectory of the Chernobyl fallout, the soft deposits of the middle to eastern GOF contained the highest radioactivity in 1992–1995: up to 2.4 kBq/kg ww (Kankaanpää et al. 1997, Outola et al. 2014). The highest radioactivity measured in the GOF sediment was 31 000 Bq/m^2, and 11.4 Bq/kg dw was detected in benthic animals (the isopod *Saduria entomon*; Outola et al. 2014). The gamma and beta radiation emitting layers are now well isolated from the GOF ecosystem and are considered to cause no major hazard to the health of organisms except for the benthic fauna that lives in their close proximity.

Algal toxins

Algal toxins (also called phycotoxins) are hazardous substances often produced in high concentrations by harmful phytoplankton species. Harmful algal blooms (HABs) are nowadays a common global phenomenon. In the BS, cyanobacterial HABs are the predominant ones, covering areas up to about 100 000 km^2 (Hansson 2006). They are supported by excess nutrients – especially inorganic phosphorus – in seawater and favourable physical conditions during the summer. The blooms are natural in the sense that cyanobacteria have been present in the BS for millennia. The blooms have, however, intensified since the 1960's (Poutanen and Nikkilä 2001).

Many algal toxins bioaccumulate to biota to some degree (Eriksson et al. 1989, Falconer et al. 1992, Sipiä 2001). Flounder, cod, salmon, herring, three-spined sticklebacks, and especially bivalves have been found to accumulate cyanobacterial toxins. Human exposure to algal toxins via fish is unlikely since they accumulate mainly in fish liver, which is not often consumed by humans. Some fish species, such as trout and flounder, can recover quickly from severe acute liver damage (Kankaanpää et al. 2002, Vuorinen et al. 2009). Chronic exposure to cyanobacterial toxins may, however, promote cancer.

It is likely that aquatic organisms have become more or less adapted to various phycotoxins during their co-evolution. However, laboratory studies have shown that a short-term exposure of bivalve and crustacean species to the cyanobacterial toxin nodularin and/or *Nodularia spumigena* extracts causes negative effects at the molecular and biochemical level (Lehtonen et al. 2003, Kankaanpää et al. 2007, Turja et al. 2014). Supposedly, the most likely and ecologically relevant impact of phycotoxins could be to add up to mixture toxicity, i.e., triggering combined effects with anthropogenic

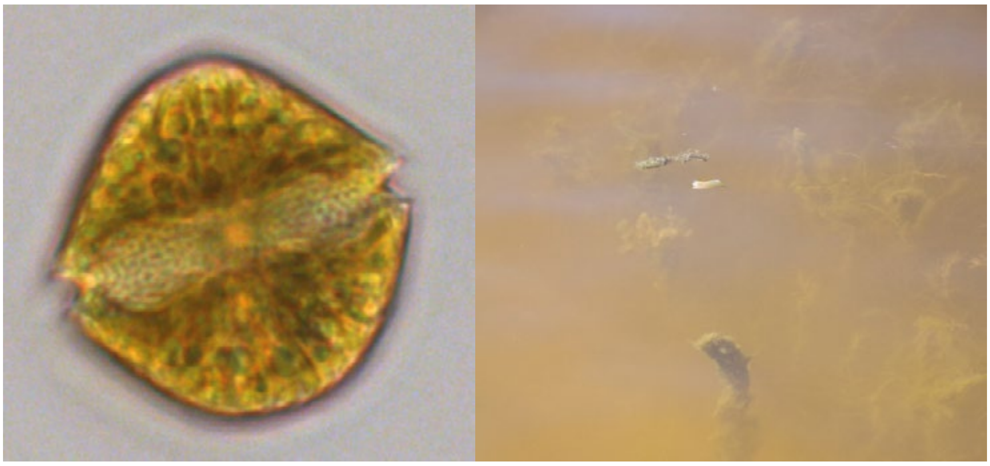


Figure 21. Left: *Alexandrium ostenfeldii*, which produces two neurotoxins: saxitoxin and gymnodimine. The former can cause paralytic shellfish poisoning and the latter induces neurological effects. Right: Exceptionally dense bloom of > 6 million cells/L of *A. ostenfeldii* at Föglö (Åland) in August, 2014. Photo: Anke Kremp, Elin Lindehoff.

contaminants. Since the concentrations of phycotoxins can be locally extremely high in the late summer they can modulate the effects of other chemicals present in the seawater.

There are several species known to produce toxins in the GOF phytoplankton community. The known phycotoxins include:

- nodularin-R: synthesized by the cyanobacterium *Nodularia spumigena*
- microcystin-LR: synthesized likely by cyanobacteria of the genera *Anabaena*
- polyether-structured pectenotoxins, dinophysistoxins, and okadaic acid: synthesized by species of the genera *Dinophysis*. The latter compound is found only in flounder and blue mussels
- saxitoxin-group compounds, such as saxitoxin and gonyautoxins 2 and 3: synthesized by the dinoflagellate *Alexandrium ostenfeldii* (Fig. 21).

Although not persistent in the same sense that the industrial persistent organic pollutants are, phycotoxins may be hazardous due to their toxicity during blooms. Hepatotoxic nodularin-R and microcystin-LR are produced and constantly accumulated in biota. They are able to induce acute and long-term carcinogenic effects in target organisms. These toxins are annually monitored in seawater, plankton, herring, and flounder as part of the Finnish MSFD monitoring program.

The blooms of *Nodularia spumigen*a are a recurrent, annual phenomenon in the GOF, and so is the presence of the nodularin-R. Hepatotoxins were abundantly present in Baltic herring's liver tissue when analyzed for the first time in 2014. Due to their preferred accumulation and rapid detoxication in the liver, no markedly elevated concentrations have been measured in the Baltic herring's muscle tissue (Kankaanpää et al. 2002). The WHO EQS limit for potable water of 1.0 µg/l has also been set for seawater in the Finnish MSFD monitoring, and this limit is usually not exceeded. Currently, there are no EQS limits for hepatotoxin concentrations in marine organisms, but the WHO tolerable daily human intake (TDI) value of 40 ng/kg per day for cyanobacterial hepatotoxins can be applied (Barda et al. 2015).

Scattered or indirect evidence shows that polyether toxins and neurotoxins of the saxitoxin family are also present in the northern BS ecosystem, at least sporadically. These neurotoxins consist of alkaloids that can elicit rapid acute effects. Some of the species producing these toxins (*Dinophysis* spp. and *Alexandrium ostenfeldii*) are at times abundant in the Åland archipelago area, but are also present in the phytoplankton community of the GOF. Thus, the occurrence of these toxins in the area is possible, if not probable.

Biomarkers

Hazardous substances in the environment can be detected by measuring not only their concentrations but also their effects. Monitoring of biological effects of contaminants has been largely underdeveloped in the BS as a whole (Lehtonen et al. 2006), and in the GOF in particular. Only until rather recently, some international research projects (e.g., EU BEEP, BONUS+ BEAST, and BALCOFISH) have made efforts in developing integrated biological-chemical monitoring of hazardous substances in the area.

Biomarkers – covering molecular, biochemical, cytological, and physiological indicators of pollution induced stress – are useful in detecting exposure to and effects of hazardous substances. Many of them have strong links to pathological disorders and diseases, and provide early-warning indications whenever the health of organisms is compromised, and have prognostic value for effects occurring at population, community, and ecosystem levels. Field studies using biomarkers have recently been carried out in the GOF on various invertebrate and fish species to assess their health status. The methods applied include biomarkers of neurotoxicity, oxidative stress, xenobiotic metabolism, genotoxicity, cardiac activity, bioenergetics, and general stress (Lehtonen et al. 2006, Turja et al. 2013, 2015, BONUS BEAST project, unpubl.).

Until now, no regular monitoring of biological effects has been carried out by Finland, Estonia, or Russia. The HELCOM CORESET project has identified several biological effects to be recommended for the monitoring toolbox for the BS to fulfill the requirements of the EU MSFD (HELCOM 2012). Finland has started a monitoring programme of lysosomal membrane stability (LMS) that is a biomarker of general stress; at first for herring in the offshore area in 2014, and then for perch in the Finnish coastal waters in 2015, including the GOF. Some sporadic measurements have already been made in different parts of the BS, both in blue mussels and fish (Figs. 22 and 23).

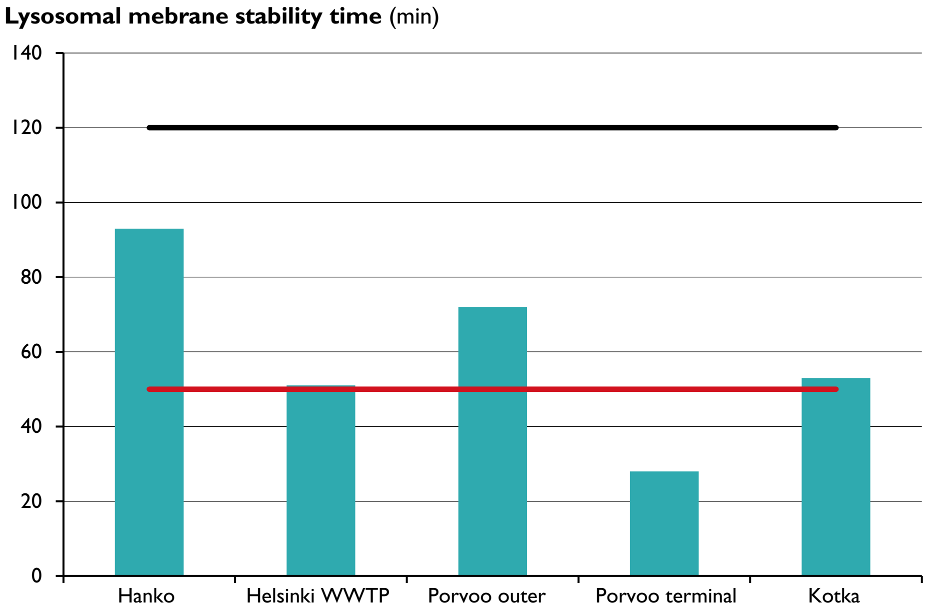


Figure 22. Lysosomal mebrane stability (LMS) time in caged mussels (*Mytilus trossulus*) in the Finnish coastal area, measured using the Neutral Red retention method on live haemocytes (Moore et al. 2014). OSPAR/ICES background (BAC, black line) and environmental (EAC, red line) assessment criteria thresholds for LMS in mussels are also shown. The key for interpretation: a short LMS time indicates poor condition of the individual. Source: Turja et al. (2015, unpubl.).

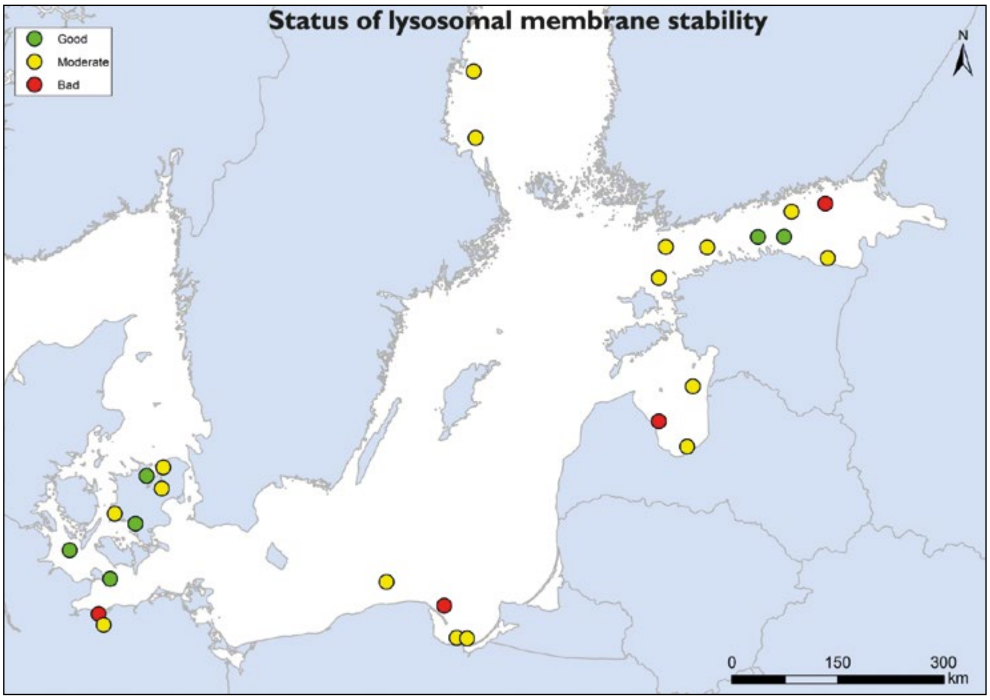


Figure 23. The status of the LMS indicator (histochemical method, Moore et al. 2014), based on measurements in flounder, eelpout, and herring by using the "one-out-all-out" principle, i.e., showing the lowest status class at each site. Green colour: good status, yellow: moderate status, and red: bad status (by the EAC threshold, see the previous caption). Source: BONUS+ BEAST project data in 2009–2010 (Lehtonen et al. manuscript).

Conclusions

In general, most of the hazardous substances that are of concern in the GOF are persistent and bioaccumulative. In addition, a chemically highly variable group of so-called emerging substances is regarged as a new threat. With regard to biological effects the hazardous substances present in the area may be acutely toxic or cause various sublethal effects, such as disturbances in hormonal balance, that can lead to effects at higher biological levels (population, community, ecosystem) through reduced fitness and reproduction capacity of individuals.

The most recent HELCOM assessment of hazardous substances (HELCOM 2010) noted that the confidence of the assessment regarding available data from the GOF was among the lowest in the BS, both quantitatively and qualitatively. It is therefore of utmost importance to arrange monitoring and to coordinate analytical methods and quality objectives of hazardous substances in a more coherent manner between Estonia, Finland, and Russia. Without geographically well-covered and quality assured monitoring data, a reliable status assessment cannot be made. Likewise, without a continuation of the monitoring it is not possible to assess the outcomes of management actions.

Most of the persistent and bioaccumulative substances introduced to the sea are still circulating in the ecosystem, and some, such as the versatile group of perfluorinated substances, are still on their way from the watershed to the marine realm. In addition to more regular monitoring, there is an urgent need for proactive screening campaigns targeted at new emerging compounds, some of which have similar hazardous properties as have the compounds that are already known and currently monitored.

Despite of the restrictions in use and observed declines in some of the monitored substances, people around the GOF are still exposed to persistent hazardous

White-tailed eagle is one success story in the conservation of the BS. Photo: Juha Laaksonen.

substances, mainly by fish consumption. However, the levels of dioxin and dl-PCBs in fatty species, such as herring, salmon, and sea trout, have decreased from the very high values of the past. In the light of the present data, PBDEs and perfluorinated compounds (e.g., PFOS) as well as TBT mainly occur in relatively low concentrations in fish, but the risks they pose are difficult to estimate due to scarce spatial and temporal data and no information on their biological effects. More hot spots are likely to be found in the vicinity of larger cities and ports. These compounds also currently lack maximum allowable concentrations in food. Regarding the "classical" trace metal contaminants Cd and Hg in the GOF, concentrations in small herring have remained at a low and constant level. Due to biomagnification in the food web the concentrations of Hg may occasionally exceed the threshold levels for human food in large predatory fish.

Due to their continuous usage, pharmaceutical compounds are found excessively not only in effluents but also in coastal waters. There is an urgent need for more information on both concentrations and effects of these compounds.

Regarding information on biological effects of hazardous substances on the biota of the GOF, the situation has been improving recently due to various targeted projects. The results show clearly that the concentrations of substances in areas close to hot spots, such as cities, ports, and WWTP discharge sites, are high enough to elicit various biomarker responses in organisms affecting their fitness and health. However, without any regular monitoring data no reliable assessment can be made on the current seriousness and extent of the problem, nor on its future development, nor on its linkages to observed population changes, e.g., in commercial fish species.

Recommendations

According to the results of HELCOM's most recent integrated assessment 1999 – 2007 of the status of hazardous substances, the entire BS is an area characterized by a high contamination level (HELCOM 2010). Waters off all larger cities were commonly classified as having a moderate or poor status concerning the levels of hazardous substances and their effects. The assessment stated that certain hazardous substances lack ecologically relevant threshold levels required in risk assessment and their environmental fate is poor. Such substances include, e.g., all PFAS and pharmaceuticals. However, their concentrations in the marine environment are already significant and may still increase. Therefore, it is next to impossible to suggest any targeted measures to improve the situation as long as the knowledge on their main emission sources, transport mechanisms, and spatial distribution is not there. There is a critical need to implement the measures that have already been agreed upon within different international frameworks for the protection of the marine environment (e.g., HELCOM BSAP, EU MSFD), and to plan for future measures.

As a result of the current compilation of data and assessment on hazardous substances in the GOF presented in this chapter, a list of actions presented below is recommended for improving the situation in the GOF area.

- Improved statutory monitoring of hazardous substances and reduced emissions to water:
  - more information about the use, emissions, and occurrence of hazardous substances with regard to industrial and other activities needing an environmental permit to clarify possible associated risks
  - more reliable emission inventories enabling cost-efficient targeting of emission reduction measures
  - better technology for hazardous substance removal in WWTPs
  - developing of a set of regional priority substances for the monitoring of both old and emerging substances
  - harmonization and selection of methods for the assessment of biological effects
  - development of common threshold values (environmental quality standards) for chemicals / substances and their effects to enable comparable status assessments
  - establishment of a trilateral expert group for the harmonization and optimization of monitoring activities
  - development of a joint open-access database for the available monitoring data
- More accurate emission inventories of hazardous substances and reduced air emissions: more reliable emission inventories enabling cost-efficient targeting of emission reduction measures.
- More research on emerging problems, including pharmaceuticals and microplastics: targeted research on ecotoxicity, emission sources and pathways, environmental levels and impacts, and cost-efficiency of emission reduction measures of pharmaceuticals and microplastics for risk assessments and risk reduction measures.
- Dredging of contaminated sediments to be minimized and performed in an environmentally acceptable manner:
  - minimizing the resuspension of hazardous substances from the sediments to the marine food web during dredging and disposal of materials
  - assessment on hazardous substances and ecotoxicity of sediments prior to dredging and disposal activities
  - evaluation of clean-up measures

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BIODIVERSITY

Chapter coordination: Markku Viitasalo, Finnish Environment Institute

Viewpoint

Sergey Golubkov[1]*, Markku Viitasalo*[2]

[1] *Zoological Institute, Russian Academy of Sciences*
[2] *Finnish Environment Institute*

Life in the salinity range

The Baltic Sea (BS) is usually considered a low-diversity ecosystem due to its salinity level that is, east of the Danish Straits, unfavourable for most of the freshwater and marine organisms. However, if also sea areas having almost fresh water and the shallowest sublittoral are taken into account, the diversity may not be particularly low. This subject has received much attention in the recent past (Telesh et al. 2011, Ptacnik et al. 2011). Zettler et al. (2014) counted 2 035 macrozoobenthic species living in the BS, of which 480 taxa occupied the Gulf of Finland (GOF). Furthermore, an inventory done for the eastern GOF revealed about 200 taxa of macrozoobenthos (Balushkina et al. 2008).

Although the salinity range limits the number of species in the GOF, the diversity is increased by the existence of various environmental gradients and high geodiversity, which creates an array of habitat types suitable for specific communities. Also, various human induced pressures deriving from, e.g., cities, agriculture, fisheries, industry, maritime transport, and tourism create additional gradients across the GOF. Finally, the high seasonality creates variability that especially affects the communities consisting of short-lived organisms, such as plankton and filamentous algae.

Photo: Mats Westerbom.

Frames for marine life

Eutrophication, the climate change, harmful substances, habitat modification, and arrival of non-indigenous species all affect the GOF ecosystem. The pronounced nutrient load and gradually-inclined water temperature lead to offshore blooms of phytoplankton and cyanobacteria and to intensive growth of filamentous algae in the coastal GOF (Golubkov 2009). The sea surface temperature has increased by 1.6 °C during the last two decades, and the duration of ice period in the eastern GOF has become shorter by 15 days (Eremina et al. 2013). Both of these factors favour algal growth. Decomposition of large biomasses of decaying algae causes oxygen depletion, which for its own part has deteriorated the benthic communities in the GOF (Lehvo and Bäck 2001, Berezina and Golubkov 2008, Gubelit and Berezina 2010).

The ecological state of the GOF has not markedly improved despite the reductions in the land-based nutrient load (see chapter Eutrophication). The status of the GOF is apparently not only determined by human-induced factors, but also by climate-driven changes in hydrography and biogeochemistry.

Cyanobacterial and filamentous algal blooms: typical examples of nearly monocultures in the sea. Increases in biomass and biodiversity do not go hand-in-hand. Photo: Riku Lumiaro.

The open boundary between the Gotland Basin and the GOF makes the GOF sensitive to processes taking place outside it. The anti-clockwise current pattern of the BS transports surface water and associated nutrients and plankton from the Gotland Basin into the GOF, and the recurrent inflows of the Gotland Basin deep water poor in oxygen at times suffocates the deep benthic communities. While the inflows of the North Sea water into the BS improve the state of the Gotland Basin, they may worsen the state of the GOF by pushing the stagnant, nutrient-rich water into the GOF, with potential negative effects on the local communities (Laine et al. 2007, Eremina and Karlin 2008). For instance, the macrobenthos disappeared almost completely from the eastern GOF after the intrusion of oxygen-poor waters in 1996 (Golubkov et al. 2010). Similar impoverishment of benthic communities was observed both in the Estonian and Finnish waters, too (Pitkänen et al. 2003).

In addition to deterioration of water quality, habitat destruction is an important threat for biodiversity at the shallow coastal zones of the GOF. Construction activities and land reclamation, frequently including dredging and dumping, have caused losses of breeding and feeding areas of fish and seabirds in the eastern GOF (see chapter Geology ja geodiversity).

Travellers from abroad

Non-indigenous species have become one of the main factors affecting the species and functional diversity of the GOF in the modern period (see chapter Non-indigenous species). Low salinity – the same factor that restricts the diversity of the native flora and fauna – enables both low-salinity tolerant marine species and halotolerant limnic species to invade the GOF. The consequences of eutrophication have favoured the establishment of certain hypoxia-tolerant alien species into the GOF (Golubkov and Alimov 2010). For instance, the spreading of the American polychaete worm *Marenzelleria arctica* has possibly been facilitated by the decline of native glacial relict crustaceans *Saduria entomon* and *Monoporeia affinis* that took place a few years earlier (Maximov 2003, Maximov et al. 2014). Also, the eutrophication-induced increase of filamentous algae in the shallow sublittoral zone has probably facilitated a proliferation of non-indigenous amphipods *Gmelinoides fasciatus*, *Pontogammarus robustoides*, and *Gammarus tigrinus* (Berezina 2007).

In the planktonic realm, the size structure of zooplankton community and trophic interactions have been changed due to the predation by a non-indigenous cladoceran *Cercopagis pengoi* (Lehtiniemi and Gorokhova 2008, Golubkov et al. 2010). The studies in the Neva Estuary show that the invasion of alien species has brought about notable re-configuration of the planktonic and benthic food chains, and considerably reduced fish productivity of the area (Golubkov et al. 2010).

To conclude, biodiversity of the GOF is affected by diverse anthropogenic factors affecting the underwater habitats and the inhabiting communities both chemically (nutrient and contaminant loads) and physically (dredging, land reclamation) as well as by biomass removal (fisheries), by species introductions (maritime traffic), and by disturbance (leisure activities). Both eutrophication and climate change have facilitated many of the community changes. To prevent destruction of habitats, it is necessary to control coastal construction bringing about dredging and dumping, and to develop a coherent network of marine protected areas.

Watching over biodiversity

Samuli Korpinen[1], *Alexander Antsulevich*[2], *Markku Viitasalo*[1]

[1] Finnish Environment Institute
[2] St. Petersburg State University

Monitoring

Benthic soft-bottom invertebrate fauna has been the target of continuous monitoring in the GOF at least since the 1950's and even older data is available from Russia. The efforts are divided between offshore sampling by research vessels and coastal sampling by smaller vessels and boats. While the offshore sampling is carried out by coordinated methods (HELCOM 2014), there are national differences in the coastal sampling methods and monitoring practices. Shallow soft-bottom biotopes are monitored only in Estonia, where abundance of charophytes and vascular plants are part of the coastal monitoring programme.

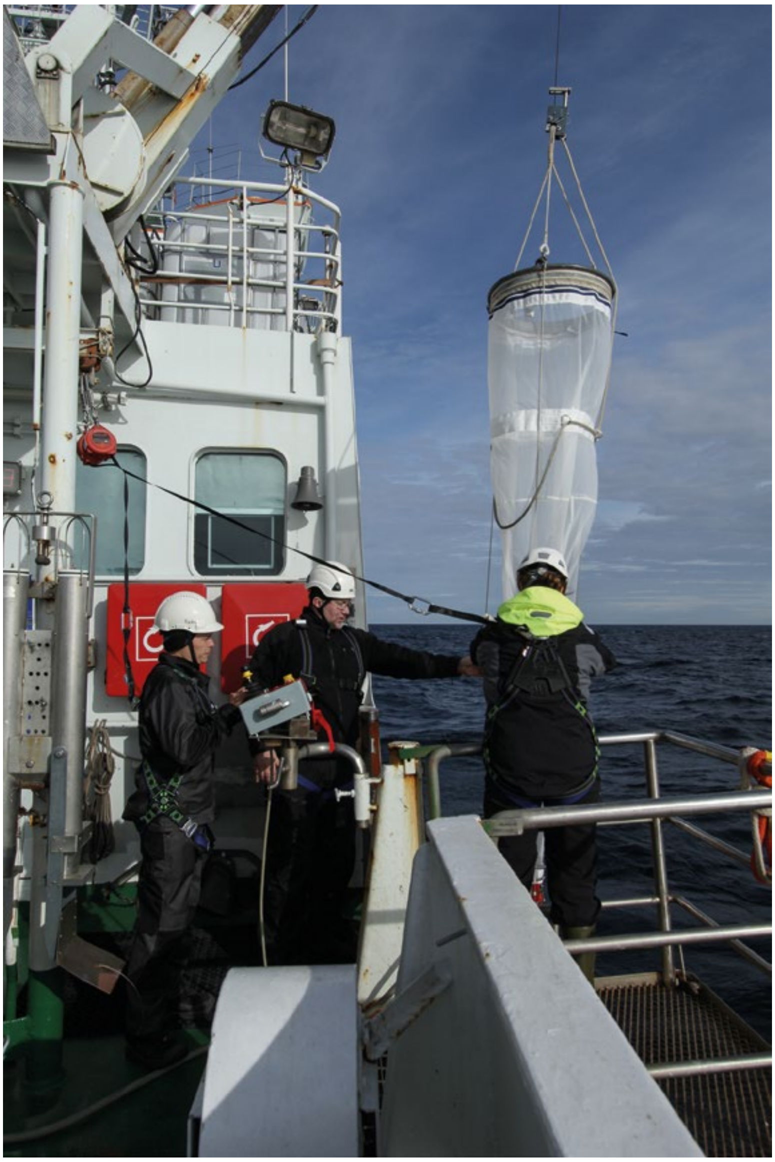
Hard bottom substrates host diverse communities of fauna and flora but there is no basin-wide coordination to follow their status in the GOF. National monitoring in Finland and Estonia focuses on macroalgae and some invertebrates (mainly blue mussel). In Russia, no monitoring of hard substrates exists.

Many of the shallow water habitats, such as rocky reefs, sheltered bays, and lagoons, harbour a high number of species, and many of these habitats are also threatened by human activities. To assess which of these habitats are in need of protection or restoration, their state and trends should be included in monitoring programmes. Spatial surveys, such as the Finnish VELMU Programme (the Inventory Programme for the Underwater Marine Environment), could serve as a good basis for such monitoring.

Monitoring of phytoplankton and zooplankton has been coordinated by the HELCOM Phytoplankton Expert Group (PEG) and the Zooplankton Expert Network (ZEN). However, the national sampling strategies differ. In Estonia, sampling takes place once a month, whereas in Finland the open sea sampling takes place one to three times per year. In Russia, long-term plankton monitoring has been carried out by at least two institutes.

Fish monitoring in the GOF is implemented by i) pelagic trawling surveys coordinated by ICES, which focus on herring and sprat, but also produce data on other species, ii) fisheries catch data collected by national fisheries institutes, iii) coastal gillnet monitoring, which focuses on coastal species, and is coordinated by the HELCOM FISH-PRO project, and iiii) monitoring of migratory fish (salmon, sea trout, eel) in rivers and river mouths (see chapter Fishes and fisheries). The catch data, coastal gillnet monitoring, and salmon monitoring are carried out by all three countries, whereas the trawl surveys are only performed in Finnish and Estonian waters.

Population sizes of the two seal species occurring in the GOF, the grey seal and the ringed seal, are monitored by aerial censuses in the three countries. The HELCOM coordination group for seal monitoring has discussed the need to further develop the ringed seal monitoring in order to increase the reliability of the population estimates. Also, there is no established monitoring programme for harbor porpoises. HELCOM



The handling of WP-2 zooplankton net is not meant for novices. Photo: Mika Raateoja.

maintains a database of porpoise sightings in the BS, and a Baltic-wide research project SAMBAH recently surveyed their abundance.

Monitoring of seabirds in the GOF focuses on three periods annually: i) the wintering seabirds, ii) the spring migration (mainly on the Finnish coast), and iii) the summertime counting of breeding pairs (or nests) in all three countries. There is a new coordinated effort and methodology for seabird monitoring under HELCOM.

Lack of resources limits the density of the monitoring network and the sampling frequency. Therefore, rapidly varying parameters, such as abundance and species composition of phytoplankton, are challenging to monitor and assess.

Most of the monitoring methods are based on laborious sampling and microscopical analyses. Cost-effective methods are therefore being sought after. Aerial photography, laser scanning (LIDAR), satellite-based imaging, and underwater video methods are tested for monitoring of habitats, and probes based on the genetic signals are developed for detecting species. These methods can in the near future complement the traditional methods and provide a more holistic view of the spatial and temporal dynamics of inhabiting species and communities.

Indicators

Assessments of marine biodiversity in the BS have been made under HELCOM (HELCOM 2009). Few quantitative indicators have been used so far, and therefore HELCOM started to develop Baltic-wide core indicators. At the moment, there are > 20 biodiversity-related core indicators. These address zooplankton, macroalgae, benthic invertebrates, fish, seabirds, seals, and non-indigenous species (Table 1). Also, a set of indicators for the assessment of biodiversity has recently been developed by the MARMONI project (Martin et al. 2015), some of which have been tested also in the GOF (Auninš and Martin 2015).

The HELCOM core indicators have been developed to assess whether the marine environment is in good environmental status (GES). To be fully operational, the indicators need to have a threshold value – a GES boundary – which shows whether the GES has been attained (HELCOM 2012). Determining such boundaries is not straightforward, and often only preliminary boundaries have been suggested. Nonetheless, the value of indicators is not only in the comparison against the GES boundaries, but also in showing temporal trends occurring in the ecosystem.

Table 1. HELCOM core indicators for biodiversity in the GOF. Source: HELCOM.

Category	**Indicator characterization**
Water column	Zooplankton mean size and biomass
Seabed	State of benthic fauna; Population structure of benthic bivalves; Number of red-listed biotopes
Fish	Abundance of key coastal fishes; Abundance of key functional fish groups; Proportion of big fishes; Abundance of salmon; Abundance of sea trout
Seabirds	Abundance of breeding birds; Abundance of wintering birds; Productivity of white-tailed eagle
Mammals	Seal abundance; Seal pregnancy rate; Seal nutritional status; Number of by-caught seals by fisheries
Non-indigenous species	Trends in arrival of new non-indigenous species

Phytoplankton

Andres Jaanus[1], Sirpa Lehtinen[2], Marco Nurmi[2], Andrey Sharov[3], Evgenia Lange[4]

[1] *Estonian Marine Institute*
[2] *Finnish Environment Institute*
[3] *Scientific Research Center for Ecological Safety, Russian Academy of Sciences*
[4] *Russian State Hydrometeorological University*

Phytoplankton species composition is one of the key parameters for detecting environmental changes in the GOF. In addition to reflecting human-induced eutrophication, changes in the species composition in phytoplankton communities can also reflect changes taking place in higher trophic levels of the food web. However, the rapid spatio-temporal dynamics of the phytoplankton community challenges any interpretation of the causes behind the changing composition.

Eutrophication does not necessarily lead to a decreased biodiversity in phytoplankton. On the contrary, Olli et al. (2014) showed how the phytoplankton diversity actually increased due to changes in the phytoplankton resource-use efficiency (RUE; algal biomass per unit of limiting nutrient). This contrasts with the paradigm of the global biodiversity loss in stressed environments. On the other hand, the species composition has at the same time changed in such a way that the phytoplankton represents currently a food source of lower quality than before for micro- and mesozooplankton (Suikkanen et al. 2013). This may prevent the energetical benefit of a more diverse phytoplankton community of higher biomass from being transferred to higher trophic levels.

Nodularia spumigena – a former icon of the eutrophication of the GOF – has lately decreased in its numbers. Photo: Seija Hällfors.

Seasonal succession

In the GOF, phytoplankton succession shows different patterns from north to south and east to west. Both hydrography and nutrient conditions affect the development of the communities.

The dinoflagellate *Scrippsiella* complex (*S. hangoei*, *Biecheleria baltica* and *Gymnodinium corollarium*) dominates the spring phytoplankton community of the central GOF (Table 2). The importance of the *Scrippsiella* complex decreases towards the east, and when the spring proceeds, *Scrippsiella* complex is gradually replaced by *Peridiniella catenata* and other dinoflagellate species (Jaanus et al. 2006), usually in the second half of May. Diatoms have traditionally been dominated by two species: *Pauliella taeniata* and *Thalassiosira baltica*, but since the early 2010´s the diatom communities have been dominated by *Skeletonema marinoi*, at least in the southern and central parts of the GOF.

Spring blooms are usually most intense after severe winters (Jaanus 2011). The spring bloom also terminates earlier after mild winters and the post-bloom species, such as the phototrophic ciliate *Mesodinium rubrum*, appear among the dominant species in the western and middle GOF in May.

The transfer to summer phytoplankton community occurs from the end of May in the western GOF to the end of June in the north-eastern part. Temperature and salinity are the main factors shaping the summer phytoplankton community; the decreasing salinity towards the tip of the GOF is reflected in a gradual disappearance of some abundant taxa (*Nodularia spumigena*, *Heterocapsa triquetra, Prymnesiales*), and the rise of some oligohaline and freshwater species (*Dolichospermum* spp., *Pseudanabaena* spp.). While June is usually the period of the summer clear water phase, July is the period of the high-summer maximum phase with filamentous cyanobacteria constituting over 50 % of total phytoplankton biomass. Other important taxa in high summer are dinoflagellates (*Heterocapsa triquetra* and *Dinophysis acuminata*) and *Mesodinium rubrum*. Nanoplanktonic flagellates constitute on the average 20 % of the total autotrophic biomass.

In the autumn, diatoms (mainly *Coscinodiscus granii*) may become the dominant component of the phytoplankton. Also the dinoflagellate *Prorocentrum cordatum*, a potentially toxic non-indigenous species, reached bloom-like concentrations in the autumn of 1999 and 2003 (Olenina et al. 2010).

Table 2. Dominating phytoplankton taxa in April, June, and August according to monthly mean biomass (ww). * a phototrophic ciliate (Gustafson et al. 2000). Source: Estonian monitoring data, GOF2014 dataset.

Area		**April** (the spring bloom period)	**June** (the mid-summer minimum phase)	**August** (the late summer)
Tallinn and Muuga Bay (southern seaboard of the GOF)	1993–2000 (1994–1999 for April)	*Pauliella taeniata*	*Aphanizomenon flos-aquae*	*Aphanizomenon flos-aquae*
		Peridiniella catenata	*Dinophysis acuminata*	*Heterocapsa triquetra*
		Scrippsiella complex	*Scrippsiella complex*	*Nodularia spumigena*
	2011–2014	*Scrippsiella complex*	*Mesodinium rubrum**	*Aphanizomenon flos-aquae*
		Pauliella taeniata	*Skeletonema marinoi*	*Heterocapsa triquetra*
		Thalassiosira baltica	*Aphanizomenon flos-aquae*	*Coscinodiscus granii*
LL3A (offshore middle GOF)	1996–1999			*Aphanizomenon flos-aquae*
				Nodularia spumigena
				Snowella litoralis
	2011–2013			*Aphanizomenon spp.*
				Dinophysis acuminata
				Chrysochromulina spp.

Distribution in time

The total summertime phytoplankton biomass (as Chl *a*) in the GOF has increased during the past four decades (Suikkanen et al. 2013). At the community level, the changes have been more complex; the shifts taken place in the plankton community are probably caused by interactions between warming up of seawater, eutrophication, an increased top-down pressure, and the resulting trophic cascades.

Many coastal phytoplankton communities subjected to an increased nutrient load have shifted towards the dominance of small-sized species, which has been interpreted as a symptom of eutrophication (e.g., Niemi 1975, Andersson et al. 2006). Furthermore, the increased abundance of diatoms in the coastal waters of the GOF – especially some fragile species, such as *Skeletonema marinoi*, *Cyclotella choctawhatcheeana* and *Ceratoneis closterium* – has also been attributed to increased eutrophication (Finni et al. 2001, Weckström et al. 2007, Jaanus et al. 2009).

Jaanus et al. (2011) analyzed changes in summer phytoplankton biomass in different parts of the BS in 1990–2008, and reported that the total phytoplankton biomass increased and cyanobacteria started to occur earlier in large numbers in the GOF in the late 1990's–the early 2000's. In a study for this assessment, the two monitoring periods in August were compared; 1980/1993–2005 (depending on the station / area), and 2005–2014. The trends were diverse, indicating 20 to 100 % increase of the total phytoplankton biomass in the western and the easternmost GOF, while in the southern and central parts the biomass decreased by 30 to 50 % (Fig. 1).

In general, Chl a concentration increased in the late 1990's and the early 2000's in the GOF, but this development levelled out in the early 2000's and turned to a decrease (see chapter Eutrophication). The decreasing trend was not detected with phytoplankton biomass probably because the former period included times prior to the phytoplankton biomass increase reported by Jaanus et al. (2011).

The cyanobacterial biomass increased during the last decade mainly in the western GOF, but also in the north-east part, and in the Koporye and the Luga bays (Fig. 2). In contrast, the blooms of *Nodularia spumigena* have become less intensive at least in

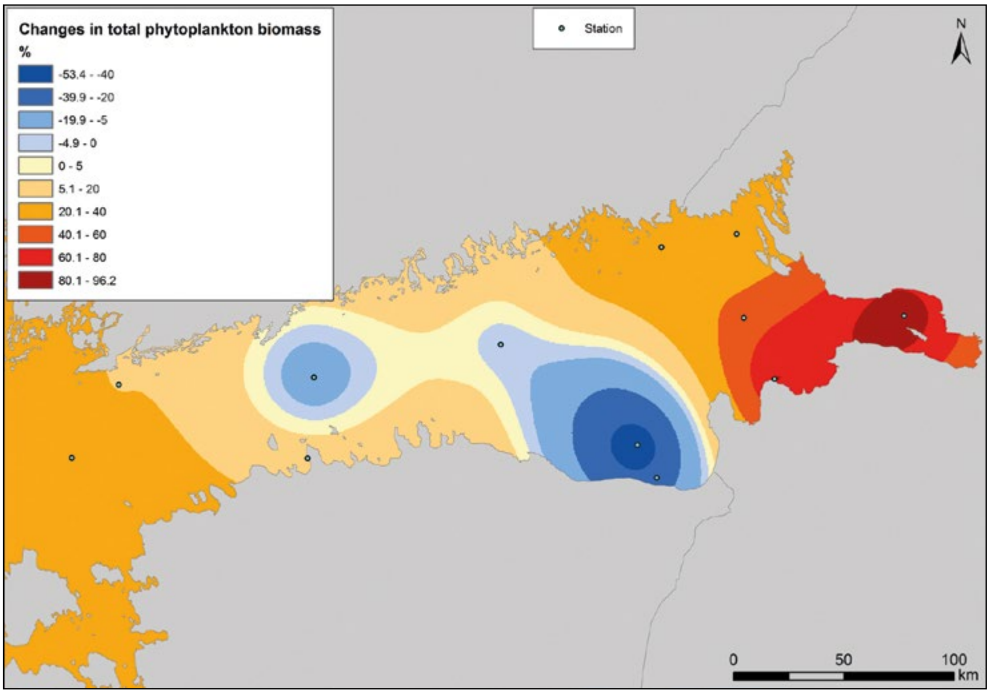


Figure 1. Relative change (%) in the late summer (August) total phytoplankton biomass between the periods 1980–2004 (1990–2004 in the coastal areas) and 2005–2014. Source: GOF2014 dataset. Graphics: Marco Nurmi.

the southern and central GOF, compared to the late 1990's and the early 2000's. More generally, a decrease in the cyanobacterial biomass is observed in the central offshore area and in the Narva Bay, but also in the shallow water area of the eastern GOF. To wrap up these somewhat contradictory trends, the proportion of cyanobacteria increases towards the west, and the proportions of diatoms and green algae towards the east (Fig. 3).

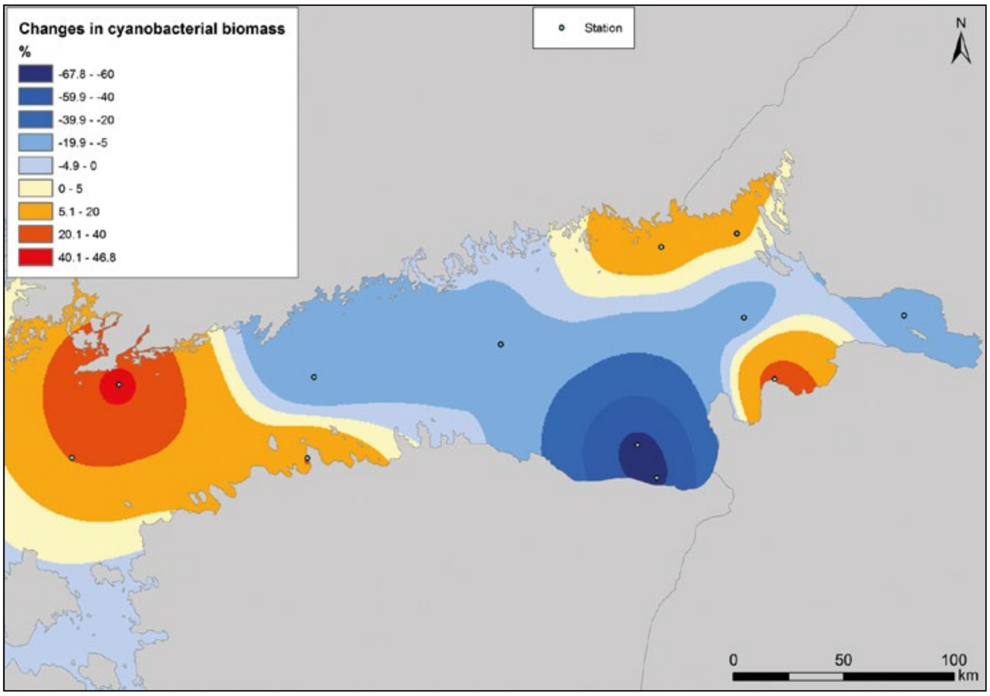


Figure 2. Relative change (%) in the late-summer (August) cyanobacterial biomass between the periods 1980–2004 (1990–2004 in the coastal areas) and 2005–2014. Source: GOF2014 dataset. Graphics: Marco Nurmi.

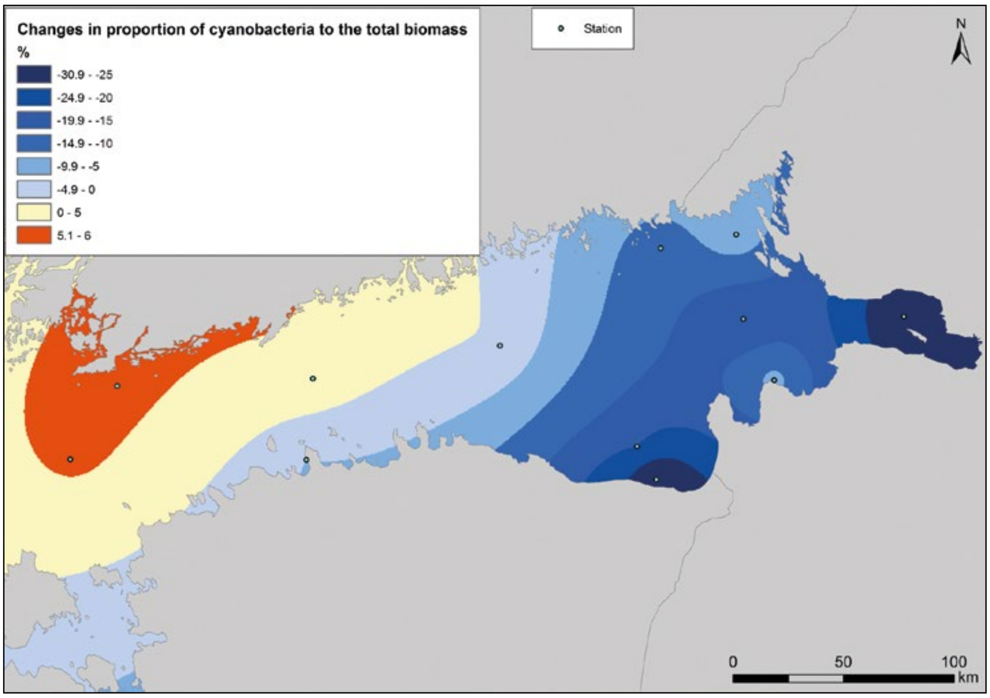


Figure 3. Change in the proportion of cyanobacteria to the total phytoplankton biomass in August between the periods 1980–2004 (1990–2004 in the coastal areas) and 2005–2014. Source: GOF2014 dataset. Graphics: Marco Nurmi.

Phytoplankton under the pressure of salinity

Evgenia Lange
Russian State Hydrometeorological University

The east-west gradient in water salinity from practically fresh water to brackish water of 5 to 6 g/kg taking place in the eastern GOF has its impact on the taxonomic composition of the phytoplankton community. Oligohaline species, mainly related to green algae (Chlorococcales), drop out from the plankton community with increasing water salinity. This reflects in a lower taxonomic diversity of phytoplankton in general (Fig. 4).

For instance, a potentially toxic cyanobacteria *Planktothrix agardhii* has occurred regularly in the eastern GOF from the late 1980's (Makarova 1997, Tereshenkova 2006, Basova and Lange 1998, Nikulina 2003). This species tolerates salinity up to 3.5 to 4 g/kg, and it is therefore rarely found west of the Seskar Island (Makarova 1997, Eremina and Lange 2007).

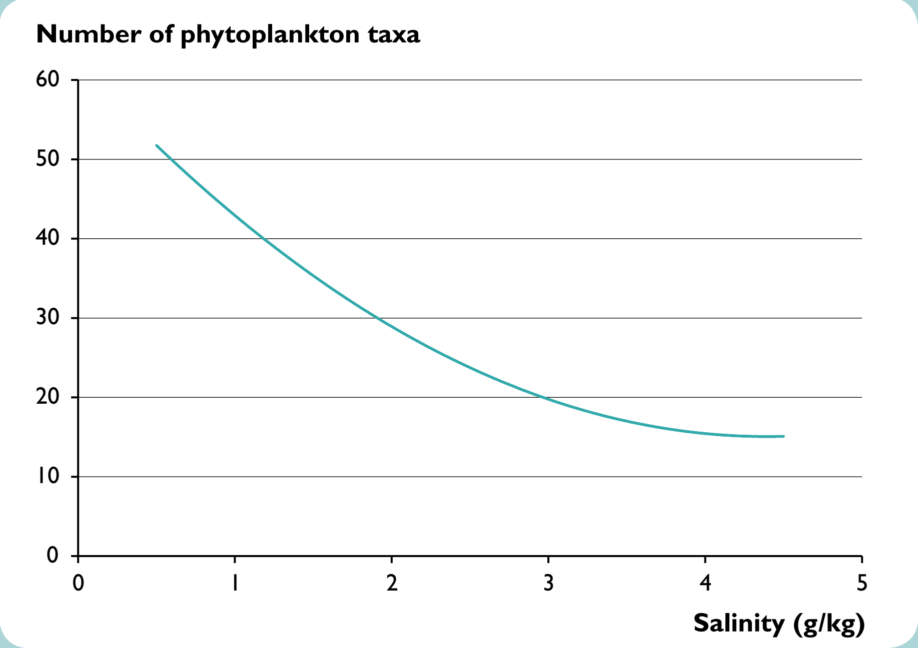


Figure 4. The number of phytoplankton taxa as a function of salinity in the eastern GOF in July–August 2002–2014. Source: Evgenia Lange, trend visually interpreted from original data.

Zooplankton

Maiju Lehtiniemi[1], Arno Põllumäe[2], Larissa Litvinchuk[3]

[1] Finnish Environment Institute
[2] Institute of Ecology and Earth Sciences, University of Tartu
[3] Zoological Institute, Russian Academy of Sciences

The composition of the zooplankton community of the BS ranges from freshwater – brackish water species to marine species, depending mainly on the distance from the Danish Straits. In the GOF, zooplankton is dominated by freshwater and brackish water species of copepods, cladocerans, and rotifers. Spatio-temporal changes in the zooplankton species composition have been attributed to changes in salinity, temperature, and the degree of eutrophication (e.g. Viitasalo 1992, Viitasalo et al. 1995, Suikkanen et al. 2013). Changes in the pelagic food web have also been caused by the introduction of non-indigenous species, especially by the predatory cladocerans *Cercopagis pengoi* and *Evadne anonyx*, which are currently a permanent part of the GOF's zooplankton community (Rodionova and Panov 2006, Lehtiniemi and Gorokhova 2008).

Long-term trends

Copepods (including nauplii) and rotifers have dominated the late-summer zooplankton community of the offshore GOF between the GOF2014 and the previous Gulf of Finland Year 1996 (Fig. 5).

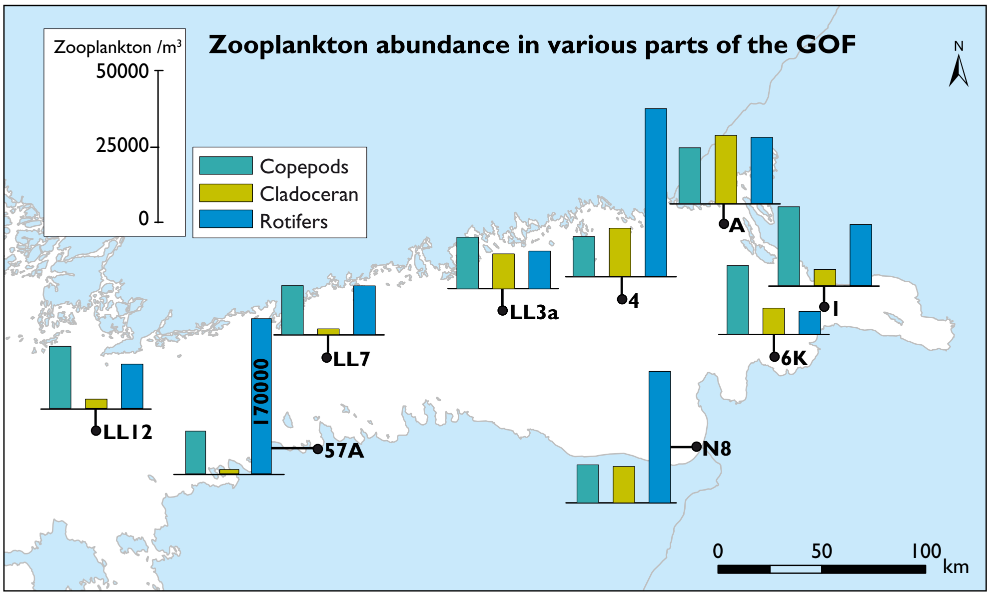


Figure 5. Zooplankton abundance in various parts of the GOF in 1996–2013. Source: GOF2014 dataset.

No marked trends could be detected in the zooplankton abundances in the western and middle offshore area over the study period, except at LL3A where abundances of all major groups were higher in 1996–2000 than in more recent times (data not shown). Cladocerans have typically been the least abundant of the three major groups, while copepods and rotifers have appeared in approximately similar numbers peaking at 20 000 to 30 000 individuals/m^3.

In the Estonian coastal zone, rotifers have clearly been the most abundant zooplankton group, having notably high peak abundances (> 180 000 individuals/m^3) in the Tallinn Bay (57A). In the Narva Bay (N8), the zooplankton abundances decreased in the 2000's (data not shown).

In the easternmost GOF, the abundances of all major zooplankton taxa have increased over the study period. After pooling data from the stations 1, 4, A, and 6K together, we could note that the abundances of copepods, cladocerans, and rotifers in 2011–2012 were four-fold, four-fold, and seven-fold, respectively, as compared to the abundances in the period of 1996–2010 (data not shown)

In the shallow area (depth about 10 m) of the Tallinn Bay, the population peaks of all major zooplankton groups were observed to appear in September (Fig. 6). This figure arises an important point. Zooplankton monitoring in its current form covers well the whole GOF area but is spatio-temporally varying; Finland samples zooplankton in the offshore once a year in late summer, while Estonia and Russia have coastal sampling stations, which are visited several times a year. The results of the frequent sampling clearly show strong seasonal dynamics in the zooplankton community, and indicate the importance of temporally high-frequency sampling in a routine monitoring. Sampling done once a year may easily miss the population peak and lead to flawed conclusions on the observed temporal changes in the zooplankton communities.

