# SEVIRA Status assessment report- Coastal monitoring

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## Contents

# Coastal monitoring and assessment

Main purpose of the coastal monitoring work in the SEVIRA project was to create up to date information on the quality and ecological status of coastal waters within the study area, i.e. the North-Eastern parts of the Gulf of Finland (GOF). One of the key themes was to increase co-operation and exchange knowledge between Finland and Russia, and the monitoring and assessment part followed this line. In particular, the partners planned and arranged jointly specific field campaigns in the Bay of Vyborg during the project lifetime. In addition, the project made use of Finnish national monitoring in the easternmost part of Finnish coastal waters. During the project lifetime, from 2019 to 2021, the project carried out sampling campaigns in the coastal sea areas on the Finnish and Russian sides. The monitoring material from the field campaigns, arranged both in the Bay of Vyborg and in the Finnish coastal waters close to the border, in particular the Virojoki Bay, was used to assess the current state of these coastal water areas. In addition to this the assessment workpackage in SEVIRA  analysed long-term monitoring results in the coastal waters of the Eastern GOF. For this, the project took advantage of measurements made on both sides of the border since 1996. In addition to station sampling, the project utilised also satellite observations and an archive of automated on-line measurements collected by a ferrybox-system, Alg@line. Satellite observations were used to generate annual maps of chl-a level for the state assessment of these coastal waters. In addition, the project set up a chain of virtual monitoring station sites that will continue to provide satellite observations within the study area after the SEVIRA project. The long-term status assessment shows that water quality and condition in the coastal area of the eastern GOF have improved over the last decade. There is a long-term positive trend in the quality of the coastal water areas of Bay of Vyborg and shallow, partially enclosed Bay of Virolahti. The same applies to the adjacent inner and outer archipelago regions in the easternmost part of Finnish coastal wates. These positive trends show in all analysed water quality parameters, each of which act as an indicator of eutrophication.

# 1 Joint monitoring in Russian and Finnish coastal waters

During the project lifetime, the partners carried out sampling and measurement campaigns in the sea areas on the Finnish and Russian sides. The monitoring material from the field campaigns, arranged both in the Bay of Vyborg and in the easternmost parts of the coastal waters of Finland (focus in the Virolahti Bay), were used to assess the current state of these areas. For the Bay of Vyborg, the planning of the monitoring was a joint effort and co-operation between the partners (Fig.1). On the Russian side, the key partner in organizing the water quality monitoring was the Northwest Administration for Hydrometeorology and Environmental Monitoring (North-West AHEM) and on the Finnish side, the ELY Center for South-East Finland. SYKE was responsible for the production and analysis of the satellite observations of water quality. The sampling cruises were carried out and organized by the Russian partner. Water quality data on the Finnish side was obtained through a monitoring program commissioned by the ELY Centre (Monitoring Program for National Water Management Planning). Minor additions to this were made based on the requirements by the SEVIRA project.

## 1.1. Coastal station sampling

The purpose of the monitoring actions was to draw a coherent overview of the water quality in the coastal area under study. For this purpose, the sampling periods for the specific field campaigns arranged were agreed for the same weeks both in the Bay of Vyborg and in the easternmost parts in Finland. The station sampling was complemented with satellite observations from the same area and concurrent periods.

The coastal study area covered the easternmost GOF. Special attention was put on these areas (Fig. 2):

- The Vyborg Bay (the inner bay area in front of the city of Vyborg over to the mouth of the bay) in the Russian side.
- The coastal waters of the municipality of Virolahti and nearby the city of Hamina (including an inner archipelago area Tammio, which is isolated due to islands and bottom thresholds).
- The eutrophicated Virolahti Bay on the Finnish side close to the border.
- The easternmost outer archipelago area in Finland (areas from the Huovari region at the border zone to the "offshore" Haapasaari islands in the city of Kotka).

In the Bay of Vyborg, specific attention was put on the river Rakkolanjoki estuary and on the river water route towards the open sea areas in the eastern GOF. The stations (Fig. 2) were mostly chosen based on earlier sampling sites (see chapter 4.1.1.1) and thus enable the analysis of the changes in eutrophication within the bay starting as early as 1996.

On the Finnish side of the coastal study area, the project utilized altogether seven monitoring stations out of a larger set of stations belonging to the national water quality monitoring programme. These stations belong to the ELY Centre's monitoring program and partly to the environmental permit monitoring program for the fish farms at the Virolahti bay (Fig. 2). Like the stations in the Bay of Vyborg, the selected ones provide long-term information on the water quality and can thus be used to analyze the changes in the eutrophication.

*Figure 1. Water sampling at a coastal monitoring in the Vyborg Bay by North-West AHEM during the project.Photo provided by Liubov Fomina.*

During the SEVIRA project, three annual joint sampling periods were arranged during mid-August. During these periods, a sampling cruise was arranged both in the Bay of Vyborg and at the sampling stations in the Finnish coastal region (19.−23.8.2019, 10.−14.8.2020 and 9.−13.8.2021). The water quality sampling focused on surface water and near-bottom water samples. Same water quality parameters and sampling depths were applied in both countries (Table 1). Samples taken from the Bay of Vyborg were analyzed at North-West AHEM's laboratory in St. Petersburg and Finnish coastal samples according to the national monitoring program (at Eurofins Environment Testing Finland Oy's laboratory). The monitoring efforts focused on determining the changes in eutrophication; therefore, the most relevant parameters were nutrients (e.g. total phosphorus and nitrogen, full list in Table 1) and chlorophyll-a (chl-a). Chl-a is a green pigment used by phytoplankton and algae in photosynthesis. Its concentration reflects the abundance of phytoplankton present in the water. In Finnish monitoring programs, the total amount of phytoplankton in water is measured by analyzing the chl-a content of a water sample. Chl-a is used widely as a water quality classification parameter, like in the EU's Water Framework Directive (Ferreira et al., 2007) and in the surface water trophic state determination in Russia (Vincent, 1960). Where possible, measurable parameters were supplemented with analyzes for satellite data interpretation, such as Secchi depth and the absorption of Colored dissolved organic matter (CDOM, laboratory analyzes on the Finnish side, Table 1).