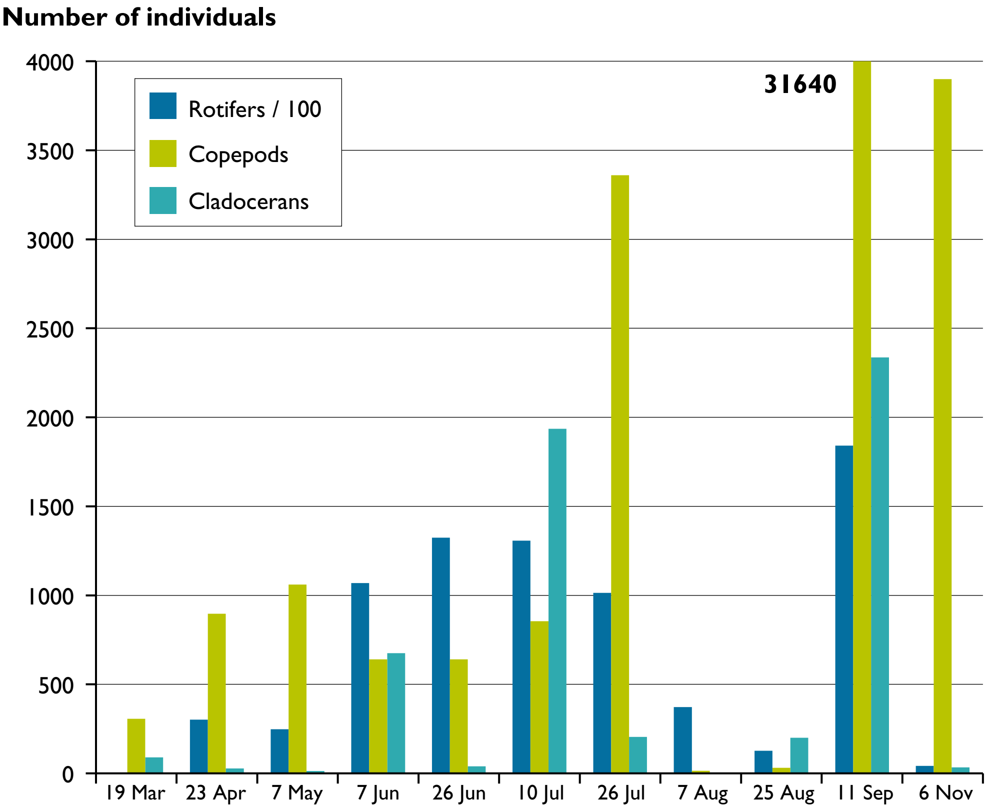


Figure 6. Annual pattern of 2001 in the zooplankton abundance at 57A on the Estonian coast. The number of rotifers has been divided by 100. Source: GOF2014 dataset.

The number of zooplankton species (including meroplankton) found in the monitoring samples clearly increased towards the easternmost coastal areas of the GOF where a total of 117 taxa (species or higher if not identified to the species-level) were found during the study period. For a comparison, only 42 taxa were found in the western offshore area and 49 taxa in the southern coastal area. Although traditions in sample processing and taxonomical identification vary between the countries, the result indicates the input of the representatives of freshwater fauna to the coastal zooplankton community of the easternmost GOF. The 42 taxa found in the westernmost GOF are also found in the easternmost areas, while most of the 117 taxa found in the Russian coastal area are of freshwater origin and not found in the more saline areas of the GOF.

Conclusions

The zooplankton communities in the GOF vary in terms of species number and abundance between the western offshore areas, the middle GOF (less diverse, less abundant), the southern coastal area (more abundant), and the easternmost GOF (more diverse). The differences are mainly explained by differences in salinity, which is the main regulating factor for most of the zooplankton species in the northern BS (Viitasalo et al. 1995, Vuorinen et al. 1998).

Alike phytoplankton, the rapid dynamics of zooplankton communities poses a challenge to zooplankton monitoring. A sampling programme with bi-monthly or monthly sampling during the ice-free period would be needed to be able to interprete the relationships between zooplankton taxa and the environment, and to assess the interactions between zooplankton and their predators, especially Baltic herring and sprat.

Benthic communities

Deep bottoms

Alexey Maximov[1], Henrik Nygård[2], Ilmar Kotta[3]

[1] *Zoological Institute, Russian Academy of Sciences*
[2] *Finnish Environment Institute*
[3] *Estonian Marine Institute*

Macrozoobenthos is a widely recognized indicator for changes in the environmental conditions. Compared to planktonic organisms, macrobenthic animals are relatively sedentary and long-lived, and hence, the effects of the changes in the environmental parameters accumulate on them.

Distribution in space

In general, the number of limnetic species in the offshore GOF increases in an eastward direction along with decreasing salinity. However, owing to a salinity stratification taking place in the water column, the changes in the macrozoobenthic community are strongly associated with depth. Altogether about 70 macrobenthic taxa were recorded in 1996 – 2012. The species richness decreased with depth, and consequently, the deep areas were inhabited by only few species (Fig. 7). The most common invertebrate species were the priapulid *Halicryptus spinulosus*, the polychaetes *Bylgides sarsi* and *Marenzelleria* spp., the bivalve *Macoma balthica*, and the glacial relict crustaceans *Monoporeia affinis*, *Pontoporeia femorata*, and *Saduria entomon*. In the easternmost Neva estuary, the freshwater oligochaetes and chironomids were also abundant.

Also the abundance and biomass of macrozoobenthos were lower in the deep areas than in the shallow coastal waters. The highest abundance was observed in the eastern GOF because of a mass development of small-sized limnetic species (Fig. 8). High biomasses were found also in the Estonian coastal waters, due to dense populations of large marine bivalves *M. balthica*, *Cerastoderma glaucum*, *Mya arenaria* and *Mytilus trossulus* (Fig. 9).

Marenzelleria invasion

The assessment period was preceded by a drastic deterioration of the near-bottom oxygen regime in 1996 (Maximov 2003, Laine et al. 2007, Norkko and Jaale 2008). The subsequent short-term recovery of the benthic community was interrupted by a hypoxic event in 2003, when oxygen-poor saline water penetrated to the eastern GOF (Fig. 10). Populations of *Macoma balthica* and glacial relict crustaceans were wiped out, and by 2004 the bulk of the deep bottom areas of the GOF was a virtually lifeless desert. Benthic communities survived mainly in the shallower areas that were not affected by the oxygen depletion (Fig. 11). At the deepest sub-halocline station LL12 (depth 82 m) macrofauna did not recover during the assessment period after its collapse.

Many of the sites were re-colonized by the hypoxia-tolerant non-indigenous polychaete *Marenzelleria* spp. The invasion seemed to begin earlier (the mid-2000's)

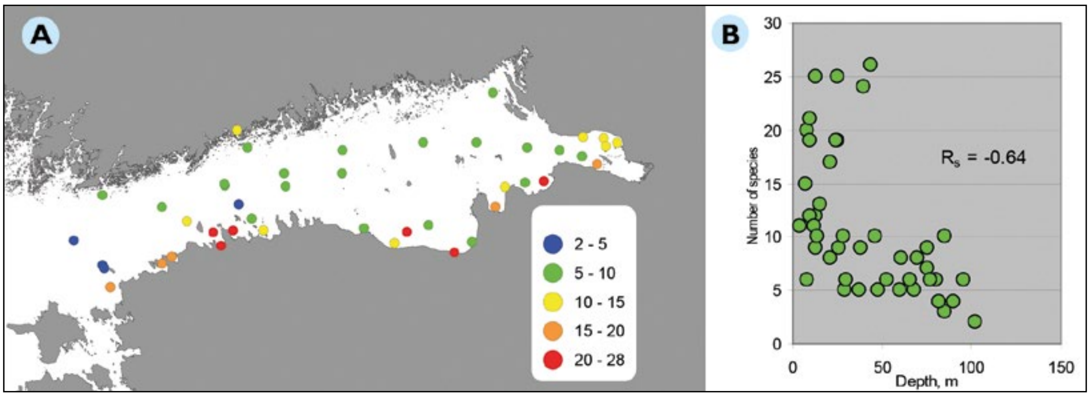


Figure 7. Number of benthic invertebrate species in the GOF in 1996–2012. A: spatial distribution, B: species number as a function of depth. Source: GOF2014 dataset, Zoological Institute (Russian Academy of Sciences), Russian State Hydrometeorological University.

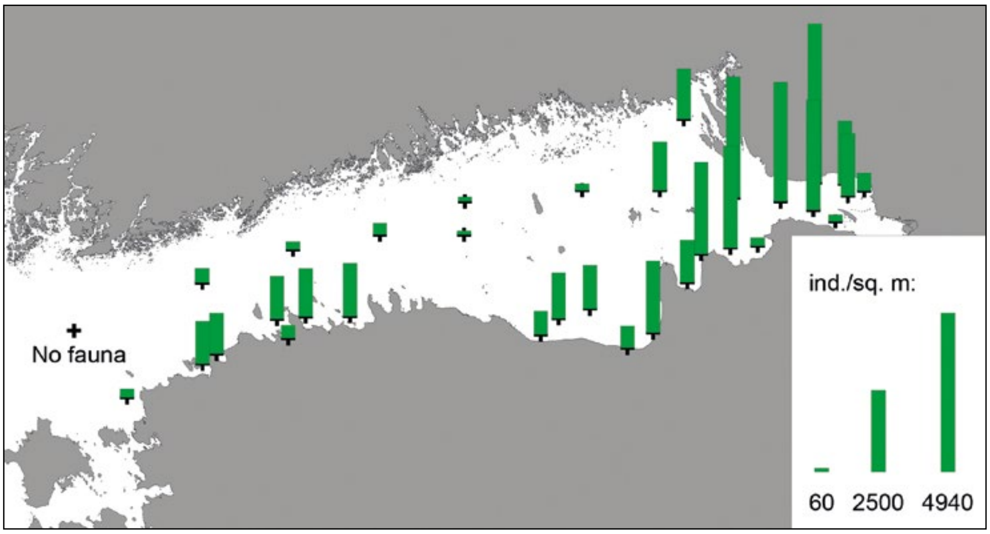


Figure 8. Macrozoobenthic abundance (individuals/m^2) in the GOF in 2012. Source: GOF2014 dataset, Zoological Institute (Russian Academy of Sciences), Russian State Hydrometeorological University.

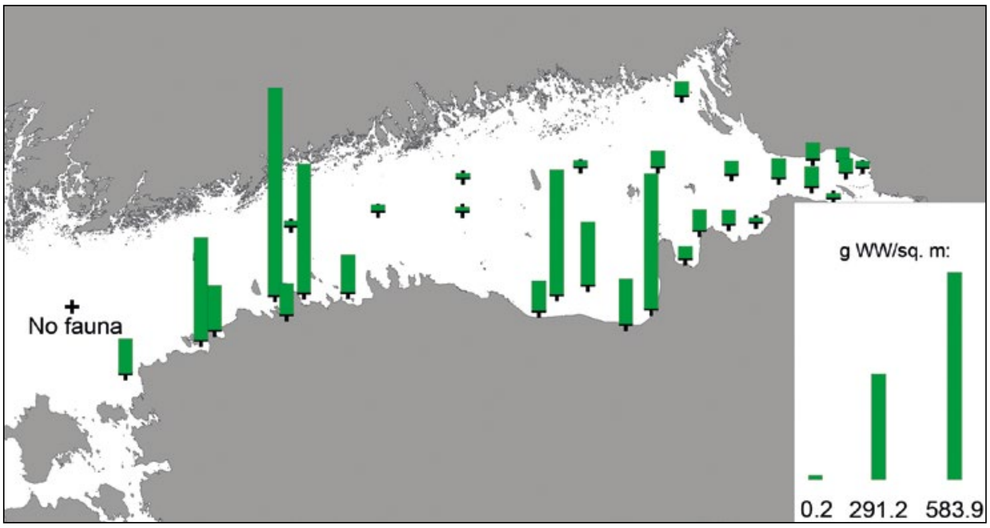


Figure 9. Macrozoobenthic biomass (g/m^2, ww) in the GOF in 2012. Source: GOF2014 dataset, Zoological Institute (Russian Academy of Sciences), Russian State Hydrometeorological University.

in the western GOF than in the eastern parts. By 2011, *Marenzelleria* spp. occupied the entire GOF area and had become the dominant component of the soft-bottom communities. It also colonized the sites where other macrofauna had been eliminated, and consequently, the macrofauna at these sites consisted practically of a monoculture of *Marenzelleria* spp.

The total biomass of macrozoobenthos increased strongly as a result of the *Marenzelleria* invasion especially in the deep areas of the eastern GOF. The mass development of *Marenzelleria* in the deep-water areas of the GOF in the late 2000's was apparently connected with the introduction and establishment of an arctic representative of the genus, that is, *Marenzelleria arctia* (Maximov 2011). It seems to be better adapted to the low temperature of sub-thermocline waters than the other boreal *Marenzelleria* species, i.e., *M. viridis* and *M. neglecta.*

Oxygen condition and biological invasion are the two main factors, constant and episodic, affecting the deep-water benthic communities in the GOF. The most significant changes prior to 2008 were connected with hypoxic events, while a large-scale expansion of *Marenzelleria arctia* has played a fundamental role as of 2009. The invasion-induced change was most obvious in the shallow eastern areas with a more favorable oxygen regime. In the western GOF, benthic communities have still largely been controlled by variations in the deep-water oxygen condition.

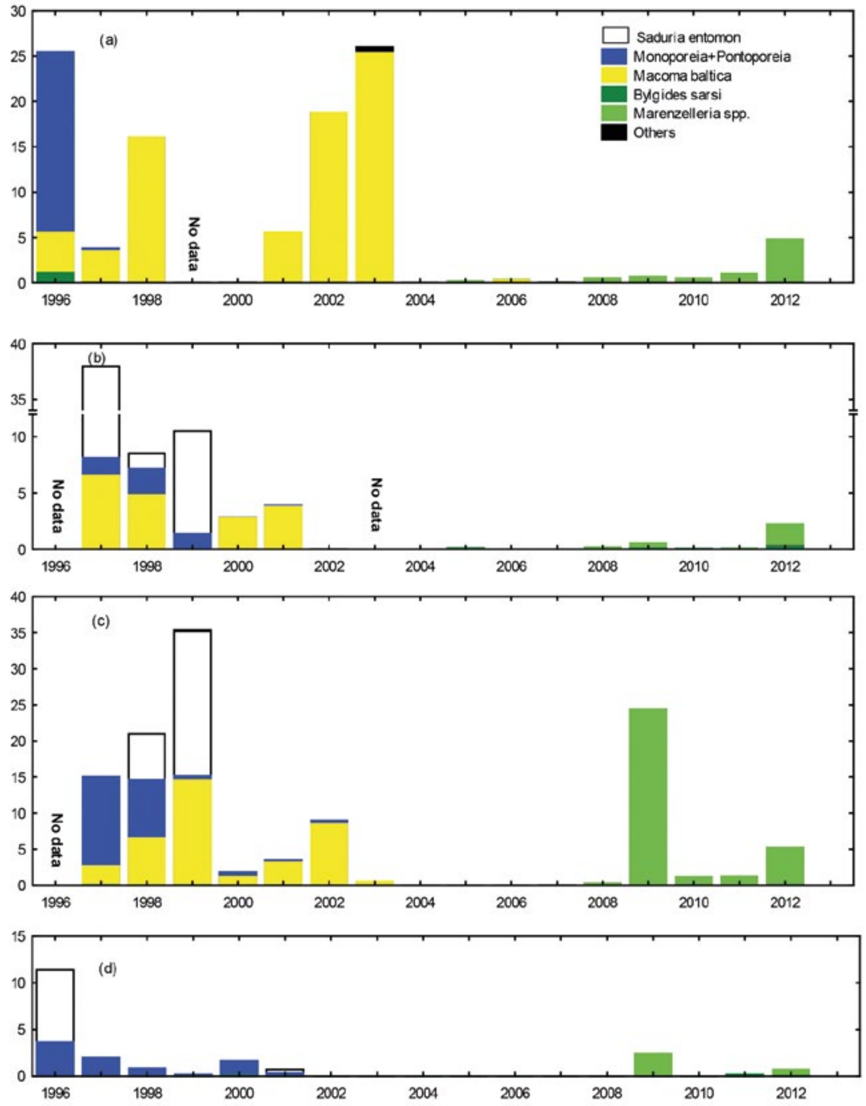


Figure 10. Biomass (g/m^2, ww) and species composition of macrozoobenthos as a function of time at monitoring stations in the western and middle GOF. A: LL9 (depth 66 m), B: LL7S (77 m), C: LL5 (70 m), D: LL3A (68 m). Source: GOF2014 dataset.

The hypoxia-induced changes in macrozoobenthos have been a common phenomenon in the GOF (Andersin and Sandler 1991, Maximov 2003, Laine et al. 2007). In contrast to these reversible changes, replacement of the native benthos by *Marenzelleria* will probably be irreversible. The only factors that may cause a widely-spread non-indigenous species population to withdraw are drastic changes in their environment, or an establishment of a new alien species that is an even fiercer competitor than the current one.

The current composition of soft-bottom macrofauna in the GOF resembles those of the Arctic estuaries where benthic communities are dominated by polychaetes, glacial relict crustaceans, priapulids, and certain bivalves (Denisenko et al. 1999). Hence, the observed change is not entirely a negative phenomenon. *Marenzelleria* improves the oxygen conditions of the seafloor by its deep bioturbation and irrigation (Norkko et al. 2012, Maximov et al. 2014). In the eastern GOF, the *Marenzelleria* induced shift in nutrient cycling has been suggested to decrease nutrient availability to cyanobacterial blooms (Maximov et al. 2014). On the other hand, the replacement of native crustaceans by these deep-burrowing worms has diminished the food availability for Baltic herring, which at older age also feed on the nectobenthic crustaceans swimming on the seafloor.

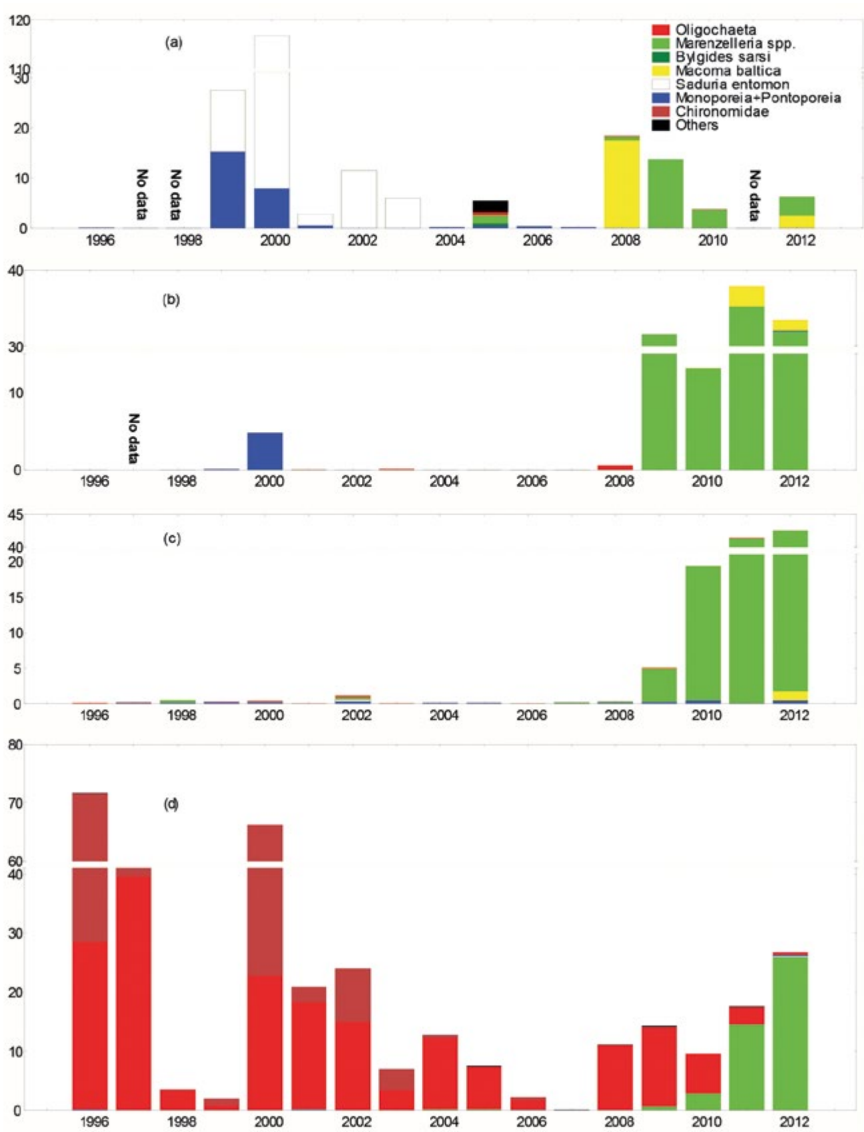


Figure 11.
Biomass (g/m², ww) and species composition of macrozoobenthos as a function of time at monitoring stations in the eastern GOF.
A: 4 (depth 61 m),
B: 3 (48 m),
C: 1 (29 m),
D: 21 (14 m).
Source: GOF 2014 dataset, Zoological Institute (RAS).

Shallow and littoral zones

Jonna Kotta[1], Samuli Korpinen[2], Marina Orlova[3], Merli Pärnoja[1]

[1] Estonian Marine Institute
[2] Finnish Environment Institute
[3] Zoological Institute, Russian Academy of Sciences

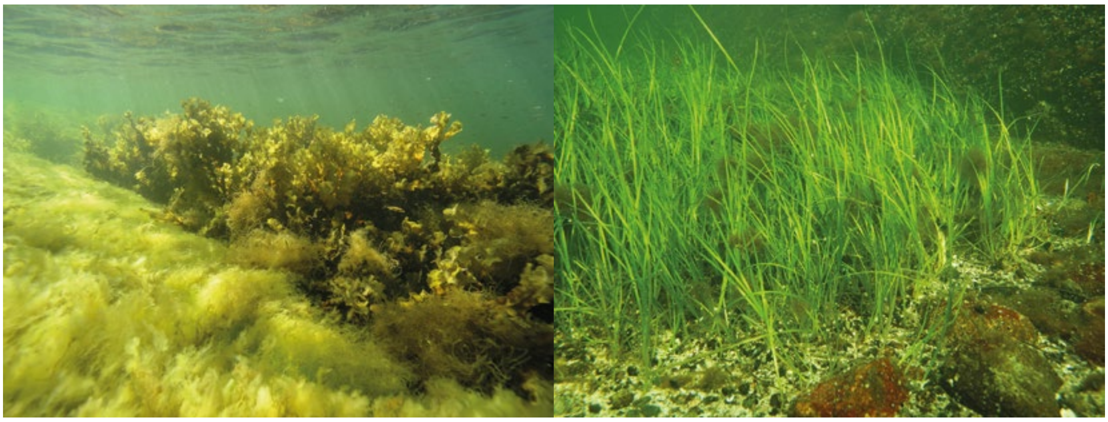
The shallow waters of the GOF have a relatively low benthic habitat diversity inhabited only by a few dozens of benthic macrophyte and macroinvertebrate species. Despite this uniformity, benthic communities are well developed and contribute to important functions for the GOF ecosystem.

Functional groups

We studied the contribution of the key gradients affecting benthic invertebrate communities of the GOF. Altogether 88 benthic invertebrate taxa were identified within the shallow water ecosystem of the GOF. Among different functional groups, herbivores had the highest taxonomic richness and suspension feeders had the lowest one, represented by 32 and 14 taxa, respectively.

Suspension feeders and herbivores were numerically the most dominant, and sometimes abundances > 10^6 individuals/m^2 were found at the seafloor. Deposit feeders and carnivores appeared in numbers > 10^5 individuals/m^2. The most abundant taxa were:

- herbivores: *Jaera albifrons, Peringia ulvae, Theodoxus fluviatilis, Gammarus salinus, Radix balthica, Gammarus oceanicus, Gammarus zaddachi, Idotea chelipes, Idotea balthica, Hydrobidae*
- carnivores: *Hydracarina, Cyanophthalma obscura, Trichoptera, Saduria entomon, Turbellaria, Halicryptus spinulosus, Ephemeroptera*
- deposit feeders: *Chironomidae, Oligochaeta, Macoma balthica, Chelicorophium curvispinum, Marenzelleria* spp., *Corophium volutator, Bathyporeia pilosa, Hediste diversicolor*
- suspension feeders: *Mytilus trossulus, Amphibalanus improvisus, Dreissena polymorpha, Cerastoderma glaucum, Mya arenaria*



Meadows of *Fucus vesiculosus*, *Cladophora glomerata*, and *Zostera marina* are typical for shallow littoral zones of the GOF. Photo: Heidi Arponen / FINNMARINET.

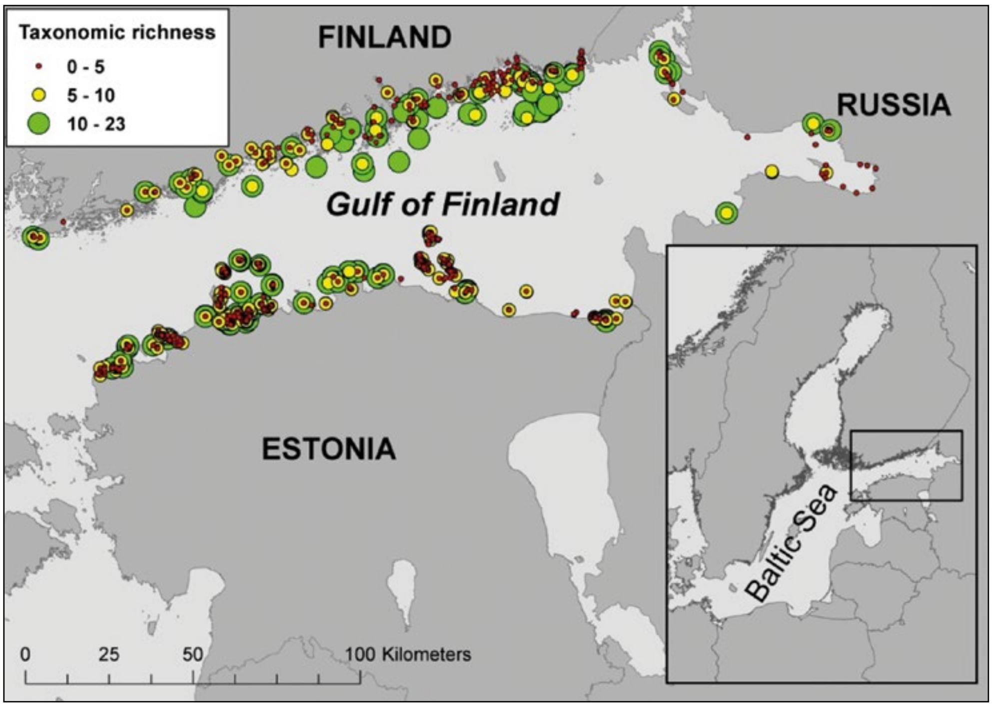


Figure 12. Spatial variability in taxonomic richness (number of taxa) of benthic invertebrate communities in the GOF in 2009–2014. Source: Jonne Kotta.

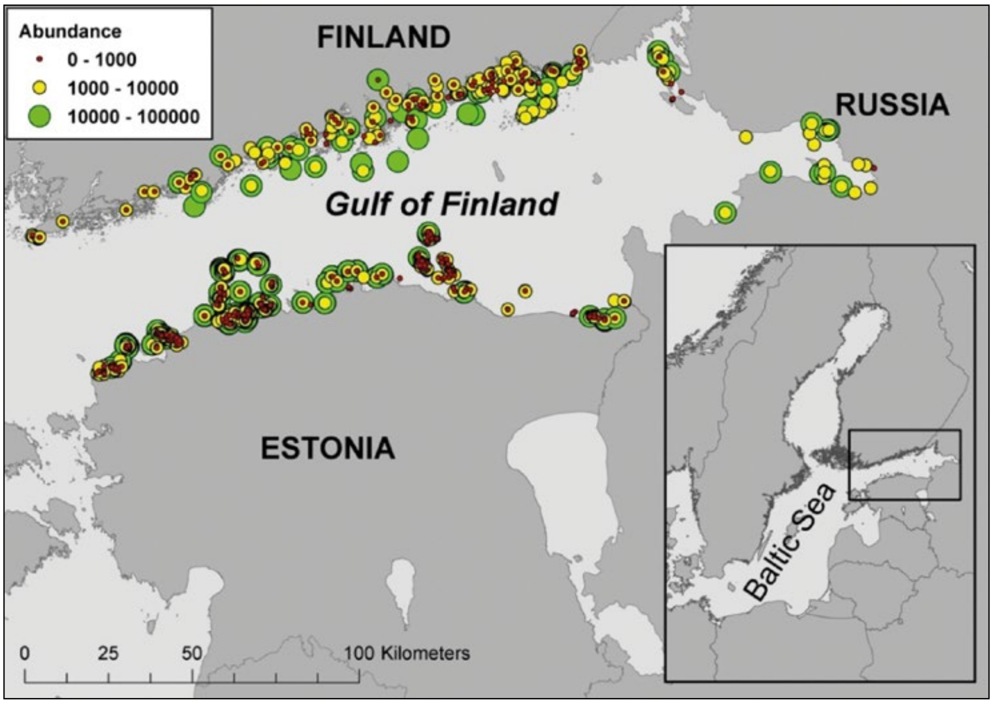


Figure 13. Spatial variability in the abundance (individuals/m^2) of benthic invertebrate communities in the GOF in 2009–2014. Source: Jonne Kotta.

All the four functional groups had representatives from the major taxonomic groups of molluscs, insects, and crustaceans of both marine and freshwater origin. The majority of these key taxa are native to the GOF, but some species, especially those among deposit and suspension feeders, are non-indigenous.

Distribution in space

The taxonomic richness of the benthic invertebrate communities has a large spatial variability in the GOF. Such variability is primarily due to two gradients: i) decreasing salinity gradient from west to east, resulting in lower species richness in the eastern GOF and ii) inshore-offshore gradient in the archipelago areas, with lowest number of taxa in the inner archipelago (Fig. 12). On the other hand, abundance maxima are driven by the area's level of exposure to waves and the intensity of hypoxic events in the area. More specifically, high exposure areas are characterized by suspension feeding mussels, moderately exposed near-coastal areas by phytophilous amphipods, and sheltered near-coastal areas by insect larvae, e.g., chironomids (Fig. 13).

Benthic invertebrate richness and diversity were mostly a function of depth and the near-bottom water temperature (averaged over ice-free season) with the highest species richness and diversity being recorded in the shallowest areas and at moderate temperatures. The variability in the invertebrate abundance was described by the annual average of the level of exposure to waves and salinity with the highest abundances recorded at the high end of both of the gradients. Locally, depth also contributed to invertebrate abundance; the densest communities were found in the shallower areas.

Diversity within a changing environment

The variability in richness, diversity, and abundance of the benthic invertebrate functional groups were caused by the combined impact of different environmental gradients. The following principles apply:

1. Depth was often an important environmental variable explaining richness, diversity, and abundance. Deposit feeders were most abundant at intermediate depths, but most species-rich in the shallowest areas. Suspension feeders were the most species-rich, diverse, and abundant at intermediate depths, whereas herbivores were most species-rich and abundant in the shallowest areas. These patterns can be attributed to the variability in the underwater habitats (highest in the shallow areas), food availability, and abiotic environmental stress. As for food conditions, the herbivores find lush macroalgal communities in the shallow areas, whereas suspension and deposit feeders get more suitable food at intermediate depths. In deeper waters, sediment may contain high-quality food for deposit feeders, but occasional hypoxia may render such habitats unhospitable.
2. Bottom substrate contributed to the richness, diversity, and abundance. In general, an increasing cover of hard bottom elevated the richness, diversity, and abundance of suspension feeders, herbivores, and carnivores. Deposit feeders were favoured by the increase in the share of sand and gravel substrate within the habitat.
3. The number of benthic invertebrate species decreased with decreasing salinity. However, when benthic invertebrate groups were split into functional groups, such a relationship only applied to herbivores. Also, the relation of salinity to the abundance was significant only for suspension feeders which were more abundant at higher salinity.

Although eutrophication is considered among the most severe stressors of the GOF ecosystem, our analyses demonstrated that Chl *a* and water transparency were not negatively correlated with the taxonomic richness of benthic invertebrates inhabiting the photic zone of the GOF. On the contrary, in the areas where Chl *a* was an important player of biotic variability, it mostly showed a positive relationship with the biotic variables concerned. Thus, increasing primary production adds benthic richness, diversity, and abundance in the majority of the GOF range (see also Kotta et al. 2015).

To conclude, the shallow water benthic communities of the GOF are relatively well developed, compared to deep benthic communities, and only moderately and locally affected by water quality issues. It is to note that the analysis did not include long-term eutrophication signals, such as hypoxia or organic matter concentrations, which have been shown to reduce benthic diversity (Korpinen et al. 2010, Conley et al. 2011). In the long-term, eutrophication also plays a role here, often resulting in a lower overall richness and changed diversity patterns in benthic communities.

Seabirds

Jukka Rintala[1)], *Julia Bublichenko*[2)], *Sergey Kouzov*[3)]

[1)] *Finnish Natural Resources Institute*
[2)] *Saint-Petersburg Research Centre, Russian Academy of Sciences*
[3)] *St. Petersburg State University*

The seabird populations in the GOF have varied significantly during the past few decades. There are spatial trends as well. For instance, the majority of common eiders (*Somateria mollissima*) in the GOF (13 000 to 18 000 pairs during the 2010's) live on the Finnish side of the GOF. In the Estonian waters, the number is currently < 5 000 pairs and in Russian waters about 200 pairs. The general eastward-declining trend in population numbers applies to many other species as well. A holistic view of all populations in the GOF is however lacking, because the methods and seabird monitoring strategies have only recently been coordinated under HELCOM. Thus, the current view on seabird populations is based on national monitoring efforts, of which examples from Finland and Russia are given below.

A flock of common eiders during their north-bound migration. Photo: Riku Lumiaro.

Finnish archipelago

In the first half of the 20th century, the seabird populations remained low because of unlimited hunting and collection of eggs by the people living by the sea. The improving living standards after the World War II diminished the need for hunting. Furthermore, oil spills from ships reduced, and nature conservation areas were established in the archipelagos. Consequently, the seabird populations started to increase and, during the next four decades, the numbers of ducks / cormorants (ducks, geese, and cormorants counted together) increased roughly 10-fold, from < 25 000 pairs to almost 250 000 pairs. A similar increasing trend was also seen in gulls / terns. The next major turn took place in the 1990's, when populations of both ducks / cormorants and gulls / terns started to decline. Mainly due to the collapse of duck numbers, the total number of the duck / cormorant group declined by 40 %, from 250 000 to < 150 000 pairs.

Reasons for population variations

The recent decline in the number of several seabird species has probably been caused by the worsened environmental state of their breeding and wintering areas. For the common eider, the main reason has been the lowered fledgling production caused by viruses, against which the young do not get antibodies from the mother. The lack of antibodies in the females may be caused by the lack of good-quality food, especially blue mussels. Also nest predation by fox, raccoon dog, and American mink has contributed to the decline, as also has the increase of the white-tailed sea-eagle (*Haliaeetus albicilla*) population, especially in the south-west archipelago. The populations of the common eider have again started to increase since 2010 due to an excellent fledgling production in 2007 and 2008.

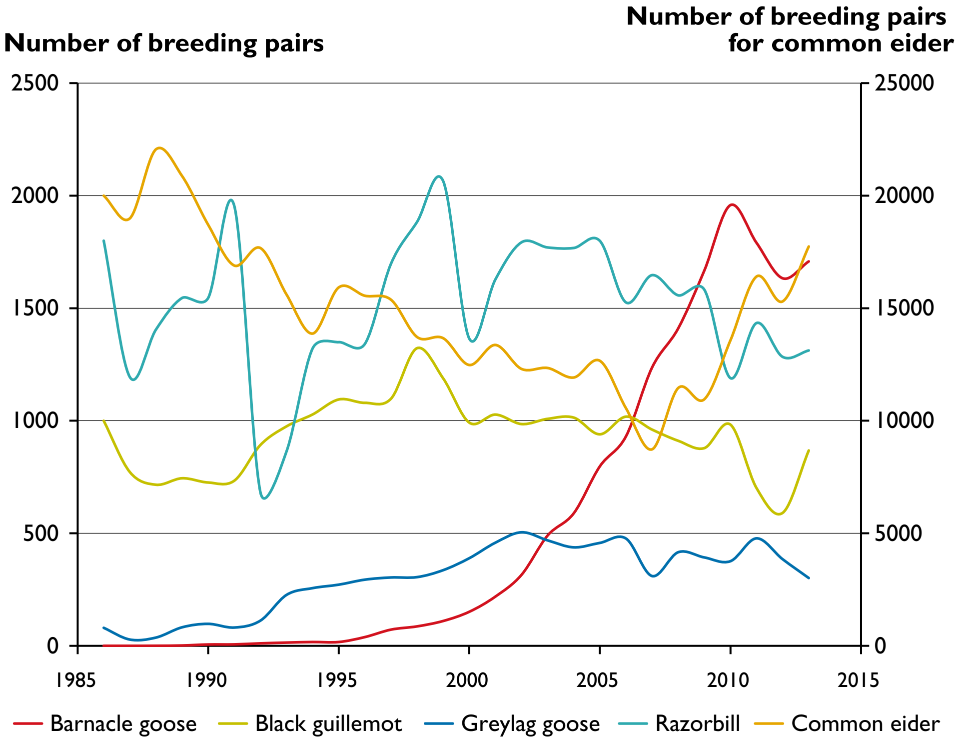


Figure 14. Number of breeding pairs of common eider, black guillemot, razorbill, greylag goose, and barnacle goose as a function of time in the Finnish sea areas of the GOF. Source: Finnish Natural Resources Institute, Finnish Environment Institute.

Some waterfowls feel quite comfortable in the cities. Barnacle geese seem to even know how to follow traffic regulations. Photo: Riku Lumiaro.

Populations of auks have also varied dramatically. The razorbill (*Alca torda*) suffered from massive die-offs in the eastern GOF in 1992, 2000, 2006, and 2010. Reasons for these mass mortalities are not confirmed. Regardless of these die-offs, the population has recovered every time (Fig. 14). In contrast, the black guillemot (*Cepphus grylle*), which mainly feeds on bottom-dwelling fish, has not suffered from similar sudden die-offs, but has been declining since the turn of the millennium particularly in the eastern GOF. The decline has been attributed to predation by the American mink in breeding colonies and to by-catch in fish nets in the wintering area in the southern BS. The common guillemot (*Uria aalge*), in turn, has been favoured by the increasing numbers of cormorant colonies, because breeding inside a colony protects them from predation.

The long-tailed duck (*Clangula hyemalis*), which is migratory and partially wintering in the GOF, is the most numerously hunted sea bird species in the area. The species has been declining from the early 1990's mainly due to lowered reproduction in the breeding grounds in the western Siberia. During the past few years, the numbers of wintering birds in the GOF have, however, increased again due to the mild winters.

The winners

Certain seabird species have increased markedly during the past few decades. The greylag goose (*Anser anser*), which was protected against hunting in 1947 because of the risk of extinction, is now so common that hunting is again allowed. The number of breeding pairs is presently about 400. Also the population of the barnacle goose (*Branta leucopsis*), which have nested in Finland only since 1981, has now grown to 4 000 to 5 000 pairs. The population increase has been particularly intense in the GOF. The barnacle goose is still strictly protected by the EU Birds Directive (EU 2009).

Another species that has markedly increased of late is the cormorant (*Phalacrocorax carbo sinensis*). The cormorant returned to Finland as a breeding species after a break of about 200 years. The first breeding in the modern time took place in the GOF in 1996, and in 15

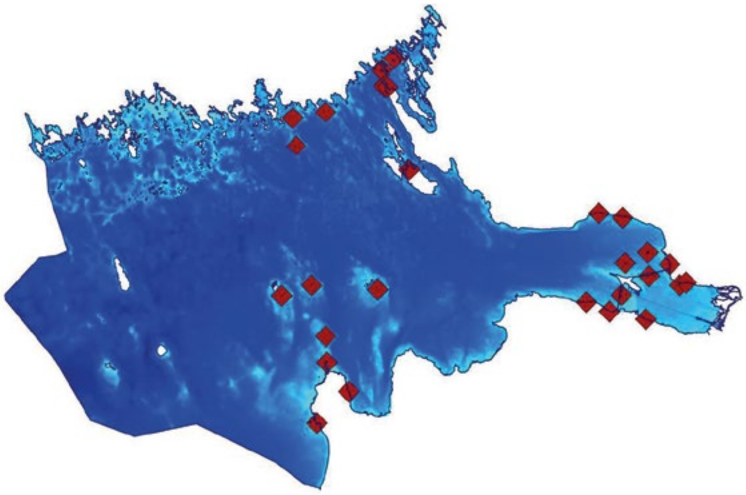


Figure 15.
Bird monitoring sites on the area investigated.

years the population in the GOF had increased to about 6 000 pairs (Rusanen at al. 2011). During the recent years, the population growth has been most intense in the eastern part of the Finnish sea area. The increase of the cormorant has fostered a fierce debate due to the visible change of the vegetation in the breeding colonies and its accused effects on the fish populations. Research on the feeding habits of cormorants has however shown that their predation is mostly directed to fish species with low commercial value and to smaller-sized fish not preferred by fisheries (Gagnon et al. 2015), and that the assumption on their negative effect on commercial fish catch is unwarranted.

Easternmost Gulf of Finland

The easternmost part of the GOF is inhabited by 234 bird species for nesting, foraging, and resting during seasonal migrations (Khrabriy 2008), which makes this part of the BS one of the most important regions for the conservation and protection of birds.

A total of 97 species of birds were registered on the islands of the Eastern GOF in 1992–2014 (Fig. 15), and among those, 60 species of 7 classes were nesting.

The most typical nesting habitats in the eastern GOF for waterfowl and aquatic birds were the following:

1. Reed beds (*Phragmites australis*) are the largest single biotope and pose a breeding area for 22 bird species (Bublichenko and Bublichenko 2007, Bublichenko 2014)
2. Rush beds (*Schoenoplectus lacustris*) are usually formed in places of soil erosion. They have increased during the recent 10–12 years, especially in the Neva Bay after the construction of the St. Petersburg Flood Protection Facility, and around the Kotlin Island (Bublichenko 2014)
3. Coastal meadows, which are relatively sheltered on the islands but often disturbed by the people on the mainland coasts
4. Boulder ridges and stony placers at the coastline are used by a few species as nesting habitats
5. Sandy, sandy-gravel coasts, and dunes. The longest sandy-gravel area in the GOF (> 20 km long) exists in the Repino-Komarovo-Zelenogorsk area, and poses a suitable area for nesting of many birds. However, the sandy beaches are actively used for recreational purposes and have lost their attractiveness for birds as nesting sites
6. Man-made habitats, such as shore houses, piers, and some larger rock buildings, give possibilities for many bird species to breed. Also several parts of the St. Petersburg Flood Protection Facility can be used as such habitats

Long-term trends

Gaviiformes. Until recently, there were few documented nestings of loons in the eastern GOF. In 2013–2014, several nestlings were observed near the Moschny Island and the Gogland Island, and in the area of the Portovaya Bay.

Podicipediformes. The great-crested grebe (*Podiceps cristatus*) is the most numerous breeding species in this region. The population suffered a drastic reduction in the Kurgalsky peninsula in the 1990's, but has stabilised afterwards.

Cormorants. The first two nesting colonies of this species were found in 1994 in the northern sector of the eastern GOF. Since then, a rapid population increase took place; 9 500 nests were counted in 2014. Over the past few years, the nesting colonies have gradually moved from the old northern colonies to the southern and central areas of the GOF.

Anseriformes. The common eider has increased since 1972, mute swan (*Cygnus olor*) and greylag goose since 1987 – 1989, and barnacle goose since 1995 (Bublichenko 2007a, 2007b, 2007c, 2011). In contrast, the populations of pintails (*Anas acuta*), garganeys (*Anas querquedula*), pochards (*Aythya ferina*), goosanders (*Mergus merganser*), red-breasted mergansers (*Mergus serrator*), and velvet scoters (*Melanitta fusca*) have decreased.

Waders. During the past few decades many wader populations, such as ringed plover (*Charadrius hiaticula*), ruff (*Philomachus pugnax*), and great snipe (*Gallinago media*), have decreased. An increasing recreational pressure on open shore areas and the disappearance of some wetlands due to the construction activities in the Neva Bay are behind this trend. Some other species, such as lapwing (*Vanellus vanellus*) and oystercatcher (*Haematopus ostralegus*), have increased, and also the common ringed plovers have again gradually increased in their numbers (Kouzov and Kravchuk 2010a, 2010b, Lovchenko 2012).

Larids. Several gull species, such as Heuglin's gull (*Larus heuglini*) and herring gull (*Larus argentatus*), have decreased during the past few decades, probably due to disappearance of a number of fishery and fish-processing factories and dumps. Also, an increasing recreational pressure and invasion of carnivores into the nesting islands have had their impact. These populations have, however, stabilised over the past few years. After a decline that started in the 1990's, the black-headed gull (*Chroicocephalus ridibundus*), arctic tern (*Sterna paradisaea*), and common tern (*Sterna hirundo*) have increased in their numbers during the recent five years. Caspian tern (*Hydroprogne caspia*), in turn, has undergone a drastic decrease during the most recent decade caused by the disappearance of the single breeding colony in the Bol'shoy Fiskar Archipelago.

Auks. The razorbill and the common guillemot populations have gradually increased over the most recent decade.

International cooperation is needed

The sea areas of the eastern GOF are threatened by the increase in maritime oil transportation and building of ports and other structures. Building activity and non-regulated public access in the resting and nesting places affects negatively its avifauna. Further development of nature reserves and restrictions of movement of the public in the vicinity of the nesting places may improve this situation. Human-induced changes in the environment have consequences to sea birds, and hence, sea birds can be used as indicators for the health status of the marine ecosystem. International cooperation is however necessary in order to produce reliable information on the spatio-temporal changes in bird populations.

Marine mammals

Mart Jüssi[1]*, Markus Ahola*[2]*, Mikhail Verevkin*[3]*, Olli Loisa*[4]

[1] *Pro Mare*
[2] *Finnish Natural Resources Institute*
[3] *St. Petersburg State University*
[4] *Turku University of Applied Sciences*

Seals

There are historical records of all modern Baltic seals from the GOF area, but today only two species of seals – Baltic grey seal (*Halichoerus grypus macrorhynchus*) and Baltic ringed seal (*Pusa hispida botnica*) occur there regularly. The occurrence of harbour seal (*Phoca vitulina*) has been suggested by Bogoljubov (1906) who describes summer-breeding seals from the Kotlin area in the easternmost GOF, but the review of representative zoological collections in the area do not confirm the presence of the species in described period (Michail Verevkin, pers. comm.).

The Baltic grey seal suffered a population depression in the 1970's with only 1 500 to 3 000 individuals inhabiting the BS in that period (Harding and Härkönen 1999). In the early 1980's, their numbers in the GOF were still low (Popov 1978, Tormosov and Esipenko 1986), but the population has been steadily recovering since then (Fig. 16). Their numbers (during moulting time) have increased from 490 to 1 121 in 2003 – 2014 (HELCOM SEAL, unpubl.), and they can be spotted at all coasts of the GOF all year round. Main haul out sites in Finland are on the most exposed skerries outside of

Grey seals are thriving in the GOF. Photo: Riku Lumiaro.

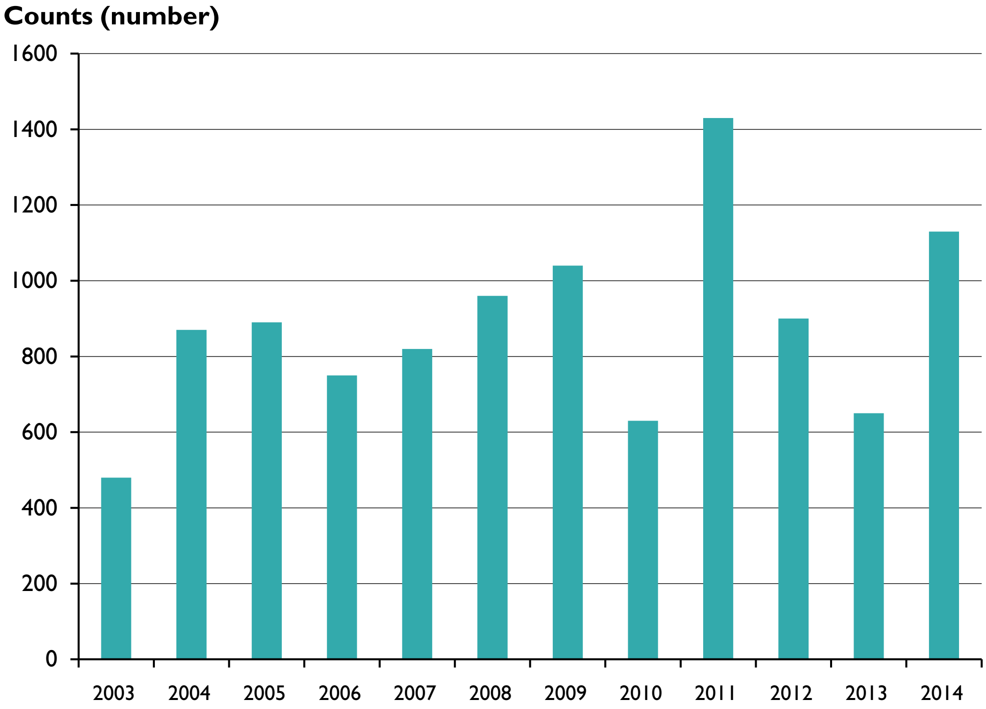


Figure 16. Grey seals in the GOF as a function of time. Source: HELCOM seal monitoring database.

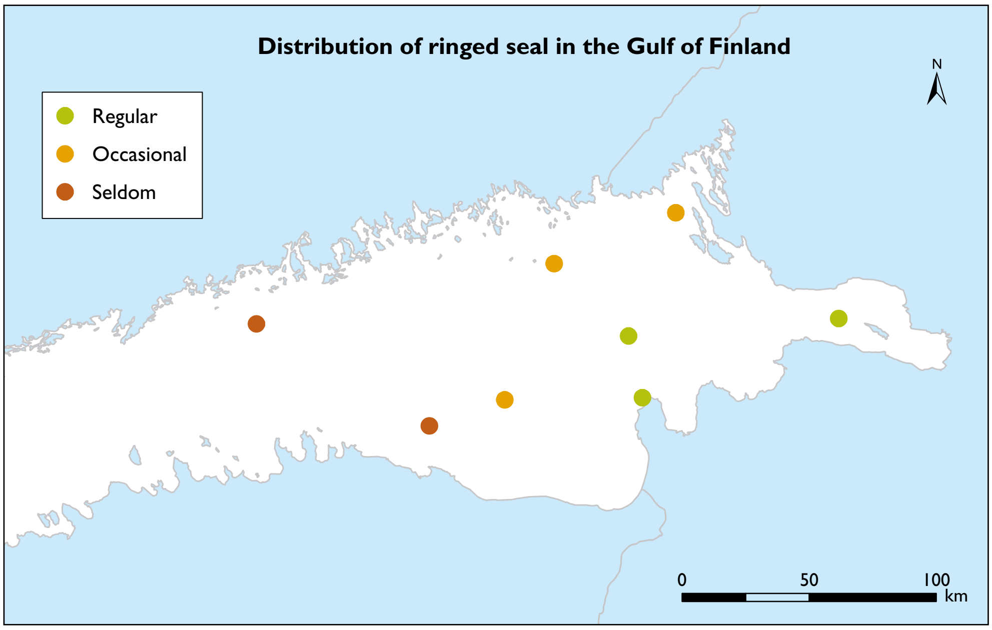


Figure 17. Current distribution of ringed seal in the GOF. Colours denote the usage of the sites by seals: green = regular, yellow = occasional, red = seldom. In the 1980's, all sites were in regular use by dozens of ringed seals. Source: Ad hoc HELCOM Seal Expert Group, Copenhagen, Denmark, 15 - 17 October, 2013. Reference: HELCOM SEAL 7/2013.

Porvoo and Porkkala, on reefs and islets close to the Kurgalskii peninsula in Russia, and on skerries of Malusi and Uhtju in Estonia. Telemetric studies have shown that they travel long distances from the GOF to the other Baltic sub-basins and back (Finnish Natural Resources Institute, unpubl.).

The Baltic ringed seal populations suffered a severe decline in the 20th century (Harding and Härkönen 1999). The species was counted in thousands in the GOF in the 1970's and the 1980's (Härkönen et al. 1998), but the GOF population suffered a dramatic decline in the 1990's. This decline was caused by poor breeding conditions and a mass mortality of adults due to reasons unknown (Stenman and Westerling 1995). The current population consists of < 200 individuals (Verevkin et al. 2012), most of which inhabit the easternmost GOF (Fig. 17). Telemetric studies of four seals in 1998–1999 (Härkönen et al. 2008) and of four seals in 2014 (Jüssi, unpubl.) indicate that the ringed seal is much more stationary than the grey seal; the individuals of the eastern GOF population rarely travel west of the 25°30′E longitude (about Helsinki-Tallinn line).

Disturbance to seals is caused by increased shipping (particularly in icy period), habitat destruction, noise, and pollution. Recreational fisheries on sea ice also disturb breeding seals and increase the risks of entanglement and poaching. Mild winters amplify many of these problems due to diminished ice cover. Potential impacts of unknown magnitude include marine litter, especially "ghost nets", as well as offshore and coastal infrastructure development. For adequate conservation measures, it is necessary to identify and quantify these pressure factors. International cooperation on all levels is a prerequisite for success.

Harbour porpoise

The harbour porpoise (*Phocoena phocoena*) is the only cetacean species that inhabits the BS. Historical evidence shows that it has been common and widespread in the entire BS until the first half of 20th century, although it has probably always occurred in relatively low numbers. There are also several records of hunted, by-caught, and stranded animals as well as bone remains along the whole coastline of the GOF from the 1880's to the 1930's (Pyöriäistyöryhmä 2006, Trukhanova et al. 2014, HELCOM 2015). The BS population collapsed in the mid-20th century due to environmental pollution and by-catch. No current explicit population estimates exist, but the dramatic decline has been documented in the whole BS area (Koschinski 2001).

The Ministry of the Environment of Finland launched a campaign in 2001 to collect opportunistic sightings from the public. During the campaign, 16 observations of 42 animals have been made so far in the Finnish sea areas of the GOF, the most recent ones being from Kirkkonummi-Helsinki area in June – July 2014 and off the Hanko Peninsula in June 2015 (Fig. 18). There are no recent confirmed sightings from the

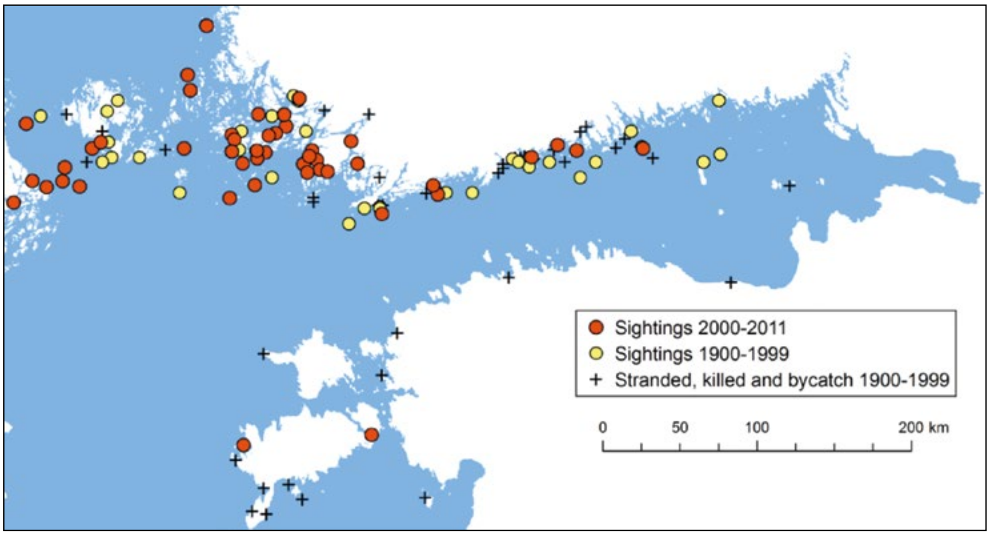


Figure 18. Harbour porpoise sightings in the GOF, Archipelago Sea, Åland Sea, and the Northern Gotland Basin. Source: HELCOM map and data service. Graph: Markku Viitasalo.

Figure 19.
Whales are known to go astray into the GOF from time to time. A 6 000 year old bone fragment rescued from an 18 m long skeleton of a yet unidentified whale. The skeleton lies at 70 m depth in the halfway between Helsinki and Tallinn. It was found during the acoustic surveys by Nord Stream AG. Source: Granskog et al. (2013).

Estonian and Russian territorial waters (Loisa et al. unpubl.). The first international acoustic survey to estimate the abundance and distribution of the BS population was conducted in 2010–2015, and the preliminary estimate is about 450 individuals (Carlström et al. unpubl., sambah.org).

The records and recent sightings involve several oceanic cetaceans that have visited the BS. There are observations of bottlenose dolphins (*Tursiops truncatus*, most recently in November 2015 at Västervik, the east coast of Sweden), white-beaked dolphins (*Lagenorhynchus albirostris*, most recent observation near Tallinn in 2008), and humpback whales (*Megaptera novaeangliae*) in the 19th and the 20th century. A skeleton of a large baleen whale, assumed to be either a fin whale (*Balaenoptera physalus*) or a blue whale (*Balaenoptera musculus*), was found during the Nordstream pipeline environmental impact assessment surveys in 2005–2009 (Hanski 2014, Fig. 19). The age of the skeleton was estimated to be about 6 000 years old but the species is still unconfirmed.

The Gotland Basin population of the harbour porpoise is currently classified as critically endangered by the IUCN (International Union for Conservation of Nature). By-catch is considered the most severe issue for the population survival. Also contaminants, underwater noise, and other anthropogenic disturbance threaten the population.

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FISHES AND FISHERIES

Chapter coordination: Heikki Peltonen, Finnish Environment Institute

Viewpoint

Lauri Urho[1]*, Hannu Lehtonen*[2]

[1] Natural Resources Institute Finland
[2] University of Helsinki

Fishes started to colonize the present Baltic Sea (BS) area after the last glacial period about 14 500 years ago. Various periods in the Baltic history (Baltic Ice Lake, Yoldian Sea, Ancylus Lake, and Litorina Sea) shaped the emerging fish fauna as a mixture of diadromous (species migrating between marine and fresh waters), marine, and freshwater species (Urho and Lehtonen 2008).

The fish fauna was basically established approximately 4 000 years ago. Since then, changes in the taxonomic composition of fish fauna have been rather small, except for the very recent changes due to anthropogenic influence: unintentional species introductions with maritime traffic, new channel connections, and aquaculture as vectors as well as eutrophication and climate change.

Environmental preferences

Altogether 93 fish species have been caught in the Gulf of Finland (GOF) or its adjacent waters. However, a representative value of annually observed species number in the GOF is 63 species, being lower in the less saline easternmost part. Of these, 23 species are marine ones, which do not ascend to freshwater, and are thus more numerous in the more saline waters of the western GOF.

There are 21 cyprinid species (14 or 15 of them indigenous) in the fish fauna of the GOF. The abundance of several cyprinid species has increased along with progressing eutrophication. Although cyprinids are freshwater species, their distribution has

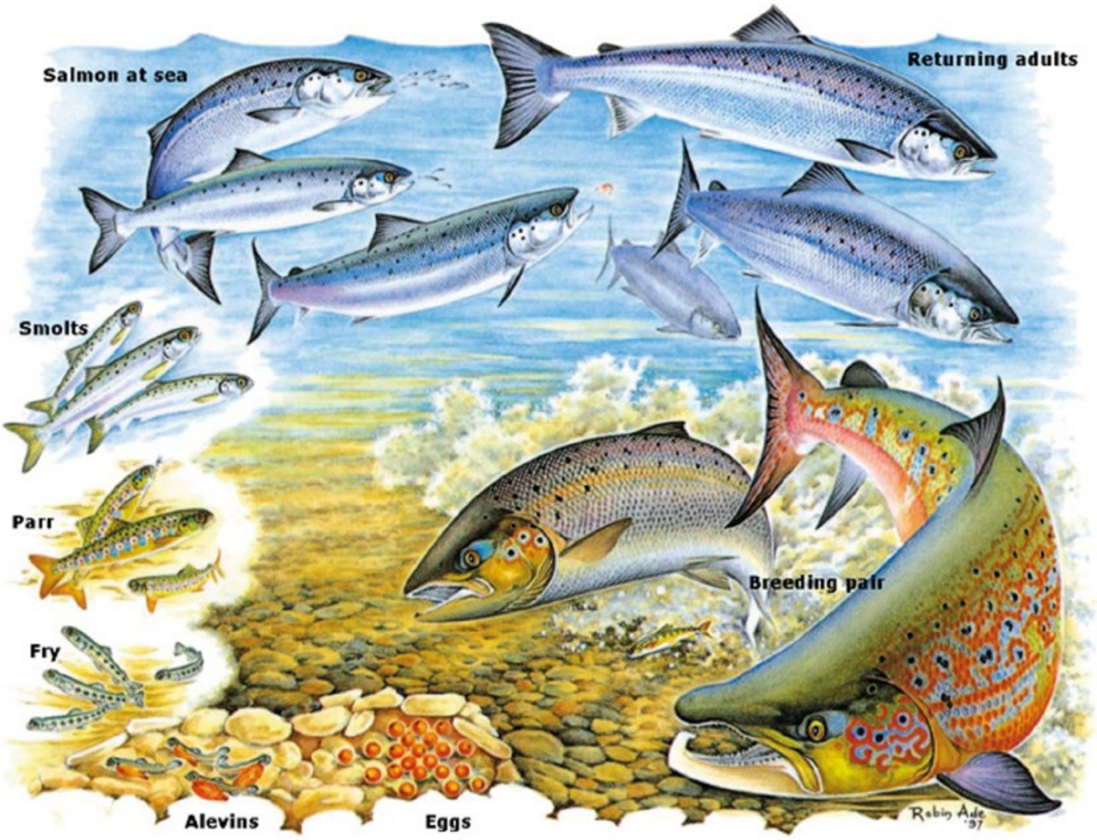
Photo: Riku Lumiaro.

extended towards the offshore areas during the recent decades (Lappalainen et al. 2000, Ådjers et al. 2006).

Anadromous species are dependent on reproduction in freshwaters. Salmon (*Salmo salar*), brown trout (sea trout, *Salmo trutta*), river lamprey (*Lampetra fluviatilis*), and dace (*Leuciscus leuciscus*) are clearly anadromous, but have also landlocked populations, the whole life cycle of which takes place in the fresh water. For vimba bream (*Vimba vimba*) and sichel (*Pelecus cultratus*), only the anadromous form is known.

Some freshwater species, such as roach (*Rutilus rutilus*), can reproduce in low salinity waters (< 4 g/kg, Härmä et al. 2008). The abundance of many species, such as tench (*Tinca tinca*), white bream (*Blicca bjoerkna, Abramis bjoerkna*), and pikeperch (*Sander lucioperca*), is dependent on warm summers (Pekcan-Hekim et al. 2011), and hence, they reproduce in shallow unexposed coastal waters. Species such as butterfish (*Pholis gunnellus*), snakeblenny (*Lumpenus lampretaeformis*), smelt (*Osmerus eperlanus*), and burbot (*Lota lota*) prefer cold waters and therefore occur in the outer archipelago and offshore areas during the summer.

Currently, the composition of fish fauna in the GOF is about to change. For example, several recent observations of young-of-the-year garfish (*Belone belone*) suggest that the reproduction of garfish may have become regular in the Finnish waters (Urho 2011). Also, the reproduction of the round goby (*Neogobius melanostomus*) started in the 2000's (Ojaveer 2006, Urho and Pennanen 2011), and sichel has recently become more abundant in the eastern GOF (Pennanen et al. 2013, Popov 2014). The white-finned gudgeon (*Romanogobio albipinnatus*) was for the first time registered in the eastern GOF in 2005, though its distribution area is still rather poorly known (Naseka et al. 2011). Its main distribution area is in the Ponto-Caspian region, but it was recently found also in the Saimaa Canal (Urho 2014, Urho and Pennanen 2014). Fish that cannot reproduce in the GOF but are annually caught are eel (*Anguilla Anguilla*) and cod (*Gadus morhua*); they have always been considered to belong to the fish fauna of the GOF.



Life cycle for anadromous species. Source: North Atlantic Salmon Conservation Organization.

Life history of salmon and trout

Tapani Pakarinen, Natural Resources Institute Finland

The anadromous species (i.e., species which reproduce in rivers and migrate to sea for feeding) salmon and sea trout return to their home rivers for spawning after the feeding migration. Spawning takes place in the autumn. Laid eggs ripen in the bottom gravel over the winter and yolk sac alevins hatch from eggs in the spring. After a few weeks, alevins burrow out from the gravel and transform as fry. They develop camouflaging stripes along their sides and enter the parr stage. Parr stay in the river for 1–3 years, after which they are physiologically transformed for survival in saline water, i.e., they smoltificate. About 15 cm long smolts migrate to the sea. During their feeding migration in the sea, salmon and sea trout grow fast and return to their home rivers for spawning after 1–3 years. Salmon grows larger that the sea trout; a salmon spent three winters at sea can weigh up to 20 kg. Salmon and sea trout can repeat spawning in consecutive years if the fishing pressure is not too high.

Damming of rivers and land-based nutrient load have impacted most significantly on the anadromous fish stocks. The recent efforts to reduce nutrient load into the sea and to construct fish ways in the rivers have improved the state of the populations of anadromous species. Re-introductions have also supported this recovery process.

Reproduction strategies

Most fish species in the GOF belong to non-guarding lithophils or phytophils – according to the classification by Kryzhanovsky (1948, 1949) and Balon (1990) – which lay their eggs among, e.g., gravel or vegetation to seek protection for their embryos. Three-spined stickleback (*Gasterosteus aculeatus*) can use both these substrates for building a nest for the eggs, thus being an example of a species with a great plasticity in its reproduction. Pikeperch even guards its eggs, but after hatching the larvae disperse. Other guarders, such as gobies and sculpins, both hide the eggs and guard them before the larvae disperse into the pelagic area. The non-native round goby (*Neogobius melanostomus*) has relatively large eggs and larvae, similarly to most species in the cottidae family, which hide and guard their eggs. Their offspring settle down quite early as their larvae are well developed soon after hatching (Urho 2002a). Bearers, such as pipefishes, carry their rather low number of embryos until hatching. The eelpout (*Zoarces viviparous*) is the only one to give birth to their 4 to 5 cm long offspring.

Many fish species in the oceans lay eggs that are left buoyant in the water. However, in the lower water density of the GOF the eggs are not typically boyant, which may compromise their survival. Indeed, there are few pelagic-spawning species in the GOF. Of those, sprat (*Sprattus sprattus*) is currently very abundant because of the favourable environmental condition; mild winters during the most recent two decades have favoured its reproduction in the BS. Cod can at times be abundant in the GOF, although its spawning areas are located in the southern BS. However, during the recent decades there have been few cod in the GOF because of the unfavourable environmental condition for their reproduction, and high fishing pressure in their principal distribution area.

Cod is the fish in-demand for the GOF. Photo: Riku Lumiaro.

Anthropogenic pressures are influencing

Changes in climate (increased temperature, changes in precipitation) affect fish populations in the northern hemisphere (Eaton and Scheller 1996). Climate models for the northern Europe indicate that mild and wet winters are expected to occur up to five times more frequently in the next decades than today (Palmer and Räisänen 2002). Fishes live within a complex web of interactions and processes, which includes predator-prey interactions, competition, and reproduction (Lehtonen 1996). Possible changes in these interactions and processes will alter the composition of fish communities. Changing habitats due to climate change (e.g., increased vegetation) may affect the fitness of species, and hence, the species and size composition of the fish community (DeAngelis and Cushman 1990).

Global warming will probably support the dominance of cyprinids and percids, together with the expected decrease in the abundance of salmonids and other cold water fish populations (Lehtonen 1996). Changes in the spawning and hatching times of certain cold water species, such as burbot and whitefish (*Coregonus lavaretus*), have already taken place (Urho 2011).

Newcomers and on the way out

The escalated arrival of non-indigenous species in the GOF suggests for more pronounced changes in the fish fauna in the future. For instance, Chinese sleeper (*Perccottus glenii*) and tubenose goby (*Proterorhinus marmoratus*) have become more abundant in the eastern GOF and are expected to expand their distribution (Naseka et al. 2011). Invasive alien species, such as round goby and gibel carp (*Carassius auratus* m. gibelio), have in the past 10–15 years extended their distribution almost over the entire coastal area of the GOF (Vetemaa et al. 2005, Urho et al. 2010, Naseka et al. 2011, Urho 2011, Urho and Pennanen 2011, Urho et al. 2014). Today, round goby occur in greatest numbers around ports due to its arrival vector, that is, the ballast waters of ships.

Some marine fish species that have their distribution areas close to the GOF may in the future become more abundant. For example, anchovy (*Engraulis encrasicolus*) has been caught a few times during the past four years. On the other hand, twaite shad (*Alosa fallax*) has been caught only temporarily during the past decades, compared to the more frequent catches especially in the first half of 20th century. At that time, twaite was more abundant in the southern BS and rather large numbers were caught, and some individuals were even found to enter the River Narva (Veldre 2003) and the eastern GOF (although the reproduction of this species has not been observed there; Kudersky 2002). Not only expansion from other sea areas, but also intentional introduction of species has had its effect on the fish fauna of the GOF. Examples follow: peled whitefish (*Coregonus peled*), belica (*Leucaspius delineates*), brown bullhead (*Ameiurus nebulosus*), and longnose sucker (*Catostomus catostomus*) are all introduced into the GOF or into a watercourse discharging into the GOF. The Atlantic sturgeon (*Acipenser oxyrinchus*) that once disappeared from the GOF has again been met due to its introductions into rivers running to the Gotland Basin. Sturgeon has never been observed to reproduce in the BS, but only in the rivers discharging into it.

Genetic diversity of Salmonids

Marja-Liisa Koljonen[1], Riho Gross[2]

[1] Natural Resources Institute Finland
[2] Estonian University of Life Sciences

Genetic diversity is the main resource for evolution for all living species. In case the genetic diversity is lost, species´ ability to survive and adapt to environmental changes decreases drastically.

Salmonids are a group of species being at high risk for losing its genetic diversity as the species of the group are usually distributed into many different breeding populations in various rivers. The genetic integrity and separation of these river populations is maintained by precise homing behaviour of the spawners. These river populations need to be conserved in order to maintain the overall genetic diversity of these species. The maintenance of these species therefore requires information of the structure and distribution of their current genetic diversity.

Salmonids are also the most threatened group of fish species, as they have specific environment requirements, are very valuable as catch fish, and are thus targeted to fisheries both in the sea and in the rivers. International conservation and management activities are needed to maintain salmonid fisheries in the GOF at a sustainable level.

Sea trout

There are currently about 101 rivers or brooks draining into the GOF, which contain anadromous brown trout (sea trout) populations. Of these populations, 85 can be regarded as native wild stocks (ICES 2013), while the remaining populations have been supported by hatchery releases. For about 30 populations, the conservation status is very poor. The status is weak and uncertain for another 30 populations. In order to create a management and conservation strategy in which the original genetic structure of the sea trout populations could be taken into account, the genetic relatedness of the populations were analysed (Fig. 1).

A phylogenetic tree based on the genetic differences among all populations shows a clear and logical grouping, which follows closely the geographical distances between the populations and the form of the coastline (Fig. 2). Five major genetic similarity groups could be formed: Finnish populations (G1-4), Finnish-Russian border river populations (Bay of Vyborg area including the River Virojoki, G5), eastern Russian populations (G6), southern Russian populations (G7), and Estonian populations (G8). The Finnish populations could be divided into four groups: Archipelago Sea type populations (1), the River Aurajoki hatchery type populations (2), the River Ingarskilanjoki type populations (3) and the River Isojoki hatchery type populations (4).

Exceptions for the geographical order along the coastline were the known hatchery population releases of the River Isojoki and the River Aurajoki sea trout in Finland. In addition, the release history explains the similarity of the River Ingarskilanjoki trout

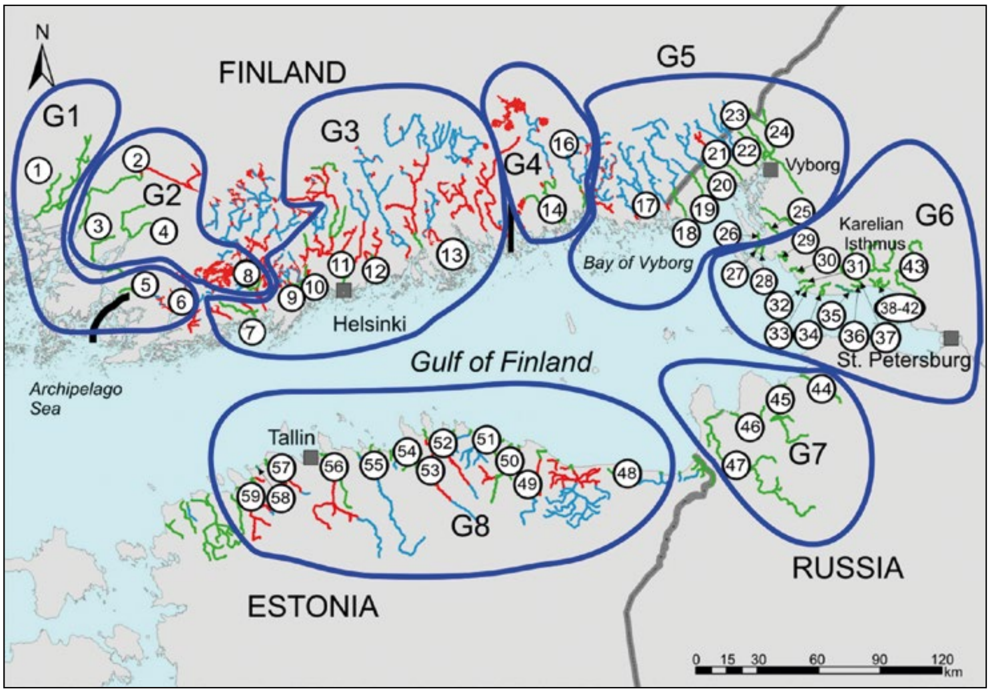


Figure 1. The brown trout rivers in the GOF. The color of the river indicates its quality as a spawning site and potential environment for brown trout. Red: river is closed; blue: irregular reproduction occurs; green: open river with regular natural production. A total of 59 watersheds: 1) Aurajoki, 2) Paimionjoki, 3) Purilanjoki, 4) Uskelanjoki, 5) Kiskonjoki, 6) Fiskarsinjoki, 7) Ingarskilanjoki, 8) Siuntionjoki, 9) Mankinjoki, 10) Espoonjoki, 11) Vantaanjoki, 12) Sipoonjoki, 13) Koskenkylänjoki, 14) Kymijoki, 15) Isojoki (hatchery stock, not in the map), 16) Summanjoki, 17) Virojoki, 18) Urpalanjoki, 19) Santajoki, 20) Vilajoki, 21) Tervajoki, 22) Rakkolanjoki, 23) Mustajoki, 24) Kilpeenjoki, 25) Römpötinpuro, 26) Myllyoja, 27) Koivistonpuro, 28) Penttilänoja, 29) Kello-oja, 30) Lohijoki, 31) Papinoja, 32) Toivolanpuro, 33) Notkopuro, 34) Jukkolanpuro, 35) Inojoki, 36) Pikkuvammeljoki, 37) Vammeljoki, 38) Tyrisevänoja, 39) Hurrinoja, 40) Terijoki, 41) Huumosenoja, 42) Kuokkalanpuro, 43) Rajajoki, 44) Voronka, 45) Sista, 46) Havlonka, 47) Luga, 48) Pühajõgi, 49) Kunda, 50) Toolse, 51) Selja, 52) Loobu, 53) Valgejõgi, 54) Pudisoo, 55) Mustoja, 56) Pirita, 57) Vääna, 58) Keila, 59) Vasalemma. The location of the eight genetic similarity groups (G1 to G8) of the sea trout stocks in the GOF are defined by blue lines. Source: Koljonen et al. (2014).

with the River Koskenkylänjoki and River Vantaanjoki populations, into which it has been released.

The Russian populations grouped very precisely according to their geographical distances. The Bay of Vyborg populations formed a tight group, and also all the Russian populations from the Karelian Isthmus grouped together. The River Rajajoki (River Siestarjoki) formed an intermediary type to the southern coastal Russian group, in which the River Luga has the largest smolt (i.e., the young salmon migrating from a river to the sea) production. Interestingly, the Estonian trout populations clearly differed from this Luga type of trout, and were very similar to each other. Some effects of hatchery fish releases could be traced, as trout populations in the River Pudisoo and the River Pühajõgi were genetically very similar, and the River Pudisoo trout is known to have been released into the River Pühajõgi.

Stock groups in the Finnish coast

Catches of fisheries reflect how the sea trout populations of the GOF – wild fish of different origin or hatchery-released fish – mix with each other. A DNA-analysis of the catches was conducted to clarify to which extent wild Russian and Estonian fish are caught in Finnish coastal fisheries (Fig. 3). The majority (78 %) of the total coastal catch originated from Finnish sea trout populations, 7 % came from Russian, and 15 % from Estonian populations. At least one fifth of the fish in the catches originated from rivers with natural production.

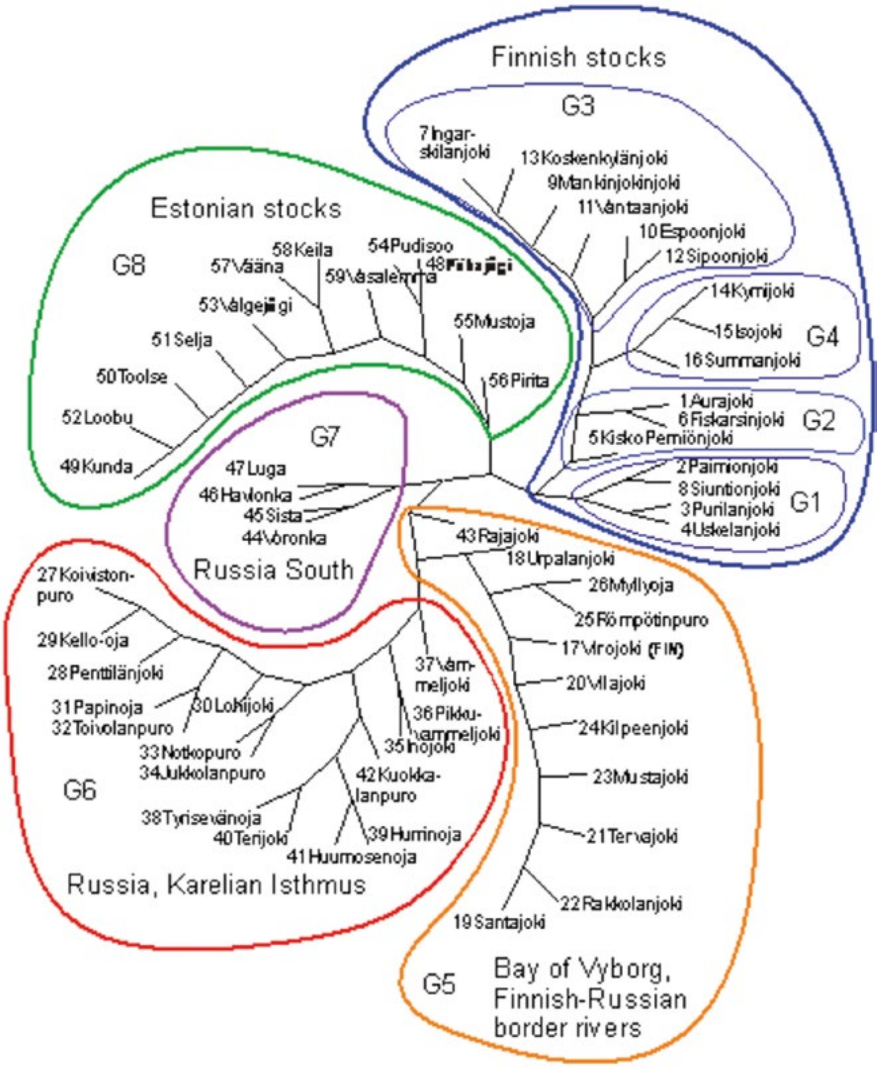


Figure 2. Genetic similarities and grouping among anadromous brown trout stocks in the GOF. Watersheds numbers from Fig. 1 are presented here together with the river names. Source: Koljonen et al. (2014).

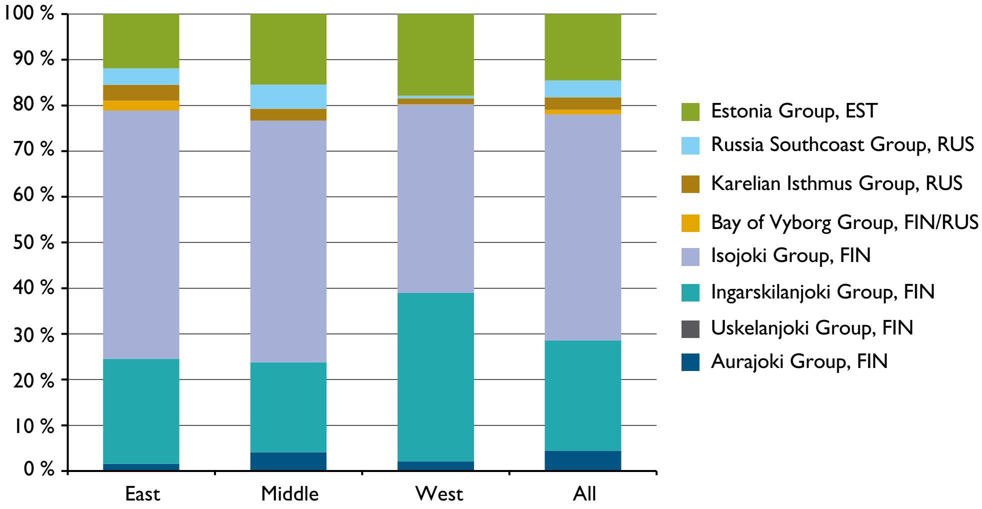


Figure 3. Stock group proportions in trout catches by fisheries in different parts of the Finnish coast. Source: Koljonen et al. (2014).

Atlantic salmon

There are no original naturally reproducing river populations of Atlantic salmon left on the Finnish coast. The salmon stock of the River Neva origin is thus used in Finland for salmon smolt releases, mainly into the River Kymijoki. In the Russian rivers of the GOF, salmon is relatively rare and more common only in the River Luga and its tributaries. In Estonia, a few salmon stocks are known to occur in the River Kunda, the River Keila, and the River Vasalemma. Hatchery-released Neva salmon makes a large contribution to the Finnish coastal catches, while salmon from wild Estonian populations do usually not occur there.

Hatchery releases have a significant impact on the genetic integrity of a native salmon population; these may compromise the population's local adaptations (Vasemägi et al. 2005). For instance, Estonian hatchery stocks were more variable than the corresponding small native populations in the 1990's. However, a clear trend of increasing genetic variation in native populations has occurred since 2005. This is explained by straying and admixture (interbreeding between two or more previously isolated populations) with genetically more variable hatchery reared salmon that were stocked in neighbouring rivers (Gross et al. unpubl.). Also, the initial level of differentiation and genetic distances between native Estonian populations and hatchery stocks has gradually decreased during the 17 years of stocking activities.

Herring and sprat: dynamics, status, and catches

Jukka Pönni[1], Jari Raitaniemi[1], Tiit Raid[2], Alexander Antsulevich[3], Andrey Pedchenko[4]

[1] Natural Resources Institute Finland
[2] Estonian Marine Institute
[3] St. Petersburg State University
[4] The State Research Institute on Lake and River Fisheries (GOSNIORH)

Herring

The state of the Baltic herring (*Clupea harengus membras*) stocks is annually assessed for sustainable fisheries. The assessment includes for instance estimates of stock biomass and age structure, and provides a forecast for the future. The GOF herring was assessed as the separate stock until 1990. Since then, it has been assessed and managed as a part of the Central Baltic herring stock, which comprises of a number of local populations in the ICES sub-divisioning (Fig. 4). These populations utilize common areas during the feeding period, but differ in their biological characteristics and population dynamics. Several attempts were made to explore whether the quality of the assessments can be increased using smaller assessment units, which would better follow the geographical pattern of the supposed natural populations. Those attempts gave no reason to change neither the present procedure nor the assessment unit.

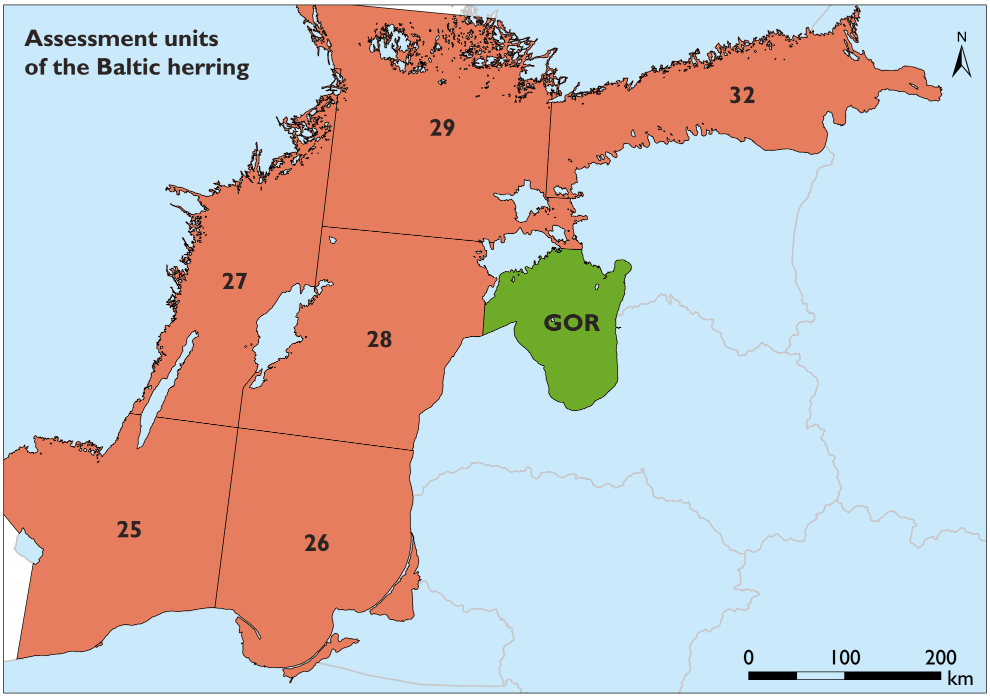


Figure 4. Assessment units of the Baltic herring. Areas 25 to 32: Central Baltic Herring; GOR: Gulf of Riga herring. Bothnian Sea herring and Bothnian Bay herring units are not shown. Source: ICES (2014). Graph: Marco Nurmi.

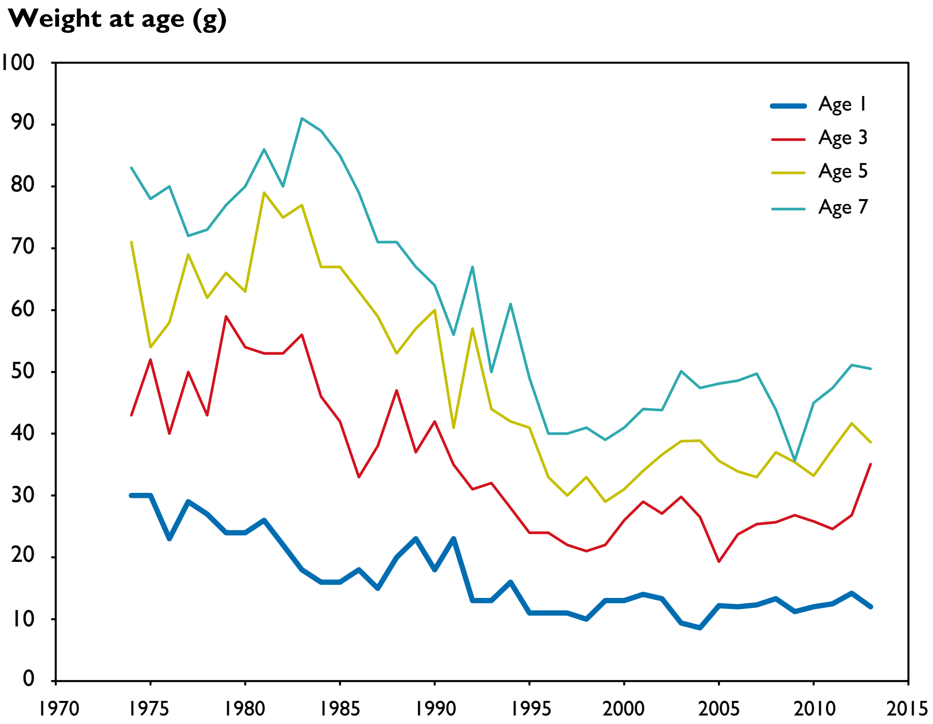


Figure 5. The mean weights-at-age (g) for Central Baltic Sea herring as a function of time. Numbers refer the age in years. Source: ICES (2014).

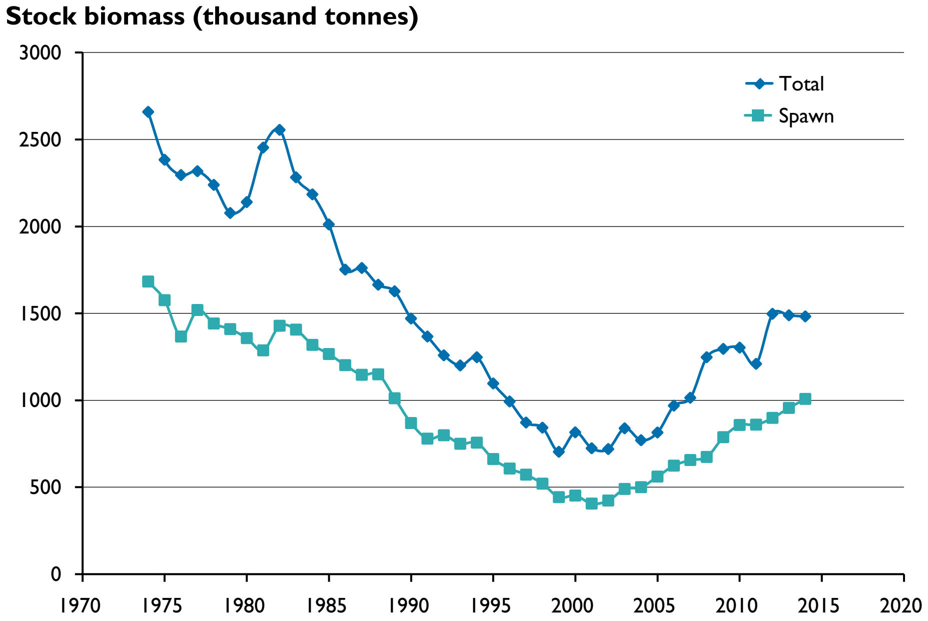


Figure 6. The total stock biomass (total in thousand tonnes) and spawning stock biomass (spawn in thousand tonnes) of Central Baltic Sea herring as a function of time. Source: ICES (2014).

Salinity is one of the key factors affecting herring production and biomass; it affects herring directly through physiology, and indirectly via zooplankton community structure (the quality of food for herring). Sprat preys on and influences the zooplankton community as well, and competes effectively with herring.

Predation by cod has a major impact on herring. Size selective feeding of cod on herring contributed to the exceptionally large weight-at-age of herring during the early 1980's. The mean weights-at-age decreased substantially thereafter, and since 1998 it has fluctuated at a low level without any clear trend (Fig. 5). Relatively similar trends have been noted in all Baltic sub-stocks, but the decrease in weight-at-age has been more pronounced in the Northern Gotland Basin and in the GOF. The sprat stock has been concentrated there since the early 1990's, inducing severe competition for food resources.

Both stock biomass and spawning stock biomass of the Central Baltic herring have decreased since the mid-1970's. This decline has clearly been driven by decreasing mean weight, since the stock size estimates in numbers have shown a much more stable trend. In the early 2000's, the stock biomasses and the numbers started to increase again, being now in about the same level as in the early 1990's (Fig. 6).

Although herring can tolerate low salinity, the easternmost GOF is still an extreme area for this species of marine origin. The expected climatic changes will affect the hydrography of the GOF, thus influencing on the spawning and feeding of herring, and contributing to its stock sizes and catches (Pedchenko 2011). In 2006–2013, the total herring biomass varied from 6 600 to 15 800 tonnes in the Russian part of the GOF, the maximum annual catch being 3 700 tonnes.

Sprat

Sprat in the BS is at the northern limit of its geographic distribution. It is considered as one population covering the whole BS, i.e., without any distinguishable sub-stocks. Sprat, like herring, is a prey species of cod, and sprat biomass is strongly dependent on the abundance of cod. Sprat biomass was low in the 1970's and the 1980's when cod was abundant in the BS. A decline in cod biomass and favourable conditions for sprat recruitment led to the peak of sprat biomass in the 1990's (Fig. 7). The high stock size led to competition for

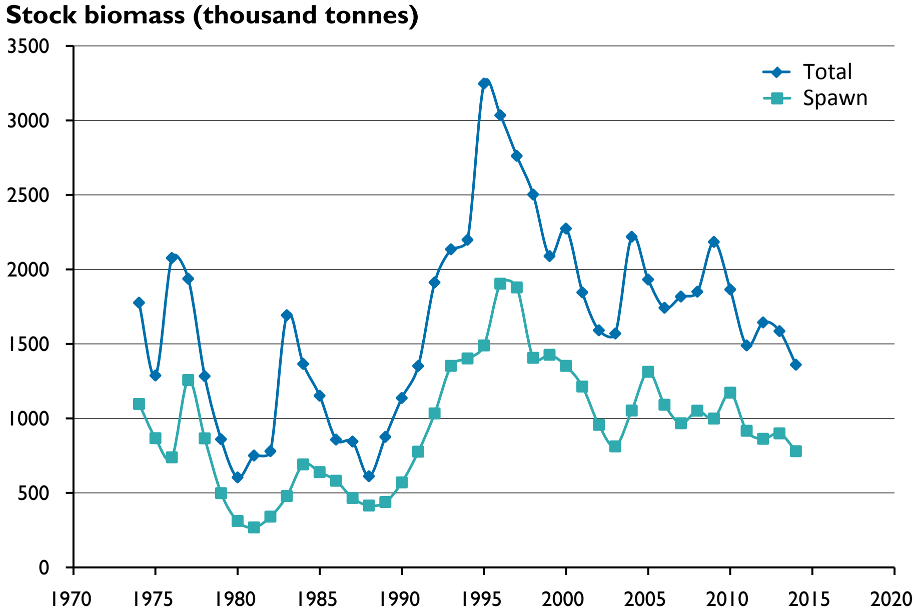


Figure 7. Total stock biomass (total in thousand tonnes) and spawning stock biomass (spawn in thousand tonnes) of the Baltic sprat as a function of time. Source: ICES (2014).

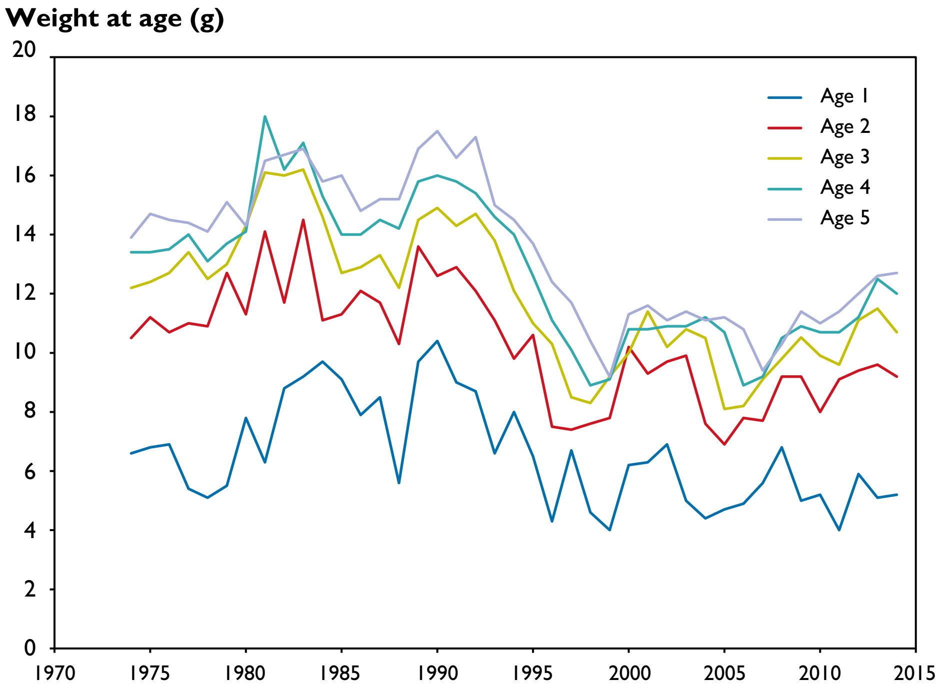


Figure 8. The mean weights-at-age (g) of the Baltic sprat as a function of time. Numbers refer the age in years. Source: ICES (2014).

food resources and resulted in a marked decline in sprat mean weights. This development was most pronounced in the northern areas (Subdivisions 27 to 29 and 32, i.e., the Central and Northern Gotland basin and the GOF), where cod decrease was most pronounced. The mean weight-at-age decreased by about 40% in 1992–1998 (Fig. 8). Since then, it has fluctuated with no clear trend, albeit at a markedly lower level than in the 1970's and the 1980's.

The acoustic and trawl surveys in 2013 (BIAS and BITS, respectively) found that of all Baltic basins, the GOF and the Northern Gotland Basin had the highest abundances of herring and sprat.

Catches of herring and sprat

Besides market demand, also the state of a fish stock, the catch quota, and the changes in the overall volume of the fishing sector influence the resulting catch. The total catches of herring and sprat in the GOF have varied substantially during the assessment period (Fig. 9). At the turn of the century, both of the catches totalled > 30 000 tonnes. After that, a drastic decline was observed, and both of the catches were dropped down to < 10 000 tonnes by 2003.

The annual Finnish herring catch in the GOF has varied from 1 000 to 23 000 tonnes in 1980 – 2013. The largest catches were taken in the 1980's. In the recent years, the annual catches have been around 3 000 to 5 000 tonnes, commercial fishing by trawling taking most of the catches (for example about 90 % in 2013). The annual Estonian herring catches in the GOF have varied from 3 000 to 21 500 tonnes since 1995. There was a decreasing trend in the catches in 1995–2004, but they have been rather stable since 2010 (6 000 to 9 000 tonnes).

Sprat catches have also varied a lot during the past three decades. In Finland, they were only 40 tonnes at minimum but reaching almost 17 000 tonnes in the year 2000 (Fig. 9).

A well-deserved break. Fishing boats resting in the port. Photo: Riku Lumiaro.

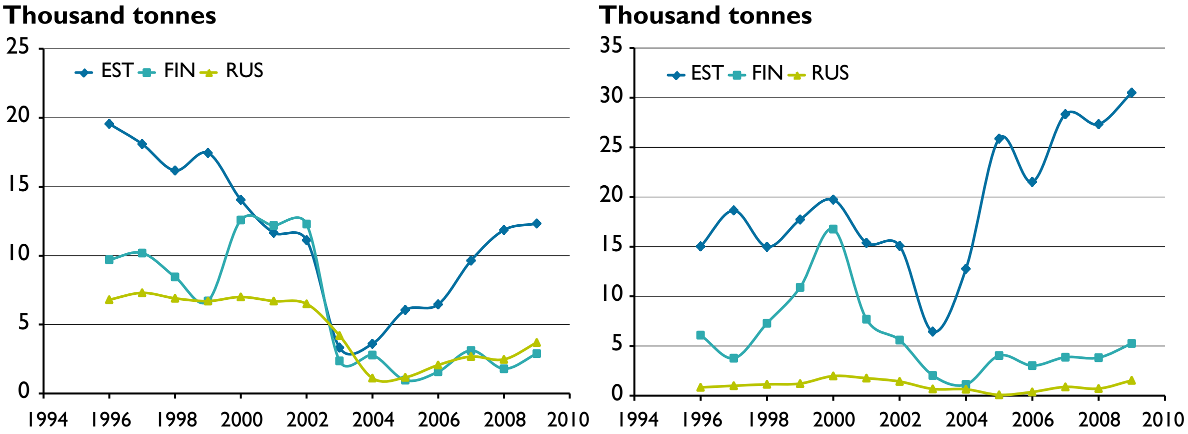


Figure 9. Catches of herring (left) and sprat (right, thousand tonnes) in the GOF as a function of time. Note: also Sweden, Denmark, and Germany contributed to the catches, only their impact was minimal and are not presented. Source: FAO, Shurukhin et al. 2015.

In recent years, the annual catches have varied from 3 000 to 5 000 tonnes. In practice, the whole catch is taken with trawls by commercial fisheries. The Estonian fisheries have caught 7 000 to 30 000 tonnes of sprat in the GOF annually since 1995. The catches have been rather stable in the most recent period: 20 000 to 30 000 tonnes since 2005.

Marine species (herring and sprat) provide for 61 to 85 % of the average annual catches in the Russian part of the GOF. The occasional arrival of sprat in the Eastern GOF significantly contributes to the total Russian catch of marine fish; the annual catches of sprat have varied from 2 000 to 3 000 tonnes in many years (1966–1967, 1971–1979, and 1981). The highest catch of 15 800 tonnes was recorded in 1977, while in 1983–1994 sprat fishery was completely absent. In 2014, there was a slight increase in the catch of sprat (Shurukhin et al. 2015).

Salmon and sea trout: dynamics, status, and catches

Tapani Pakarinen[1], Martin Kessler[2], Sergey Titov[3], Markku Kaukoranta[1]

[1] *Natural Resources Institute*
[2] *Estonian Marine Institute*
[3] *The State Research Institute on Lake and River Fisheries (GOSNIORH)*

How to bring back wild salmon?

For many years, the state of wild migratory Salmonid fish stocks (salmon and trout) has been critical in the GOF and in the rivers discharging into it. Damming of the spawning rivers and overfishing in the sea are the main reasons contributing to this. Improved regulation of fishing in the sea and the restoration of rivers have, however, brought back some of the naturally reproducing stocks. Crucial for the recovery of the salmon and trout stocks is to enable adult fish to enter the spawning grounds. In the GOF, salmon has suffered even more than trout, because it spawns in larger rivers that have been severely damaged due to anthropogenic actions. In the declaration of the Gulf of Finland Year 2014 there is an initiative to restore the four biggest salmon rivers: the River Kymijoki, the River Luga, the River Neva, and the River Narva. The story behind the decline or loss of the salmon in those rivers is not always the same. Nevertheless, the salmon stocks in all of them can be restored.

- The River Kymijoki lost its original salmon stock in the 1930's when the river was closed by hydro-power plant construction. In the 1970's, salmon was restocked to the river by using the River Neva salmon. Management measures to restore the migratory fish populations in the river included the opening of a new fish pass in the Korkeakoski hydro-power plant in 2016, and gravelling of spawning areas.

- The main reason for the decline of salmon in the River Neva has been dredging of the spawning grounds for deepening the maritime waterways. These spawning grounds can be relatively easily and also economically restored by narrowing parts of the waterways and bringing gravel for spawning substrate.

- The River Luga has suffered less than other main salmon rivers of the GOF. The main channel has not been dammed or heavily dredged, and most of the former spawning grounds still exist, only are in poor condition. As a result, the present annual smolt production is extremely low (2 000 to 8 000) as compared to the potential (100 000 to 150 000). The management plan for the restoration of salmon in the river has been developed in the HELCOM-supported BASE project, and is concentrating on fishery regulation, guarding, and enhancement of the spawning grounds. Potentially, the river could support a stock of at least 15 000 to 20 000 spawning salmons.

The upstream travel of fish used to end here: Korkeakoski hydro-power plant in the River Kymijoki. Photo: Riku Lumiaro.

- The River Narva lost its salmon stock in 1955 when a hydro-power plant was built. The former salmon spawning grounds were drowned by the Narva Reservoir. About ten hectares of these former spawning grounds could be restored, if at least 15 m^3/s of water could be re-directed to the original river channel. Construction of a fish pass in the vicinity of the Narva dam would allow the fish reach their former spawning grounds in the upper reaches of the river.

Natural vs. hatchery salmons

The River Kunda, the River Keila, and the River Vasalemma are the only remaining rivers in Estonia that still have native salmon stocks. Their smolt production capacity is still very small, although it has improved since 2010 (Fig. 10). Particularly, the River Keila and the River Vasalemma have improved substantially in their smolt production as a result of better fisheries control. In the River Kunda, the population status has varied strongly, partly due to natural factors and partly due to poaching.

Apart from wild salmon rivers, there are ten other rivers in the area where natural reproduction takes place. These stocks are also supported by smolt releases. The largest natural reproduction in these so-called mixed rivers takes place in the River Kymijoki, from which about 28 000 smolts migrated to sea in 2014. Also the River Luga has a substantial production potential.

The total natural reproduction in the rivers of the GOF – wild and mixed salmon stocks included – is still negligible as compared to hatchery releases. It has gradually increased in the recent years, however, and was about 60 000 smolts in 2014. At the same year, ten times that much of hatchery-reared smolts (670 000) were released in the rivers of the GOF (Fig. 11). Smolt releases are carried out in order to compensate for the lost natural reproduction due to damming of rivers for the hydropower production, or due to other activities that have spoiled the spawning grounds.

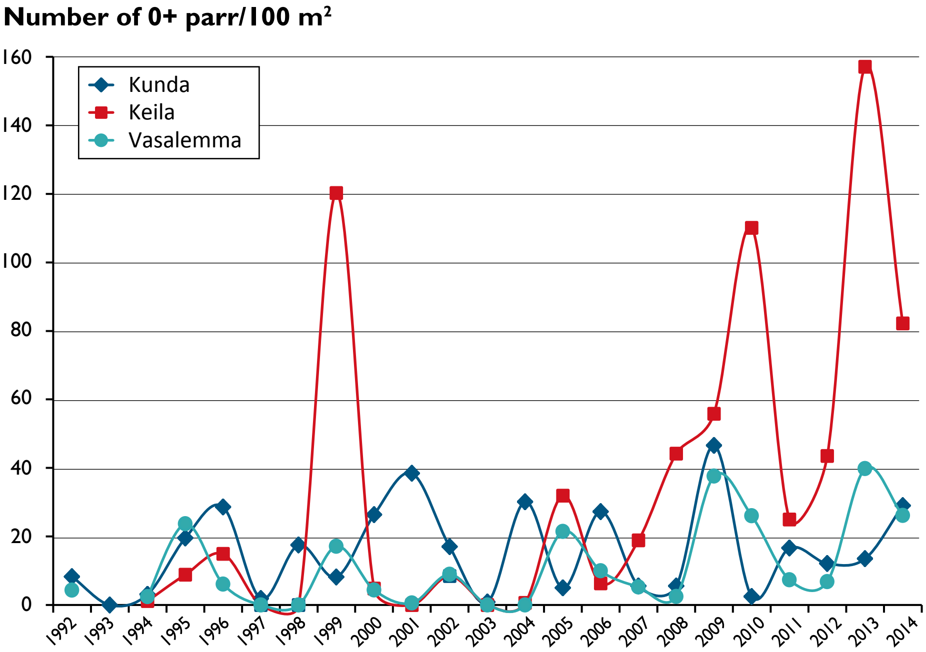


Figure 10. Densities of 0+ (one-summer old) salmon parr (individual/m²) as a function of time in the three Estonian salmon rivers having native salmon stocks. Source: ICES (2015).

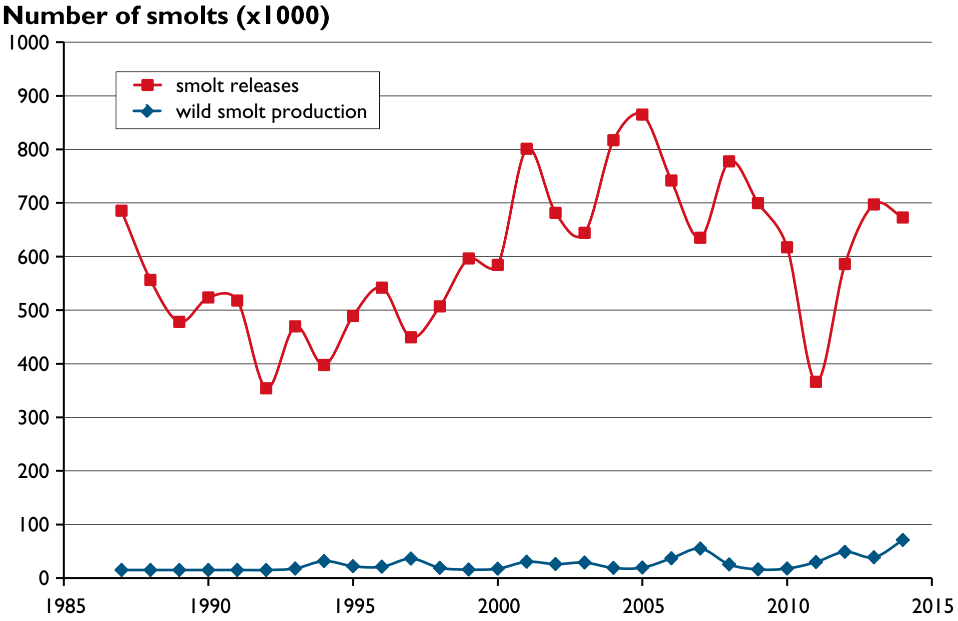


Figure 11. Natural salmon smolt production and smolt releases (thousands) in the GOF as a function of time. Source: ICES (2015).

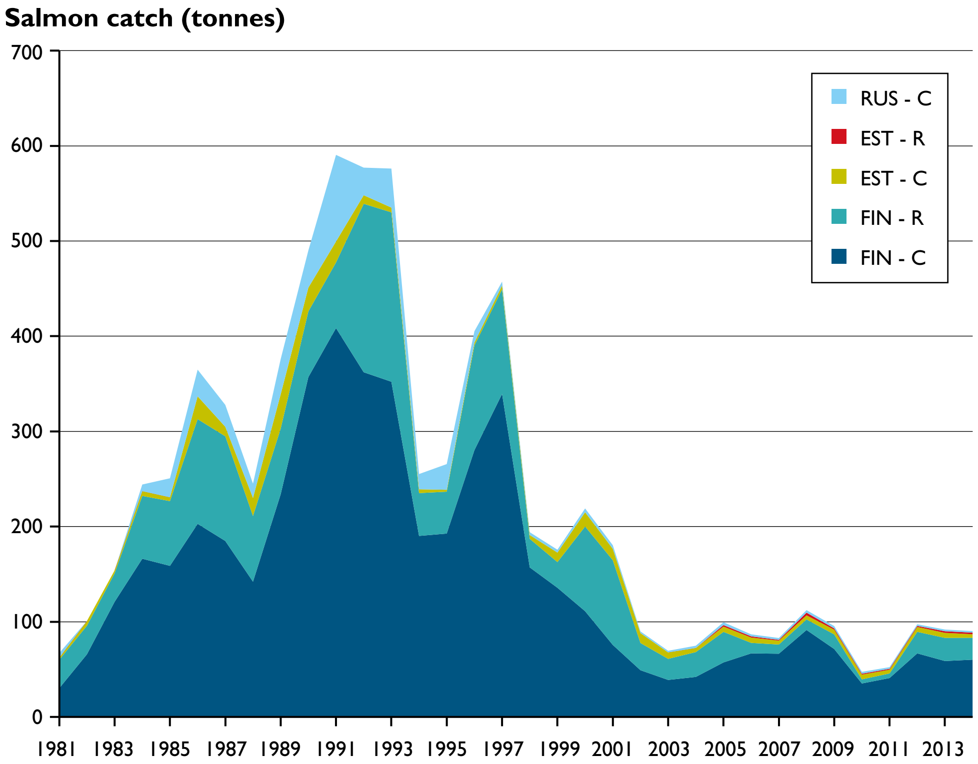


Figure 12. Salmon catches (tonnes) of commercial (C) and recreational (R) fisheries in the GOF as a function of time. Estimates of recreational catch are highly uncertain. Source: ICES (2015).

Commercial salmon catches

In 2014, the total commercial salmon catch in the GOF was 64 tonnes (9 430 salmons). The Finnish commercial salmon fisheries have caught about 90 % of the total fishing quota of the management area in 2010–2014 (Fig. 12). So, most of the catch in 2014 was caught by 180 seal-protected trapnets by 60 fishermen in the Finnish coastal region between Porvoo and Kotka. The Finnish fishing effort has been more or less the same for the past decade.

In Estonia, there is no commercial fishery targeting particularly on salmon. Salmon is caught as a by-catch in the coastal fishery where the main targeted species are sprat, European flounder, and perch. The share of salmon in the total coastal catch of Estonia is < 1 % (8 tonnes in 2014), and mostly caught by commercial fishermen by gillnets.

No fishery targeting particularly on salmon takes place in Russia either, and Russia has not reported salmon catches in the sea fisheries in the past few years. Salmon may be caught as a by-catch on the coast, where the main targeted species are herring, sprat, smelt, perch, and pikeperch. However, there are no official statistics of by-catches in Russia. In 2014, Russian fishermen caught 1.7 tonnes of salmon in the rivers for the brood stock purposes.

In the early 1990's, driftnet and longline fishery took place in the off-shore areas. At that time, about 25 % of the total catch originated from the offshore area. The offshore fishery has gradually ceased since then as a result of increased grey seal population, and substantially increased maritime traffic. In the early 1990's, about 50 Finnish vessels operated in the salmon offshore fishery. Nowadays, few vessels make sporadic efforts with longlines inside the 4 nautical mile zone, and their total annual catch has been < 100 salmons.

Grey seal populations in the GOF has constantly increased since the mid-1990's, and today, their existence frequently hinder the fishing at the traditional trapnet sites in the outmost fishing grounds. As a result, fishing has moved closer to the archipelago.

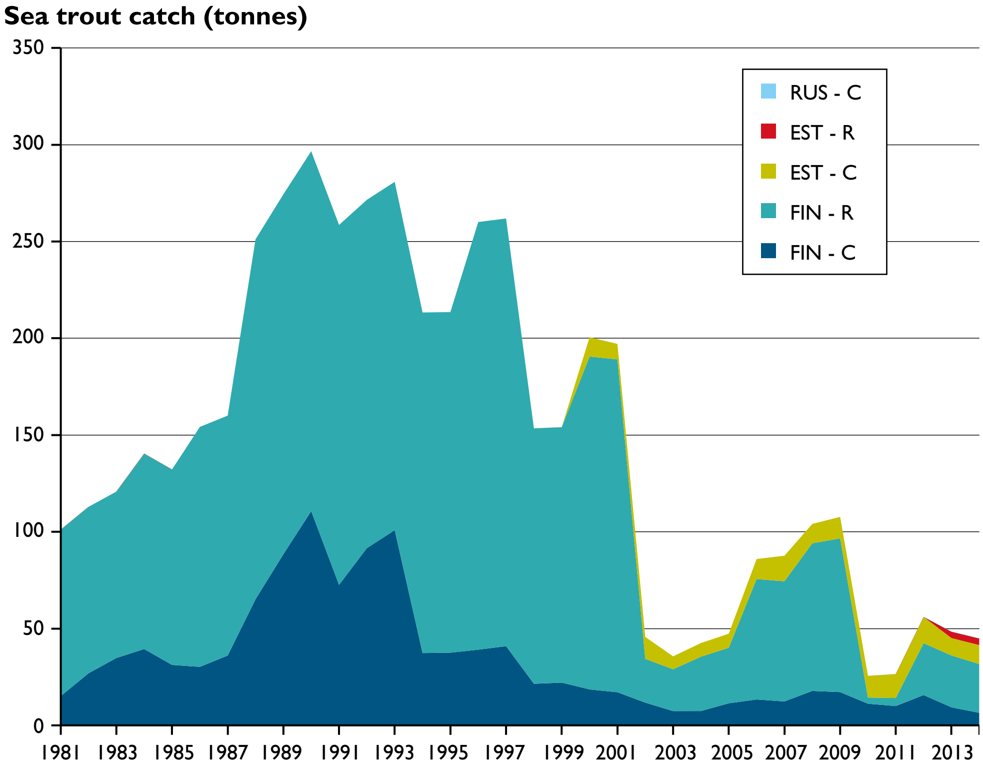


Figure 13. Sea trout catches (tonnes) of commercial (C) and recreational (R) fisheries in the GOF as a function of time. Estimates of recreational catch are highly uncertain. Source: ICES (2015).

However, damages due to seals occur to some extent also there. According to Finnish logbook records, the number of caught and later discarded salmons, damaged by seals, equalled 1 063 fish (7 tonnes) in the GOF, which is about 10 % of the total commercial catch in the GOF. The damages have recently gotten smaller due to the use of seal-proof fishing gear. In Estonia, the seals have caused similar problems for coastal fisheries, but no quantitative estimates of these damages are available.

Non-commercial salmon catches

In 2014, recreational fishing caught about 25 tonnes of salmon (4 300 salmons) in the GOF, but these estimates are very uncertain. The major part of the recreational salmon catch in Finland is a by-catch in the gillnet fishing for other species.

Rod fishing is important in the Finnish and Estonian rivers. The River Kymijoki comprises the major proportion of the recreational river catches (3.5 tonnes, 580 salmons in 2014). In Estonia, angling with the special license is allowed in the River Narva, the River Purtse, the River Selja, the River Valgejõgi, the River Jägala, the River Pirita, and the River Vääna. The catches from these rivers remain < 1 tonne.

In the Russian part of the GOF, there is currently no recreational fishing for salmon. However, unofficial information indicates a presence of significant poaching of salmon both in the coastal area and in the rivers.

A chance for recreational fishing is a valued treasury amongst the people, whether the target is sea trout or herring, as in this case. Photo: Riku Lumiaro.

Commercial sea trout catches

The total commercial sea trout catches in the GOF were 16 tonnes in 2014 (all three countries included). In the beginning of the 1990's, the corresponding catch was about 100 tonnes (Fig. 13).

In Finland, there is no commercial fishery focusing particularly on the sea trout, but it is caught as a by-catch in the fisheries for other species. The same goes for Estonia. Majority of the fish is taken by gillnets.

There is no commercial fishery targeting particularly for sea trout in Russia, and no trout catches have been reported there, because sea trout has been a protected species since 2002. Like salmon, also sea trout can be caught as a by-catch in the coastal fishery (by trap nets and gillnets), only in Russia there are no official statistics of by-catches. In 2014, 100 kg of sea trout were caught in the rivers of Russia for the brood stock purposes.

Non-commercial sea trout catches

In 2014, the estimated catch of recreational sea trout fishery in the GOF was about 29 tonnes, from which the Finnish share was 25 tonnes. According to tagging data, most of the Finnish catch is taken by the bottom gillnets, which are set out for other species, such as whitefish and pikeperch. As a comparison: the total catch in the early 1990's was about 200 tonnes, though the estimate is very uncertain.

In Estonia, there is a small scale non-commercial gillnet fishery on the coast harvesting < 20 % of the total trout catches. Alike with salmon, angling of trout is allowed with a special license in some rivers (see above). Sea trout fishing also takes place in the River Vihterpalu watershed, but since fishing there is not regulated with special licenses, the catches are unknown.

Alike commercial fishery, there is currently no recreational fishery for sea trout in the Russian part of the GOF. However, unofficial information indicates the presence of significant poaching both in the coastal area and in the rivers.

Whitefish

Lari Veneranta[1)]*, Aare Verliin*[2)]*, Andrey Pedchenko*[3)]

[1)] Natural Resources Institute Finland
[2)] University of Tartu
[3)] The State Research Institute on Lake and River Fisheries (GOSNIORH)

Dynamics and stocks

Whitefish has high economic and social importance for fisheries in the northern BS and in the GOF. There are at least two ecotypes of whitefish, a migratory river-spawning type and a more stationary sea-spawning type. Both ecotypes occur also in the GOF. They have nearly identical appearance, but they can be distinguished by growth. In most cases, the sea-spawning ecotype remains smaller at maturity. Especially in the eastern GOF, the sea-spawning ecotype has a slightly slower growth rate and remains smaller in size than the migratory one. In Finland, the migratory ecotype is classified as an endangered species and the sea-spawning ecotype as vulnerable species in the red list of Finnish species (Urho et al. 2010). Several small populations have restricted spawning areas in the southern parts of the GOF (Sõrmus 1976, Sõrmus and Turovski 2003), and spawning grounds are also located in the vicinity of the large islands in the eastern GOF (Sendek 2012).

Migratory ecotype

Natural reproduction of whitefish in the rivers practically ceased in the 1960's, and annual catches have decreased strongly from the earlier levels of 150 to 200 tonnes due to unfavourable changes in the rivers (Salojärvi et al. 1985). In Finland, the lost reproduction capabilities of migratory whitefish have been compensated since the 1980's with vast stockings of one-summer-old fingerlings and newly-hatched larvae. The magnitude of stockings has varied from year to year, but for example in 2007, about 1.3 million one-summer-old fingerlings and 1.2 million newly-hatched larvae were stocked (Natural Resources Institute Finland, unpubl.). The stocked whitefish belong mostly to the migratory ecotype, originating from various stocks.

Migratory whitefish can still reproduce in several coastal rivers, even in the small ones. For instance, newly hatched larvae has been found from the River Kymijoki, the River Summajoki, the River Koskenkylänjoki, the River Mustionjoki, the River Vantaanjoki, the River Espoonjoki, and the River Mankinjoki. However, the abundance of whitefish larvae has been low in all these rivers. The annual larval production is 2 to 5 million in the River Kymijoki and 0.5 million in the River Summajoki (Koivurinta and Vähänäkki 2004, Raunio and Nyberg 2013). Regardless of the importance of whitefish, there is still an evident lack of knowledge on its spawning run, spawning sites, and larval production in the rivers. The improving environmental state of the

One week after hatching the larvae, migratory whitefish are 15 to 17 mm long. Photo: Lari Veneranta.

rivers may have enhanced its possibilities for natural reproduction, and in many rivers, the stockings have increased its numbers running up the rivers for spawning.

In Finland, the migratory whitefish has a long history of intense stockings. There are genetic differences between the stocks, but in many cases the original stocks have been mixed. The sea-spawning ecotype is supposed to be more of an authentic origin, but its genetic diversity has not been thoroughly studied.

There is no historical evidence of reproducing anadromous whitefish populations in the Estonian rivers. However, small numbers of whitefish have been observed at lower parts of certain rivers (the River Jägala, the River Pirita, the River Kunda) in the late autumn. Whitefish is also known to enter the River Narva (Sendek 2012).

Sea-spawning ecotype

The spawning areas of the sea-spawning whitefish ecotype have diminished due to eutrophication and climate change (Veneranta et al. 2013). However, there is still natural reproduction occurring especially in the eastern GOF and in some parts of the western GOF (Natural Resources Institute Finland unpubl.). There is an evident lack of recent data on the state of the sea-spawning ecotype in the GOF.

The possibilities for natural reproduction of both ecotypes of whitefish should be enhanced. More knowledge should be gathered on restoration of reproduction areas and construction of fish ways for those rivers that are dammed or otherwise artificially altered. Whenever possible, the spawning run of whitefish and other migratory fishes should be supported by removing dams and other structures, which prevent the fish from entering suitable spawning sites. Early results from currently ongoing studies encourage the use of these kinds of acts to enhance the state of whitefish stocks by supporting its natural reproduction.

Catches

Whitefish is a desired catch species, especially within recreational fishermen, who use mostly gillnets and angling. The Finnish fishermen's annual whitefish catch has fluctuated from 50 to 390 tonnes in 1980–2013, peaking in the early 1990's. The commercial catch is mostly taken by trap nets.

In the Finnish coastal areas of the GOF, the share of recreational fishing of the whitefish catch is high. For example in 2008–2013, the reported annual whitefish catches of Finland in the GOF varied from 41 to 49 tonnes for commercial and 45 to 127 tonnes for recreational fishing (Official Statistics of Finland 2014, Fig. 14). A significant part of whitefish catch in the GOF is caught during the spring and early summer by angling (Urho 2011).

The increase in the annual commercial whitefish catch in the GOF from 20 to 57 tonnes in the latter half of the 1990's (Söderkultalahti 2001) was most likely due to intensive stockings. The yields from stockings of migratory whitefish have varied from 100 to 250 kg per 1000 one-summer-old fingerlings (Raitaniemi et al. 1996). The present catches indicate that the survival of stocked fingerlings and larvae has remained relatively stable.

Whitefish stocks in the GOF are relatively highly exploited. Gillnet fishing removes the largest individuals and affects the length distribution of the fish stock (Heikinheimo and Mikkola 2004). Most of the whitefish are caught at the age of 4–6 years.

Whitefish catches were small during the 1980's along the southern coast of the GOF because the fishing effort in the Estonian coast was almost completely inhibited due to the very strict border regime imposed by the Soviet Union. Catches increased gradually during the 1990´s and peaked at the turn of the century, a couple of years after the Finnish peak in catches (Fig. 14). According to recent studies, 77 % of the 42 whitefish specimens collected along the coast of Estonia were stocked as 0+ fingerlings, and they most likely originated from the northern GOF (Rohtla unpubl.).

Total catch of whitefish in the Russian part of the GOF varied from 11 to 76 tonnes in 1935–1940, increased to 97 tonnes by the early 1950's, and dropped sharply in the second half of the 1980's. In the 1990's, the annual catch was < 1 tonnes. Since the mid-2000's, the catch increased up to 3.5 tonnes in 2010, up to 12.4 tonnes in 2011, and stabilized at around 8 tonnes in the recent years. Despite this positive trend in the

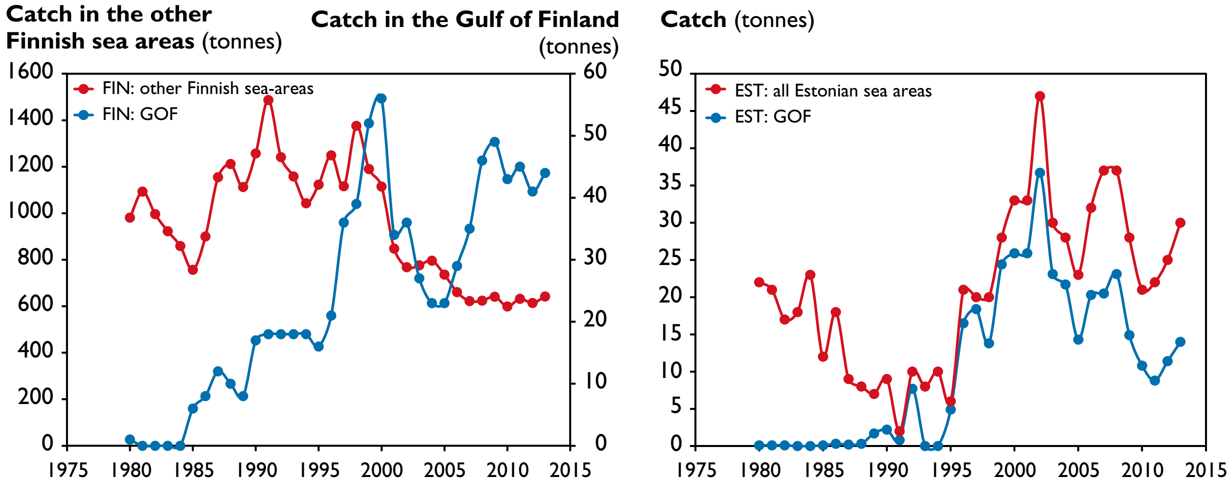


Figure 14. Annual whitefish catches of the professional fishing in the northern (left) and southern GOF (right) as a function of time. Source: Official Statistics of Finland (2015), Verliin (unpubl.).

catches, the whitefish abundance is low in the eastern part of the GOF considering the potential production in this area (Shuruhin et al. 2015).

The total reported whitefish catch from the Estonian part of the GOF has varied from 12 to 28 tonnes in 2008–2013. The majority of these catches are taken by commercial fishermen who use mainly gillnets. The share of recreational gillnet fishing is roughly 25 to 33 % of the total whitefish catches. As there are no significant whitefish spawning grounds in the area, fisheries target almost completely the feeding aggregations.

Coastal species

Antti Lappalainen1), Outi Heikinheimo1), Lauri Saks2), Alexander Shurukhin3), Andrey Pedchenko3)

1) Natural Resources Institute Finland
2) Estonian Marine Institute
3) The State Research Institute on Lake and River Fisheries (GOSNIORH)

Pikeperch and perch: dynamics and stocks

The pikeperch and perch (*Perca fluviatilis*) stocks exhibit wide fluctuations in year-class strength, which are caused by variation in the summertime water temperature (Lappalainen et al. 1996, Pekcan-Hekim et al. 2011). For example in the Archipelago Sea, the water temperatures in July and August explain about 80 % of the variation in the year-class strength (Heikinheimo et al. 2014). Both species have benefited from the warming climate and eutrophication. The fluctuations in the abundance of these species reflect to the development of commercial catches, which have generally been on a higher level in the 1990's and the 2000's, as compared to the 1980's. The changes in pikeperch and perch abundances are synchronous in different parts of the Finnish coast of the GOF (Lappalainen et al. 1996).

In Finland, the pikeperch and perch stocks are monitored by an annual sampling program for commercial catches (EU Data Collection Framework). In addition, experimental gillnet monitoring of fish stocks (targeting mainly on perch) has been carried out in the sea areas off Helsinki and Hanko since 2005. The fluctuations in the abundances reflect the changes in summer temperature (Fig. 15).

On the Estonian side, data on the dynamics of coastal fish species is derived mostly from gill-net monitoring in the Käsmu and Vaindlo monitoring areas, the former being located around a peninsula and the latter in the vicinity of an isolated island. Perch is the dominant species in Vaindlo area, making usually up to 60 % of the total monitored

Somewhere between a lake and an ocean. This duality of the GOF is described by the coexistence of perch and bladder wrack (*Fucus vesiculosus*). Picture for a stamp drawn by Signe Hammarsten-Jansson.

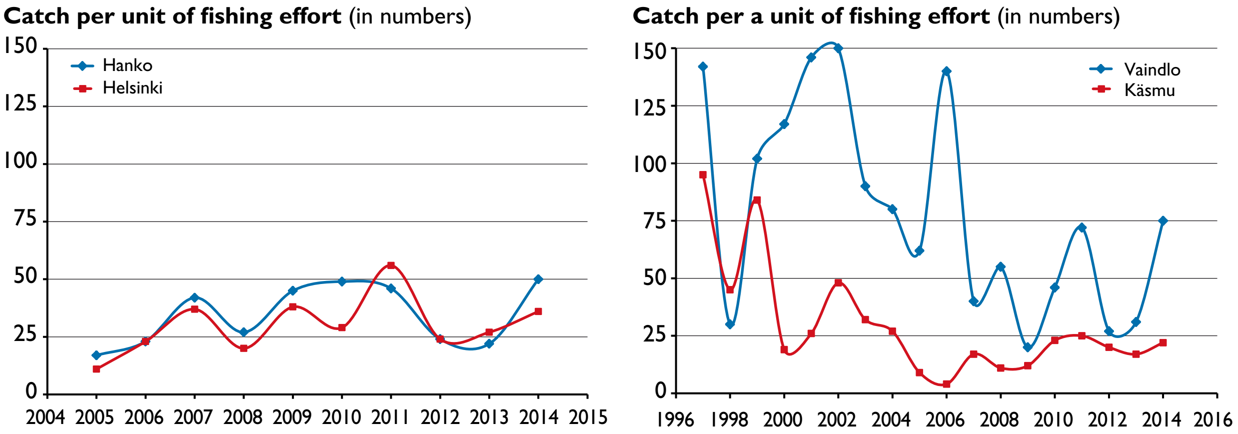


Figure 15. Catch per unit fishing effort (in numbers) for perch as a function of time. Left: off Hanko (Tvärminne) and off Helsinki, right: in Vaindlo and Käsmu areas. Source: Natural Resources Institute Finland, Estonian Marine Institute.

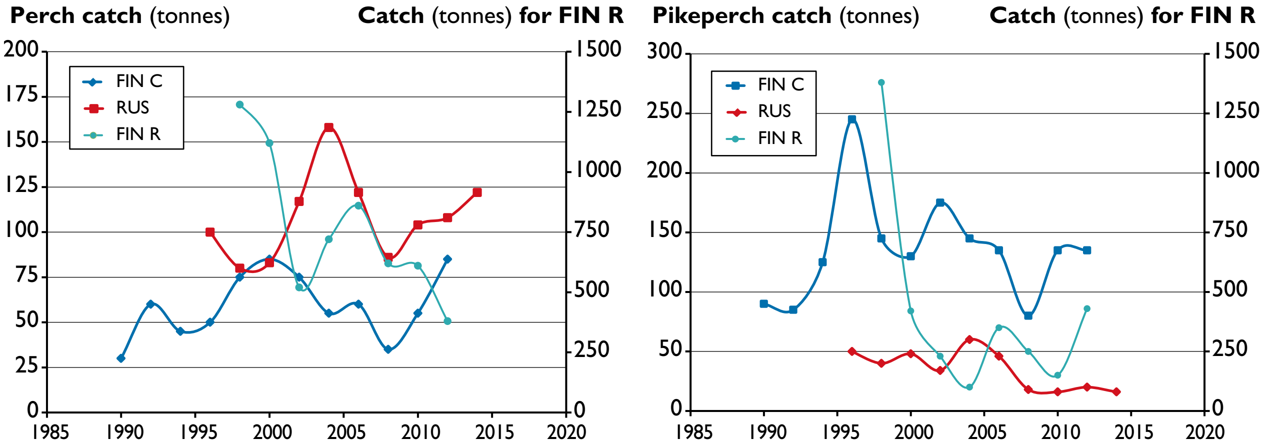


Figure 16. Finnish perch and pikeperch catches in the Finnish coast of the GOF as well as Russian catches in the eastern GOF as a function of time. C = commercial, R = recreational. Source: Natural Resources Institute Finland, Pedchenko (2016).

catches. Besides perch, herring and sometimes also smelt are numerous. While being the dominant species, the numbers of perch have been generally declining in the area (Fig. 15). This most likely reflects the general dynamics of perch in the Estonian coast, because perch at Vaindlo area originates from the populations in the adjacent coastal areas that have suitable areas for spawning. The abundance of perch has also declined in the Käsmu monitoring area.

Pikeperch and perch: catches

Pikeperch and perch are the two most important coastal freshwater species in the Finnish part of the GOF, caught by both commercial and recreational fisheries. Recreational catch forms the bulk of the total catch for both of the species (Fig. 16). The Finnish annual pikeperch catch has varied from 100 to 1 500 tonnes in 1980–2013, being greatest in the mid-1990's. In 2013, the recreational fishermen in Finland caught pikeperch almost four times the catch by the professional fisheries. One third of this was taken with gillnets and two thirds with rods and lines. The commercial fisheries mostly used gillnets.

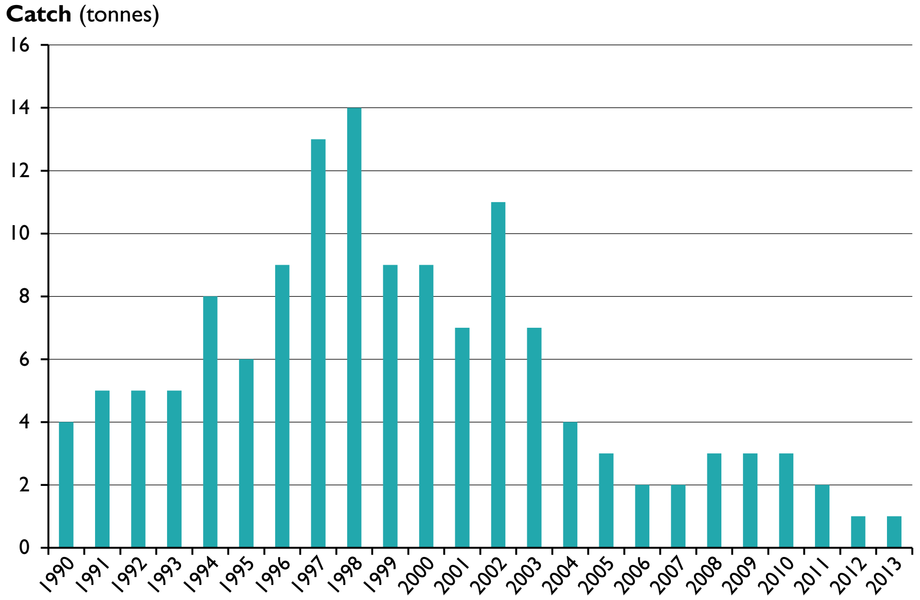


Figure 17. Flounder catches (tonnes) as a function of time in the Finnish commercial fishery in the GOF. Note that also decreased fishing effort has influenced the observed decline in the recent years. Source: Natural Resources Institute Finland.

In Russia, the catches of pikeperch peaked in the 1980's, when the annual average was 245 tonnes and the maximum 384 tonnes. The pikeperch stocks declined rapidly in the eastern GOF in the early 1990's. This has been linked to adverse conditions for reproduction and growth; in 1993–1999, conditions (thermal regime, the volume of freshwater runoff) for fish reproduction in the spring were unfavorable. The decrease of prey fish abundance has also contributed to this decline (Pechnikov 2014a). Furthermore, part of the spawning grounds in the Neva Bay and the Gulf of Vyborg were lost due to sediment deposition and dredging operations. The annual catches varied from 31 to 60 tonnes in 1995–2006, and in subsequent years they decreased to < 20 tonnes (Shurukhin et al. 2015, Fig. 16). The recent state of the stock is unsatisfactory (Shurukhin et al. 2015). In 2013, the number of commercial stock (fish age 3+ and older) has been estimated to be about 1.0 million individuals (419 tonnes), and the spawning stock size to be one tenth of that (fish aged 5–7 years).

The annual Finnish perch catch in the GOF has varied from 500 to 2 500 tonnes in 1980–2013 (Fig. 16). The catches peaked in the early 1990's. The recreational catch has been considerably higher compared to the commercial catch; for instance, it was seven times the commercial catch in 2013. The commercial catch is taken mostly with fyke nets or pound nets and the recreational catch with rod fishing, gillnets, and wire traps.

Flounder

Flounder (*Platichthys flesus*) is a marine species that lives at the brink of its distribution area in the GOF. There is no long-term monitoring data available on the flounder stocks on the Finnish coast of the GOF, but the commercial flounder catches have decreased there in the past 10–15 years, which suggests for a decrease in flounder abundance (Fig. 17). The reasons for this decline, widely noticed by recreational fishermen, are still unknown (Jokinen et al. 2015). Decreases in catches have also been observed in the Archipelago Sea and in the Estonian coastal waters of the GOF.

Hiding out. Flounder catches have been decreasing. Photo: Mats Westerbom.

Cyprinids

Cyprinids, such as roach, bream (*Abramis brama*), and white bream (*Blicca bjoerkna*), are abundant in the sheltered archipelago areas of the GOF, and often dominate gillnet survey catches both on the Finnish and Russian coasts (Lappalainen et al. 2000). Cyprinids have increased in their numbers recently, at least in the Finnish coastal area of the GOF. Eutrophication in the reproduction areas, locating in the innermost archipelago and inner bays, together with the gradually increasing temperature, has favored them during the most recent decades (Lappalainen 2002). However, no similar increase in their abundance has been observed in the Estonian monitoring areas, where fish communities are dominated by perch, smelt, and herring. This is probably due to, e.g., the lack of sheltered shallow bays on the Estonian coast. In the Finnish coastal waters, cyprinids have not much value for commercial fishery and the increased abundance of cyprinids has merely been regarded as a nuisance, especially in gillnet fishery. There have been, however, some pilot projects aiming to find new markets for Cyprinids and to establish targeted commercial fishery for them.

While not demonstrating as distinct effect of eutrophication via the dominance of the cyprinids as in Finland and Russia, the fish community in Estonia has also gone through considerable changes during the last decades. Some of these dynamics can be explained by, e.g., changes in the abundances of smelt, perch, flounder, and sprat. However, a drastic shift in the community structure taken place since 2011 can be attributed to a considerable increase in the abundance of two invasive species: gibel carp and round goby. Their catch per a unit of fishing effort has risen up roughly by 10-fold during the past few years. Their abundance and distribution area, especially for round goby, have drastically increased in the GOF in the recent past.

Roach shows a relatively stable stock state in the Russian part of the GOF. For the last four years, its commercial stock biomass and catches have exceeded the long-term average. The commercially exploited roach stock was estimated to be 22.6 million individuals in 2013, and the biomass 1 027 tonnes. In 2014, the roach catches were 187 tonnes (Shurukhin et al. 2015).

Other coastal species

The annual Finnish burbot catch in the GOF has varied from 20 to 300 tonnes in 1980–2013. The highest burbot catches were taken in the 1990's, and they have decreased since then. Burbot is an important species in recreational fishery, most catches are taken with gillnets from under the ice during the winter months. In 2012, three-fourths of the total catch was taken by recreational fishermen.

The European smelt is one of the main commercial fish species in the eastern GOF. The fishing is performed mainly in the spawning season at the mouth of the River Neva (near Sestroretsk), and to a lesser extent in the Bay of Vyborg. In 1996–2006, the average spawning smelt stock abundance was 31.3 million individuals, suggesting a decrease by a factor of 3.5, as compared to the period 1963–1995. The number of smelt is forecasted to increase in the coming years (Gosniorh unpubl.). The total catch of smelt amounted to 522 tonnes in 2014, which was > 100 tonnes higher than in the previous year, and the highest catch during the most recent 13 years.

Reproduction of fish in the coastal areas

Meri Kallasvuo[1], Tiit Raid[2]

[1] Natural Resources Institute Finland
[2] Estonian Marine Institute

Key fish habitats consist of areas, volumes of water, and bottom substrates that provide the most favourable environments for fish populations to feed, mature, and reproduce throughout their life cycle (Cross et al. 1997). In particular, the availability of habitats used for reproduction delimits fish production (Houde 1989, Urho 2002b).

Both marine and freshwater fish reproduce in the GOF, and consequently, there are species-specific differences regarding reproductive behaviour, life-history traits, and habitat requirements for the early life stages. Gradients in the environmental conditions further limit the reproduction of certain species to taking place in certain parts of the archipelago. The reproduction habitats of coastal fish were studied in the Finnish national VELMU inventory programme (2004–2015).

The majority of the coastal freshwater fish species spawn in the spring or early summer, and use estuaries and shallow (depth < 10 m) archipelago areas for their reproduction (Urho et al. 1990). A good example is pikeperch, which has its reproduction habitats restricted to the shallow and sheltered inner archipelago bays, where water temperature increases rapidly in the spring (Fig. 18, Veneranta et al. 2011). Another such example is roach; its reproduction habitats are restricted by low salinity (Härmä et al. 2008). Suitable vegetation is often an important prerequisite for freshwater fish reproduction, and especially coastal reed belts have been shown to be important for many species, e.g., roach and other cyprinids (Kallasvuo et al. 2011).

The majority of the marine fish of the GOF reproduce within the archipelago zone, too, but are not that strictly limited by salinity to the innermost parts of the archipelago. Baltic herring, for example, uses large parts of the archipelago zone as its reproduction habitat; in the Finnish coastal area, 99.5 % of the water area is suitable

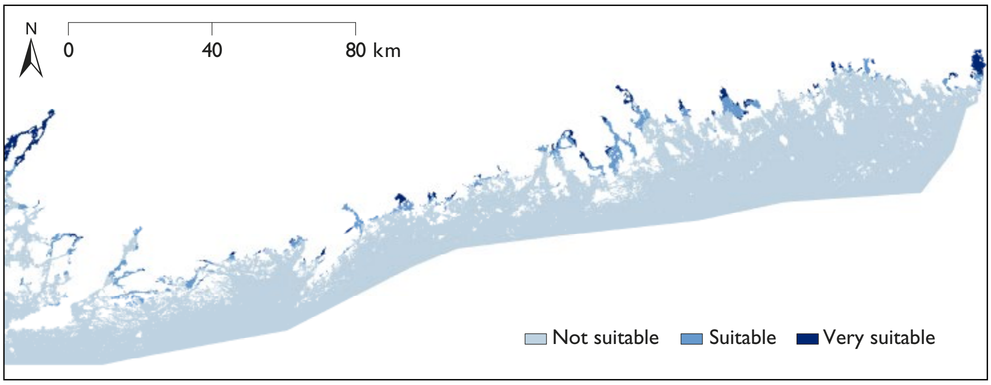


Figure 18. The reproduction habitats of pikeperch at the northern coast of the GOF. Source: Natural Resources Institute Finland, VELMU programme, Kallasvuo et al. (submitted).

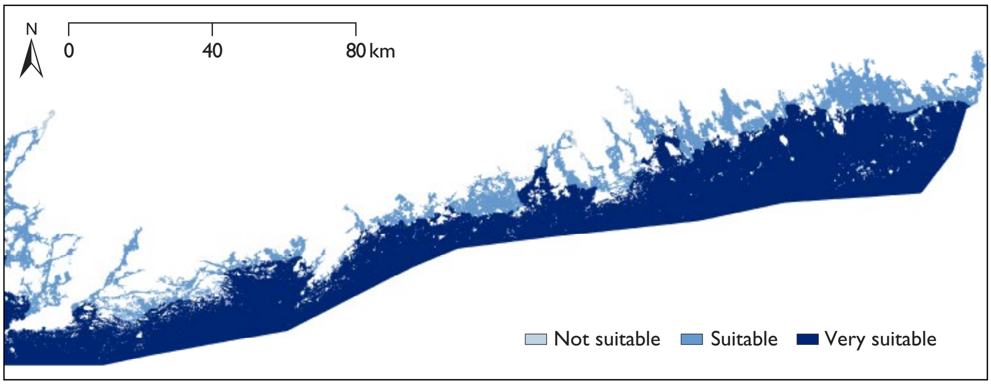


Figure 19. The reproduction habitats of Baltic herring at the northern coast of the GOF. Source: Natural Resources Institute Finland, VELMU programme, Kallasvuo et al. (submitted).

for Baltic herring's larval production (Fig. 19, Kallasvuo et al. submitted). Basically, Baltic herring reproduces almost everywhere along the southern and northern coasts of the GOF with the exception of the inner parts of the Neva and Vyborg Bays. The areas with optimal conditions for proper egg development, i.e., good aeration and availability of suitable spawning substrates, play a key role in the reproduction of the GOF herring (Raid 1985).

Another common clupeid species in the GOF, sprat, seems not to reproduce in the Finnish coastal area of the GOF (project VELMU unpubl.). According to some older studies (Parmanne et al. 1994), sprat is known to reproduce in the offshore western GOF. However, due to limiting environmental conditions, particularly low salinity, the importance of the GOF in sprat reproduction remains marginal.

The main pressures for fish and key fish habitats in the GOF are caused by fishery and environmental changes, such as eutrophication and climate change. Fishing affects fish stocks by removing mature fish prior their reproduction. This can be avoided by fishing restrictions and management measures, such as minimum legal landing size. The environmental changes, on the other hand, affect the early life stages of fish due to altered conditions of reproduction habitats, and are more challenging, if not impossible, to manage. Often the most important reproduction habitats are also the most heavily exploited parts of the archipelago zone. Important reproduction habitats can also be damaged by local anthropogenic acts, such as dredging. Effective marine spatial planning offers an effective tool to allocate actions and protect the key fish habitats.

Fishing and fishermen

Tapani Pakarinen, Pirkko Söderkultalahti
Natural Resources Institute Finland

The number of professional fishermen in Finland decreased rapidly in the 1980's and the 1990's. In the 1980's, there were 370 active professional fishermen in the professional fishermen's register, while in 2013, there were only 230 left. The number of vessels registered to commercial fishery has also decreased by about one fourth.

Fishing methods in the Finnish commercial fishery have experienced notable changes during the most recent decades. The number of trawl vessels has decreased, and especially the larger trawlers. Most of the fishing vessels in use are currently < 12 meters in length and are mainly used in coastal fisheries for freshwater species. In 2012, there were 9 vessels registered for off-shore fishery in the GOF, compared to 52 vessels in 1996.

In Finland, gillnets are used in commercial fisheries for pikeperch, perch, and burbot. Traditional trap nets and fyke nets have been largely replaced by push-up trap nets in salmon and whitefish fisheries due to increased predation from and the fouling of the fishing gear by grey seals.

Offshore fishery is slowly diminishing. Where will these boats find their masters from in the future? Photo: Riku Lumiaro.

The great cormorant: friend or foe? Photo: Riku Lumiaro.

In Estonia, gillnets and trapnets are the main fishing gear in coastal fishing. The biggest catches taken from the GOF with these nets are those of herring, but also of flounder, perch, whitefish, smelt, and sea trout (Fisheries Information Centre 2014).

The Russian fishery in the eastern GOF in the 2000's incorporates both commercial and recreational fishing. About 20 trawl vessels were used in herring and sprat fisheries in the mid-1990's. Since 2003, their number has decreased, and during the most recent years only 2 to 4 small vessels are left. In the coastal commercial fishing, traditional tools, such as gillnets, traps, and seines are used, and basket traps are also in use in the lamprey fishing. The share of the recreational fishing is < 15 % of the total catches (Pechnikov 2014b).

The triangle of seals, cormorants, and fisheries

Outi Heikinheimo
Natural Resources Institute

The abundances of grey seal (*Halichoerus grypus*) and great cormorant (*Phalacrocorax carbo sinensis*) have increased markedly in the BS during the recent past. As both are top predators in the ecosystem, a debate is continuing about the potential impacts of their predation on the fisheries and on the fish stocks.

The number of grey seals in the whole Finnish sea area has been steadily around 10 000 individuals since 2006. They are highly mobile, and therefore, there is no estimate of their abundances in the GOF, but most of the population lives in the south-western Archipelago Sea and waters around Åland. The other seal species, Baltic ringed seal (*Phoca hispida botnica*), is very rare in the GOF.

An adult grey seal consumes 4.5 to 7.5 kg fish / day. Its diet consists of > 20 species, herring being the most important prey species. The seals cause harm to fisheries by damaging the gear and the fish caught in them. In some areas, commercial gillnet fishing has ceased because of the disturbance by seals, and seal-safe trap nets have been developed to maintain the commercial fisheries in the coastal areas.

Rapid growth of the cormorant population in the GOF started in the early 2000's and has not levelled out yet, which has already happened in the Archipelago Sea and the Bothnian Sea. The number of breeding pairs in the GOF reached 8 000 in 2014.

An adult cormorant consumes 0.4 to 0.5 kg fish / day, and the number of prey species in the coastal waters exceeds 30. The diet in the GOF consists mainly of perch, roach, and eelpout. Cormorants may also take fish from the fishermen's gear, or damage the catch. The effect of cormorants on natural fish stocks is a controversial issue. Even if the amount of fish eaten by the population is large and also includes commercially valuable species, the effect can hardly be distinguished in the abundance of the prey fish. In the end, the population size of the prey fish, such as perch and pikeperch, is mainly regulated by environmental conditions. In addition, the predation partly targets prey fish that would not grow to the catchable sizes for fisheries, or would die from other causes. Moreover, compensating processes, such as density-dependence of growth and mortality, counteract the effect of predation.

In 2014, the commercial fishermen discarded 6 % of the salmon catch, 7 % of the whitefish catch and 4 % of the pikeperch catch because of damage caused by seals in the GOF. According to the catch records, the share of discarded whitefish, pikeperch, and perch catch due to damages caused by cormorants was < 2 %.

Fisheries management

Antti Lappalainen[1)], *Lauri Saks*[2)], *Markku Kaukoranta*[1)], *Sergey Titov*[3)], *Alexander Shurukhin*[3)]

[1)] *Natural Resources Institute Finland*
[2)] *Estonian Marine Institute*
[3)] *The State Research Institute on Lake and River Fisheries (GOSNIORH)*

In the BS, stocks of the four main offshore species - herring, sprat, cod, and salmon - are internationally managed according to recommendations of International Council for the Exploration of the Seas (ICES). Stock assessments of these species are based on standard data delivered by all riparian countries of the BS, and the assessments are carried out annually in the working groups of ICES. EU Commission together with Russia determines the total allowable catches (TACs) for each stock, which are then allocated for each country. In Estonia, the quotas are further divided for individual trawling companies. The fishery authorities in each country monitor the catches; commercial fishery for a given species will be closed whenever the annual TAC is reached. Sprat, herring, and cod caught in the GOF belong to larger stocks including, e.g., the Gotland Basin, and thus TACs for these species are not set for the GOF only. There are, however, annual salmon TAC specifically for the GOF to protect the remaining original populations.

The coastal fish species around the GOF form more or less local stocks and the state of these stocks are not systematically assessed. In addition, a large share of the total catch is taken by non-commercial fishermen, meaning that any management based on total quotas is next to impossible to realize simply for practical reasons. Thus, the management of coastal species is mainly based on technical regulations, such as minimum mesh-size regulations in gill-net fisheries and minimum legal landing sizes, which are usually similar for commercial and recreational fishery. In Finland, for example, there are minimum legal landing sizes for pikeperch, sea trout, and salmon set by the state.

There are slight differences in the management practices of coastal fisheries between Estonia, Finland, and Russia. Finnish specialty is a system where coastal waters are mainly privately owned. However, angling as well as spinning or trolling with one rod is allowed also in private waters, the former being allowed for everyone and the latter requiring the payment of a national fee. The use of passive gear, such as gillnets, trap-nets, and longlines, is regulated by water owners. They typically limit the access for fishery with passive gears by limiting the number of permits they sell, or by limiting the amount of gear that can be used. The water owners and local fishery associations have also set minimum mesh-size limits for gill-nets, e.g., in pikeperch and whitefish fishery.

In Russia and Estonia, the coastal waters are owned by the states. In Estonia, recreational fishermen have similar rights for rod fishing to their Finnish colleagues, and they have a possibility to use passive gears, too. The commercial coastal fishing rights (gear usage quotas) in Estonia are distributed on the basis of the historic usage principle. This means that a total limited number of permits for the use of commercial gear (e.g., fyke nets and gill nets) are determined on a regional basis, and that these

No matter whether you are a recreational fisherman or a professional, a great catch puts a smile in fisherman's face. Photo: Riku Lumiaro.

permits are allocated to individual fishermen. In addition to the limitations in gear number, several nation-wide and local measures (e.g., mesh-size limits for gill-nets and fyke nets, minimum legal landing sizes, closed areas and seasons) are employed in Estonia for a sustainable management of fisheries.

In Russia, recreational fishermen have free fishing rights for rod fishing but the use of passive gears is allowed only for commercial fishing. For commercial fishermen, individual or regional quotas exist only for pikeperch. For all other commercially valuable fish species, TACs are determined for the whole Russian part of the GOF. Fishermen are obliged to send weekly information on their catches to the managing authority, which will close fishing as soon as the common quota for a species has been exhausted. There are regulations on minimum legal landing sizes, closed areas and seasons, and on mesh-sizes, too. The number of fishing gears is not limited. When the TACs are determined for each year, scientific organizations estimate catches of the recreational fishermen based on expert knowledge.

Summary

The fish fauna of the GOF became largely established during the early phases of the BS thousands of years ago. Although there are no endemic species in the BS, i.e., species specific for this area only, environmental variations and anthropogenic influences have shaped the characteristics of the local populations. Due to the gradients and local variations in environmental factors, the GOF provides a multitude of marine habitats with different configurations of abiotic and biotic environmental factors for the inhabiting fish species.

Climate change already influences the fish stocks; species preferring warmer waters thrive, and cold-water species suffer. The fish communities and fisheries in the future will depend on a multitude of anthropogenic impacts influencing the sea together with the climate change. As most species are living close to their tolerance limits with regard to one or more environmental factors, environmental variations may have rapid influences on the fish communities.

Habitat requirements of the fish vary in different life history stages. The habitats used for reproduction are those that delimit stock sizes and catches of species. The majority of the coastal freshwater fish species, but also, e.g., herring use estuaries and shallow archipelago areas for their reproduction. In these areas, the anthropogenic impacts are particularly strong. Application of spatial mapping information about the distribution of species and various marine habitat types supports the estimation of habitat quality considering fish production, and can be utilized in the marine spatial planning, and in the management of the fish stocks.

The fish resources of the GOF are exploited by commercial fisheries from Estonia, Finland, and Russia, and by numerous recreational and subsistence fishers. There are country-specific differences in the collection and publishing of fishery data bringing substantial uncertainties in the fishery statistics. It is still apparent that marine fish species, sprat and herring in particular, overwhelmingly dominate the catches. They are mainly exploited by commercial fisheries, whereas recreational fisheries take the largest share of most of the coastal freshwater species.

During the most recent two decades, the rapid recovery of grey seal and the re-colonization of cormorant have become issues of concern for fisheries. In addition to competing of fish resources with fisheries, both grey seal and cormorant can also damage fishing gear. However, their impacts on fish stocks are difficult to estimate, e.g., due to the complexity of the food-web effects they induce. They feed on the species important for fisheries, but they also feed on low valued species which compete with the target species for fisheries.

Recommendations

Currently, monitoring of other fish species than sprat, herring, cod, and salmon is not systematic, and the existing data is scattered. It is therefore difficult to estimate the state and dynamics of many fish species in the GOF. More coherent international data collection and sharing would be needed.

The genetics of trout should be taken into account in the planning of enhancement and hatchery release activities. The genetic composition of each population in the GOF should remain diverse and viable enough for the future evolution of sea trout populations in the GOF watersheds. Mixing genetic material between these groups should be avoided.

River-spawning species, such as the Atlantic salmon and trout, are intensively exploited, and unfavorable environmental changes in the marine areas and rivers have decimated almost all original salmon stocks. Restoration of streams, including removal of unnecessary dams and enhancing the water quality, would provide river-spawning migratory fish suitable areas for their reproduction. This would benefit not only salmon and trout, but also other river-spawning species, such as whitefish, which is another highly valued and intensively exploited species.

Few fish species are abundant especially in the pelagic zone. These can be considered as key species for the ecosystem function. Unwanted consequences may occur if any of those species disappear due to, e.g., intensive fishing. Collapse of local populations may enable unwanted alien species to invade and become established in the GOF. In fisheries management, particular care should be focused on a sustainable management of key fish species, but also on maintenance of local fish fauna adapted for the conditions of the GOF.

Both national efforts and international co-operation should ensure sustainable use of fish and other marine resources. Considering economics and not sustainability in the use of natural resources is a major and acute problem. The economic value of fisheries is low compared to, e.g., many industries, whereas the value of the recreational fisheries is very challenging to determine, but is huge nonetheless. Major steps should be taken to employ the ecosystem approach in the management of the seas and the fish stocks.

Marine ecosystems are at a constant change. Sufficient monitoring and research should be maintained to understand the processes in the sea well enough in order to make clever decisions in the management and exploitation of marine resources, and in the allocation of environmental protection resources. The pressures to cut down funding from monitoring and research will challenge the sustainable management of marine ecosystems and their fish stocks.

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Non-indigenous species

Maiju Lehtiniemi[1], Alexander Antsulevich[2], Jonne Kotta[3], Alexey Maximov[4], Henn Ojaveer[3], Marina Orlova[4]

[1] *Finnish Environment Institute*
[2] *St. Petersburg State University*
[3] *Estonian Marine Institute*
[4] *Zoological Institute, Russian Academy of Sciences*

Viewpoint

Species that are introduced outside of their natural range and outside of their natural dispersal potential are called alien species or non-indigenous species (NIS). Their presence in the given region is due to intentional or unintentional introduction by humans, or they have arrived there from an area in which they are alien (a secondary invasion). NIS do not necessarily cause harm in their environment. However, a growing number of evidence show that some of these species, called invasive alien species (IAS), pose serious threat to native biodiversity, habitats, and ecosystem functioning. They may also harm economy and/or human health. As a consequence, the introduction of new IAS has been identified as one of the major threats to marine ecosystems.

Maritime traffic is an efficient vector of transport for alien species enabling species to overcome natural dispersal barriers. The increases in ships' size and drive speed have increased the number of successful invasions globally. During the last two centuries, about 120 NIS have been recorded in the BS, and over half of them were introduced unintentionally by ships' ballast water, tank sediments, hull fouling, or by spreading from their primary sites of introduction (Leppäkoski and Olenin 2000, Zaiko et al. 2011, AquaNIS 2015). One of the busiest shipping routes in the BS goes through the GOF. During 2013, about 25 000 port visits were made by vessels that entered the GOF, most of which were transporting cargo (HELCOM AIS data, Finnish Transport and Safety Agency). All these vessels were potential vectors for new species invasions.

The Baltic Sea (BS) is not the only corridor for the NIS to enter the Gulf of Finland (GOF). The opening of canals has facilitated active or passive spread from adjacent fresh-water

Photo: Riku Lumiaro.

and brackish-water systems. River systems and canals connect the BS with the Black Sea, the Caspian Sea, and the White Sea, and several geographical invasion corridors open into the BS, of which Volga-Baltic waterway is the most important concerning the invasions to the GOF (Leppäkoski et al. 2002, Panov et al. 2007).

The GOF is one of the highest risk areas for NIS introductions in the BS, along with the Gulf of Riga and other coastal lagoons (Leppäkoski et al. 2002, Panov et al. 2003). Although low salinity and low temperature during the winter limit the number of successful establishments into the GOF, a low number of native species and thus available ecological niches have facilitated the establishment of NIS (Paavola et al. 2005). To date, many species capable of reproduction have invaded the area. The eradication of new species is in practice impossible after invasion and establishment, thus prevention of new introductions should be in focus. Altogether 38 NIS have been recorded in the GOF. Of these, 21 have been spotted in the Finnish waters, 22 in the Estonian waters, and 36 in the Russian waters.

Frequently commuting merchant ships are a prominent spreading vector for NIS. Photo: Riku Lumiaro.

Figure 1. *Cercopagis pengoi* - a photogenic NIS. Photo: Soili Saesmaa.

A wide variety of NIS

The GOF hosts various NIS from several taxonomic groups, including phytoplankton and zooplankton species inhabiting the pelagic environment as well as littoral shallow water invertebrates (crustaceans and molluscs), and fish. Most of the wide-spread species are of Ponto-Caspian origin or from the North America, e.g., the predatory cladocerans *Evadne anonyx* and *Cercopagis pengoi* (Fig. 1), the gammarid amphipod *Gammarus tigrinus*, the hydrozoan polyp *Cordylophora caspia*, bloody-red mysid shrimp *Hemimysis anomala*, round goby *Neogobius melanostomus*, and the spionid polychaetes *Marenzelleria* spp. (Fig. 2), which are found in the whole GOF (AquaNIS 2015). The Chinese mitten crab *Eriocheir sinensis* is also found in all three countries but it is not common in the GOF. Sightings are infrequently reported by fishermen as the crabs are found being caught by the fishing nets.

As ship traffic is intensive in the relatively small GOF, one would think that the fauna and flora would spread easily, and thus be more or less homogenously distributed in the GOF. However, this is not the case. Many NIS that enter the GOF via the Volga canal system establish permanently in the easternmost GOF, but do not necessarily spread to the western parts, or at least it may take many years for them to do so. Examples of such species are tubenose goby *Proterorhinus marmoratus*, Amur sleeper *Perccottus glenii*, the Baikalian amphipod *Gmelinoides fasciatus*, the cumacean *Pseudocuma graciloides*, and the cladoceran *Cornigerius maeoticus*. All these species are found in the easternmost GOF, but are not yet found on the southern or northern coasts (Orlova et al. 2006, Antsulevich 2007).

Areas of warm water discharge at the nuclear power plants in Loviisa, Finland, and Sosnovy Bor, Russia, may serve as a small refuge for the warm-water NIS (for example, mussel *Mytilopsis leucophaeata*, Laine et al. 2006). How did *M. leucophaeata* get there in the first place is still a mystery, which merits special attention and careful study. It was thought for a long time that this mollusk is unable to reproduce and overwinter outside of these warm water areas, but in 2011 few mussels were found in the Archipelago Sea, and later in the port areas nearby, giving evidence of this mussel’s adaptation to cold waters.

Figure 2. A representative of *Marenzelleria* spp. is a familiar NIS (left). A tiny (< 5 mm long) gastropod species is a newcomer; it is abundant in Hamina area but remains unidentified (right). Photo: Jan-Erik Bruun, Katriina Könönen.

Vessels as vectors for NIS

For introductions of NIS, the amount of ballast water discharged in the port area is in the essence. This cannot, however, be estimated solely as based on the number of vessels visiting the port. The vessel types have a certain role, too. Tankers and bulk carriers have larger ballast water tanks than have container ships, but the latter release their ballast water more often. At first sight, tankers are the most important carriers of NIS due to their huge ballast water volume. The bulk carriers, however, are just as important due to their tendency to commute between the ports, and because they often manage their ballast water in the shipyard areas (Niimi 2004). They also comprise a relatively large fraction of all non-personnel maritime traffic.

Maritime traffic may bring NIS into the GOF originating from basically any part of the World Ocean. These kind of visits are, however, rather rare. Most of the vessels coming from outside the BS have left the central ports of Middle Europe, such as Rotterdam. A total of 1 096 tankers visited the Kilpilahti oil terminal in Porvoo in 2012. Of those, 74 % released ballast water into the port waters. Of those, 78 % were coming from other parts of the BS, mainly from Swedish ports or from other Finnish ports. The rest of the tankers came mainly from the coasts of the north-east Atlantic, and only few steamed from the other parts of the World Ocean.

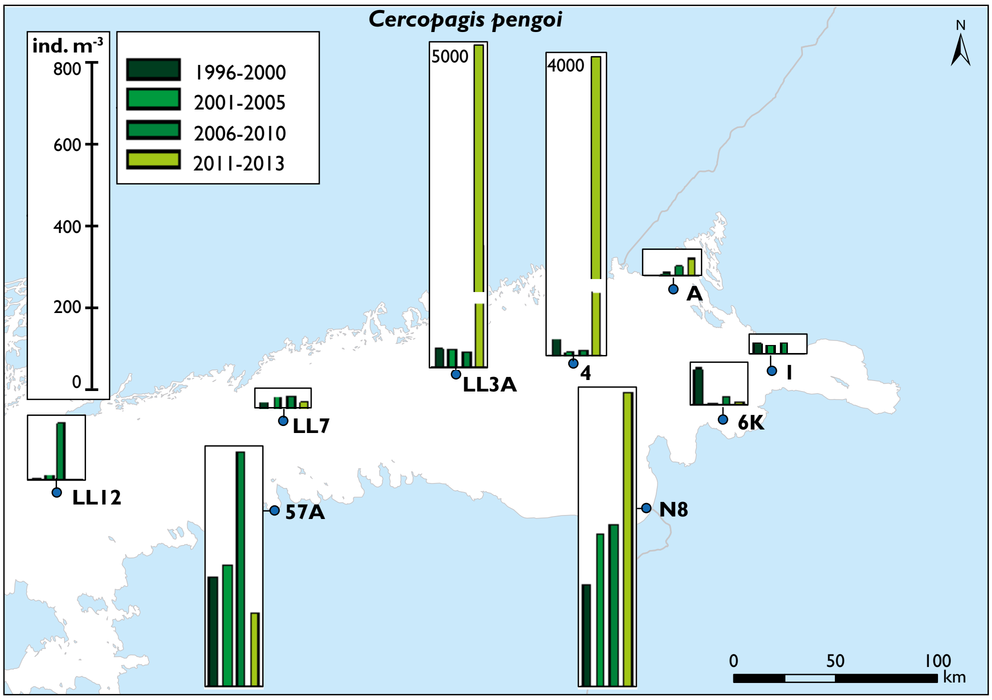

Figure 3. Abundance (individuals/m^3) of *Cercopagis pengoi* in the GOF in 1996–2013. Source: GOF2014 dataset. Graph: Maiju Lehtiniemi, Marco Nurmi.

Trends of some NIS

The two widely spread species in the GOF, *C. pengoi* and *Marenzelleria* spp., exhibit certain trends over the temporal and spatial scales.

C. pengoi is native to the Black Sea and the Caspian Sea, and was found in the GOF for the first time in 1992. It appears in greatest numbers above the thermocline during the warm summer months (Lehtiniemi and Gorokhova 2008). Although there is variation in its abundance in the GOF, long-term plankton data reveal some patterns (Fig. 3). The abundances have increased from the 1990's to the present at most of the stations investigated. This trend is most evident in the offshore areas in the western and middle GOF (stations LL12, LL3A, and 4) and on the coastal areas in the Narva Bay (N8) in the middle GOF. The abundances are many times lower in the easternmost GOF, compared to the middle and western GOF, both in the offshore and the coastal areas.

The polychaetes of the genus *Marenzelleria* were found for the first time in the GOF in 1990, and since then they have spread and increased in their numbers on both shallow and deep soft bottoms. At present, they are presented by three sibling species (Kauppi et al. 2015). The abundance of *Marenzelleria* spp. varies in the GOF (Fig. 4). The abundances are roughly similar in deep bottoms and in the coastal areas, except at the two coastal stations (15, 18L) and the offshore station (LL5). In the deep bottoms of the middle GOF, *Marenzelleria* spp. have decreased in abundance from 2006 to the present, whereas the opposite trend is seen in the western GOF. On the southern coastal areas, its abundance gets clearly higher from the western parts towards the Narva Bay in the east.

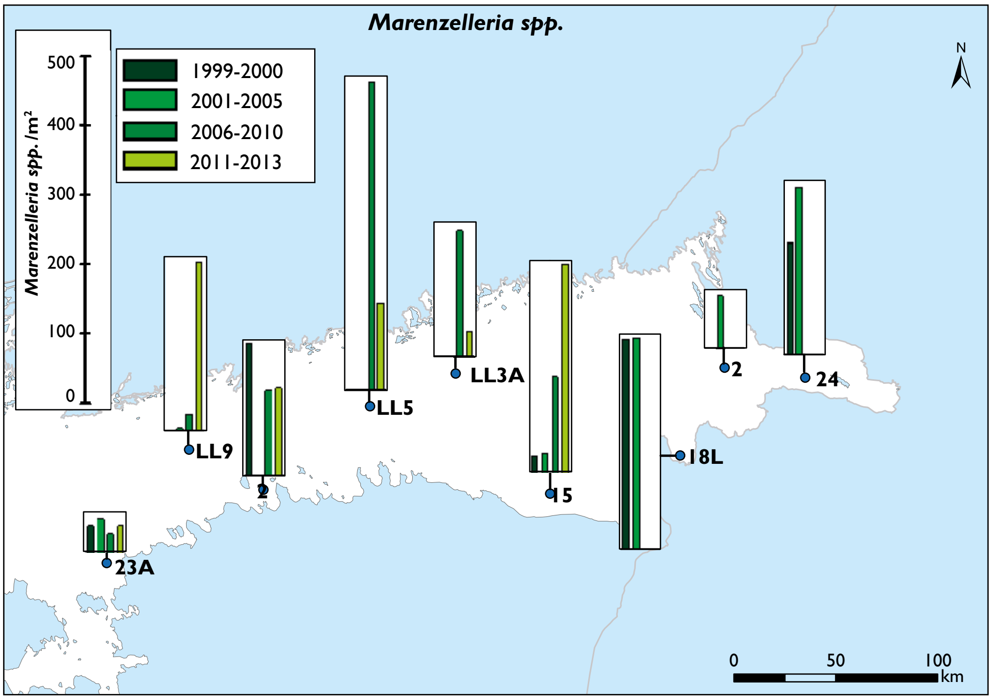

Figure 4. Abundance (individuals/m^2) of *Marenzelleria* spp. in the GOF in 1999–2013. Source: GOF2014 dataset. Graph: Maiju Lehtiniemi, Marco Nurmi.

Impacts of NIS

The impacts of the NIS are highly species-specific. *Marenzelleria* spp. and *Dreissenia polymorpha* (a.k.a. the Zebra mussel) are those of NIS and cryptogenic species (i.e., species of unknown origin) having the largest documented impacts, although the latter only occurs in the eastern GOF.

Marenzelleria spp. dominate the soft-bottom benthic communities in many areas of the GOF and of the whole BS as well. They are shown to alter the nutrient fluxes between the bottom sediments and the water column, and to aid native animals to recolonize the bottoms suffering from oxygen depletion (Viitasalo-Frösén et al. 2008, Norkko et al. 2012, Maximov et al. 2014, 2015).

D. polymorpha may form dense colonies and act as new substrates for native species and other NIS. They are powerful ecosystem engineers that modify physical, morphological, biological, and bio-geochemical properties of the benthic environment, and can also act as biodiversity hot-spots. They may also compete with native bivalves, bioaccumulate toxins – as they are effective filter feeders – and clog pipes of industrial facilities utilizing seawater in their cooling systems.

There are also other NIS that have large impacts in the GOF (Zaiko et al. 2011, Ojaveer and Kotta 2014).

- The barnacle *Amphibalanus improvisus* is one of the oldest cryptogenic species in the BS – first sightings date back to the 1840's – and has spread over the almost whole BS. It is very common and abundant also in the GOF, and affects the shallow benthic communities through competition for space. It is a nuisance species attaching effectively to hulls of the boats.
- The amphipods *G. tigrinus* and *Pontogammarus robustoides* are effective competitors increasing in their abundance, and there are indications of their aggressive behavior that may reduce the survival of native gammarids (Kotta et al. 2013).

- The predatory cladoceran *C. pengoi* affects the pelagic food webs through effective predation on smaller zooplankton, food competition with native invertebrates and planktivorous fish, and as a food source for several fish species (Antsulevich and Välipakka 2000, Ojaveer et al. 2004, Lehtiniemi and Gorokhova 2008). It is also a nuisance species clogging fishing gear with slimy, large aggregates that clumps of hundreds of individuals form when they entangle to each other by their caudal appendages.
- Round goby is the only non-native fish species causing currently large effects in the BS. It is known to be an effective predator on benthic fauna and may thus outcompete native species. Its aggressive behavior during the nesting period may hamper the reproduction of native fish.

The eastern GOF serves as an example of possible changes in the community structure due to NIS. A tubificid oligochaete *Tubificoides pseudogaster* is one of the most common macrobenthic species in the littoral zone and estuaries of the North Sea. In the BS, it was first sighted in the southern part: the Kattegat, the Belt Sea, and the Arkona Basin. In 1995, it was found for the first time in the GOF; at station 2 north-east of the Seskar Island. After its introduction into the GOF, it spread out gradually, although the rate of spread was only 1 to 2 km / year. The scattered original fauna made way for its spreading into the area; the original fauna was largely absent due to periodic intrusions of waters poor in oxygen from the western GOF since the mid-1990's (Maximov 2007). So, there were niches for NIS. In the late 2000's, *T. pseudogaster* occupied a local area of about 400 km^2 near the Seskar Island, where it had become a dominant species (Maximov and Tsiplenkina 2012). The invasion was accompanied by a drastic decline of the native amphipod *Monoporeia affinis* populations. After 2003, the benthic community has been dominated by various NIS, with *Marenzelleria* spp. and *T. pseudogaster* being the most abundant species (Fig. 5). Because most monitoring programs do not target oligochaetes down to species level, the actual distribution of T. pseudogaster in the GOF, or other sea areas and basins as well, is not possible to define. Its distribution area may well be larger than presently known, only it has not been detected in other parts of the GOF yet.

Mud crab (*Rhithropanopeus harrisii*) is spreading and increasing in abundance in several areas of the BS. It is an effective omnivore and can strongly influence littoral communities. Photo: Maiju Lehtiniemi.

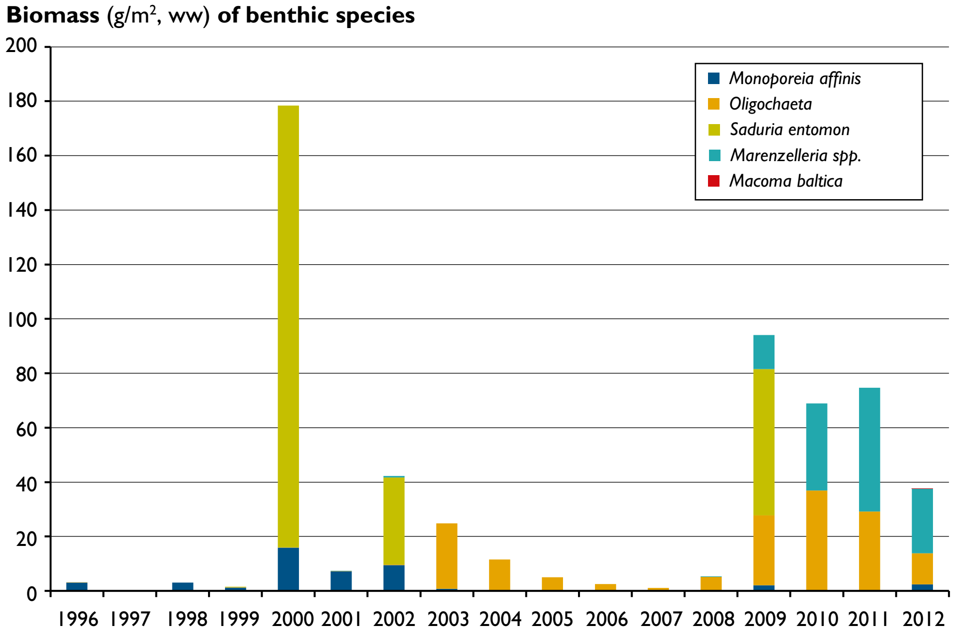

Figure 5. Profound changes occurred in the biomass (g/m^2 ww) and composition of macrozoobenthos at station 2 after the appearance of the oligochaete *Tubificoides pseudogaster* in 2002. In the figure, it is included in *oligochaeta*. Source: GOF2014 dataset and Zoological Institute, Russian Academy of Sciences. Graph: Alexey Maximov.

New NIS continue to arrive

New species are constantly introduced into the GOF. One of the most recent invaders is the polychaete species occurring at very high densities in Pärnu Bay, Estonia, in 2012. It represents the sabellid genus *Laonome*, only it could not be assigned to any of the previously described species (Kotta et al. 2015). It survived a very cold winter and by now has established a permanent population. It was described to be *Laonome* sp. Nov. by examining living specimens with scanning electron and light microscopic methods supplemented by molecular methods.

Another new polychaete species was found in the Archipelago Sea in 2014. It seems that the species is different from the one found in Estonia, and its identification is under way (Katriina Könönen, pers. comm.).

In 2013, a tiny gastropod species belonging to the tribe *Murchisonellidae* was found in Hamina, Finland (Warén 2015, Fig. 2). This species is highly abundant in Hamina area, but has not been observed elsewhere in the GOF. Also in this case the species description is under way.

These are not the last NIS arriving to the GOF.

Management (?) of NIS

New species are frequently introduced to the BS. Which of them are the ones that will establish a permanent population? In the low-salinity GOF it is difficult to predict. In order to detect newly arrived species rapidly after their arrival it would be important to establish regular species monitoring in the busiest ports (Lehtiniemi et al. 2015). Estonia has ongoing monitoring in the port of Muuga and in its vicinity; Finland and Russia will hopefully take the same step in their busy ports. A collaborating monitoring programme would help to obtain the information needed concerning the NIS for the requirements of the EU MSFD (EU 2008). The public may provide with additional help for the NIS monitoring concerning easily identified species; they can report their NIS observations via net portals.

Using citizen observations for monitoring NIS is already in use in Finland, and could also be used in Estonia and Russia. In short, the neighbouring riparian countries should start to exchange information on the new NIS found in the area and on the current state of the previously introduced species.

The eradication of new species is in practice impossible after its invasion and establishment, thus prevention of new introductions should be the priority. International efforts are needed in order to prevent – or at least to decrease – the current spreading rate of new species. Only international legally binding agreements will make the difference, and decrease the worldwide transport and spread of NIS. As ship traffic is the most important vector of transport for NIS, it would be of utmost importance to get into force the IMO's (International Maritime Organization) International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWMC), made already in 2004. Of the countries around the GOF, Russia has ratified it while Finland and Estonia have not, but are in the process of doing so.

The BWMC comes most likely into force in 2016. Then, it would oblige ships to treat their ballast waters before discharging them to sea to eliminate most of the organisms transported in the ballast tanks. Ship owners have a possibility to seek exemptions from the BWMC. If it can be shown, based on a risk assessment, that there is no risk of transporting a certain harmful species between the two specific ports, the ship may be granted an exemption for a maximum time period of five years. It is most likely that ship owners of the passenger vessels sailing, e.g., between Helsinki and Tallinn will seek such exemptions for their ships. The GOF and the eastern BS are geographically limited areas, and a ballast water treatment for vessels steaming only in these areas is hardly reasonable, because possible NIS have plenty of chances for self-dispersal, although ships may speed up the spreading.

Although the BWMC comes into force, the issue of ships being a vector for the NIS will not be history. There are ongoing efforts to tackle this problem in the IMO, but no comprehensive solution has been found yet. Ships will still transport NIS to the GOF, albeit in much smaller numbers.

Another international effort aiming at dealing with the NIS is the new EU regulation on the prevention and management of the introduction and spread of invasive alien species (EU 2014) that came into force on the 1st of January, 2015. It aims to stop the handling, selling, buying, and transporting of harmful NIS.

Large ports are hot-spots for NIS appearance: Vuosaari in Helsinki. Photo: Riku Lumiaro.

Recommendations

The GOF hosts a variety of NIS and more are about to come. The most important vector for the spreading of new species is maritime traffic, which is very intensive in the GOF. In order to decrease the number of new arrivals, the International Convention for the Control and Management of Ships' Ballast Water and Sediments should get into force; Estonia and Finland should ratify this as soon as possible, Russia has already done it.

The monitoring of NIS should be started in the busiest ports of the GOF to rapidly find newly arrived species. Only Estonia has an on-going monitoring program in the port of Muuga. Information exchange concerning the new NIS found in the GOF and on the current state of the previously introduced species should be made operational.

Public awareness concerning NIS could be increased to prevent intentional transports of non-indigenous fish and crabs from one area to another by, e.g., recreational fishermen. Citizen observations of NIS could be collected to a web portal, as is done in Finland.

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Marine litter

Outi Setälä1), Jan-Erik Bruun1), Hanna Haaksi2), Marek Press3)
1) Finnish Environment Institute
2) Pidä Saaristo Siistinä ry
3) Hoia Eesti Merd mtü

What is marine litter?

Littering was for a long time considered as a land-based problem in the vicinity of, e.g., industrial sites and densely populated urban areas. After the discovery of the Eastern Garbage Patch in the Northern Pacific Gyre in 1999 the problems caused by litter in marine environment were revealed to a wider audience (Moore 2008). Currently, litter is one of the most ubiquitous environmental pressures in both marine and freshwater environments, receiving increasing publicity and causing a lot of concern. Marine litter has harmful effects not only on the economy and welfare of people living by the sea but also on marine ecosystems.

Marine litter is always man-made: plastic, metal, glass, processed wood, paper, cardboard, rubber, textiles. Over 6 million tonnes of litter is disposed in the seas annually and no decrease in that amount is predicted to take place in the near future, and a substantial part of that flow is made of plastic (Cheshire et al. 2009).

The modern lifestyle favors single-use or cheap plastic products that are easily discarded into nature without second thoughts. The increase in the amount of litter in the environment goes hand-in-hand with the global trends in the production and use of plastic products that have been growing almost exponentially in the recent past (PlasticsEurope 2015). Small wonder then that 60 to 80 % of marine litter is made of plastic of some form or another (Thompson et al. 2004, Barnes et al. 2009, Andrady 2011). The ever-growing production and use of plastic will continue to pile up the amount of plastic litter in marine habitats (Andrady 2011).

The marine litter problem is worse than we can readily experience. Only a fraction of marine litter is visible to human eye, and the large part of the litter that is visible settles to the seafloor or floats submerged in the water. Approximately 0.27 million tonnes of

Photo: Riku Lumiaro.

plastic debris was estimated to float in the World Ocean (Eriksen et al. 2014). This is at least ten times lower than the amount of plastic disposed in the seas annually, even though it is difficult to reliably estimate the amount of plastic entering the marine environment (Derraik 2002).

And why should we care?

The most obvious harms caused by marine litter are the loss of aesthetical values and entanglement of marine animals. However, marine litter causes a wide variety of environmental, social, economic, and public health problems. UNEP (2009) has listed different ways how litter affects marine environment, which helps to understand the magnitude of the problem. The list includes

An all too common sight. Photo: Aarno Torvinen (SYKE photo bank).

Day-trippers can experience the nature at its best. This, however, comes with a responsibility of taking care of the garbage. A tremendous increase in environmental consciousness has taken place during the past three decades. Photo: Tapio Heikkilä (SYKE photo bank).

- environmental harm (e.g., entanglements, ingestion, blockage of filter feeding mechanisms, smothering, leaching of harmful chemicals)
- social harm (e.g., loss of aesthetics and indigenous values)
- economic harm (e.g., costs to tourism, vessel operators, fisheries, aquaculture, and costs for cleanup)
- hazard to swimmers and divers (cuts, abrasion, puncture injuries)

Municipalities on coastal regions spend millions of € in cleaning up their shores and harbors (Mouat et al. 2010). No studies on the economic costs of cleaning up the coastal areas in the Gulf of Finland (GOF) or elsewhere in the Baltic Sea (BS) has been carried out yet.

Sources and distribution of litter

Most of the litter (60 to 80 %) found in the marine environment originates from land-based sources while the rest is discarded directly into the sea (Gordon 2006, Andrady 2011). However, sources or marine litter differ between areas. Shipping and fisheries are significant contributors in the southern North Sea (Kershaw et al. 2011) while tourism is a major source in the Mediterranean. In the BS, the main sources are considered to include transport, fisheries, household activities, as well as coastal recreation and tourism (HELCOM 2009).

Marine litter does not respect borders between countries; litter can be found near its area of origin or it can be transported by currents and winds. Particles can float on the surface or drift submerged in the water column, sink to the bottom, or get washed ashore. This makes the assessment of the distribution and sources of marine litter challenging.

Methods for an adequate assessment of the distribution and sources of beach litter are now in use in Finland and Estonia but methods for other litter types and habitats

An abandoned fishing net, fortunately thrown onto the shore by a storm. Typically, nets continue their work after they have been lost or abandoned, and they do this for a very long time. Photo: Riku Lumiaro.

Ghost fishing

A litter type that is not visible to human eye is lost or abandoned fishing gear (ALDFG = abandoned, lost, or otherwise discarded fishing gear), better known as ghost nets. Ghost net retrieval campaigns have been organized by WWF Poland in the waters of Poland and Lithuania (Szulc 2013). The amount of retrieved ALDFG in these waters is stunning. The actions taken so far in the Polish waters have resulted in the retrieval of 27 tonnes of ALDFG, but the remaining amount in the sea is estimated to be up to 800 tonnes.

The amount of ALDFG varies between areas of the BS and depends on, e.g., the activity and type of fishing as well as bottom topography. These assessments from the southern BS cannot therefore be applied in the GOF. Both Estonia and Russia have expressed their concern due to very cheap gillnets used by recreational fishermen. It seems that such nets are easily abandoned. To clarify the magnitude of this problem, Estonia has started the mapping of hot-spot areas for ALDFG in its waters in 2015. Altogether four test areas are studied with sonars before any retrieval campaigns are planned. Finland will follow and start mapping areas that would be targets for future retrieval campaigns.

are still being tested and developed. There is an especial need to assess the amount and distribution of underwater litter; only 15 % of the litter entering marine environments is to be found on beaches, another 15 % floats on the sea surface or submerged in water column, while most of the litter settles onto the seafloor (OSPAR 1995, HELCOM 2009).

Litter monitoring in the Baltic Sea

Marine litter is classified by its size: particles > 25 mm in diameter belong to macrolitter, 5 to 25 mm to mesolitter, and < 5 mm (lower limit of size not determined) to microlitter (Arthur et al. 2009). Until rather recently, most of the information gathered on marine litter concerns macrolitter simply because it is easily visible to human eye.

Marine litter work within the HELCOM project CORESET II (operationalization of HELCOM core indicators) launched the development of methods and indicators for assessing distribution and impacts of macrolitter and microlitter. In the first stage, the development of indicators for beach litter, seafloor litter, and microlitter are being developed. At the time of writing this text, the beach litter indicator is most advanced. For the development of microlitter indicators, more information on the methods for sampling and analyses is needed.

Beach litter monitoring

Macrolitter is most visible for human eye on beaches or floating on the surface. Some data on the amounts of litter on the coasts of the BS is available already from the late 20th century. This information is based on campaigns carried out by various non-governmental organizations or on observations by coastal municipalities. It is not, however, possible to quantitatively compare the results between the campaigns because different methods have been used for collecting litter and estimating their amounts. The number of persons doing the clean-up has a strong impact on the results, too. Generally, the results from beach litter monitoring can be biased by not selecting the most representative beaches for the campaign. Meteorological, hydrographical, and geographical parameters must be considered when a monitored beach is being selected.

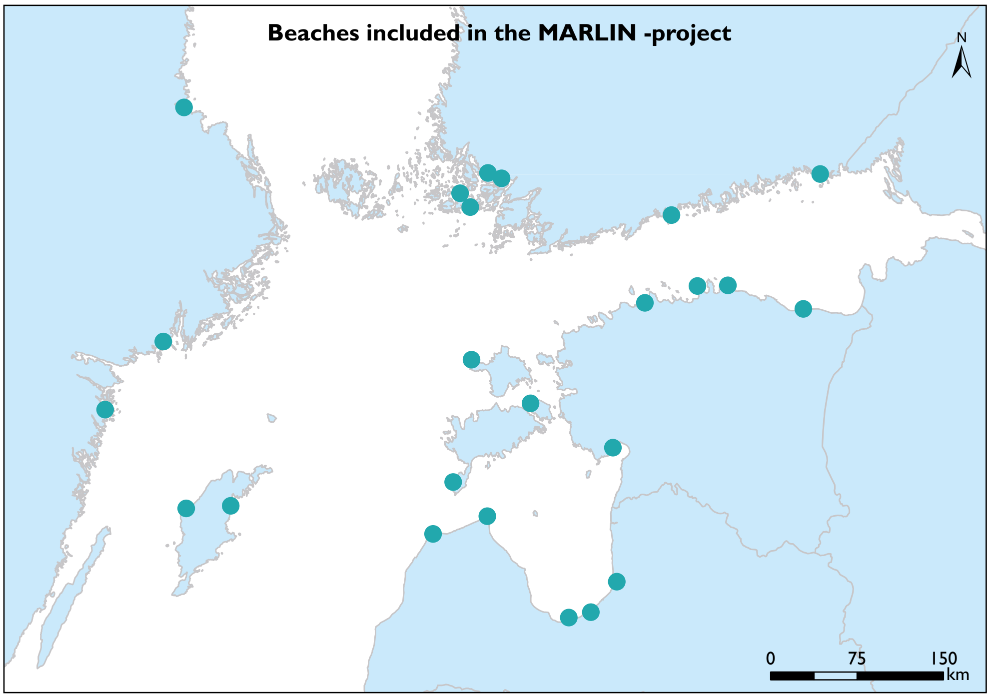

Figure 1. Beaches included in the MARLIN project. The survey included seven beaches in the GOF that were monitored in 2012–2013. All litter items larger than 2.5 cm in diameter were collected along a 100 m strip of beach and categorized by their material. Source: MARLIN (2013). Graph: Marco Nurmi.

Table 1. Top ten litter types found in the beaches of the GOF in 2012–2013. Source: MARLIN project.

Material type	Litter type	Share (%) of all found litter items
Plastic	Other	27.8
Foamed plastic	Foam (insulation and packaging)	9.1
Plastic	Plastic bags	4.5
Plastic	Bottle caps and lids	3.9
Plastic	Food containers, candy wrappers	3.7
Plastic	Fiberglass fragments	3.3
Glass & ceramic	Glass or ceramic fragments	3.2
Plastic	Strapping	2.7
Wood	Processed timber and pallet crates	2.6
Foamed plastic	Foam sponge	2.2

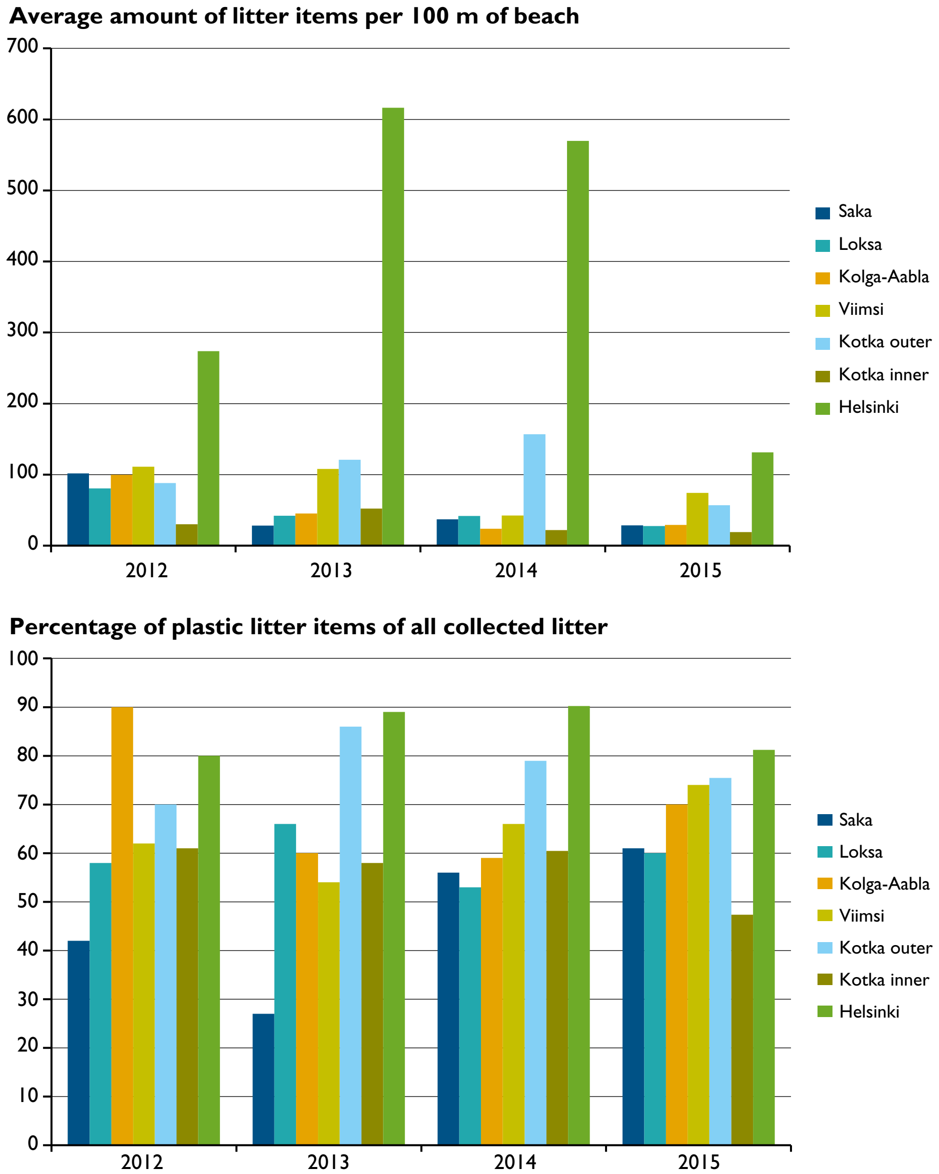

Figure 2. Above: amount of litter (items per a 100 m beach strip) on the Estonian (Saka, Loksa, Kolga-Aabla, Viimsi) and on the Finnish beaches (Kotka outer, Kotka inner, Helsinki Pihlajasaari) in the GOF. Below: the percentage of plastic items of all collected litter items. Kotka outer and inner are located in the same island; outer on the seaside, inner facing the land. Source: Hoia Eesti Merd, Pidä Saaristo Siistinä. Graph: Outi Setälä.

In Finland, a detailed study on beach litter was carried out in 1994 (Tuomisto 1994). A total of 15 beaches from different areas were included in the survey. An average of 260 pieces of litter was found along a 100 m strip of beach, together weighing 11 kg. In the Bothnian Sea and Åland archipelago, litter items were identified to originate from the passenger ferries cruising between Finland and Sweden, as well as from leisure boating. In the western GOF, most of the litter originated from cargo ships. Fishing related litter items were common in all areas studied.

The present protocol for assessing beach litter in Finland and Estonia is based on the collaboration within an EU-funded marine litter project MARLIN together with Sweden and Lithuania. During the project, the amounts of different litter types were assessed on selected beaches (Fig. 1). Most importantly, for the first time around the BS area, all the countries collected and categorized the litter using the same harmonized method based on the protocol of UN Environment Programme on beach litter (Cheshire 2009).

The results of this project showed that most of the beach litter in the GOF was composed of plastic (Table 1). Plastic products or remains of them formed 59 % of all litter items on urban beaches, 50 % on rural beaches, and 53 % on semi-urban beaches. When all beaches and survey occasions were combined, the amount of litter was highest on the Finnish beaches, and especially on the beach that situated in Helsinki (Fig. 2). The overall trend can at least partly be explained by the fact that the Finnish survey included more urban beaches than Swedish and Estonian ones; urban beaches tend to contain more litter than the rural ones. The physical character of the fragmented Finnish archipelago may favor the accumulation of litter as well.

Finland and Estonia have continued the monitoring of these beaches in 2014–2015, and Finland has also adopted this protocol into its national monitoring programme. The work is being organized by Pidä Saaristo Siistinä ry, who is responsible also for training new volunteer groups for the surveys, and setting up new monitoring beaches.

Monitoring seafloor macrolitter

In the southern parts of the BS, seafloor monitoring has been combined with the annual fish stock assessments using bottom trawling. This method cannot obviously be applied in the GOF, where no bottom trawling is being carried out. In Finland, a first trial for monitoring of seafloor litter was carried out off Helsinki in 2014 (Majaneva and Suonpää 2014). Rather unexpectedly, of all the study sites (Eläintarhanlahti, Eiranranta–Hernesaari, Kulosaari, and Uutela), the most rural area, Uutela, had the highest number of litter items (including a shopping chart). The most common litter types were glass bottles, glass fragments, and aluminum cans. Unidentified plastic fragments of the size of 10 to 30 cm were found at all sites. Close to construction sites, electrical wires were also common on the seafloor. The employed method was considered to be suitable for further litter assessments with some restrictions related to visibility and water clarity close to urban areas.

Microlitter

Marine microlitter derives from a variety of sources, such as traffic, industry, and households. Most of the information on marine microlitter comes from the World Ocean (e.g. Moore et al. 2001, Thompson et al. 2004), while in the BS only few studies on its distribution have so far been carried out (Magnusson and Noren 2011, Magnusson 2014, Setälä et al. unpubl.). Now, when the problem of marine litter has been acknowledged also in the BS, there is an urgent need for collecting data both on the sources and distribution of microlitter, as well as on its impact.

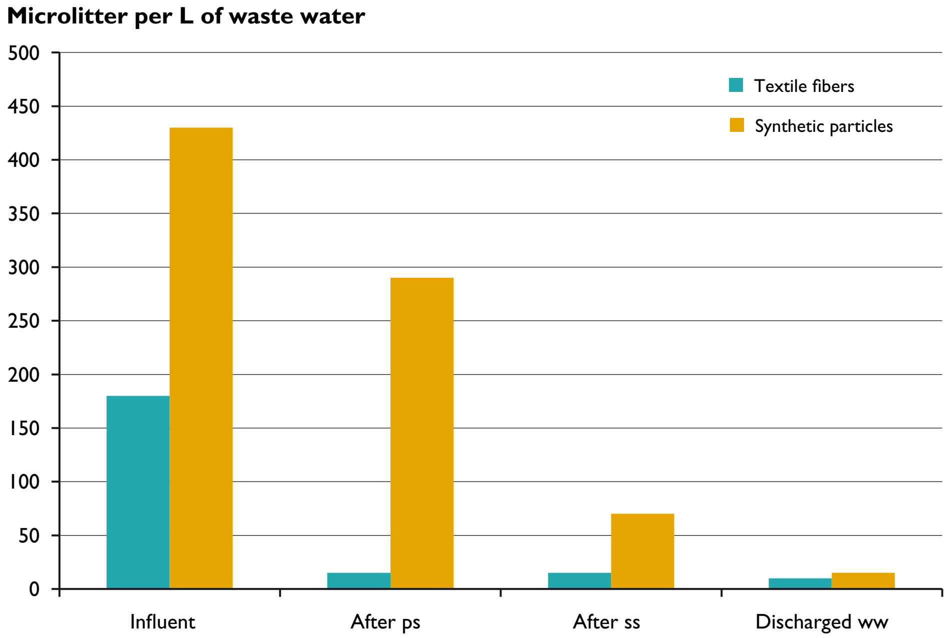

Figure 3. Microlitter concentration (particles/L) in the various phases of the waste water treatment in Viikinmäki WWTP. PS = primary sedimentation, SS = secondary sedimentation, WW = waste water. Source: Talvitie et al. (2015).

Microlitter includes both non-synthetic and synthetic particles, the latter consisting mostly of different types of plastics. Microplastics are either intentionally small or fragmented from larger plastic items. Primary microplastics, especially from personal hygiene products and cosmetics, enter marine systems mostly either via municipal waste waters or directly from the production process of plastic items (GESAMP 2015). The weathering and fragmentation produces so-called secondary microplastics that can in some areas be the main source of marine microplastics (Verschoor et al. 2014). Plastic microlitter is considered to potentially pose a severe threat on marine life, and possibly also on humans.

Early studies in the Gulf of Finland

Municipal waste water treatment plants (WWTP) are thought to act as a gateway for microplastics to the sea, although the large majority of the microplastic load is retained in the sewage sludge (Magnusson and Wahlberg 2014). Processed municipal wastewaters contain, e.g., textile fibers from washing of clothes, and granules from cosmetics, such as abrasive plastic fragments from cleaning agents.

Pilot studies on microlitter in the effluent waters of Viikinmäki WWTP in Helsinki, as well as microlitter sampling in the recipient were initiated as a collaboration between the City of Helsinki Environmental Center and Helsinki Region Environmental Services Authority (Fig. 3). Regardless of efficient purification process, a total of > 13 000 pieces of microlitter per m^3 were observed in the effluent suggesting that a WWTP can act as a noticeable hot spot area for microlitter. Further studies in Viikinmäki WWTP are presently going on and include a stepwise assessment of the efficiency of the different purification processes in microlitter removal from waste waters.

According to the study of Magnusson et al. (2016), if the WWTPs are equipped with chemical and biological treatments most of the litter particles in the influent will be retained in the sewage sludge. The study showed that in the Swedish and Finnish WWTPs > 99.7% of the microlitter particles of ≥ 300 µm in diameter carried by the influent were retained. Still, in the recipients of these WWTPs, the microlitter concentrations were found to be significantly higher in the effluent plume than at the reference site.

The role of WWTPs as a gateway for marine microplastics into the GOF was also studied in Russia, where HELCOM initiated a case study on the role of a WWTP in the microlitter input to the eastern GOF (HELCOM 2014). The study was carried out together with Vodokanal of St. Petersburg and Helsinki Region Environmental Services, and included assessment of microlitter both from the influent and the effluent. Over 95 % of incoming pieces of microlitter were retained during the purification process. Still, due to the vast volume of waste water passing through the plant (8 350 million m^3 annually), the plant can act as a regional source of microlitter.

Microlitter monitoring

There is not yet a sound and harmonized methodology in use in the BS region – or anywhere else, as a matter of fact – for assessing the distribution and types of microlitter. Guidance for the implementation of methodologies is produced by, e.g., the EU MSFD Technical Subgroup on Marine Litter (TSG-ML). The development of microlitter indicator will continue under the work of HELCOM PRESSURE. The idea is to monitor microlitter from the water surface, although some countries have already adopted the use of seafloor sediment as the main subject for microlitter monitoring. The possibility of monitoring microlitter on beaches must also be considered. When useful protocols for microlitter monitoring are being developed, it is good to remember that the sample collection itself is a source of contamination (e.g., fibers from clothing, airborne dust).

Microlitter samples have been collected in the GOF by Finnish and Estonian researchers in 2013–2015 from the surface water. The aim of these surveys has been to get first-hand information on microlitter distribution in the GOF, and to test the suitability of the current sampling methods for monitoring purposes (Fig. 4).

Comparison of sampling methods was initiated in 2013 when Finnish and Swedish researchers collaborated during a research cruise in the GOF (Setälä et al. unpubl.). The amount of microlitter in the GOF was in the same order of magnitude in all parts of the gulf (Fig. 5). The highest microlitter concentrations were observed at the station LL7, which is hardly surprising since this area is subject to the most intense maritime traffic in the GOF.

Figure 4. A Manta trawl in action. Manta is a special type of a surface neuston net with a mesh size of 0.33 mm. It is presently used globally for collecting surface microlitter. Photo: Mika Raateoja.

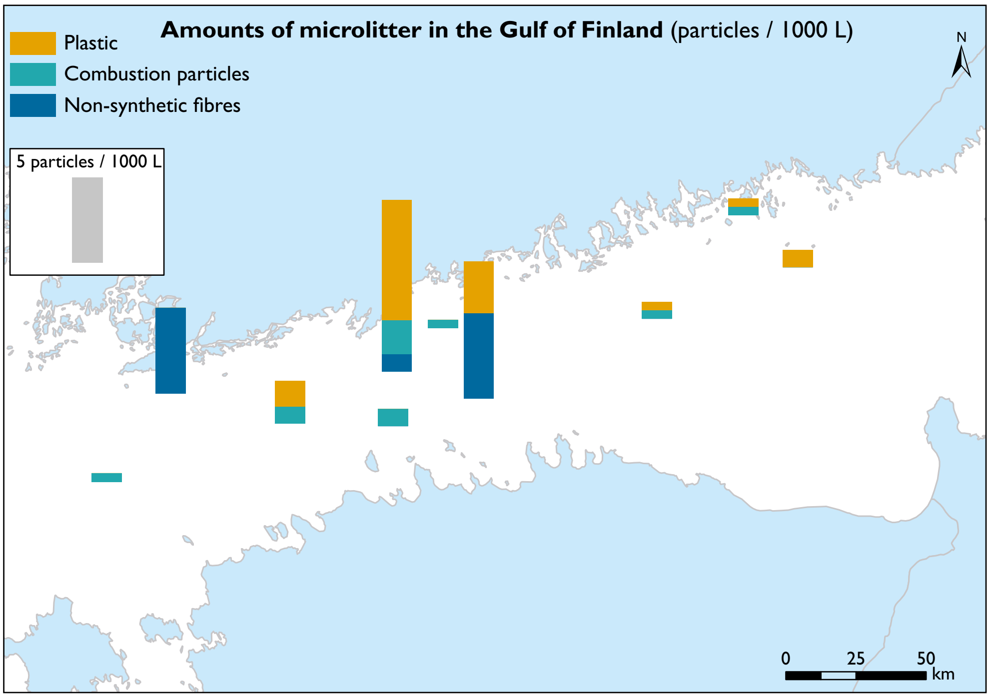

Figure 5. Concentrations (particles/m^3) of various microlitter types in the GOF. Particles > 0.1 mm in diameter were counted. Source: Setälä et al. (unpubl.). Graph: Marco Nurmi.

Environmental harm caused by marine litter

Litter causes harm to a variety of marine organisms particularly because of entanglement and ingestion of litter items (Laist 1987, Andrady 2011). Especially marine mammals, birds, sea turtles, and fish have been reported to suffer from marine plastics (Derraik 2002). At least > 200 marine species are known to be affected by entanglement (NOAA 2014).

Only rather recently, studies on the harm of litter to marine ecosystems have started to include field observations of ingested microplastics. They have been found in filter-feeding organisms (Van Cauwenberghe and Janssen 2014) and bottom feeding animals (Murray and Cowie 2011). Laboratory experiments have proven that many marine invertebrates like bivalves, echinoderms, amphipods, and zooplankton can ingest microplastics (Browne et al. 2008, Graham and Thompson 2009, Cole et al. 2013).

Studies on the pathways of microplastics within the planktonic food web and coastal communities have recently been studied in the south-west coast of Finland (Setälä et al. 2014, 2016). Various organisms were able to readily ingest plastic polystyrene microspheres, and also transfer them in the food web amongst both plankton and benthic communities. Some of the organisms studied were more active in the uptake of microspheres than others, e.g., planktonic larvae of the polychaete *Marenzelleria* spp. and bivalves (*Mytilus trossulus* and *Macoma balthica*, Fig. 6).

Marine animals ingest and accumulate microplastics also in their natural environment which has received a lot of attention and concern. For example, both bivalves and fish can ingest plastic fragments and fibers in natural conditions (Rochman et al. 2013, Van Cauwenberghe et al. 2015). Pilot studies to assess the magnitude of this problem have been initiated in Finland in 2015 - 2016.

Alike larger litter items, ingested microplastics are suspected to cause internal mechanical damage, and thus reduce feeding and induce problems due to their chemical characteristics. Plastics often contain risky additives, e.g., plasticiers, surface-active compounds (perfluoroalkyl substances, PFASs), and flame retardants (polybrominated diphenyl ethers, PBDEs), and they may also absorb hydrophobic persistent organic pollutants (POPs), such as organochlorine substances (Mato et al. 2001, Derraik 2002). The smaller the plastic fragment is, and larger its ratio of area to volume, the more effectively

A quite famous swan, carrying a drying stand for clothes, alive and kicking in the Lake Tuusulanjärvi in the southern Finland. The publication of this photo in the social media triggered an extensive debate of people's disinterest towards the nature. Photo: Piia Pasanen.

it can absorb environmental chemicals and transfer environmental pollutants into marine food webs.

It is not yet known whether marine microplastics will turn out to be a health hazard for humans. This topic is presently under extensive research and knowledge is piling up rapidly. The issue of microplastics is especially topical for aquaculture because some cultured animals, such as bivalves, are especially efficient filter feeders. They ingest microplastics while feeding. The depuration from microplastics in bivalves seems inefficient (Van Cauwenberghe and Janssen 2014), and bivalves cultured for human consumption may also contain more microplastics than the wild ones.

Management of the marine litter problem in the Gulf of Finland

For the management of marine litter, not only the amounts and distribution but also the main sources and gateways for marine litter need to be mapped. If the sources of marine litter are not known, it is not possible to manage the flow of incoming debris. Good waste management aims both at reducing the generation of waste and at dealing with the waste that has already been generated.

The implementation of EU MSFD (EU 2008) has been the most important driver for promoting marine litter studies in European seas. Implementation and enforcement of regulations and standards are needed in an international, regional, and national level. These management methods, combined with the awareness among main stakeholders and the general public are the key elements in the battle against litter. Litter has also been addressed as part of the UN Resolution of the Law of the Sea (UN 2006).

The recently-adopted HELCOM Marine Litter Action Plan (HELCOM 2015) to achieve a significant reduction of marine litter by 2025 recommends the contracting parties of HELCOM to jointly develop both regional actions and voluntary national actions to combat marine littering in the BS. The types of actions are divided into three different categories: i) mitigation of land-based sources, ii) mitigation of sea-based sources, and iii) actions for education and outreach.

In Estonia, the national management of marine litter includes actions on the implementation of microplastic pilot monitoring, reducing the use of single-use plastic

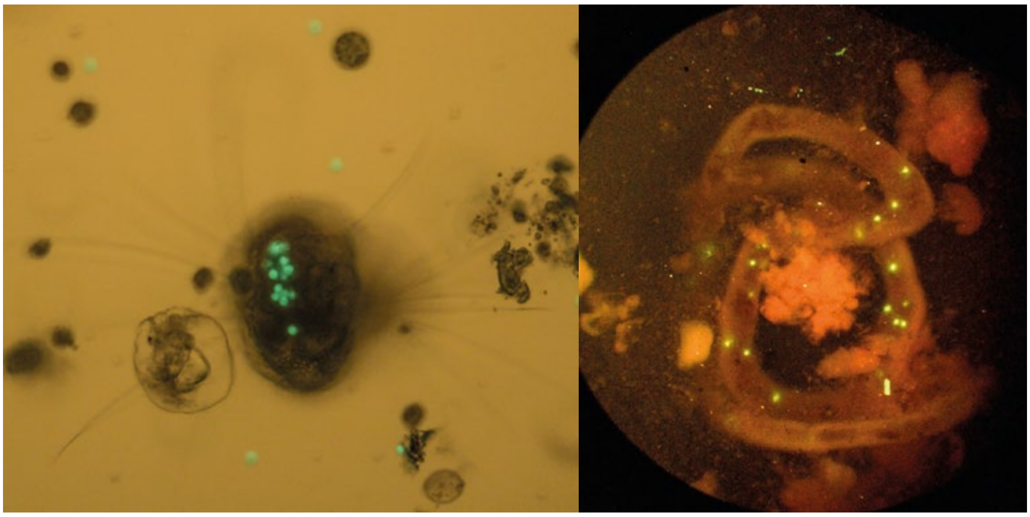

Figure 6. Invaded by litter: *Marenzelleria* spp. larva with ingested microspheres (left), and the intestine of *Mytilus trossulus* containing plastic microspheres (right). Photos: Outi Setälä, Pinja Näkki.

bags, prevention of abandonment of fishing gear and organizing their retrieval, establishing no-special-fee waste reception systems in the harbors, and a general reduction of marine litter as a part of the implementation plan for 2014 - 2017 of the National Waste Management Plan (Alkranel oü and Marine Systems Institute at Tallinn University of Technology 2015).

The management actions to combat marine litter in the Finnish Marine Strategy's Program of Measures (Laamanen 2016) are planned to include three phases of action. In the first phase, a thorough assessment of the amount, type, and distribution of litter is carried out. The most important target is to gain information of sources of litter and how to cut the litter load coming from them. The potential harm of microlitter to marine life and humans will be studied as well as the effectiveness of different management measures. In the second phase, the environmental targets regarding marine litter are set. On the third phase, management measures are being designed, especially from the point of view how to decrease the load of plastics to the marine environment and the amount of plastics in it. This process is carried out following closely the implementation of different measures in the other BS countries, and collaboration is initiated based on HELCOM recommendations.

Raising awareness on marine litter is one of the key issues of the measures. A joint research project between Sweden, Finland, Estonia and Latvia (EU CB project BLASTIC; Pathways of plastic waste 2016 – 2018) will focus on the assessment of urban sources of plastic waste and concentrate especially on the riverine discharge of plastic litter into the sea, Estonian coast of the GOF being one of the pilot study areas. During the project, options for management will be developed, including awareness raising campaigns.

Macrolitter management in Russia

The Federal legal framework in Russia recommends sharing responsibilities between municipal, regional, and federal authorities in the implementation measures on the protection of water bodies. Consequently, various public authorities in cooperation with non-governmental organizations as well as educational and commercial organizations are involved into the action mitigating littering of aquatic environment.

From the Russian perspective, the highest priorities regarding the land-based sources is set for systematic cleaning of the coastal area, maintenance of the river coasts and public beaches as well as raising awareness campaigns. Establishing the facilities for a reception of ship waste in the ports has the highest priority of the sea-based actions. The problem of lost fishing gear is not at the moment prioritized for at least the coastal waters of Russia.

Increasing awareness - beach cleaning campaigns

Organizing beach cleaning campaigns is the most efficient way to increase awareness of marine litter issues amongst the citizens. Most of marine litter found in the urban coastal areas is in one way or another originating from local residents / households. A good thing here is that this part of the litter load into the sea can be reduced with fairly simple actions.

During the Gulf of Finland Year 2014, comprehensive beach cleaning campaigns were arranged both in Estonia (Tallinn 21st Apr–15th May, 2014) and Finland (whole coastline 12th–25th May, 2014). Estonia has longer traditions for cleaning their beaches as it has been participating to the annual Earth Day Litter Cleanup activities, while in Finland the nationwide campaign (Siisti Biitsi) was launched in 2014 by Pidä Saaristo Siistinä ry. Beach cleaning campaigns in Russia were initiated on 27th May, 2014. They became extremely popular in the autumn 2014.

Clean-up campaigns around the GOF in 2015 included an on-line opening ceremony by the Mayors of Helsinki and Tallinn. In Russia, thousands of citizens, not only in St. Petersburg region, but also in other municipalities by the GOF and in its drainage area, participated the Cleanup Day on 27th Sep, 2015.

The cities of Tallinn, Helsinki, Turku, and St. Petersburg all joined the Litter Cleanup day in 23rd Apr, 2016. As in the previous years, thousands of volunteers were cleaning the beaches for a cleaner coastline.

Beach cleaning campaigns were launched in Estonia (above), Finland (middle), and Russia (below). Photos: Tallinn City Environment Department, Saara Reinimäki, Centre for Environmental Projects "Ravnovesie".

In St. Petersburg region, prevention of land-based litter to enter the GOF includes the cleaning of floating litter from the coastline, treating the bottoms of the channels and rivers, and the identification of illegal dump areas. Altogether 32 rivers and channels were covered by the bottom-cleaning projects in 2000–2015. About 8 900 items (including concrete, rail-tracks, timber etc.) were collected from the rivers and channels in 2013–2015. A total of 44 illegal dump sites in St. Petersburg were found and removed in 2013–2015.

Conclusions

Marine litter is always man-made, consists of various materials, and has different types of plastic items and their fragments as most common litter types. Of all marine litter, plastics are considered the major threat. They are abundant and persistent in the environment, and can cause both physical and chemical hazard to animals from small zooplankton to marine mammals.

The chemical harm of marine litter concerns especially microplastics. Such particles are suspected to act as accumulation hot spots for compounds that are hazardous to marine life and even to humans.

The impacts of marine litter on the biota of the GOF are still poorly known. However, research and monitoring on marine litter has been active especially during the most recent years. This activity has included the development of monitoring methods on both macrolitter and microlitter, and experimental work on the behavior of microlitter in the environment and within the food web.

Recommendations

The management of marine litter is only possible if the sources are correctly mapped. Litter pathways vary between countries and they should be assessed separately utilizing the available information from other sea areas.

The removal of litter is time-consuming and expensive, if not impossible. Cost-efficient estimates should be applied to choose between the removal of litter in the marine environment and closing pathways of litter to the marine environment.

Beach litter monitoring is presently the most cost-efficient way to monitor the amount and character of marine litter. However, the litter on beaches comprises only a fragment of the total litter load. It is recommended that Finland, Estonia, and Russia all carry out beach litter monitoring with a comparable methodology, and jointly agree on the spatial coverage of the monitored area.

The harm of marine litter to marine biota and people living around the GOF has not been assessed yet. More information is needed of the chemical hazard posed by long-lived plastics and small plastic fragments on marine animals. Once they have entered enter the sea, they cannot be removed.

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UNDERWATER SOUNDSCAPE

Underwater soundscape

Jukka Pajala1), Aleksander Klauson2), Janek Laanearu2), Heikki Peltonen1), Mirko Mustonen2)
1) *Finnish environment institute*
2) *Tallinn University of Technology*

Underwater world is not silent. On the contrary, the underwater soundscape is diverse, filled with a variety of sounds. A commonly-accepted classification of underwater sound follows a division to sounds of natural and anthropogenic (i.e., man-made) origins.

Natural sound sources

Natural sound sources encompass geophysical events (e.g., rain, waves, movement of ice, thunder, seismic activity, thermal noise). These sounds cover a wide frequency range. At the lowest frequencies, 0.1–10 Hz, ocean turbulence and microseisms are the primary contributors to the background noise. Wind-induced surface noise (breaking waves and bubbles) is the main source in the waveband of 40 Hz to 8 kHz. Rain produces sound mainly in the band of 500 Hz to 5 kHz but also contributes to higher frequencies. Thermal sound resulting from molecular agitation is dominating at frequencies > 100 kHz. Different forms of ice have their own specific sounds ranging from a loud impulsive sound to a delicate tinkle; ice creates sound while forming, fracturing, hummocking, ridging, rafting, and melting.

Natural sounds also include vocalization by animals. Sound is central for their communication. Here, the frequency range is even wider: a few Hz to several 100 kHz. The duration of these signals range from very short (a few tens of µs) to very long (tens of s).

The background noise present in the sea, or ambient noise, has many different sources and varies with location and frequency. Most of these sources are natural. In many areas

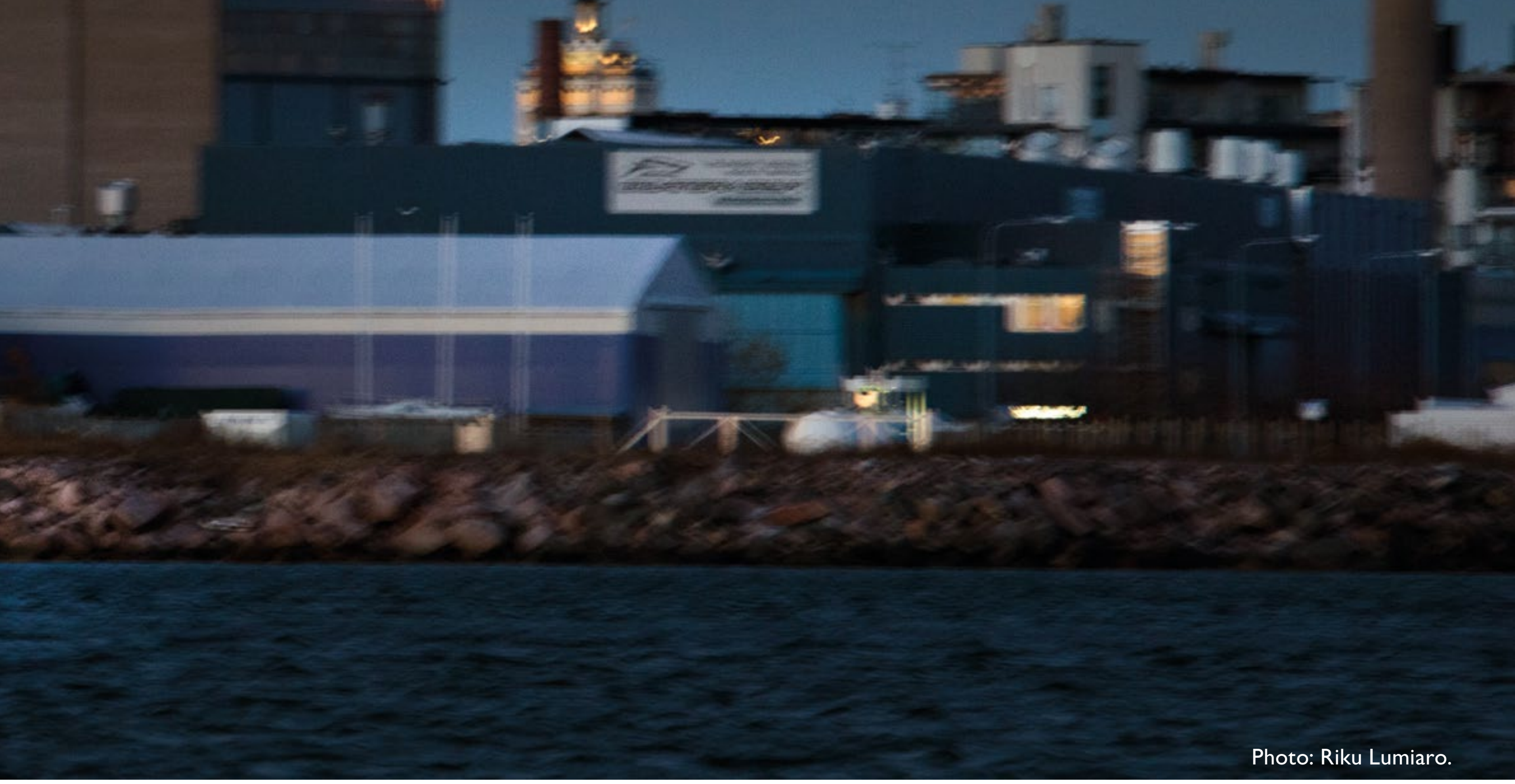

Photo: Riku Lumiaro.

including the GOF, distant ship traffic is one of the dominant noise sources at calm weather for frequencies of 40 to 200 Hz.

Marine mammals

The perception of sound is an essential sensory ability for the marine vertebrates such as cetaceans, seals, fishes, but also for some invertebrates, such as crustaceans. Marine mammals perceive sound as cyclic pressure changes, whereas some fish species experience sound by sensing particle motion. Some fish species are also capable to observe both sound pressure changes and particle motion.

Ice sheet creates a multitude of sounds. Photo: Jukka Pajala.

Harbour porpoises have sonars of their own. Photo: Solvin Zankl, Fjord & Bælt.

Light attenuates quickly in the Gulf of Finland (GOF) water, and visual detection of the animals is often restricted to a distance of a few meters. Sound is transmitted very well – much better than in the air actually – and many aquatic animals have good hearing abilities. Depending on its frequency, underwater sound can propagate over several tens of km or even throughout the whole GOF. This makes the ability to detect sound an effective sense for aquatic animals. Sound is essential for orientation, migration, communication, mating, foraging, and avoiding predators for many marine animals.

The sole native cetacean inhabiting the Baltic Sea (BS), harbor porpoise (*Phocoena phocoena*), uses sounds to find prey, to observe its environment, to navigate, and to communicate (Møhl and Andersen 1973, Clausen et al. 2011). It has a sophisticated biosonar, and relies on narrow-band ultrasonic clicks of about 130 kHz, similar to those used for echo-location. Due to their high frequency, the clicks attenuate quickly and a maximal communication range is thus < 1 km. The hearing range of the harbour porpoise is exceptionally wide; it can hear noises of > 500 Hz, but the hearing is most sensitive at 16 to 140 kHz (Kastelein et al. 2002, Miller and Wahlberg 2013).

Also seals vocalize underwater. Phocid seals produce diverse underwater vocalizations (rough, grunt- or bark-like sounds peaking at a few hundred Hz), the functions of which are mostly unknown. It is known, however, that harbour seals (*Phoca vitulina vitulina*) use vocalization solely in connection with mating, either by males to attract females or in male-to-male competitions. Ringed seal (*Pusa hispida botnica*) has a vocalization range of 400 Hz to 16 kHz, with most energy on frequencies < 5 kHz (Stirling 1973, Cummings et al. 1994). Grey seal's (*Halichoerus grypus*) vocalization concentrates on 100 Hz to 3 kHz (Asselin et al. 1993). Seals do not actively echolocate, but instead, seem to use passive listening to obtain information of their surroundings, sometimes referred to as passive biosonar (Schusterman et al. 2000). Phocid seal's hearing is generally more sensitive underwater than in the air (Schusterman 1981). Ringed seal's and grey seal's hearings are most sensitive at frequencies of 1–50 kHz (Terhune and Ronald 1975).

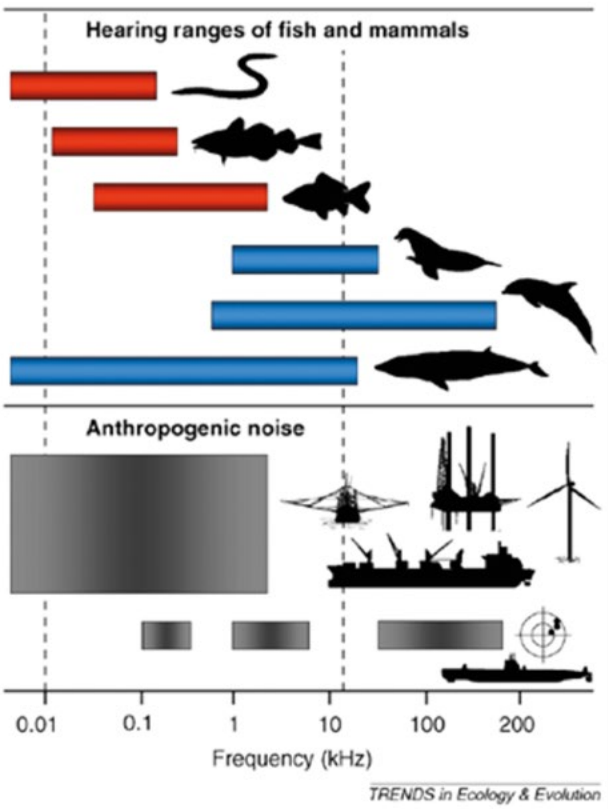

Figure 1. Main frequency bands for the anthropogenic noise sources and the hearing ranges of marine mammals and fish. Source: Slabbekorn et al. (2010).

Fishes

Fishes are known to communicate using sounds, such as grunts, honks, and groans. They produce sounds mainly within the human hearing range. Herring and sprat have a canal from the swim bladder to the anal opening where air can be released, generating a high-pitched sound presumably for communication. Males use sounds during mating to attract females and to chase off other males. In Scandinavian waters, gadoids develop muscles in the spring that can be used for drumming on the swim bladder, creating a very low-pitch sound that is used during mating. Many fish species produce sound during aggressive interactions; for instance, gobids generate sound when threatened or scared away from their territory, presumably by grinding their teeth. The majority of fish species can detect sounds from < 50 Hz up to 500 to 1500 Hz, while some can detect sounds to > 3 kHz, and few to > 100 kHz (Popper and Hastings 2009, Fig. 1).

Anthropogenic sound sources

The main anthropogenic sources of underwater noise are commercial shipping, fishing, military activities, construction, seismic explorations, recreational boating, and wind farms. The produced noise may propagate over long distances from the source, and, depending on its intensity and frequency, may disturb marine animals (HELCOM 2010).

The anthropogenic noise includes impulsive noise (e.g., sonars, piling, explosions) and less intense sounds of longer duration (e.g., shipping, wind farms, pipelines; Slabbekoorn et al. 2010). When impulsive sounds are repeated at intervals, such repetition may become diffuse with distance and become indistinguishable from a continuous noise (HELCOM GEAR 2013).

Continuous sound is essentially produced by shipping. In addition to a world-class intensity of cargo and personnel transport in the GOF, heavy recreational boat traffic

Physical definition of sound

Sound in the water is a combination of progressive waves in which water particles are alternately compressed and decompressed. Sound can be measured as a pressure variation within the medium around a point of equilibrium defined by the hydrostatic pressure. This pressure variation, called acoustic pressure, propagates in every direction with small amplitudes compared to the hydrostatic pressure. Sound pressure is described using a logarithmic scale known as the decibel (dB) scale. dB is a relative unit with respect to a reference acoustic pressure level (1 μPa in underwater acoustics). A dB level is therefore an absolute measure as long as the reference level is specified. The sound pressure level (SPL, re 1 μPa at 1 m) of the underwater sources varies (Fig. 2):

- wind and rain 40 to 90 dB
- cod grunting 150 dB
- loud ships 190 dB
- dolphins 230 dB
- lightning strike, seismic eruptions and underwater explosions 260-280 dB

It is good to note that the reference level cannot obviously be specified for natural phenomena (how you determine a 1 m distance to rainfall?). These are thus not directly comparable to phenomena whose origin can be pin-pointed.

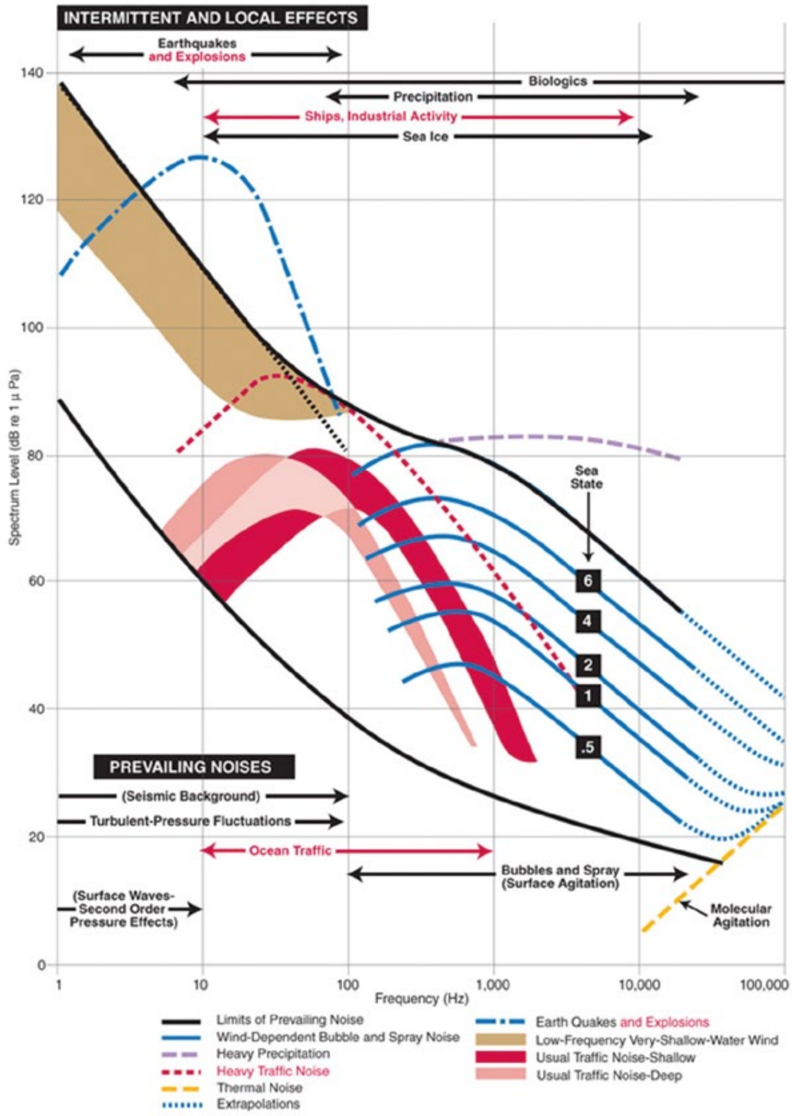

Figure 2. Wenz curves showing typical noise spectra, including wind and rain: noise spectral density (dB re 1 μPa) as a function of frequency of sound. Source: Wenz (1962).

Large cruisers are a major source of anthropogenic sound. Photo: Anton Krasheninnikov.

takes place there during the summer. Seismic underwater monitoring has been carried out in Estonia, Finland and North-West Russia since the 1960's. At present, the seismic surveys are related to a construction of structures, such as ports and bridges. They are also involved in the installing of underwater communication cables and pipeline routes. Several large wind farms and pipelines/cables are planned to be constructed in the GOF in near future, which will add more noise to the marine environment.

Acoustic measurements in the Gulf of Finland

The GOF is a relatively small gulf, and consequently, sound propagates there from coast to coast within a minute. The shallowness of the GOF filters efficiently low frequencies, setting the GOF acoustically apart from the World Ocean. There are a number of factors that affect the sound field of the GOF:

- The fragmented seabed topography of the northern part of the GOF and a diverse sediment stratigraphy have significance for the underwater acoustics. Soft bottom absorbs and hard bottom reflects sound waves. The acoustical classification of the sea floor is therefore crucial for the modelling of underwater noise.
- The speed of sound depends on water temperature and salinity. In the GOF, these parameters show considerable variation both spatially, vertically, and seasonally. The resulting large gradients in sound speed profile affect sound wave reflection. The speed of sound rises with temperature in the physiological domain. It is highest at the surface and lowest in the cold intermediate layer. Furthermore, it is higher in the surface layer in summer than in winter. The overall range of variation of the sound speed in the GOF is 1400 to 1500 m/s. In the summer, the sound speed is about 1490 m/s in the upper mixed layer, about 1430 m/s in the cold winter water, and about 1440 m/s in the deep water.
- The GOF freezes at least partly every year. Acoustic condition in the wintertime and under the ice differs from that in the summertime in many ways; sound velocity is nearly uniform with depth. There are no surface waves to cause natural sound, but ice movements and internal stresses create sounds of their own. Furthermore, the ice surface reflects sound efficiently.

Figure 3. Deployment positions in the BIAS project. Source: BIAS project.

One of the major tasks of the BIAS Life+ project was to carry out the acoustic field survey in the BS. For this purpose, a total of 39 hydrophones were deployed, of which five in the GOF (Fig. 3). Some of the sensors were deployed in noisier areas near the shipping lanes and the others in more quiet places to record natural noise.

The SPL tends to wane with the growing distance from the source. In an example recording, the first noise peak (at about 10 min) corresponds to the close passage of a tanker at a 400 m distance, and the second one (at about 47 min) to the passage of a cargo ship at a 1500 m distance (Fig. 4). By examining various frequency bands, we can notice that the 2 kHz third-octave SPL had the highest baseline between the ship passages. This baseline represents the ambient noise due to weather conditions. The 125 Hz one described the sound field generated by the ship in near-field and the 63 Hz one in far-field. Partly the differences stem from the differences in the sound source spectrum between the two ship types.

The daily estimate of SPL cannot identify individual ship passages, but instead it gives us an idea about the ambient and anthropogenic noise levels (Fig. 5). BIAS23 station – locating itself far from the main ship lanes – had 8 dB higher ambient noise level at 63 Hz frequency band than had BIAS20 station – locating itself near the ship lane in the middle GOF. BIAS23 was less exposed to the shipping noise, and thus able to collect natural noises of the open sea. On the other hand, BIAS23 had 10 dB lower anthropogenic noise level at the same band than had BIAS20. BIAS20 station experienced heavy ship traffic whereas the natural noise from waving was smaller compared to the Northern Gotland Basin.

As the large bulk of SPL comprises of ambient noise, the next step was to explore the correlation between ambient noise and significant wave height. The temporal patterns of the wave height and the received SPL were quite well correlated confirming the importance of the contribution of waves in the overall noise (Fig. 6).

The Automatic Identification System (AIS) makes it possible to identify individual ships and to investigate their noise level (Fig. 7). In general, the higher speed, the higher SPL.

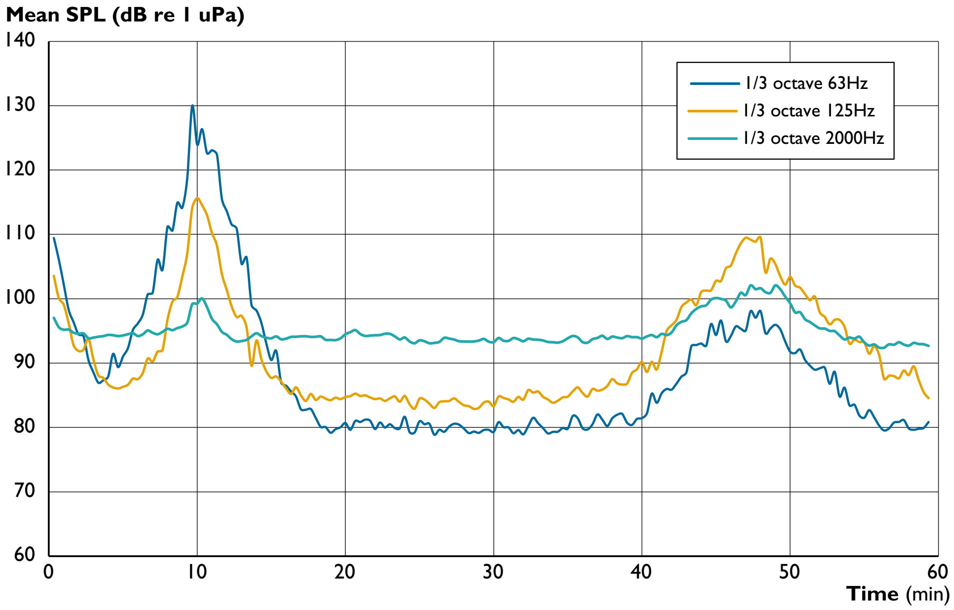

Figure 4. A 59-min recording of hydrophones deployed at a depth of 80 m. A 20-s mean SPL (dB re 1 μPa) for the tersbands of 63, 125, and 2000 Hz. Source: BIAS project.

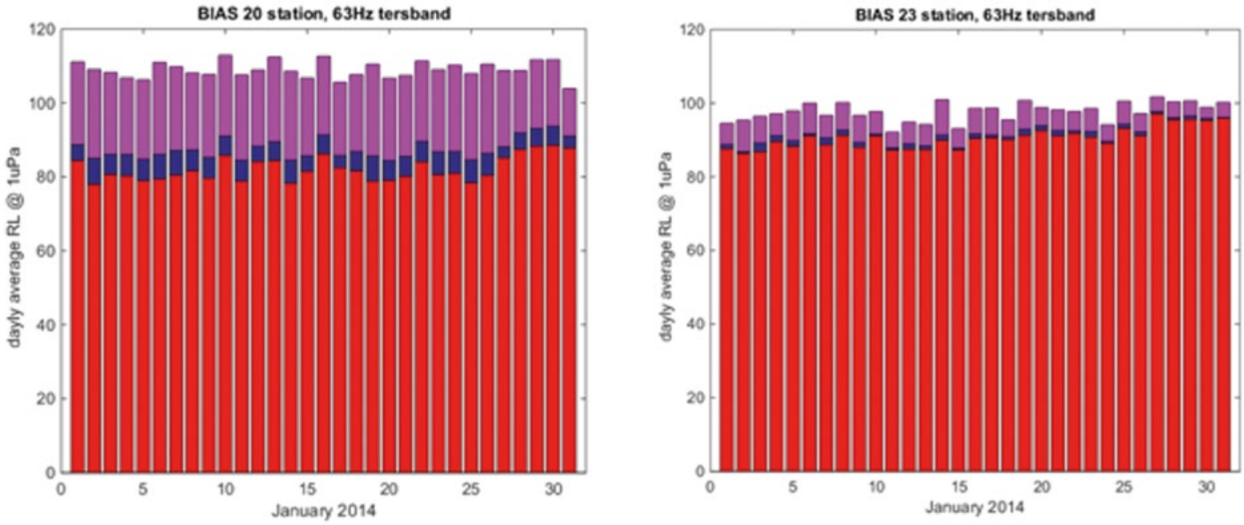

Figure 5. BIAS20 and BIAS23 stations in January 2014: daily statistics of the received SPL for the tersband of 63 Hz. Mean / median levels indicating ambient noise (blue / red), and a 90th percentile value indicating anthropogenic noise (magenta). Source: BIAS project.

Noise - a form of pollution

Anthropogenic activities have induced substantial changes in the underwater soundscape. The spatial range and magnitude of anthropogenic noise are often much greater than those of natural noise.

There is growing evidence on the detrimental impacts of the increased noise levels on marine fauna. However, these impacts are still poorly understood. The effects of exposure to sound on marine life include mortality, physical injury, auditory tissue damage, permanent or temporary auditory threshold shift, and behavioural changes (Popper and Hastings 2009). High-intensity sounds, such as explosive blasts, pile-driving, or air-guns, can damage internal organs or sensory hair cells of fish and mammals, causing death or permanent loss of hearing. Pile driving and explosives are known to

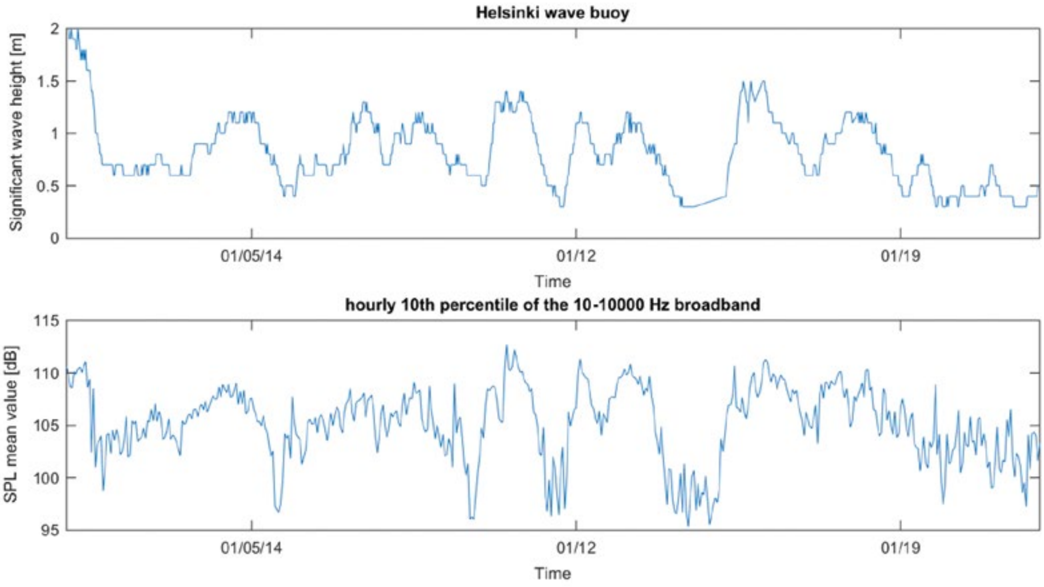

Figure 6. Above: significant wave height registered by Helsinki wave buoy in January 2014, situating at about 30 km distance from the acoustical recorder. Below: hourly 10th percentile of the minimum received SPL (a proxy for the pure ambient noise, including only natural noises) for BIAS20 and the same period. Source: BIAS project, Finnish Meteorological Institute.

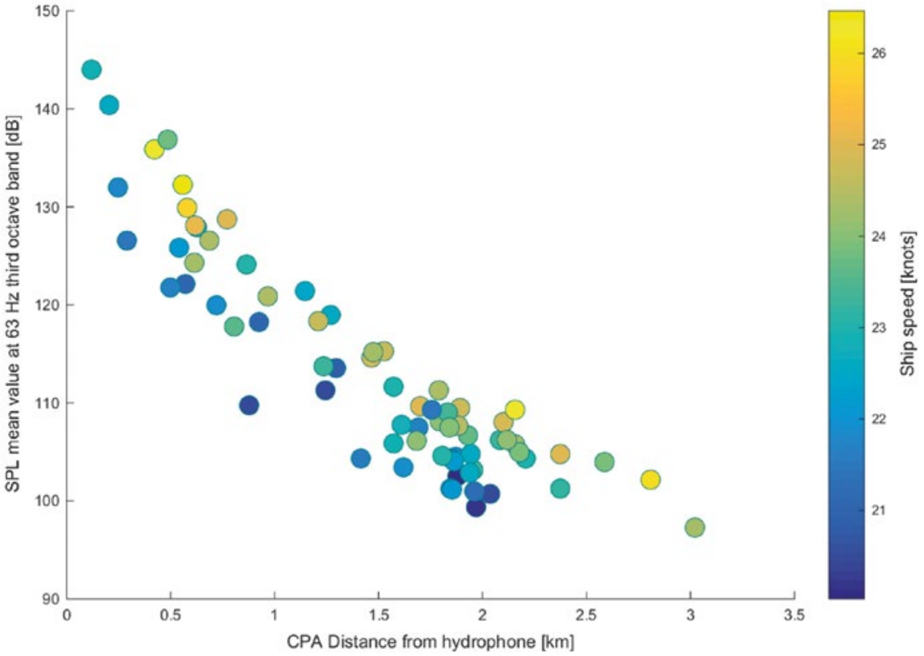

Figure 7. The received SPL (dB re 1 µPa) from passenger ships as a function of the perpendicular distance, recorded in January 2014. The color of the dot is related to the speed of the ship. Source: BIAS project.

Unnatural sounds can sometimes deceive marine mammals, like this unlucky sperm whale. Photo: Riku Lumiaro.

cause severe physical damage at a relatively close distance for fish, at a distance up to 400 m for seals, and at a distance up to 1800 m for harbour porpoises (Thomsen et al. 2006, Popper and Hastings 2009).

Even when anthropogenic noise does not directly damage an animal, it decreases the audible range, i.e., the space where the marine fauna can observe biologically-relevant sounds. The audible range diminishes always when the anthropogenic noise exceeds the natural noise level. Whenever marine fauna loses sensitivity to hear biologically-relevant sounds, critical functions, such as acoustic communication, predator avoidance, and prey detection, are compromised (Slabbekoorn et al. 2010).

Marine mammals

Anthropogenic noise impacts marine mammals through various mechanisms. Direct physiological effects, such as temporary or permanent shift in hearing threshold, can be caused by impulsive loud sounds (Finneran et al. 2002, Nachtigall et al. 2004, Lucke et al. 2009, Kastelein et al. 2012). Strandings resulting in death of marine mammals have been linked to military operations involving use of loud sonars (Frantzis 1998, Houser et al. 2001, Fernández et al. 2005). Behavioral responses include temporary to permanent displacement (Bryant et al. 1984, Morton and Symonds 2002, Castellote et al. 2012, Rako et al. 2013), changes in diving behaviour (Aguilar de Soto et al. 2006), changes in swimming direction, and other disruption in behaviour or activity (Ng and Leung 2003, Pirotta et al. 2014). Furthermore, noise can mask or reduce signal-to-noise ratio in the acoustical channel used by marine mammals leading the animal to miss opportunities for feeding, mating, or avoiding predators (Richardson et al. 1995, Tyack 2008).

Acoustic disturbance can cause displacement of harbour porpoises. Displacement following construction of wind farms, specifically in relation to pile driving, has been recorded in several cases (Carstensen et al. 2006, Brandt et al. 2011, Teilmann and

Carstensen 2012, Dähne et al. 2013). A decrease of buzzing activity (click trains classified as buzzes based on inter-click intervals) was observed following the use of air guns in a seismic study (Pirotta et al. 2014). On the other hand, acoustic alarm systems – meant to decrease marine mammal by-catch in gill-net fisheries – have proved to be effective for harbour porpoises (Kastelein et al. 2000, Culik et al. 2001, Johnston 2002, Olesiuk et al. 2002, Brandt et al. 2013).

The phocid seals' frequency ranges for vocalization and hearing overlap with the frequency range of shipping noise. Man-made noise has caused seals to avoid noise sources, abandon breathing holes or lairs, and change their vocalization rates (Cummings et al. 1986, Koschinski 2001, Kastak et al. 2005).

Animals adapted to life in an environment subject to ambient noise have mechanisms for compensating increased background noise. Vocal compensation methods observed in marine mammals include an increase in call amplitude (Scheifele et al. 2005, Holt et al. 2009, Parks et al. 2010), as well as change of call repetition, duration, or frequency (Miller et al. 2000, Foote et al. 2004, Parks et al. 2007, Castellote et al. 2012). Even if the animals were able to compensate elevated noise levels by adjusting vocalizations or migrating to a quieter environment, continuous noise exposure would still carry risks. The energetical costs invested in the vocalization may increase as a result of vocal compensation or the use of a suboptimal channel, and a quieter habitat may also be inferior as a shelter or a feeding ground (Tyack 2008).

Noise stress

Noise induces physiological stress (Wale et al. 2013). The relationship between noise and stress is well-known in humans and terrestrial animals (Möller 1978, Westman and Walters 1981), and lately noise-induced stress has been shown to occur with fishes (Wysocki et al. 2006) and right whales (Rolland et al. 2012). Even small behavioural changes may have substantial consequences for reproduction or survival if repeated over time (Jasny et al. 2005). Exposure to a threat or a pressure can also impact animal's vulnerability to another stressor (Tyack 2008). Multiple anthropogenic threats, such as habitat loss and degradation, environmental toxins, and underwater noise, can together inflict cumulative costs with more severe effects than any of the stressors could cause alone (Wright et al. 2013). Whenever anthropogenic noise affects survival and fitness of an individual or a population, not only the species in question, but the entire ecosystem may be influenced (Slabbekoorn et al. 2010).

Fish species have different hearing abilities and tolerance to noise, but the sensitivity to noise can further depend on the season and ongoing activity of fish. For example, even a close passing of vessels introduced only limited avoidance reactions by spawning herring (Skaret et al. 2005). The high priority given to reproductive activities apparently overruled the avoidance responses to unnatural signals.

Acoustic indicators will follow

Finland and Sweden are building a HELCOM pre-core indicator 'Continuous low frequency anthropogenic sound'. The monitoring standards prepared within the BIAS project will be used with the aim to develop a European standard, and in parallel a proposal will be made for an ISO ambient noise standard. The aim is to present a core indicator by the end of 2016. At first, the boundary value for the good ecological status might only be presented on a conceptual level due to the scarcity of data. As a number of on-going projects will provide new information about impacts of noise on marine species in coming years, there will be challenges to develop an indicator related to species-specific impacts.

Conclusions

The potential detrimental impact of the underwater noise on marine life is documented. Depending on circumstances, even the softest anthropogenic underwater noise can cause marked harm on the ecosystem's functioning. As we cannot at any point of time know the sensitivity of the local ecosystem to noise, making all unnecessary underwater noise should be avoided.

The effect of the anthropogenic noise on marine ecosystem depends on i) the characteristics of sound, ii) sound propagation losses, iii) the ratio of anthropogenic sound pressure to the natural one, and iii) the spatial and temporal sensitivity of the local ecosystem. The first two we know, the third is under consideration, and the fourth is almost unknown. We thus recommend that the sensitivity of the ecosystem to underwater noise should be examined more closely.

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MARITIME TRAFFIC AND ITS SAFETY

Chapter coordination: Jakub Montewka, Finnish Geospatial Research Institute, Aalto University

Viewpoint

Jakub Montewka[1,2], Jani Häkkinen[3], Jorma Rytkönen[3], Risto Jalonen[1]
[1] Aalto University
[2] Finnish Geospatial Research Institute
[3] Finnish Environment Institute

Maritime transportation systems are complex, encompassing human aspect, technology, and the environment. Accidents in marine transportation happen relatively frequently, compared to other technical or transportation systems (Gucma 2009). Whenever an accident occurs, the consequences for the marine environment are at worst of catastrophic scale, and the entire society is influenced via degraded ecosystem services.

One of the major threats to the marine environment is an accidental oil spill. According to global statistics, there were approximately 7 800 accidents in 1970–2014 in which an oil tanker was involved. In total, these accidents have resulted in 5.7 million tonnes of spilled oil. The most catastrophic damages to the marine environment have not been caused by the largest oil spills, but rather, by the spills that have happened in the most sensitive sea areas.

The Baltic Sea (BS) is one of these areas. The Gulf of Finland (GOF) is especially vulnerable to the effects of oil spills (Leppäranta and Myrberg 2009, Lecklin et al. 2011). Its ecosystem involves distinctive habitats inhabited by saline and freshwater species adapted to the area, and therefore the biota can be considered rather unique (Rydén et al. 2003, Lecklin et al. 2011). Furthermore, once entered the GOF, the contaminants persist there for a long time due to slow microbial decomposition (Furman et al. 1998, Lecklin et al. 2011). The BS has been designated as a particularly sensitive sea area (PSSA) by the International Maritime Organization (IMO) in 2005. At the same time, the amount and dimensions of oil tankers navigating in the BS have been increasing.

The concerns on the safety of the marine environment seem to be fully justified. The relevance of this issue is reflected in the EU Strategy for the BS (EU 2009) where the major areas for research and development for the safer and cleaner BS are indicated.

Photo: Riku Lumiaro.

Traffic development

The GOF has always been an important fairway. It is a natural shipping route for the present surrounding countries, but it has actually been a trading route since the times of the Hanseatic League and even the times of the Varangians.

Currently, sea traffic both along and across the GOF is thriving (Fig. 1). It supports the trade and transportation of cargo even to other continents and vice versa. Therefore, the importance of the GOF for the traffic scheme in the Baltic region is high on financial grounds, but in many other respects as well. Currently, there are over 2 000 vessels sailing in the BS every day. The biggest share of the cargo belongs to the liquid bulk, i.e., various oil products, crude oil, and chemicals.

The GOF is one of the areas in the world subject to most dense traffic (Fig. 2). The annual amount of ships crossing the pre-defined AIS passage line in 2013 was about 38 000 ships including about 7 000 tankers. Of the tankers, roughly the half sail eastbound in ballast while the other half sail westbound fully laden. The number of ships in 2014 was slightly smaller mainly due to the economic and political debate between Russia and EU (embark). These numbers do not include the intense ferry traffic between Helsinki and Tallinn, which consisted of about 15 000 passages in 2014.

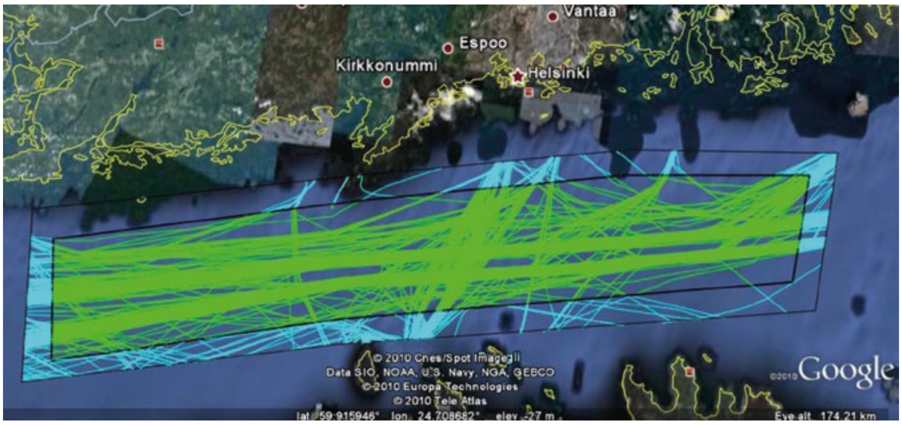


Figure 1. Ship movements the western and middle GOF on the 1st–3rd of June, 2010, based on the automatic identification system (AIS) data. Source: Berglund and Pesonen (2010).

Figure 2. Annual total crossings of vessels through the predefined AIS passage line “Gulf of Finland” between the Hanko Peninsula and Estonian coastline. Source: HELCOM. Graphics: SYKE & Kaskas Media.

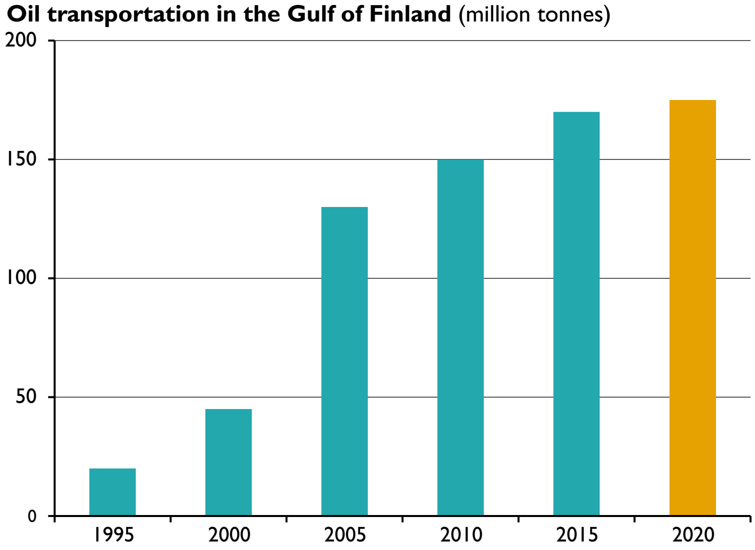


Figure 3. The development of oil transportation in the GOF. Source: Finnish Transport Agency.

The major part of the transport goes through the Russian ports and terminals. Russia has invested a lot on their terminals during the last decade, and is still developing both port and the hinterland infrastructure to achieve logistically sound solutions for Russian demands. A large terminal complex in Ust-Luga handles annually large volumes regardless of being under development.

The development of the oil transportation through the GOF has been extremely rapid. Recently, its annual volume is about 160 million tonnes (Fig. 3). The majority of oil is exported from Russia, which exports one third of all its oil via the GOF. The oil transportation through the GOF is not expected to grow. Nonetheless, there is still capacity available to reach volumes of nearly 200 million tonnes.The main ports for transportation of oil and chemicals are Primorsk, Kilpilahti/Sköldvik, and Muuga, of which Primorsk is the largest.

Tankers loading/off-loading in the oil terminal of Kilpilahti/Sköldvik in Porvoo. Photo: Risto Jalonen.

Oil tankers growing in their size

After the collapse of the Soviet Union a wide spectra of oil tankers visited the ports and terminals of the GOF. Many of those rather old ships were single hull ships. After the transport of Russian oil started to increase in its volume through the Russian ports and terminals in the Estonia and Lithuania, the tanker fleet was renewed very quickly, following the single hull vessel ban by the IMO.

The current oil tankers sailing in the GOF are rather new, flagged by a variety of countries, and much larger than 35 years ago. The design tanker size for crude oil transport in the area is mainly so-called Aframax type of between 75 000 to 115 000 deadweight tonnage. In most cases, this type is designed to traverse through the Danish Straits. The shallowness of the Danish straits does not allow ships with draught > 15.1 m to sail out of the BS. Russian oil terminals, for example, have been designed to use Aframax tankers. The storage, pumping, and docking place arrangements in the terminals has been designed accordingly.

Oil products are usually transported by smaller tankers of Handy, Handymax, or Suezmax size (Hänninen and Rytkönen 2004). Some river-going ships are also used in the eastern GOF, and mainly in the vicinity of the St. Petersburg's Big Oil Port's terminal. There, larger tankers are used as storage facilities.

A new tendency has appeared. Tankers of the VLCC (very large crude carrier) type have occasionally visited for cargo loading in the port of Muuga. These tankers have huge dimensions: length 330 m, width 60 m, and draught > 21 m. They cannot take the full load due to the shallowness of the Danish Straits, but can sail out of the BS carrying close to 180 000 tonnes of oil. The use of larger tankers reflects the general tendency of growing size of the vessels, which has been especially rapid in the case of container vessels.

Technical risk control options

The recent increase in sea traffic in the GOF – due to the growth of both the passenger traffic between Estonia and Finland and oil transportation – was one of the main reasons why Finland, Estonia, and Russia developed a mandatory ship reporting system for the GOF. Approved by the IMO, it has been named as the Gulf of Finland reporting system (GOFREP), with the amending of the existing traffic separation scheme. They were taken into operative use in July 2004.

The GOFREP is a mandatory ship reporting system under SOLAS Regulation V/11. The traffic centres Tallinn Traffic, Helsinki Traffic, and St. Petersburg Traffic monitor shipping movements, and provide advice and information about navigational hazards and weather conditions (Fig. 4). The GOFREP area covers the international waters in the GOF east of the western reporting line. In addition, Estonia and Finland have implemented mandatory ship reporting systems in their territorial waters. Vessel traffic in the area is monitored by means of radar and the automatic identification system (AIS).

According to the AIS, the merchant vessels are required to carry AIS transponders to provide information about the ship to other ships and to the coastal authorities. Information includes ship's identity, position, course, speed, and navigational status. The transponder must be fitted aboard all ships ≥ 300 gross tonnage engaged in international voyages, cargo ships ≥ 500 gross tonnage, and passenger ships irrespective of their size (Hänninen and Rytkönen 2004).

The GOFREP system has proved to be an effective tool for safety. Every year GOFREP operators note several near-miss situations while controlling the traffic in their responsibility areas. Of many cases where the GOFREP service has prevented an accident, one of the best known is the MT Lovina case on the 20th October, 2012. An Aframax type of tanker Lovina was sailing towards a shoaling embankment in the eastern GOF. The GOFREP service made an alert few minutes before the grounding, and subsequently, it was avoided. Studies afterwards confirmed that the oil spill due to the probable grounding could have been 6 000 to 16 000 tonnes (Tabri et al. 2013).

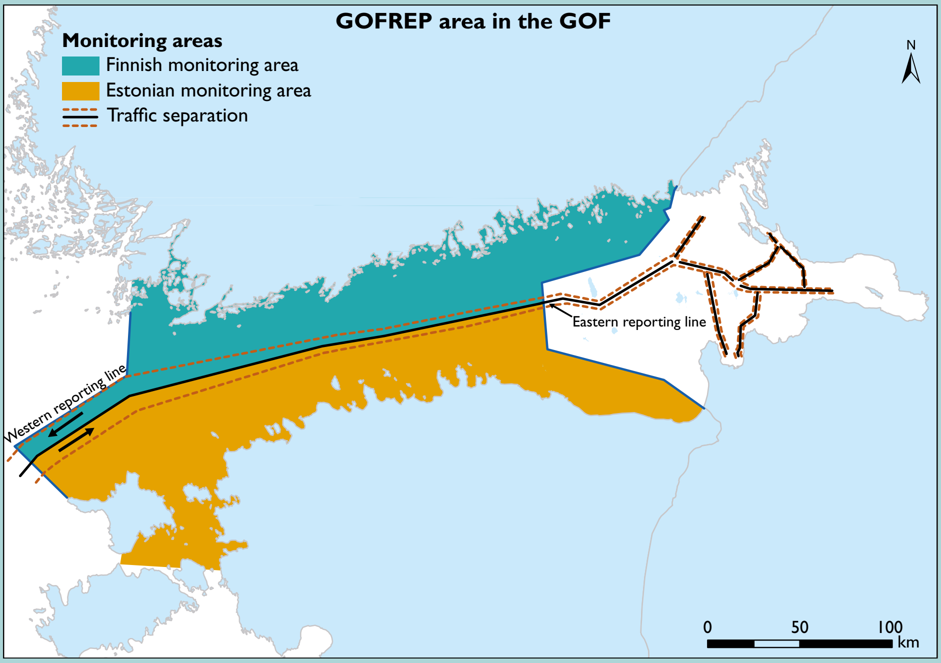


Figure 4. The GOFREP area in the GOF. Sources: Finnish Transport Agency, Rosmorport. Graph: Marco Nurmi.

ENSI is a PC-based automated navigation service that improves the preconditions for forecasting vessel traffic control, transferring data between the vessels and the marine traffic centres. The key feature of the service is that tankers send their route plans to the vessel traffic service (VTS) center before departing from the port. The route plans are then checked by the ENSI system. The VTS operators can monitor the voyage of the ship through her planned route and intervene whenever any deviation occurs from the route plan. In return, the tanker crew will have access to real-time and route-specific information about the meteorological conditions and the other traffic. In the wintertime, information about the ice conditions and the waypoints of available icebreakers will also be shared. In addition, the service enables oil tankers to optimize their schedules and thereby shorten the waiting times at ports and thus save costs (Hänninen et al. 2015). The first tanker began testing the system in December, 2012.

Seasonal traffic

Risto Jalonen[1], Jani Häkkinen[2], Jorma Rytkönen[2]

[1] Aalto University
[2] Finnish Environment Institute

Maritime traffic in the GOF is characterized by rocky shoals and an ice cover in its various forms. Thus, the environmental conditions affecting the traffic in the summer and especially in the winter call for special considerations and requirements for shipping.

The traffic between Helsinki and Tallinn is busiest in the summertime. In 2014, the number of daily foreign ship arrivals to Helsinki in June–August was on the average 27, that is, 63 % higher than in January–March. This difference is at least partly due to the high-speed crafts commuting between the two cities with several additional daily departures and arrivals. In the winter, these high-speed crafts are out of service. The number of passengers traveling between the two cities in the summer is roughly two times that in the winter.

The GOF is a popular area also for leisure traffic in May–September. It is not precisely known how many leisure boats are in active use in Finland. Boats that are ≥ 5.5 m long or have an engine of ≥ 15 kW must be registered, but smaller boats are not revealed by any statistics. Anyway, leisure boating seems to have a growing trend (Fig. 5).

Ice is a recurring feature for the maritime traffic in the GOF. The area, location, and thickness of the ice – as well as the burden on the traffic it creates – are variable, depending on the cumulative degree-days, and the changes in wind conditions. The eastern GOF and the northern coastal area get frozen every year with landfast ice. The offshore middle GOF may freeze, be ice-free, or be only temporarily ice-covered. At the tip of the GOF, the ice season lasts on the average four months, while the

Leisure traffic is thriving in the GOF. Photo: Risto Jalonen.

corresponding period at the entrance to the GOF is only one month. The average ice thickness in the eastern GOF is about half a metre during the winter, but the ice tends to form ridges. At their best, these ridges grow several metres high both beneath and above the sea surface, becoming obstacles for winter navigation.

Of the accidents during the winter, collisions and groundings are the most frequent (Jalonen et al. 2005, Valdez Banda et al. 2014). However, groundings are more frequent before the ice is present, and collisions are more frequent under icy conditions. The ships operating in the ice need to be ice-strengthened, according to the traffic restrictions, and ice-classified by the authorities. Depending on the prevailing ice conditions and the severity of the winter, the merchant ships may also need icebreaker

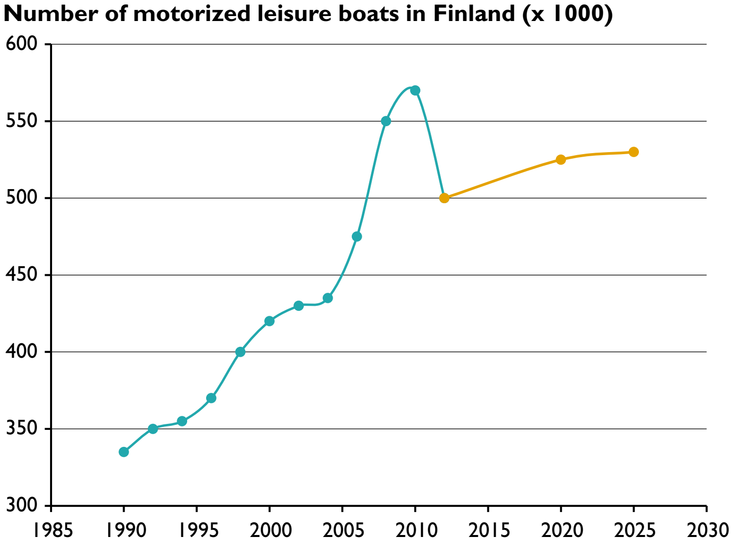


Figure 5. Motorized leisure boats in Finland. The decline in 2011 was caused by the reformation of boating register after the recognition that not all boats were duly removed from the register. The future prediction is denoted as red. Source: Mäkelä (2013).

Winter navigation in the GOF set extra requirements for the ships and their operation. Photo: Risto Jalonen.

Ice-breaking assistance is needed also under periods of darkness. Photo: Risto Jalonen.

assistance. The icebreaking assistance is a common and well-documented service. It will only be given to vessels, which meet the requirements set out in the traffic restrictions.

The Finnish-Swedish model for a joint co-operation in the winter traffic in the Gulf of Bothnia was copied to the GOF with necessary adjustments. Finland and Russia signed an agreement on icebreaking services in September 2014, which enables Finnish icebreakers to operate in the eastern parts of the GOF in the Russian territorial waters in return for compensation. Similarly, Russian icebreakers can assist vessels navigating to Finnish ports in the GOF. However, operations in territorial waters are always subject to a permit from the authorities (Finnish Ministry of Transport and Communications 2014). This agreement is expected to improve the safety of winter navigation in the eastern GOF and to make it more efficient during severe winters.

Future forecast

Olli-Pekka Brunila
University of Turku

The volume of maritime traffic in the GOF has increased in the past years, mainly as a manifestation of the opening of new ports in Russia. The Port of Primorsk started operating in 2001 as the Baltic Pipeline System was completed. Lukoil's oil and oil product terminal was opened in Vysotsk in 2004 (Hänninen and Rytkönen 2004). The second Baltic Pipeline System was connected to the port of Ust-Luga. The port constructions were in the midway at the time of the writing of this assessment, but the oil terminal was already operational (UK Trade & Investment 2010, Ust-Luga Company 2012).

The total maritime traffic in the GOF – including all cargo types as well as international and domestic traffic – equalled 292 million tonnes in 2013. Largest transported cargo type was liquid bulk; about 60 % of transported goods were oil and oil products (173 million tonnes), chemicals (4.4 million tonnes) and other liquid bulk (0.75 million tonnes, Wahlström et al. 2014). The cargo volume has lately decreased in Estonia and Finland, while in Russia it has increased constantly (Fig. 6). The reason for decreasing cargo volumes was the economical recession that started in the late 2008. It still affects the European countries quite a lot.

The Baltic Transport Outlook 2030 study concludes that the maritime freight traffic will grow by 20 % in BS area in 2010 - 2030 (Baltic Sea Action Group 2008, Baltic Transport Outlook 2011). Expressed in numbers, the total volume in 2030 will be 220 million tonnes larger than it was in 2015. The largest growth is expected in container, RoRo, and dry bulk traffic (Fig. 7). The largest growth potential will be in the St. Petersburg area with an increase of almost 30 % in total transportation, which equals 66 million tonnes. This growth will focus on container transportation (Kyster-Hansen et al. 2011).

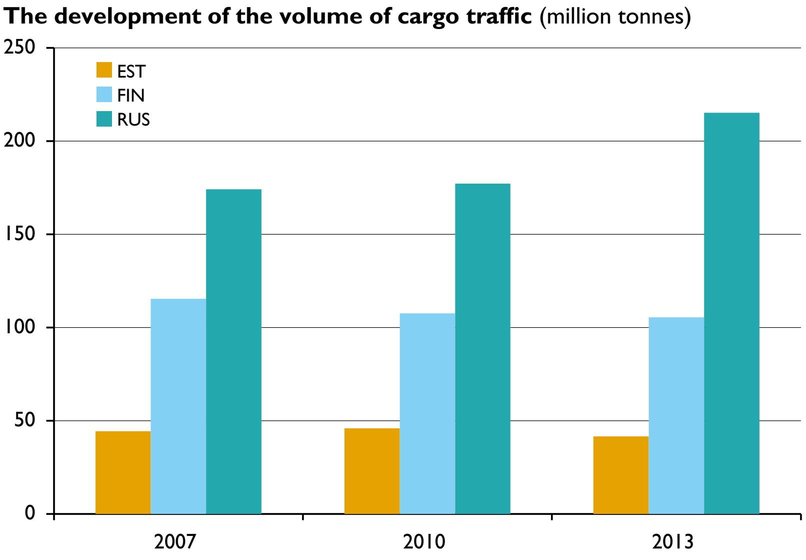


Figure 6. The development of the volume of cargo traffic (million tonnes) in 2007–2013. Statistics include all ports in the BS area. Therefore, especially Finland's share is exaggerated in the GOF scale. Source: Wahlström et al. (2014).

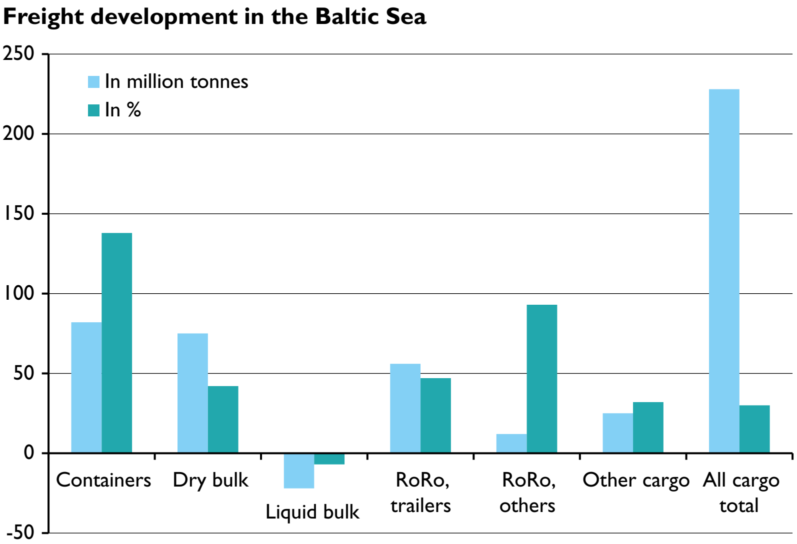


Figure 7. Freight development in the Baltic Sea in 2010–2030. Source: Kyster-Hansen et al. (2011).

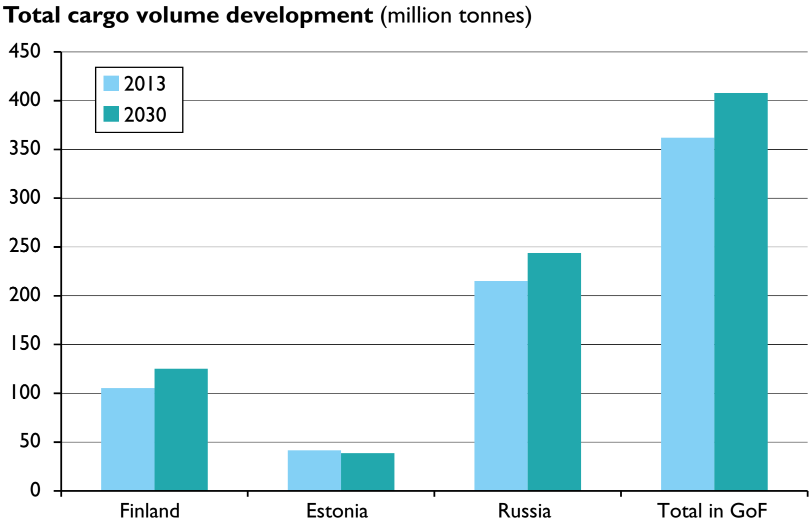


Figure 8. Total cargo volume development (million tonnes) in 2010–2030. Statistics include all ports in the Baltic Sea area, so in the GOF scale, especially Finland's share is exaggerated. Sources: Kyster-Hansen et al. (2011), Brunila and Storgård (2012).

The transported volume of liquid bulk, consisting mainly of crude oil, is expected to decrease by 7 %, mainly because of the increasing use of alternative fuel forms, such as liquefied natural gas (LNG) and biofuels. The share of liquid bulk in the total cargo is expected to decrease from 40 % in 2010 to 30 % in 2030. However, it will still remain the largest freight segment. Anyway, the development of liquid bulk transportation is mainly dependent on Russia.

Russia is the main driver for the trends in freight volumes in the GOF (Fig. 8). The freight volume is forecasted to grow by 50 to 110 million tonnes, depending on which ports are included. The volumes in Finland and Russia will increase, but in Estonia it will decrease somewhat or it will be status quo. Forecasting the future is always challenging; there are a multitude of economical and political situations that affect trade and transportation. A recent example is the Ukraine crisis, which caused economic sanctions for Russia, affecting Russian import trade of goods. Sanctions seem not to have affected Russian energy and oil trade, though.

Outlook for energy sources

Relatively low fuel prices have resulted in a lack of interest in developing alternative fuels and modern engines for the transportation sector. Even now, about 90 % of cargo ships

Choice of fuel in the maritime traffic can make a big difference. Photo: Jukka Pajala.

use heavy fuels globally, while the remainder uses diesel and marine gas oil (MGO) in their engines. Heavy fuel oil will most likely remain the main energy source for the next two decades, but changes are about to come. Increasing fuel prices, upcoming pollutant emission regulations from International Convention for the Prevention of Pollution from Ships (MARPOL), sulphur emission control areas (SECA), and the upcoming nitrogen oxide emission control areas (NECA) concern the whole shipping industry worldwide (Díaz-de-Baldasano et al. 2013).

Biofuels and other renewable energy sources have a major role in new energy and climate strategies aiming to reduce emissions and pollution. The energy mix used in shipping will be decreasingly conventional (Agyros et al. 2014). Alternative energy sources like LNG, biofuels, renewable energy, and more radical energy sources, such as nuclear, solar, and wind energy, can all become energy sources for future shipping (Det Norske Veritas 2013). With these new technologies and alternative fuels, emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x), CO_2, and particles can be reduced. In addition to these reductions, LNG can increase ships' operating efficiency (Burel et al. 2013). Studies on LNG's profitability have showed that the payback time for the installation of the LNG system is 3 to 8 years. In addition to fuels themselves, a wide array of energy efficiency technologies and abatement solutions (e.g., sulphur scrubbers and selective catalytic reduction for NO_x emission abatement) will also be used widely in ships.

The Sulphur Directive came into force in 2015 and set strict limits to ship fuel's sulphur content. According to the new limits, the content must not exceed 0.1 % in the SECA area of the BS and the North Sea (Meyer-Rühle et al. 2011). According to the Finnish Shipowners' Association, 85 % of ships use low-sulphur diesel as their energy source (Suomen tietotoimisto 2015).

Future trends in ship technology can be divided into two categories: the above-mentioned green-fuelled ships and low-energy ships (Det Norske Veritas 2013). Low-energy shipbuilding technology uses new materials, designs, and manufacturing processes. It emphasizes a low carbon development concept and green technology research in shipbuilding technology (Wua et al. 2011). The goal is to focus on improving drag and water reduction, propulsion systems, and energy efficiency in general. The main triggers for development and innovations are economical (market forces, high bunker costs) and environmental aspects (regulations, greener values; Det Norske Veritas 2013).

Accidents and their causes

Jakub Montewka[1,2], *Pentti Kujala*[1]

[1] *Aalto University*
[2] *Finnish Geospatial Research Institute*

Maritime traffic affects the environment in numerous ways. Even in routine operation, it negatively affects the environment by polluting the air, degrading the coastlines, and disturbing the marine life. Throughout the history of the maritime trade, ship collision and grounding accidents have shown to have a potential to cause major structural damage, loss of life or property, and pollution. Whenever a tanker is involved in an accident, the consequences are often disastrous and prolonged in time; long-term environmental damage and expensive clean-up procedures come to the picture.

In the GOF, the most common accidents have been ship-to-ship collisions and groundings (Fig. 9). The collisions happen most commonly in icy conditions, while weather conditions in the autumn increase the probability of groundings at that time of the year. The number of the groundings in the GOF has been low in the recent past with only a few groundings per year (HELCOM 2015, Fig. 10). Also, the number of collisions has reduced considerably there during the last decade.

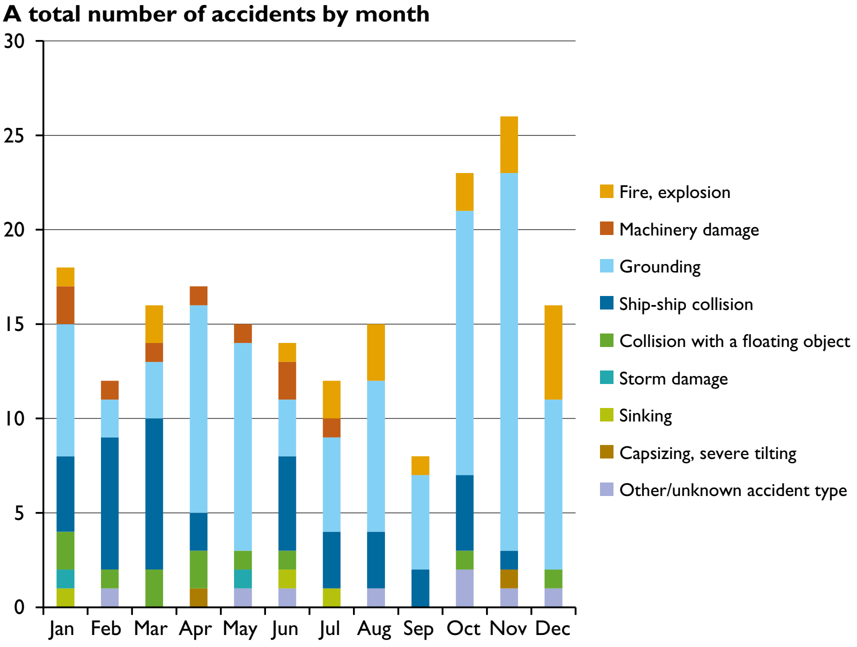


Figure 9. A total number of accidents by month in the GOF in 1997–2006. Source: Kujala et al. (2009).

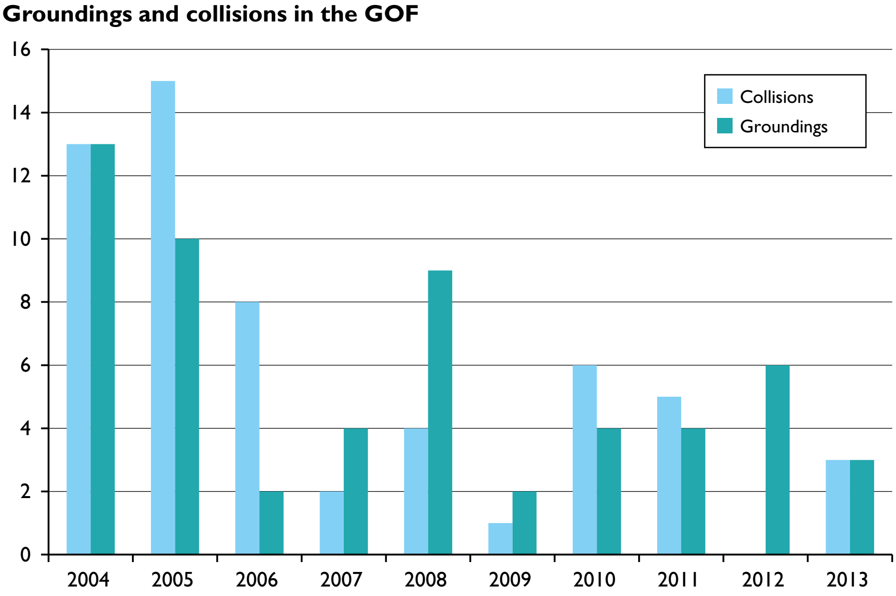


Figure 10. Groundings and collisions in the GOF in 2004–2013. Source: HELCOM (2015).

In icy conditions, the way the ships navigate changes. The ships either navigate independently through the ice or are assisted by an icebreaker. About two-thirds of all the accidents take place during ship's independent navigation. The dimensions of vessels involved in the accidents during the winter are in general smaller than those ships involved in the accidents in the open water conditions (Valdez Banda et al. 2015).

The reasons behind groundings

Marine Accident Investigation Branch (MAIB) and Safety Investigation Authority of Finland (SIAF) list factors that have the most central impact on the groundings.

1. Problems in coordination / communication / planning
2. Poor judgment / decision
3. Failures in technological environment
4. Skill-based errors
5. Features in physical environment

The most frequent active failure behind the reviewed grounding accidents was the operator's error (Mazaheri et al. 2013). Inappropriate route planning and communication can affect maritime safety as it may even override the safety factor obtained by the presence of a licensed local pilot onboard.

From reactive to proactive mitigation

Tarmo Soomere

Wave Engineering Laboratory, Institute of Cybernetics, Tallinn University of Technology

Traditionally, risks related to maritime industry are associated with potential accidents (e.g., ship collisions, sinkings or groundings, leaks from oil platforms) that may lead to loss of lives or property, or to environmental pollution. The management of the related environmental risks has been mostly focused on small areas around the installation or the ship in question. An intrinsic feature of the ocean environment is that meteorological and oceanic factors, such as wind and currents, can extend accident's consequences over long distances. This component of an environmental risk is exceptionally important in small seas that host intense ship traffic, such as the BS (Soomere and Quak 2013, Soomere et al. 2014).

The traditionally used approach to manage potential maritime pollution is a reactive one; to develop proper decision support systems and quick remedial action plans for the accident. Another approach, a proactive one, is the preventive planning strategy; for instance, the optimisation of the shipping routes, dynamical relocation of tugboats, or designation of possible policies and regulations. Their aim is to account for the effect that a pollution accident would incur before it actually happens.

A commonly accepted paradigm is that some sea areas (e.g., spawning areas) are more valuable than others. In this framework, the cost of environmental consequences of an accident depends on not only on its severity, but also on when and at which


Large-scale oil mitigation practices are central to maintaining the preparedness for oil abatement. Finnish pollution control vessels Oili and Hylje in action. Photo: Riku Lumiaro.

point the adverse impacts have been introduced. Therefore, tagging sea areas with price labels naturally yields an associated distribution of costs of otherwise similar accidents, only occurring at different locations.

A relevant method for a preventive reduction of a remote environmental risk – caused by the maritime shipping and transported by surface currents and wind impact to onshore – was developed in the framework of the BONUS BalticWay project (Soomere et al. 2014). This method is based on characterising the damaging potential of various offshore areas; in what probability oil or other pollution will be transported to vulnerable regions if an accident occurs in a specific area. Two guestions are replied: in what probability the polluting substances are transported to the nearshore and what time it takes if they come? This information is used to design environmentally optimised fairways for the GOF (Andrejev et al. 2011).

Ship-based emissions

Jukka-Pekka Jalkanen
Finnish Meteorological Institute

Baltic Sea shipping is responsible for 1.5 % of the global shipping CO_2 emissions, but carries about 11 % of the global shipping trade volume (Det Norske Veritas 2010, International Maritime Organization 2014). Furthermore, five of the ten biggest harbours of the BS reside around the GOF. This makes the GOF a vital trading route, and simultaneously subject to marked pollution from shipping sources. The bulk of the ship-based emissions are transported by prevailing wind patterns to land, but a fraction settles onto the sea.

Gaseous NO_x and SO_x emissions will contribute to aerosol formation, and thus increase the amount of particulate matter in the atmosphere. The particulates are known to be detrimental for human health, and the health impacts have been the primary driver for introducing tight requirements for the sulphur content in marine fuels. The NO_x emissions are transported hundreds of kilometers inland and have an impact both on people and the environment beyond the coastal regions. SO_x and particulate matter emissions from ships contribute to acidification and detrimental human health effects, while NO_x has a eutrophying effect.

Recent reductions in the ship fuel's sulphur content have had a positive impact on both SO_x and particulate matter emissions, but NO_x emissions are currently only loosely regulated with the IMO three-tier approach. The busy shipping lane between the Danish

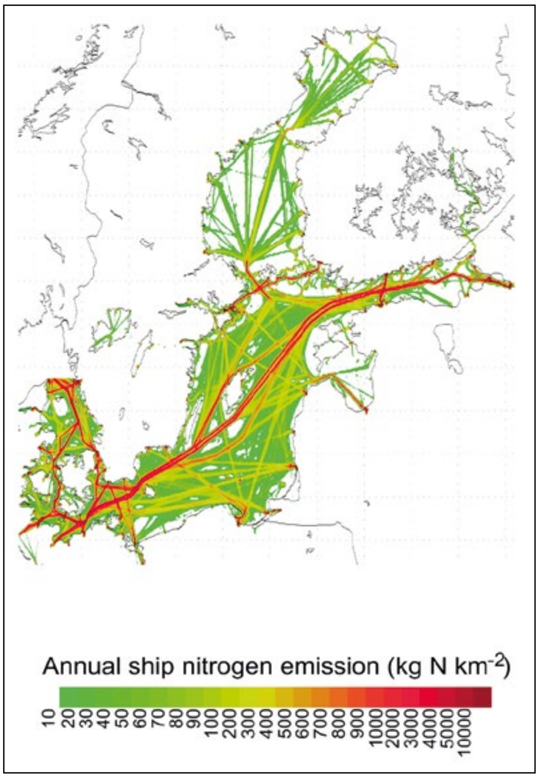


Figure 11. Annual nitrogen (N) emissions from ships (kg N/m^2) in 2008. Source: Raudsepp et al. 2013.

Straits and St. Petersburg is clearly visible with regard to the geographical distribution of NO_x emissions in the BS (Fig. 11). The IMO three-tier approach requires marine diesel engines to comply with gradually tightening NO_x limits, with the strictest limit (Tier III) necessitating the use of selective catalytic reduction (SCR) technique to meet the 80 % NO_x reduction target. The Tier III requirements are only required from new ships sailing inside a NECA.

The annual NO_x emission into the BS from the maritime traffic totalled 1 600 tonnes of N in 2008. This amount equals 10 to 12 % of the atmospheric N load. As atmospheric input represents about one fourth of the total N load into the BS (HELCOM 2010), the annual NO_x emission into the BS from the maritime traffic constitutes 2 to 3 % of the total N load (Bartnicki et al. 2011, Raudsepp et al. 2013). The impact of NO_x originating from the maritime traffic on the algal growth is also quite moderate (2 %, Raudsepp et al. 2013).

The annual ship NO_x deposition was greater in the western GOF (up to 70 kg N/km^2 per year) compared to the eastern part (Fig. 12). The western GOF is impacted by the emissions from the Gotland Basin, whereas the ship traffic in the St. Petersburg area contributes marginally to NO_x deposition in the eastern part. The area between Helsinki and Tallinn is prominently visible, being the focal point of ship traffic in the GOF.

From a legislative point of view, tools to reduce the NO_x emissions from ships are already in place because the existing IMO regulations allow the designation of certain sea areas as the NECA (International Maritime Organization 2008). However, emission restrictions for shipping cannot reduce the N load into the BS more than its share from total N input (2 to 3 %). Hence, careful analysis of both the costs and benefits of these changes must be carried out. Currently, only the North American waters and corresponding regions at the Caribbean Sea have the NECA status, which will reduce the NO_x emissions from new ships built after 2016. There are plans to apply the NECA status also for the BS and the North Sea, but the lack of political consensus needed for a NECA declaration hinders this process.

On the EU level, the discussion of emission reductions from shipping is turning to the reduction of greenhouse gas emissions from ships. To this end, an ambitious goal of 40 % reduction of CO_2 from ships by 2050 already exists, as designated in the EU transport white paper (EU 2011). To reach this target, a rapid change of ship fuel types is required. As the average lifetime of a vessel is 25 to 30 years, depending on the ship type, meeting this target would require costly retrofits of ships' engines to take place throughout the fleet. A complete switch from oil based fuels to gaseous fuels, such as LNG, can reduce the CO_2 emissions from ships by 15 to 20 %, and will simultaneously reduce emissions of NO_x, SO_x, and particulate matter.

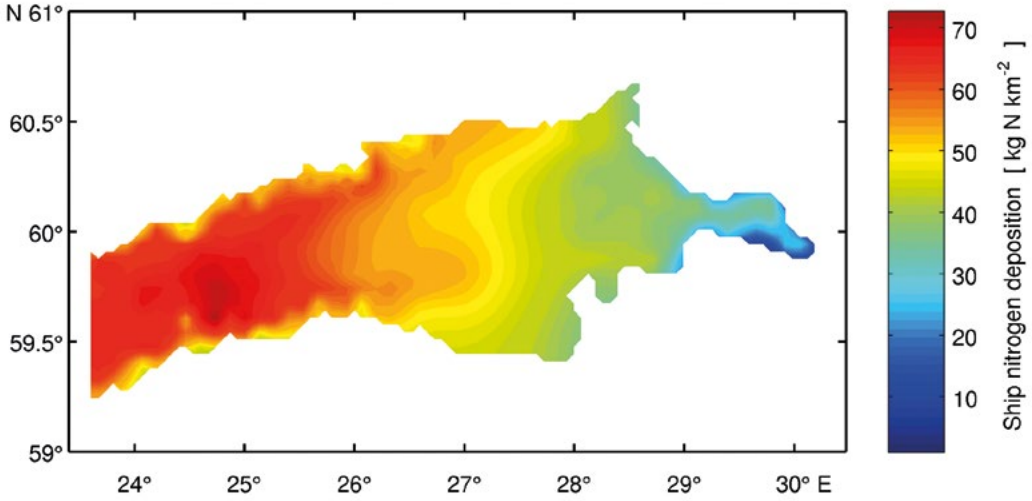


Figure 12. Geographical distribution of the annual deposition of ship-emitted N into the GOF (kg N/m^2) in 2008. Source: Raudsepp et al (2013).

Erosion by vessel waves

Tarmo Soomere
Wave Engineering Laboratory, Institute of Cybernetics, Tallinn University of Technology

Vessel waves add energy to the marine environment whenever they occur. Their contribution to the total wave-induced energy flow is negligible in the offshore and on high-energy coasts. On low-energy coasts, however, their importance has been demonstrated and quantified (Parnell and Kofoed-Hansen 2001).

The Tallinn Bay is one of the locations where vessel waves have endangered the ecosystem (Erm and Soomere 2006), and apparently have caused enhanced coastal erosion (Soomere 2005, Fig. 13). This area hosts regular traffic of large passenger ferries, with fairways located close to the shoreline (Parnell et al. 2008, Soomere et al. 2011). During the spring and summer seasons, the periods of the highest vessel wake waves considerably exceed those of wind waves (Soomere 2005). Wake waves are concentrated into periods of 10 to 20 minutes usually separated by longer time intervals.

Although the high-speed vessels ceased their operation in the Tallinn Bay in the mid-2000's, waving caused by the contemporary (large, strong-powered) ferries can be a major contributor for the energy flux even in those sections of the coast that are subject to significant natural hydrodynamic load (Kelpšaite et al. 2009). They exert unexpectedly strong impact on the coastal system. A part of this impact can be explained by a difference in the wave periods – the largest vessel waves are much longer than typical storm waves – combined with a different approach direction. For example, the net transport of water, excited by ships sailing at transcritical speeds and directed towards the adjacent coasts may lead to significant water level set-up exactly when the groups of high vessel waves arrive (Soomere et al. 2011).

Another contribution to the impact of vessel waves on the coastal processes is the particular group structure of the sequence of vessel-generated waves. The Pikakari Beach in

Figure 13. Ship traffic may exert strong erosive power on the coasts. The photos have been taken at the same spot in the western shore of the Aegna Island, north of Tallinn, in 2000 (left) and 2002 (right). The high-speed vessel traffic was thriving at that time. The shipping line situated about 1 km off the shore, and the port speed limit area did not extend to this island, allowing cruise speeds up to 30 knots. Photo: I. Kask, A. Kask.

the Tallinn Bay serves as an example (Kurennoy et al. 2011). The evolution of this relatively sheltered site is almost entirely dominated by wave action. The sandy beach, formed to the north of the Katariina Jetty that was constructed about a century ago, has evolved to an almost equilibrium state. Maximum wave heights occurred exclusively with the longest wake waves with periods of about 10 s, compared to the typical periods of wind waves of 2 to 3 s. The heights were up to 0.7 m, comparable to the highest wind waves during the study period. In relatively calm days ship wakes formed about 23 % of the energy flux, and during moderate wind conditions about 13% to the energy flux.

Both natural wind waves and vessel wakes impact the south-western shore of the Aegna Island, only they enter the shoreline from different directions (Soomere et al. 2009). During the relatively calm spring and early summer seasons (April–August), substantial amounts of sediments in the shore are apparently moved by vessel wakes to the west. During the windy seasons of the autumn and winter (September–March), the energy flux by wind waves exceeds that by vessel wakes by almost an order of magnitude (Kelpšaitė et al. 2009), and fosters sediment transport in the study site to the east. If rough waves, possibly during a storm surge, are able to exert an impact similar to ship wakes, the transport by ship wakes can be overridden. If this is not the case, the features developed by ship wakes may become quite stable.

A passing of a passenger ferry causes major displacement of water in narrow straits. Photo: Riku Lumiaro.

Maritime activities disturb marine life

Antti Below
Metsähallitus

Seals

An ever-increasing number of boats and ships in the GOF have a vast effect on the seal populations in the Finnish archipelago. Seals are sensitive to noise disturbance and may move to other areas from the most suitable one. Also small motor boats for leisure and fishing go nowadays further offshore and disturb seals on their resting islets, driving them into the sea. This is harmful especially during the spring, when seals are changing their winter fur to summer fur, and avoid swimming in cold waters. Also the seal pups might be driven into the sea.

The characteristics of the ice cover of the GOF have lately changed a lot. Fragmentation of the ice cover due to dense maritime traffic and the warming climate affect negatively the seals' breeding success. Seal pups, born on the ice in the early spring, may move long distances along drifting ice. This way, they may get loose from their mothers and become targets for predation.

It is not the large ferries but the small motorboats that distract the marine life in the archipelagos. Photo: Riku Lumiaro.

Birds

Big and powerful motor boats are rapidly increasing in their numbers in the Finnish waters, increasing not only the amount of noise in the archipelago but also direct physical disturbance there. Motor boats and water jets disturb waterfowl broods, and dispersed chicks are in danger to be attacked by gulls and other predators.

Recreational use of the archipelago is a way to experience the nature, and is something to be supported as such, but can also become a severe issue. An increasing number of people go out to the sea for daily trips or fishing. Sometimes people land on the protected islands regardless of prohibition signs. During cold early-summer days, even a short visit on the island may severely distract nesting. Also dogs are often let to run freely on the islands where birds are nesting. Not all protected islands have signs or are shown in the maps, but a part of the problem comes from the lack of people's awareness or interest on nature conservation issues.

Fishing in the vicinity of the bird islands may also disturb breeding birds. Normally this is a small scale problem because the visits are short. Fishing causes harm mostly during the cold and rainy weather in the spring and early summer, when there are eggs or small chicks in the nests. Placing fishing nets close to the colony islands of breeding birds may also cause harm; the birds are in danger to get entangled in the nets.

Hunting of the common eider (*Somateria mollissima*) males at the early June distracts sometimes bird nesting. There are still many bird islands and islets in the Finnish archipelago where the summertime hunting is allowed regardless of the bird nesting time. Hunters stay a long time or even overnight on the islands. The nesting may fail totally because the birds are not able to return to their nests. This kind of indirect destruction of nesting has been observed in many areas, even in Natura 2000 bird areas.

Consequences of oil spills

Inari Helle, Päivi Haapasaari, Riikka Venesjärvi and Annukka Lehikoinen
University of Helsinki, Fisheries and Environmental Management Group

Given the scarcity of observational data and high uncertainties related to the subject, assessing environmental effects of oil spills is evidently a challenging task.

One solution to this problem is to apply modeling approaches that acknowledge these features. Bayesian Belief Networks (BBNs; Jensen and Nielsen 2007, Fenton and Neil 2013) are probabilistic models that enable the integration of different types of knowledge (e.g., observation data, simulation results, and expert knowledge) from heterogeneous sources. Based on the lessons learned from oil spills in the past, Lecklin et al. (2011) developed a BBN model for estimating the potential impacts of oil spills on selected groups of organisms. Furthermore, they estimated the recovery of populations within a decade after a spill. Their worst-case scenario was an accident of a 150 000 dead weight tonnage tanker carrying heavy oil in the spring. The subsequent leakage would most probably lie within 10 000 to 25 000 tonnes.

The most striking consequence of an oil spill is the acute mortality of biota. The acute impacts would be heaviest on seabirds, excluding raptors. For many other groups, such as perennials, submerged plants, bivalves, gastropods, fishes, and waders, the acute impact on the abundance would be clearly smaller; the most probable reduction being < 20 % of the population size prior to the spill. There would also be differences between the groups with respect to their recovery. For auks and ducks, the long-term consequences would be the most severe. Auk and duck populations were estimated to have probabilities of 0.14 and 0.37, respectively, for recovering within a decade.

To summarize, Lecklin et al. (2011) ranked the sensitivity of the groups of organisms to the long-term impacts of oil in the following order (starting from less sensitive): raptors < bivalves < perennials < gastropods < pelagic fish < waders < submerged < plants < isopods < charophytes < phaeophytes < helophytes < annuals with seedbank < littoral fish < seals < annuals without seedbank < amphipods < gulls < ducks < auks.

The work of Lecklin et al. (2011) concentrated on the functional groups of organisms. A more species-specific approach was applied by Helle et al. (2011) who studied the acute effects of oil spills with their BBN model on selected species living in the Hankoniemi area in the western GOF. The impacts of a large oil accident would vary between species. Of the analysed species, the common eider (*Somateria mollissima*) populations would have the strongest negative impacts, while the effects on subsurface species, such as the blue mussel (*Mytilus edulis*) and Baltic herring (*Clupea harengus membras*), would be weaker.

In addition to ecological attributes, also the spatial aspects related to accidents and the spreading of oil need to be taken into account when assessing the environmental risks related to oil spills. There are certain coastal areas in the GOF that i) harbor a high number of species and habitats vulnerable to oil, and ii) have a relatively high probability to become exposed to oil after an accident (Jolma et al. 2014). In the northern GOF, for example, seashore meadows and sandy beaches are high risk areas. The recovery of seashore meadows will be slow and uncertain, and these habitats are also difficult to clean-up properly. Furthermore, knowing the occurrences of threatened or near-threatened species in the northern coast of the GOF, Ihaksi et al. (2011) estimated the ecological effects of oil spills by identifying areas that would be important to safeguard from oil because of the vulnerability of species present.

More and less famous oil spills

M/T Exxon Valdez ran aground in Prince William Strait, Alaska, in 1989, and spilled about 40 000 tonnes of crude oil. Although the accident is listed only as the 35th in the list of the world's largest ship-based oil-polluting incidents, it has become an icon of risks involved in maritime oil transportation. It is considered to be one of the most devastating human-caused environmental disasters of all time, although currently surpassed by the accidents involving oil rigs. The reputation of the ship is so notorious that the ship even made its way to represent oil tankers in general in a Hollywood film (Waterworld by Universal Studios).

It was the characteristics of the area where the accident took place – a sheltered pristine archipelago – that set this incident apart. The spilled oil eventually covered 2 100 km of coastline and 28 000 km^2 of ocean, that is, an area close to the surface area of the GOF. It has been estimated that the oil killed about 350 000 marine birds, 3 000 sea otters, and 300 seals in an instant, and even 25 years after the accident oil is found in the area. The accident triggered a trial process of epic scale, and costs equalled 0.5 billion USD. Considering that the spilled oil was less than half of the total oil volume onboard, the consequences could have been even worse if the tanker had sunk. This time, the bulk of the oil could fortunately be pumped into another tanker.

A notable oil spill took place in the GOF on the 6th of February, 1987. M/S Antonio Gramsci grounded off Vaarlahti, Porvoo. A total of 570 tonnes of crude oil ended up into the sea, which was a little proportion of the ship's cargo of 39 000 tonnes. Collecting oil in icy conditions is always challenging, and so it was also this time; oil combating was truly started after the ice melt. Oil was found mostly in the outer islands and skerries from Helsinki in the west to Pyhtää in the east. The same tanker had already grounded earlier in the BS, namely off Ventspils on the 27th of February, 1979. A total of 5 500 tonnes of oil was spilled into the water. The oil slick traversed across the Gotland Basin and ended up to, e.g., Stockholm and Åland archipelagos.

M/T Exxon Valdez grounded on Bligh Reef in the Prince William Strait. Photo: National Oceanographic and Atmospheric Administration (NOAA).

Risk analysis for maritime transport

Jakub Montewka[1,2], Jani Häkkinen[3], Jorma Rytkönen[3], Floris Goerlandt[1], Osiris Valdez Banda[1]

[1] *Aalto University*
[2] *Finnish Geospatial Research Institute*
[3] *Finnish Environment Institute*

The society has to be able to manage ecological risks emerging from maritime transportation in order to ensure the sustainability of those ecosystem services that the sea provides. Maritime transport is of vital economic importance to the BS area, but its recent growth in the area is accompanied by a clear and present risk for the occurrence of a pronounced ecological harm due to accidents. To counteract these increasing risks, adequate measures for accident prevention and spill mitigation are critically important. Several important focuses in maritime transportation have been identified, including i) international co-operation in accident prevention and response, ii) information exchange between ships and between the ships and the shore, and iii) services for post-accident operational management of ecological risks (Andrusaitis et al. 2013).

To assess the effect that technical systems, operating in the presence of uncertainty, may have on safety of the environment, risk analysis as a scientific discipline has been developed. A risk assessment is proactive and anticipates hazards before they occur. Properly conducted risk assessment can be a very efficient tool assisting the decision-making process. A formal risk assessment or management process involves: i) identifying the risks, ii) analyzing causal factors behind the risks, iii) assessing the likelihood of the occurrence and potential consequences of the risks, iv) characterizing risks in terms of their tolerability / acceptability, and v) deciding and implementing measures to reduce risks (Modarres 2006, Berg 2010).

Formal safety assessment

Risk is usually defined as the expected probability for an event to occur, and the utility of the consequences. The IMO has adopted more formal approach for the risk assessment, i.e., the formal safety assessment (FSA). It is a process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of reducing the risks. FSA has five steps (International Maritime Organization 2002):

1. Identification of hazards
2. Risk analysis
3. Risk control options
4. Cost benefit assessment
5. Recommendations for decision making

Identification of hazards

The first and most important aspect is to know what hazards the mariners face. The nature of hazards depends on ship's category, function, size, and operations. The accident category, such as collision and explosion, is also elemental. Besides these, the knowledge of past accidents, more specifically of their nature and extent, are needed for hazard identification. This first step basically deals with finding out all the possible things that can go wrong with a vessel.

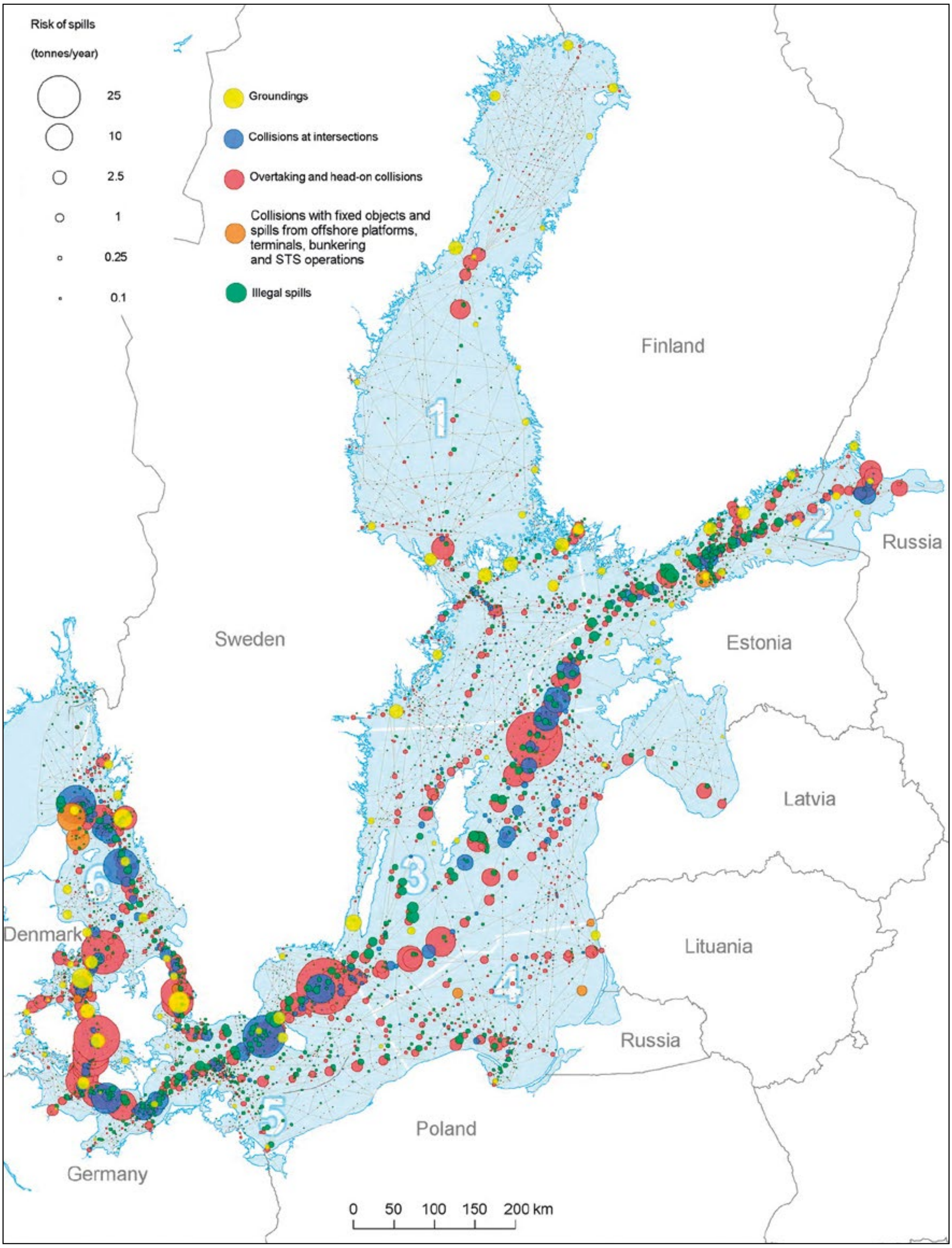


Figure 14. Risk map over the BS for the spills of oil and hazardous substances. Source: BRISK (2013).

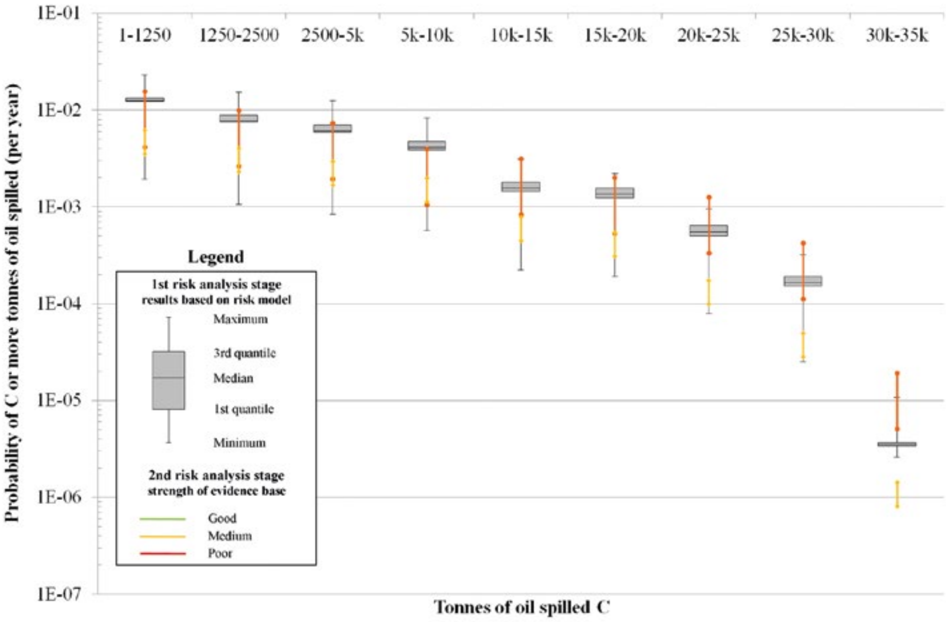


Figure 15. Probability of a collision as a function of the amount of oil spilled (tonnes). Source: Goerlandt and Montewka (2015b).

Risk analysis

A risk analysis aims to understand the nature of things that can go wrong with a vessel and the damage they can cause. This step is of high importance for the assessment of high risk areas of a vessel.

Risk control options

Here, the goal is to find all the possible ways how a hazard can be avoided or the related risks can be minimized. Of all these options, the most practically feasible ones are to be selected.

Cost benefit analysis

Cost happens to be one of the major limiting factors for feasibility of any risk control method. Essentially, the cost of solution for the risk should be less than the extent of damage that could be caused due to that risk.

Recommendations for decision making

The final step of a safety risk analysis is to make a final decision about the most suitable way to reduce risks and their consequences. The basic idea is to make sure that the chosen solution is the best of all options available; it will yield best results and is suited from the cost aspect. Expert recommendations and previous studies are useful for the decision making process.

Probabilities for oil spills

The BRISK project counted the estimated frequency of oil spills of various sizes (Fig. 14). The conclusion was that the most cost-efficient investment to reduce the risk for an oil spill in areas under intense traffic is the proper vessel traffic service (VTS) type surveillance, and

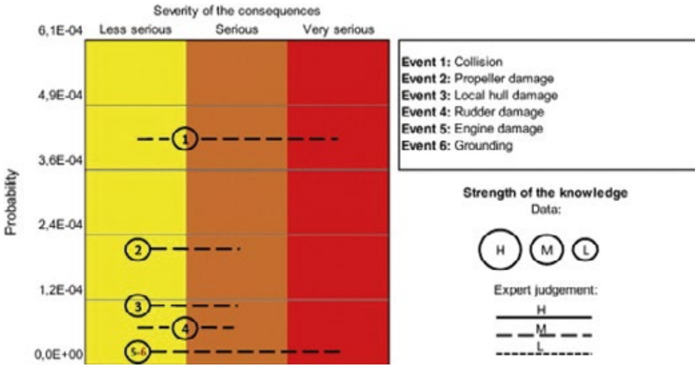


Figure 16. Visualization of the risk of events in winter navigation: all types of operations, their probability of occurrence, and the severity of these events based on the accident statistics supplemented by expert judgment. Source: Valdez Banda et al. (2015).

the launch of the traffic separation scheme. Most importantly for the GOF, investments for the additional surveillance capacity will have a better cost-benefit ratio than have any additional investments for improving the oil recovery capacity. Thus, more emphasis needs to be paid for preventory means against accidents, not forgetting the adequate response capacity in the areas having the most significant risks.

Open sea collision involving tankers

Goerlandt and Montewka (2015a) proposed a framework for a risk analysis of maritime transportation systems where an analysis is understood as a tool for argumentative decision support. A case study on an oil spill resulting from a tanker collision was carried out for the GOF with the aims of response capacity planning and ecological risk assessment. The analysis of a Bayesian Network model indicated quite stable trends (Fig. 15):

- Spills < 10 000 tonnes have an occurrence probability of 0.004 to 0.01
- Spills < 20 000 tonnes have an occurrence probability of about 0.001
- Spills > 20 000 tonnes have an occurrence probability of 0.0001 to 0.0003
- Spills > 30 000 tonnes have an occurrence probability of 0.000003, which is very unlikely.

The use of probabilistic causal BBN-models makes it possible to involve the models into the decision making process, since different options can be efficiently tested. Moreover, they offer a possibility for uncertainty assessment and model validation that are still open issues in the field of risk analysis.

Winter navigation risk

A ship independent navigation in icy conditions is the operation with the highest number of reported accidents. The majority of the vessels involved in accidents have < 20 000 dead weight tonnage, and the ice class IA accounts for the most of the reported accidents. Icebreaker operations account for less than half of the number of accidents reported on ship independent navigation. Icebreaker towing is the assistance operation with the highest probability for an accident.

Collision is the accident form with the highest probability of occurrence, and the degree of its severity seems to be higher when it is a ship-to-ship or a ship-to-icebreaker collision (Fig. 16). The majority of the reported accidents are less serious; some few cases are serious, and no cases represent very serious accidents.

Oil combating

Inari Helle, Päivi Haapasaari, Riikka Venesjärvi and Annukka Lehikoinen

University of Helsinki, Fisheries and Environmental Management Group

The GOF is a narrow sea area with a long coastline, and it has a fragmented archipelago in its northern part. Therefore, if any oil is being spilled into the GOF water, it will most likely drift to the shore, if not recovered in the offshore area. There is only a limited time to act before oil reaches the shoreline. Effective oil combating is thus essential in minimizing the harmful effects of oil accidents.

In the case of an oil spill or a chemical spill, the regional authorities around the GOF have a variety of resources for oil combating both out in the sea and in the coastline area. Finland alone has 20 recovery ships under the national oil combating authority, and, jointly with Estonia and Russia, the fleet has a preparedness to cope with 30 000 tons of oil in a couple of days. The significant tank capacity of the joint recovery fleet also makes it possible to operate effectively without any delays for tank emptying procedures during the recovery operations.

Designing oil combating

The limited oil combating resources should be targeted at areas with a high number of threatened species having a low recovery potential (Kokkonen et al. 2010, Ihaksi et al. 2011). Retention booms should be used to safeguard species that benefit from protection. Applying this approach means that for example the occurrences of many bird species may not be ranked very high, as birds are highly mobile, and thus booms may be of a limited benefit for them. Resources should be used as efficiently as possible instead of making decisions based on secondary matters, such as how charismatic or well-known the species is in the eyes of the public. The OILRISK web tool provides the oil combating officers with knowledge of those local nature values that are threatened (Altartouri et al. 2013). This is a great advantage in decision-making.

HELCOM (2001) recommends a mechanical oil recovery as the primary oil combating method in the BS. The use of dispersants is not a preferable option due to uncertainties regarding their effectiveness and impacts on the ecosystem. Furthermore, Helle et al. (2011) showed that dispersants did not seem to be effective in the GOF.

The efficiency of a mechanical recovery is highly dependent on prevailing environmental conditions, such as wave height (Helle et al. 2011). The use of oil retention booms near to the shoreline can be a good way to safeguard species, only it depends highly on the species in question. Therefore, even large investments in the mechanical recovery capacity do not ensure successful protection of biological resources.

Within the GOF, the placement of the oil combating vessels does not have a significant effect on the recovery efficiency of oil from the sea (Lehikoinen et al. 2013). Instead, the process is strongly affected by external factors independent of human action, such as wave height and stranding time of oil.

For once, the weather is nice in November. The boats of the Finnish Border Guard and the Southwest Finland Emergency Services together pull an oil boom in the Archipelago Sea. Photo: Jouko Pirttijärvi.

Costs and benefits of oil combating

Several models have been developed to evaluate alternative measures for preventing accidents. Effective preventive measures are in the essence and should be promoted, because the success of oil combating after an accident is highly uncertain due to environmental conditions, and the costs of post-spill clean-up measures can be astronomical (Helle et al. 2011, Lehikoinen et al. 2013, Helle et al. 2015, Lehikoinen et al. 2015). Consequently, Haapasaari et al. (2014) evaluated the cost-effectiveness of three types of preventive measures to reduce the risk of an oil accident in the GOF.

1. The ENSI (Enhanced Navigation Support Information) service, which facilitates the information exchange between the ships and the VTS centers related to route plans and conditions on the routes
2. Compulsory pilotage, which refers to a situation in which the use of a local pilot service would be mandatory in the GOF for all passenger ships and other vessels > 300 dead weight tonnage
3. Improving the crashworthiness of ships, which aims at decreasing the oil leak from a ship after an accident

If the theoretical oil recovery costs are used as the decision-making criterion, the ENSI service would be the most cost-effective, as it reduces the risk of accidents by about 20 %. Mandatory pilotage services and improving the crashworthiness of vessels would be even more effective in managing accident risks than the ENSI service. The former would decrease the oil accident risks by about 35 % and the latter by 30 to 60 %. The latter two options are, however, rather expensive, and therefore can not be characterized as being as cost-effective as the ENSI service. Anyhow, if the economic losses related to the degraded ecosystem services due to a major oil spill were included into the model, also the more expensive preventive measures would appear as highly cost-effective.

As very large-scale oil accidents are fortunately rare, and as the oil combating experience after such an event is limited, models can be used to assess the performance of oil combating and to plan combating and clean-up actions. They can also help to find the most cost-effective measures. Modeling thus offers aid for strategic planning, and can also be used in operational decision-making. However, it is important to remember that for example the performance of oil combating is dependent on several factors, such as weather conditions, and uncertainties are high. The models should take these uncertainties into account in an explicit manner, which will give a more realistic picture of the capability of the society to manage oil spill risks. Also, it is notable that when the environmental risks and the cost-effectivity of the risk management methods are estimated, the values given for the clean environment and healthy ecosystem typically have a remarkable effect on the end results. Thus, the expected value accepted by the public should be estimated based on a sound scientific background.

Oil dispersal in the ice

Vadim Goncharov
St. Petersburg State Marine Technical University

When crude oil is spilled from a damaged tanker in the wintertime, the oil will enter the ice channel and spread within it. Crude oil will also spill on the surface of the ice and get under the ice, but capillary forces will restrain its spreading on ice-air and ice-water boundaries (Liukkonen et al. 1997). Oil can spread on the water surface until the oil film reaches monomolecular thickness.

The main attribute of the flow of oil within an ice channel is the resistance to flow within the water surface, on borders of the channel, and on the sidewalls of ice floes filling the channel. The temperature of the water and air will affect this process; wintertime temperatures increase the viscosity of crude oil that delays the spreading.

Ice floes decrease significantly the spreading rate of oil within the channel (Fig. 17). An increase in both the average size of ice floes and the ice concentration in the channel reflect in a decrease in the spreading rate.

Crude oil spreads slower with the existence of ice floes than on open water surface with the same breadth. Difference is in range of 20 to 50 % depending on the thickness of the ice cover and the concentration of ice floes within the channel.

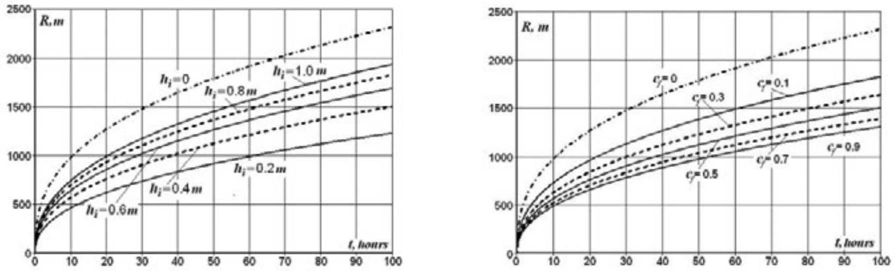


Figure 17. The spreading of oil slick within the ice channel (m) as a function of time (h). A: within the range of ice thickness in the channel (hi), ice concentration c = 0.5. B: within the range of ice concentration in the channel (cf). Thickness of ice cover hi = 0.4 m. Source: Goncharov (2009), Goncharov et al. (2015).

Chemical pollution

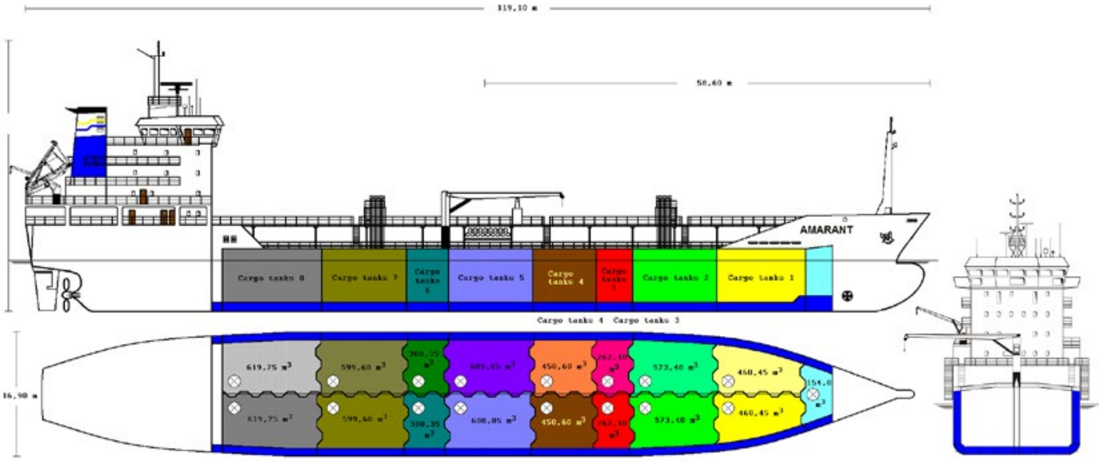
Jorma Rytkönen[1], Jani Häkkinen[1], Otto-Ville Sormunen[2]

[1] *Finnish Environment Institute*
[2] *Aalto University*

In 2010, the liquid bulk transport in the BS contained about 290 million tonnes of oil and oil products, and 11 million tonnes of liquid chemicals (Holma et al. 2011). Even though the amount of transported chemicals is much less than that of oil and oil products, the risks related to possible chemical accidents are more difficult to identify than risks caused by oil accidents. The issue is the high variety and complexity of the environmental risk profiles and potentials of the chemicals and chemical compounds (Malmsten 2001).

Risks posed by maritime chemical spills depend on accident scenario, environmental conditions, and the intrinsic properties of the spilled chemical. Basically, accidents involving chemical tankers can be classified into three groups:

1. In the offshore, a chemical spill has space to have a larger effect, or to dissolve and be vaporized. This mitigates the negative effects of the spill. On the other hand, response actions can take a longer time and environmental conditions can also be challenging.
2. The incident occurring closer to the shoreline is easier and faster to reach, even if the impact on the environment can potentially be more disastrous.
3. In the incident taking place in a closed sea area, such as in ports or terminals, the spill is usually localized and effectively restricted. However, even a small spill may elevate toxicity levels in a restricted area, affecting the workers in the area. Ports are often situated in the vicinity of densely populated areas, and there is an elevated risk of the health of the public.



A glimpse inside the hull of a chemical tanker Amarant. The bulk of the chemical tankers are so-called chemical parcel tankers that can carry a wide range of liquid cargo. They can carry 10 to 60 separate cargo tanks to simultaneously accommodate multiple cargo or parcels. Source: Hänninen and Rytkönen (2006). Photo: Transmarine Tankers ApS.

The most harmful chemicals for human health have quite opposite properties to those that are most hazardous for water biota. For human health, the most hazardous chemicals are those that: i) are very reactive, forming either toxic, irritating, or explosive gas clouds, and ii) have possible long-term effects, such as carcinogenic effects. From the environmental point of view, the most hazardous chemicals are those that: i) sink, have a high solubility, and possibly stay at the water column, and ii) are persistent, bioavailable, toxic, and can have possible long-term effects (French McKay et al. 2006, Häkkinen et al. 2013, Harold et al. 2011).

The chemicals of real concern vary depending on the sea area, since the amounts and types of chemicals transported vary in different sea areas, as do the marine environment and biota in it (Kirby and Law 2010). Many risk assessments and worst case studies are there to help finding out what impacts different chemicals would have if a spill were to happen. Examples follow:

- Law and Campell (1998) concluded that a 10-tonnes spill of an insecticide (pirimiphos-ethyl) might seriously damage crustacean fisheries in an area of 10 000 km^2 with a recovery time of 5 years.
- HASREP (2005) project identified top 100 chemicals which are transported between major European ports. The project highlighted chemicals, such as benzene, styrene, vegetable oil, xylene, methanol, sulphuric acid, phenol, vinyl acetate, and acrylonitrile. It was concluded that these chemicals were the ones that have a high probability for spillage but may not result in significant environmental impact.
- McKay et al. (2006) concluded that phenol and formaldehyde present the greatest risks to aquatic biota.
- Harold et al. (2011) evaluated human health risks of transported chemicals, and gave more weight to chemicals that either float, or form gas clouds, or are irritable and toxic, such as chlorine.
- Häkkinen et al. (2013) stated that nonylphenol is the most toxic of the studied chemicals, and it is also the most hazardous in light of maritime spills. Other very hazardous substances were sulphuric acid and ammonia.

Probability of spills

Sormunen et al. (2015) estimated the number of collisions between chemical tankers and other vessels. They used a simulation model of the GOF traffic (Goerlandt and Kujala 2011) to detect possible collisions, and evaluated the actual probability for a collision for each scenario according to probabilities laid out by Hänninen and Kujala (2012). The estimated probability for a tanker collision was once in every 17 years, and for a collision that results in a spill, that was once in every 40 years. These probabilities were for all the tankers in general. For chemical tankers, the corresponding probabilities were once in every 77 years and once in every 156 years. The areas with the highest risk of collision for chemical tankers were found to be in the traffic crossing area in the midway between Helsinki and Tallinn as well as along the route to the port of Sköldvik (Fig. 18).

Noxius liquid bulk cargo is rated as X, Y, Z, or N/A according to its toxicity, where X is the most toxic and N/A non-toxic. Of the total transported volume of chemicals going through the Finnish harbors of the GOF, the shares of these categories were 2.8, 74.3, 16.1, and 6.8 %, respectively (Sormunen et al. 2015). Later, the categories were assigned with hazard multiplier weights of 3, 2, 1, and 0 for X, Y, Z, and N/A, respectively, based on their toxicity. Multiplying the expected spill volumes with these weights, the average risk multiplier for the western GOF was 1.73 and 1.89 for the eastern GOF (Sormunen et al. 2015).

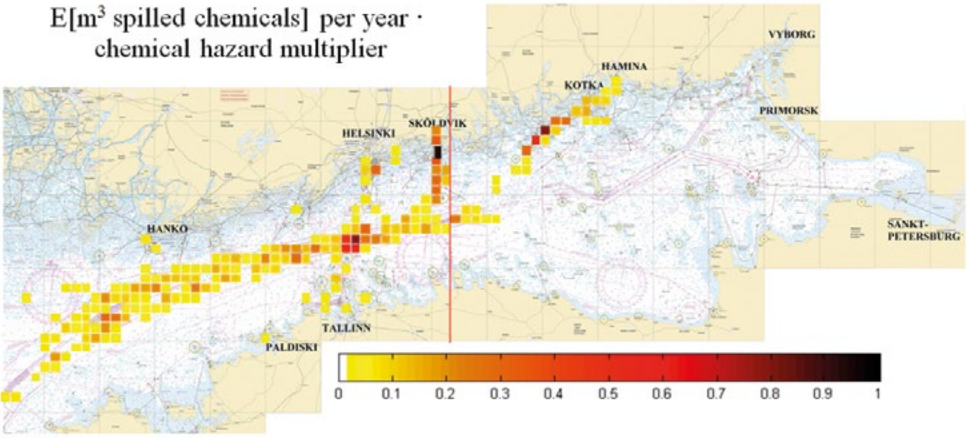


Figure 18. Geographical variation in the risk of chemical spills, weighed according to average hazard level of transported chemicals. The red line was used to divide the area into western and eastern parts (see text). Source: Finnish Transport Agency, license no. 1803/1024/2010.

Designing chemical spill combating

Response actions taken differ in every accident case according to special conditions and chemicals involved; it is nevertheless possible to demonstrate certain elements valid in all chemical incidents at sea (Marchand 2002). Following the chemical spill at sea, the response authorities must immediately take measures in order to minimize the chemical exposure to the public and to the marine environment.

Firstly, the information concerning the ship cargo is essential for an evaluation of chemical risks before any operational decisions are to be made, especially if the ship is carrying a wide variety of chemicals (Marchand 2002). In the end, the impact of the accident is related to the chemical and physical properties of the chemicals in question. Hazards to human health in the case of oil spills are generally considered to be low; the more toxic and lighter fractions often evaporate before any response action is started. Secondly, an initial assessment of potential hazards should be undertaken in order to ensure a safe working environment. In some cases, doing nothing might be the best option, as long it happens under observation (Marchand 2002, Purnell 2009).

Several international, regional, and national authorities have published operational guides to describe possible response options in case of a chemical spill (e.g., HELCOM, IMO). Usually response techniques depend on the behavior of a chemical in the environment, and on whether it is released or still contained in packaged form. In practice, the response action varies substantially.

- Techniques that are applicable in case of oil accidents may be suitable for only some floating chemicals. Some floating chemicals can also create toxic and maybe explosive vapor clouds (e.g., diesel, xylene, and styrene). If this is to happen, the spark / static-free equipment should be used. Moreover, foams or sorbent materials can also be used near the spill source.
- In shallow water areas, neutralizers, activated carbon, oxidizing or reducing agents, complexing agents, and ion exchangers can be used.
- Any chemical, whose density is higher than that of seawater, may contaminate large areas of the seabed. Recovery methods that are used include mechanical, hydraulic, or pneumatic dredges. The recovery work is time-consuming and expensive, and results in large quantities of contaminated material. Other option is capping the contaminated sediment on location (Purnell 2009).

The time involved in response operations can vary from 2 to 3 months to even several years (Marchand 2002).

An accident during the winter in the presence of ice and snow changes the big picture somewhat, and creates problems for the response actions. Some fluid chemicals may be more viscous or even become solids in cold water, and thus, are easier to recover. Collecting techniques based on fluid-like masses, however, are no longer effective. The hazardous impact of some chemicals may multiply in the cold environment because the decomposition of the chemicals slows down. Thus, chemicals may drift to larger areas, and may also accumulate in animals, decreasing the probability for an animal to survive through the winter (Riihimäki et al. 2005). Generally, it is difficult for a recovery fleet to operate, if it is surrounded by ice and snow. If chemicals have spread under the ice, detecting the spill is more difficult, and the use of dispersing agents is ineffective.

Maritime risk governance: a regional approach

Päivi Haapasaari, Inari Helle, Riikka Venesjärvi and Annukka Lehikoinen
University of Helsinki, Fisheries and Environmental Management Group

Maritime safety in the GOF is regulated by prescriptive global rules that have been agreed in the framework of the IMO. These rules are usually revised after a major accident has occurred somewhere in the World Ocean. These generic rules are not anymore regarded adequate in the GOF. Well-known risks caused by the lately increased maritime traffic there have evoked calls for regionally-effective proactive approaches to safety policy formulation to complement the international regulations.

Haapasaari et al. (2015) proposed a regional risk governance framework that regards maritime safety as a holistic system, and manages it by combining a scientific risk assessment with a stakeholder input to identify risks and risk control options (Fig. 19). The framework would require:

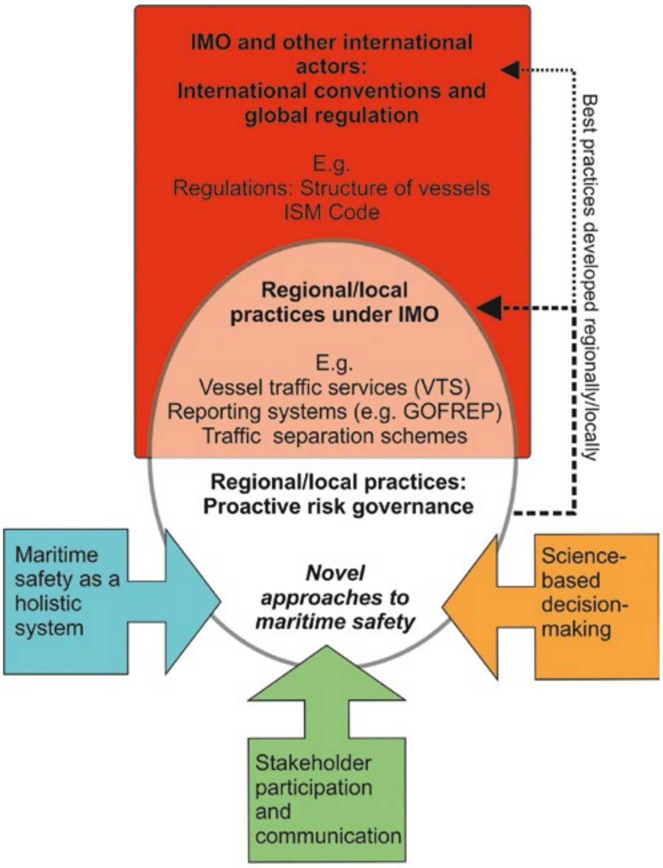


Figure 19. The proposed regional risk governance framework. In addition to IMO-regulated global (red) and regional (pink) regulative measures, there is a need for maritime safety measures that can be adopted locally/regionally (white). The best practices for developing a proactive risk governance framework include regarding maritime safety as a holistic system (adopted from nuclear risk management), having decision-making based on scientific advice (EU fisheries management), and involving the active role of different stakeholders in governing risks (the PWS case). Source: Haapasaari et al. (2015).

- A permanent stakeholder committee for contributing or even taking the responsibility for risk governance (this should be established)
- A scientific body for conducting risk assessments
- An up-to-date information source for regional risks
- The methods for assessing current and future risks, and for updating the assessment
- The agreed risk assessment criteria, the agreed acceptable and tolerable levels of risks, and the criteria for ranking alternative risk controlling measures
- A strong communication between organizations and stakeholders

Governing risks at the regional level can be advantageous because local actors have an interest in protecting their own sea areas and in investing in the management of the associated risks. Regional level risk governance focuses on real regionally relevant safety threats, and finds the most appropriate measures to manage them before disasters occur. Tailor-made safety measures can be more effective and cost-effective than the one-size-fits-all approach of the IMO regulations; the latter concentrate more on ship safety, and less on issues external to a ship.

SmartResponseWeb

Robert Aps¹⁾, Mihhail Fetissov¹⁾, Anette Jönsson²⁾, Martin Heinvee³⁾, Madli Kopti¹⁾,
Kristjan Tabri³⁾, Hannes Tõnisson⁴⁾
¹⁾ Estonian Marine Institute
²⁾ Swedish Meteorological and Hydrological Institute
³⁾ Tallinn University of Technology
⁴⁾ Institute of Ecology, Tallinn University

Advice on the sensitivity of the shoreline likely to be impacted by the oil is of critical importance in order to support decisions whether or not a response is necessary or what kind of a response is appropriate. Furthermore, choices made in clean-up strategies affect significantly the clean-up costs.

SmartResponseWeb serves for building situation awareness in the oil spill response operations. It is regarded as complementary to most of the national or regional accidental oil spill response systems, such as BORIS in Finland. Thus, it enables an on-line support to decision making in emergency situations.

It uses Seatrack Web oil drift forecasting system. Based on the amount and type of oil, duration of the oil spill, and the location of the accident, the tool allows making forecasts for areas to be potentially affected by oil. It enhances this potential by adding a dimension related to the properties and characteristics of the sea environment, and includes the following map layers (Aps et al. 2013):

1. Shoreline classification, ranked according to a scale relating to their sensitivity, their natural persistence of oil, and ease of clean-up
2. Biological resources that are sensitive to oil spills, include oil-sensitive flora, fauna, and habitats
3. Human-use resources, i.e., those areas with increased sensitivity and value because of their historic / cultural / recreational value, such as beaches, parks, and marine protected areas.

Conclusions

Shipping through the GOF waters forms a natural logistic bridge between the countries surrounding the BS. Maritime traffic in this small and sensitive sea area is intense with a significant share of tankers included. Annually close to 40 000 ships are passing the entrance to the GOF. Every day more than 20 tankers are sailing through this surveillance point, sailing eastbound for oil cargo or sailing westbound having the final destination somewhere beyond the Danish Straits.

The GOF area is unique and sensitive, where any pollution by oil or a chemical agent most likely has significant consequences endangering the nature. Thus, the current good level of preparedness needs to be maintained to ensure the rapid and effective countermeasures in the case of emergency. The expected growth of the maritime transport in the future and the noted growth of the vessel size, however, point out the need to develop and support additional actions to improve the maritime safety and security. Focus needs to be directed to the preventory means to avoid accidents. Joint exercises and training to improve the competence of both sailors and crew of the combating forces is one of the essential actions in this work.

In spite of the dense traffic and large volume of dangerous goods transported in the GOF, the number of accidents (groundings and collisions) has decreased. During the last decade, new risk control options have been taken into use, which may be one explanation for the observed trend. One of the most effective options has been the GOFREP service, the mandatory ship routeing and reporting service. Due to this service, authorities in Estonia, Finland, and Russia have joint procedures and reporting systems to formally follow the traffic and assist the merchant fleet effectively.

The two sides of the GOF traffic making their way out to the sea. The problem is how these two types of maritime traffic can be fitted to operate side-by-side within the relatively small GOF – also in the future. Photo: Jouko Langen (SYKE photo bank), Riku Lumiaro.

Should an accident occur, there is an array of response means to cope with it. For the search and rescue missions, the resources are good and competence of the responsible authorities is at high level. The preparedness for these operations is good, perhaps except against exceptional events, such as a collision of a cruise liner and an oil tanker.

The GOF oil combating preparedness follows well the main procedures of the HELCOM co-operation. In the GOF, Estonia and Finland as members of the EU have close cooperation with the European Maritime Safety Agency (EMSA). The HELCOM procedures in the oil response field, however, are still the most important local platform within the IMO regime in the GOF. Other important modes for co-operation are based on bilateral agreements among the countries.

Recommendations

In order to improve maritime safety in the GOF, a regional risk governance framework is suggested to be established. It would aim at identifying and assessing the risks, and developing tailor-made safety measures to prevent accidents from occurring. It would complement the international regulations that are agreed within the IMO, and would be based on effective communication and collaboration between relevant stakeholder groups. Thus, it has potential to enhance the positive safety culture in the shipping industry.

Oil spill risks should be reduced in a cost-efficient manner with preventive and proactive measures. As it is impossible to prevent accidents completely from happening, it is also vital to allocate available combating resources efficiently. It is also important to take ecosystem values comprehensively into account in oil combating and clean-up activities.

Since the safety of the maritime traffic relates to the safety of a socioecotechnical system, the risk models attepting to describe the system should be able to reflect this fact. Inclusion of methods evaluating human reliability and capability, as well as well-being at work of people at sea is required in order to provide a valid and reliable risk model that facilitates decision-making process aiming at improving safety at sea.

Many methods and applications for maritime transportation risk analysis have been presented in the literature. There is a recent focus on foundational issues in risk analysis, with calls for intensified research on fundamental concepts and principles underlying the scientific field. Few applications systematically account for uncertainty concerning the evidence base or in relation to the limitations of the risk model with respect of its possible outcomes. Therefore, we suggest to initiate scientific discussion on the foundations of risk analysis and its limitations in the field of maritime transportation, as well as to carry out research on the quantification of uncertainty, and on risk model validation procedures.

Maritime traffic models can support decision-making at several levels; they can be used for navigational safety assessment, emission modelling, and accident response planning. However, the existing traffic models are too simplified to address the above issues. Therefore, there is a need for further research in this field.

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SURROUNDED BY HUMANS – THE VALUE OF THE GULF OF FINLAND

Pressures on the Gulf of Finland

Harri Kuosa
Finnish Environment Institute

This section is based on the earlier chapters presented in this assessment, and integrates their messages. Here, I describe the main pressures on the Gulf of Finland's (GOF) ecosystem, and how these pressures affect the GOF's food webs.

Food web changes in the Gulf of Finland

The pelagic food web in the GOF has undergone major changes during the last century. However, with respect to the period of this report (1996–2013) minor changes and/or trends were to be detected. Compared to the natural food web structure the present food webs are highly affected by human activity (Table 1 and Fig. 1).

The GOF is vulnerable to eutrophication due to its hydrographic characteristics and high input of nutrients. The increase in the nutrient load has most often been cited and understood as a consequence of human activity. The input of nutrients has led to increased primary productivity, which at least partly is reflected as more intensive algal blooms in the spring and the summer, and increased settling of organic matter to the benthic system. A part of primary production is potentially enhancing the production of zooplankton and fuelling pelagic fish productivity, but this cascade is poorly known.

Eutrophication symptoms of the Baltic Sea (BS) include increased oxygen consumption in the deep water masses, which has a crucial effect on the GOF's benthic environment. Stratification, salinity, and oxygen environment have a complex role in zooplankton species composition with the role of large marine species changing accordingly.

Photo: Riku Lumiaro.

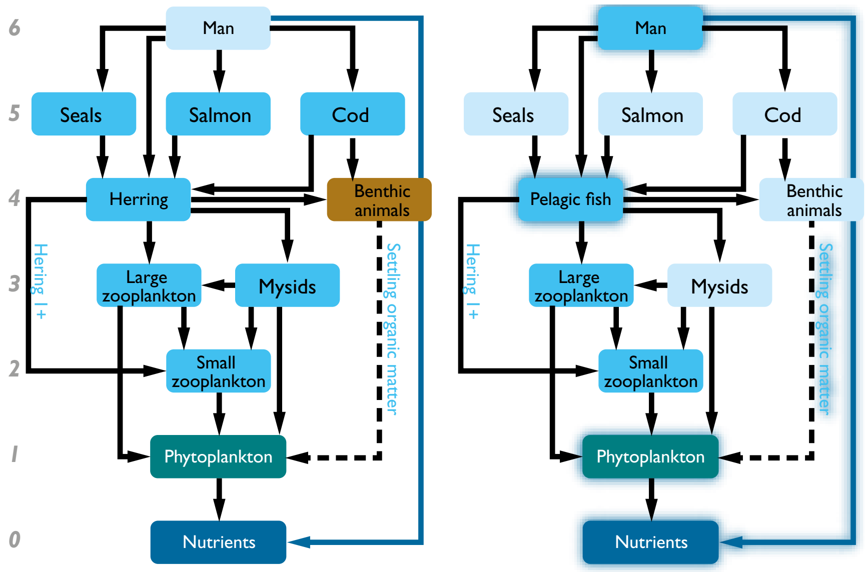

Figure 1. Simplified food webs of the GOF prior to (left) and subjected by (right) major anthropogenic influence. Numbers denote various food web levels. Light colours in the boxes represent a minor role in the food web, and shadowing a heavily increased role in the food web.

Fisheries have to a large degree compensated the weakened top-down control of pelagic fish by marine mammals and cod. This has been a long process starting about 4 000 years ago; humans hunted the BS harp seal population to extinction and continued by persecuting other seal species in the GOF during the last century. Fisheries caused the decline of Baltic porpoise populations as well.

At the time when fishery was not as effective as nowadays, the first species to benefit from food resources freed by the decline of marine mammals was cod. Strong populations migrated towards the Northern Gotland Basin in the 1950's and the late 1970's. However, the subsequent decline of cod gave room for man to take care of top-down control. This has led to obvious changes in the pelagic fish community structure as fisheries on clupeid species (Baltic herring and sprat) has not always been effective enough to control their population density. The role of salmonids (salmon and sea trout) was suppressed already in the 1940's and the 1950's by the man-made changes in the rivers suitable for breeding.

Pressures affecting the state of the Gulf of Finland

The pressures can be classified in many ways, all of those trying to summarize the complex route from activities (or drivers) to ecosystem effects. The classification of HELCOM is used here as the basis for summarizing the assessment. I will deliver a condensed view over the role of human actions to the GOF's ecosystem (Table 2).

Physical pressures

Factors: change of seabed substrate or morphology, disturbance or damage to seabed, extraction of seabed substrate, construction of infrastructure (ports, gas pipelines, landfills for urban development, etc.).

The GOF's ecosystem components range from virtually eternal – at least since the latest ice age – to rapidly changing ones. The rate of change in basic geological characteristics and

Table 1. Main features of the open GOF's food web components.

Level	Component	Change	Direct anthropogenic pressure	Specific remarks
5	Top predators	Marine mammals disappeared from the whole BS (20th century) Cod declined in the whole BS (1980's)	Input of hazardous substances Extraction of, or mortality / injury to, species Disturbance of species Input of litter (?) Input of anthropogenic underwater noise (?)	Also local populations of, e.g., seals Cod population depends on breeding success in the southern BS
4	Pelagic fish and benthic animals	Clupeids took a major role (1980's) Benthic animals declined due to oxygen deficit in the deep waters (1970's)	Disturbance or damage to seabed (to breeding / juvenile areas of fish) Input of hazardous substances Extraction of, or mortality / injury to, species Introduction and / or spread of non-indigenous species Input of litter (?)	Non-indigenous species (*Marenzelleria* spp.) overtake parts of the benthic system Non-indigenous fish species appearing
3	Large zooplankton and mysids	Marine zooplankton community followed changes in salinity regime	Introduction and / or spread of non-indigenous species Input of litter (?)	Non-indigenous species may affect competition Large interannual variability in monitoring data Mysid data not comprehensive
2	Small zooplankton	Trends not well understood	Introduction and / or spread of non-indigenous species Input of litter (?)	Data not comprehensive
1	Phytoplankton	Changes in biomass (1970's) Changes in species composition	Input of nutrients	Spring bloom starting earlier

Values of very different origin have been brought together to live side-by-side in the GOF. Photo: Riku Lumiaro.

geodiversity is low, and much of the change comes from natural hazards, such as coastal erosion and landslides. A specific case is coastal erosion caused by vessel waves, which has profound local effects on the coastal habitats. Sandy bottoms are considered an important habitat for biodiversity, but the magnitude of sand extraction and the threat it poses to biodiversity are currently poorly known. Furthermore, intensive bottom dredging may increase transport of organic material, which leads to accumulation of contaminated silts and modification of original bottom material. Simultaneously, elevated concentrations of harmful substances, such as heavy metals, are recorded in seabed sediments.

Hydrological pressures

Factors: changes in hydrological conditions, input of sound, input of other forms of energy

The GOF's hydrographical link to the Gotland Basin affects the GOF's physical environment. The hydrography of the whole BS is to a large part a combination of freshwater input, water exchange with the North Sea, and the weather. All of these are steered by the climate of the northern hemisphere, and thus, subject to the climate change. There were no notable trends in the hydrographical parameters in 1996 – 2014. However, ocean acidification has affected also the GOF mainly as a reduction in pH in the deep layer with the rate of about 0.016 units per year. The potential ecosystem effect of this change is unknown.

Anthropogenic underwater noise produced, e.g., by ships, affects marine life. Currently, the sensitivity of the GOF's ecosystem to anthropogenic noise is poorly known. A closer examination on the topic is needed.

Substance-related pressures

Factors: input of hazardous substances, input of nutrients, input of litter, input of known substances of unknown effect, (input of unknown substances).

Hazardous substances have been and still are a major concern in the GOF. They stem from a variety of activities ranging from waste water treatment to shipping. Dredging of contaminated sediments has a critical role for the GOF's ecosystem health as a number of hazardous substances already stored in the sediments are re-introduced into the food web.

When it comes to shipping there is always a potential threat of accidents. Their likelihood has been minimized by actions taken in maritime safety, and measures to minimize possible catastrophic environmental effects are continuously developed. However, a large-scale oil or chemical spill is still the biggest environmental threat for the GOF.

Marine litter is always man-made. Plastic items and their fragments are the most common litter types. Plastics are abundant and persistent in the environment. They can cause both physical and chemical hazard to animals from small zooplankton to marine mammals. In addition to other harmful effects marine litter also increases chemical pollution load into the marine environment. The impacts of marine litter on the GOF ecosystem – and in the BS in general – are still poorly known.

The main concern in the GOF has been the increased input of nutrients to the system, causing eutrophication. The symptoms of eutrophication – turbid water, algal blooms, increasing oxygen consumption in the seafloor – were recorded in local scales already in the early 20th century, but the heavily increased external load into the GOF in the 1960's and the 1970's introduced basin wide eutrophication. The external loads of both nitrogen and phosphorus have fortunately decreased by about 40 % since the late 1980's.

Admittedly to our surprise, the long-term development of the trophic state of the GOF has not followed the decreases in the land-based nutrient load in the late 1980's and the 1990's. This is partly due to the periodic penetration of oxygen-poor and nutrient-rich deep water into the GOF, and partly due to an accelerated benthic phosphorus release (i.e., internal loading). The development has led to intensified appearances of the nitrogen-fixing cyanobacteria. Positive signs with regard to trophic development are currently observable in the easternmost part of the GOF.

Even though being natural compounds, algal toxins are also considered as a category of hazardous substances. This ties the eutrophication trend and climate system together, as toxic algal species are connected to high nutrient and low mixing environment. Additionally, the spreading of non-indigenous species may promote blooms of new toxic algae.

Biological pressures

Factors: disturbance of species, extraction of or mortality / injury to species, introduction and / or spread of non-indigenous species.

In the GOF, the disturbance of species is considered to have an effect on top levels of the food web. Maritime activities, including leisure fishing and tourism, disturb seals and birds specifically during their breeding season. Ship routes also break ice during the winter affecting seal populations. Moreover, we are still largely ignorant about the role of man-made noise in animal disturbance.

Fisheries are by definition extracting important commercial or targeted leisure species. These are monitored, and a system of national quotas is used to prevent unsustainable use of fish resources. However, fisheries affect food webs especially by removing high level fish predators. The role of top level predators, such as seals and porpoise, has declined heavily in the GOF's ecosystem although some recovery has happened. The ecosystem effects of species extraction are not well understood.

The GOF is one of the highest risk areas for non-indigenous species introductions in the BS. Many species that have entered the GOF, have also been able to reproduce there. As their eradication is virtually impossible they currently belong to the GOF's ecosystem – permanently. The most important vector for species transport is maritime traffic, but also the opening of canals connecting northern Europe with the Black Sea, the Caspian Sea, and the White Sea has enabled new species to enter the GOF.

Table 2. Typology of uses and activities relevant to the marine environment by HELCOM. The pressures considering the GOF are indicated when applicable. The chapters of this assessment handling the subject at hand are also given. The last theme is an addition to the original division. *Denotes a new class used in this summary. Modified from the EU MSFD Annex III, Table 2, by the HELCOM HOLAS II project.

Theme	Activity	Sub-activity	Chapter	Pressure
Physical restructuring of seabed / coastline morphology (including construction phase)	Land reclamation (permanent changes)			
	Canalisation and other watercourse modifications	Dam building Culverting, trenching Causeways		
	Coastal defense and flood protection	Sea walls Breakwaters Groynes		
	Restructuring of seabed morphology	Dredging (for navigation purposes)	Geology and geodiversity Fishes and fisheries	Disturbance or damage to seabed Input of nutrients Input of hazardous substances
		Beach replenishment, nourishment Artificial reefs		
Man-made structures (including construction phase)	Urban development	Waste water discharges, runoff, waste disposal	Eutrophication Marine litter	Input of nutrients Input of litter
	Industrial development	Waste water discharges, waste disposal	Eutrophication	Input of nutrients
	Transport infrastructure	Bridges, tunnels, causeways	Non-indigenous species in the GOF	Introduction and / or spread of non-indigenous species
	Tourism / leisure infrastructure	Land-based structures		
		Sea-based structures (piers, harbors, marinas, slipways, beaches)	Hazardous substances Geology and geodiversity	Input of hazardous substances Disturbance or damage to seabed
	Ports and other coastal constructions		Geology and geodiversity	Disturbance or damage to seabed
	Offshore marine infrastructure (including mineral and energy extraction)		Geology and geodiversity	Disturbance or damage to seabed
	Cables, pipelines			
Extraction of mineral resources	Extraction of oil and gas	Oil and gas industry infrastructure		
	Extraction of rock and minerals	Extraction of sand and gravel	Geology and geodiversity	Extraction of seabed substrate

Theme	Activity	Sub-activity	Chapter	Pressure
Production of energy	Renewable energy generation (wind, wave, tidal power)	Wind energy production Tidal energy production Wave energy production		
	Non-renewable energy generation	Fossil fuel energy production		
	Transmission of electricity and communication	Cables, pipelines		
Extraction of living resources	Fish and shellfish harvesting (professional, recreational)	Numerous subactivities	Fishes and fisheries	Disturbance of species Extraction of, or mortality / injury to species, including target and non-targeted catches
	Marine plant harvesting	Machine collection (fucoids, kelp) Dredging (maerl) Hand collecting (seaweed)		
	Hunting and collecting (for non-food purposes)	Hunting Harvesting / collecting eggs Collecting (curios) Bait digging		
Cultivation of living resources	Aquaculture	Fin-fish mariculture Seaweed culture Shellfish mariculture		
	Agriculture		Eutrophication Hazardous substances	Input of nutrients Input of hazardous substances
	Forestry			
Tourism and leisure	Infrastructure	Marinas and leisure harbors		
	Activities	Boating, yachting, beach use	Maritime traffic and its safety	Disturbance of species
Transport	Infrastructure	Fishing harbors Industrial and ferry ports Bridges, causeways		

Theme	Activity	Sub-activity	Chapter	Pressure
	Transport – shipping	Passage of ships / boats	Maritime traffic and its safety Underwater soundscape Hazardous substances Fishes and fisheries Non-indigenous species in the GOF	Input of nutrients Disturbance or damage to seabed Input of sound Input of hazardous substances Disturbance of species Introduction and / or spread of non-indigenous species
Urban and industrial uses	Industrial uses	Oil and gas refineries Industrial plants		
	Urban uses	Urban land use		
	Waste treatment and disposal	Urban waste water treatment Industrial waste water treatment, including food industry	Hazardous substances Marine Litter	Input of hazardous substances Input of litter
Security / defence	Military operations	Military infrastructure Waste disposal (munitions)		
Catchment effects	River load	Industry Urban activities	Hazardous substances	Input of hazardous substances
	Construction	Energy production	Fishes and fisheries	Changing living conditions of biota*
Regional effects	Atmospheric input		Eutrophication	Input of nutrients
Global effects	Climate change	Climatology (temperature, precipitation)	Fishes and fisheries Biodiversity	Changing living conditions of biota*
		Local weather (storms)	Geology and geodiversity	Changing living conditions of biota*
		Acidification	Gulf of Finland physics	Changing living conditions of biota*

Towards the sustainable use of ecosystem services

Soile Oinonen, Eija Rantajärvi, Harri Kuosa
Finnish Environment Institute

The GOF has for centuries provided resources for local livelihoods, and water transport routes for trade. Agriculture and growing coastal population – today about 13 million people living in the GOF's catchment area – together with advancing technology have increased pressures on the GOF's ecosystems. The GOF is currently the most eutrophic part of the BS, and the past deterioration in its water quality has consequences, e.g., recurrent algal blooms. The recent use of the GOF has introduced new pressures, such as dredging and construction of marine infrastructures (e.g., gas pipelines and seabed cables). Furthermore, tanker traffic and other maritime transport increase the risk of oil spills.

The GOF has been actively used for recreation purposes, and thus, the public has become aware and concerned about the water quality and the environmental state of the GOF. Impacts from human activities on the GOF are controlled by the national legislation of three coastal countries, international conventions, EU directives, and HELCOM BSAP. However, there is a growing need for environmental economic analyses for policy support.

The EU MSFD, for example, aims at achieving a good environmental status of the European marine areas with the least costs to the society, and calls for wider consideration of social and economic issues in marine management actions. Expected future economic benefits from the improved ecosystem state should be higher than the costs of measures to improve the ecosystem state (Oinonen et al. 2016a, 2016b). On the other hand, marine and maritime sectors, such as aquaculture, coastal tourism, seabed mining, and marine

How important is the GOF for us? Photo: Eija Rantajärvi.

biotechnology, are expected to yield significant economic growth and new jobs. Increasing aquaculture is only possible if a good environmental state is reached. This goal benefits the recreational use of the coastal areas, too. However, large-scale activities, such as sea bed mining, must be carefully planned so as not to permanently degrade the marine ecosystem, which is the basis of the ecosystem services the GOF provides for people in the coastal countries and for those visiting the area.

The trilateral environmental collaboration of the GOF has not yet resulted in any environmental economic analyses, but the GOF2014 dataset provides paramount information for these future analyses. In this chapter, we use the concept of ecosystem services to illustrate how the existing natural scientific information and economic information could be integrated to advise ecologically and economically sound marine management.

Visualizing and valuating ecosystem services

The concept of ecosystem services emphasizes an interaction between human well-being and the nature. The nature and its resources are assets to be maintained to ensure an ongoing flow of services. Human activities are viewed through the fact that they may cause ecosystem deterioration. Resource management policies stabilize the current situation or contribute to resource improvement. The nature (the service supplier) and society (the service user) have an interaction between each other (Fig. 2).

Ecosystems provide supporting and regulating services, such as nutrient cycling and climate regulation. The contribution of these services to human well-being is not

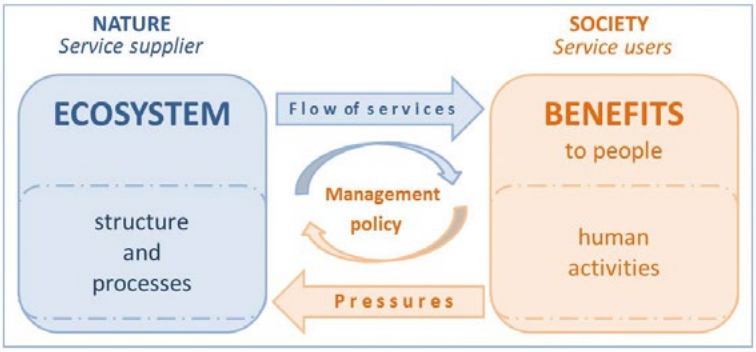

Fig. 2. The concept of ecosystem service dynamics.

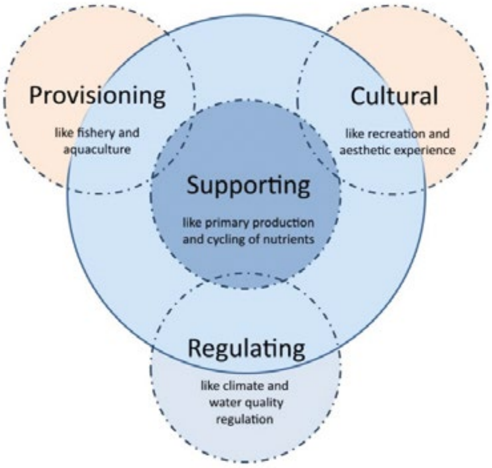

Fig. 3. The MEA ecosystem service classification. Source: Millennium Ecosystem Assessment 2005.

straightforward. Provisioning and cultural services, such as fisheries and recreation, provide more immediate benefits to human (MEA 2005, Fig. 3).

Identification and classification of ecosystem services do not necessarily emphasize their importance enough to be considered in policy making. Environmental economic analyses can be used to estimate an economic value for these services. Giving a price tag for those services that are not automatically recognized as important components contributing to human well-being – such as aesthetic experiences or recreation – might help the society to recognize even better that the ecosystem is a provider of a wide array of services.

Valuation process

Visualization and valuation of the ecosystem services starts with classification and identification of the services. An example of a provisioning service is commercial harvesting of fish for food, and an example of cultural services is healthy marine environment for recreational use. An interdisciplinary research is needed to estimate the economic value of the services. Bioeconomic theory combines fisheries population dynamic modelling to economic modelling. Environmental valuation uses ecological knowledge in describing the link between quality of the ecosystem and the quality of the services it provides. Finally, an indicator for the economic value of the service can be calculated. Indicator could be for example maximum economic yield, that is, the sustainable harvest that generates the highest value of the fishery or the amount of an environmental tax people would be willing to pay for an improved state of the sea (Fig. 4).

There is currently no exact knowledge on the ecosystem services that the GOF provides, but the current assessment begins filling the data gaps for the identification of the GOF's ecosystem services.

Fishery and recreation as ecosystem services

How the values of ecosystem services could be estimated and made visible so that they could be used to address environmental-economic tradeoffs of different policy measures? To illustrate this, we have a pair of ecosystem services as an example; one from provisioning and one with a cultural focus (Fig. 4).

The four commercially harvested offshore species of the GOF are herring, sprat, cod, and salmon. These fisheries provide food and fodder, and thus belong to the category of provisioning services. From the provisioning service perspective fish catch valuation could be conducted following the bioeconomic theory of fisheries management. However, such studies were not within the scope of research included in the GOF2014 project. Examples from the BS show that the value of the provisioning

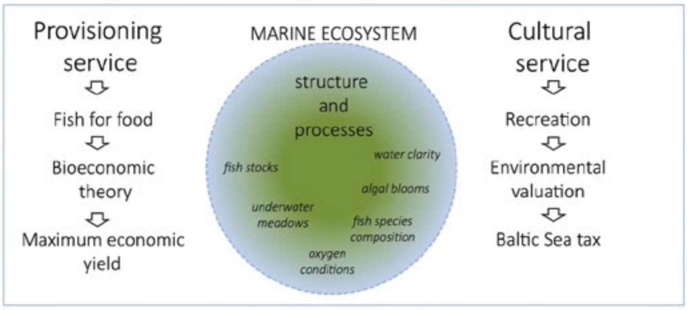

Fig. 4. Visualizing and valuating marine ecosystem services.

service could be increased if fishing mortality was diminished (Nieminen et al. 2012). At present, the management of these four stocks is based on the total allowable catch that is set for each species separately. Ecologically and economically sound management and valuation calls, however, for more holistic view and a combination of ecosystem models with economic models (Blenckner et al. 2011).

Many fish species provide significant cultural recreational services for anglers. Valuation of the services becomes, however, more complex since indicator calculation should consider optimal use of the resource to deliver both provisioning service (fishery) and cultural service (recreational angling, Kulmala et al. 2008). Furthermore, the GOF is a shared marine area, and in this context the identification and valuation of ecosystem services need to be done in the international context (Oinonen et al. 2016c).

A healthy marine ecosystem provides plenty of less tangible services than fish for food. Some services, such as good quality water for swimming and other recreational purposes, is an outcome of complicated ecosystem processes. An attempt to assign a value of these intermediate services, falling into categories of regulating and supporting services, is a challenge. However, the final services that cannot be bought from shops online or ground floor, but of which consumers still enjoy, can be valued using different environmental valuation techniques. Water quality is one of those services.

Ahtiainen et al. (2014) surveyed citizens from riparian countries of the BS and found that people would be willing to decrease their spending to other goods and services to reduce nutrient loads and improve the state of the BS. The nutrient reductions according to HELCOM BSAP would yield positive changes in water clarity, cyanobacterial blooms, fish species composition, oxygen conditions in the sea bottom, and underwater meadows. These changes in the ecosystem cascade to positive changes in the final ecosystem services. People would be willing to pay an annual BS tax to be able to enjoy the improvement in the ecosystem service flow. In the GOF, the value of the change in recreational and non-use services arising from the nutrient reductions would be 483 million € annually (Ahtiainen et al. 2014, Hyytiäinen et al. 2014).

The way forward

The GOF is a precious common property resource, and its sustainable management calls for transboundary and interdisciplinary research and collaboration. Increasing demand of maritime traffic and tourism, for example, calls for clear concepts capable of showing the interdependencies between the GOF and the economic sectors using it.

Conversion of the GOF2014 dataset and the present assessment into the format of ecosystem accounts and ecosystem services account would give us tools for directing the sustainable use of the GOF's resources. Ongoing collection on ecological data and interdisciplinary cultivation of these results can make both ecosystem services and their value more visible, and help to integrate them to decision making processes. To achieve this, the following steps are necessary:

- Identify the GOF's ecosystem services based on data produced during the GOF2014 project
- Develop physical ecosystem accounts by utilizing results from the GOF2014 project
- Develop sustainability indicators for the use of ecosystem services
- Develop economic indicators for ecosystem services
- Develop monetary ecosystem service accounts

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Epilogue

The recent development in the environmental condition of the Gulf of Finland (GOF) can in a nutshell be divided into two directions: one that is deteriorating and another that is improving. Descriptors that we use for defining the environmental state of the GOF serve as good examples of this:

- With respect to eutrophication, the GOF seems to have entered the improving phase or is just about to do so, depending on what sub-region we are talking about. The eastern GOF is undoubtedly improving due to the weakened impact of municipal and industrial discharges, while the western part suffers from the poor conditions of the Gotland Basin. In the end, it all comes down to the state of the Gotland Basin and its future development, and there is little we can do about it. It is topical to ask whether we have had unrealistic expectations for the positive development in the GOF with regard to eutrophication? Such expectations, if ever existed, would stem from an incomplete understanding of the elements affecting the GOF's nutrient dynamics. The information has been there, only scattered, and became finally fused together during the GOF2014 project. With regard to eutrophication, the value of this assessment lies in the fact that it does not content with assessing the trophic state but also explains the theoretical background behind it. From now on, with our "new" understanding we can start addressing the trophic changes of the GOF in a more reliable manner.
- With respect to hazardous substances, there are emerging concerns while old worries are literally being buried away into the sediments. It remains to be seen whether the chemical burden manifested by the new priority substances will pose a less severe, an equally severe, or even a more severe threat to the environment than the so-called classic environmental toxins.
- With respect to marine litter, the state of the GOF will most likely worsen in the future. Not because the future society will litter the environment more than what we do. Rather, now that we have started to study and monitor marine litter, magnitude of the problem will emerge to us in its full entirety. Looking at things from a positive viewpoint, for emerging issues, such as marine litter (or pharmaceuticals as well), people's everyday life is one prominent source, which may be managed through effective awareness raising. Also decision makers may feel that they have contributed this problem, so why not help to address it.

This assessment has its basis on the long-term environmental monitoring programmes. The debate of the actual value of so-called conventional (read: expensive) ship-based monitoring is a recurrent feature, and lately boosted by the novel technical (SOOP, EO, buoys, gliders) and mathematical (modelling) solutions that help us understand what is really going on below the surface. These approaches have already proven their worth, but their performance in terms of accuracy is dependent on the data collected in a conventional way. So, we face a paradox; the more we will rely on novel monitoring approaches in order to save costly ship days, the more we will need ship days to validate the collected data. There is no going around this equation; we need research vessels more than ever. The role of these new approaches, as we see it, is to supplement the conventional monitoring – i.e., to produce more data per € invested – rather than to replace it – i.e., save the amount of € invested. These approaches provide us with high resolution and/or large coverage data, and are highly valuable as such. We are not sure if this tendency was the one we were originally aiming at, though. Now that we are collecting more data than ever, where do we find enough manpower to manage the huge dataflow to get the best out of it? Presenting the data as cool figures in the website in near real-time may fulfill the definition of operational monitoring, only is just not enough.

What about the future then? HELCOM BSAP, EU MSFD's Programmes of Measures, IMO's NECA designation, to name a few, represent necessary steps towards improving the state of the GOF. These agreements / conventions are reflections of the people's ever-growing environmental consciousness, and thus it is difficult to imagine that the future state of the GOF could be any worse than it is today. And this is not to say that things could not possibly continue to deteriorate. Should this still happen, it would mean serious societal problems.

Logically thinking, things have to get better. A groundbreaking question is if this is just a case of wishful thinking because the nature under anthropogenic pressure does not necessarily behave logically. Having said this, we refer that there are rarely definite victories in the environmental front. Examples follow.

- Now that we have been able to reduce the land-based nutrient load into the GOF, we find that the nature does not respond to these reductions as directly as we once thought; we need to be patient.

- Knowing that we have been able to reduce the load of traditional polluting substances into the GOF, we find that there are chemical newcomers whose impact requires our attention; we must not be discouraged.

- Now that we have been successful in keeping the risks related to maritime traffic in the GOF in a reasonable level regardless of an increased traffic volume, we find that traffic is predicted to increase even more in the future; we have to take another step forward.

- The climate change is something that cannot be called off or postponed, and for today's world even reacting to it will take an awful lot of time. So, no victories in sight, only acceptance and adaptation.

Clearly, our work is not done; we face new and largely unknown environmental challenges, and the GOF system is continuously changing. On this basis it is next to impossible to predict the future state of the GOF at any time, and it is highly likely that new environmental crises in the GOF area will emerge. Of course, it is not the task of this assessment to make predictions; this is a state assessment in retrospect, not in prospect. But admittedly, interesting times lie ahead of us.

The GOF is not just one big pool of water. It has got many faces, and it can be experienced in many ways. Its environmental condition can also be experienced in many ways depending on where you live around it. This is good to remember.

The editors

This assessment on the environmental state of the Gulf of Finland in 1996–2014 was produced by together over 100 scientists from Estonia, Finland, and Russia in the context of the Gulf of Finland Year 2014.

The thematic year aimed at – and succeeded in – giving additional value for the protection and restoration of the Gulf of Finland environment by enhancing political presence and interaction between the private sector, decision-makers, and citizens.

This assessment concentrates on the past development and the current state of the Gulf of Finland environment and pressures affecting it. The themes include climate in the Gulf of Finland area, Gulf of Finland physics, geology and geodiversity, eutrophication, hazardous substances, biodiversity, fishes and fisheries, non-indigenous species, marine litter, underwater soundscape, maritime traffic and its safety, and environmental valuation. Each chapter also delivers expert opinions and recommendations for the future.

THE GULF OF FINLAND ASSESSMENT

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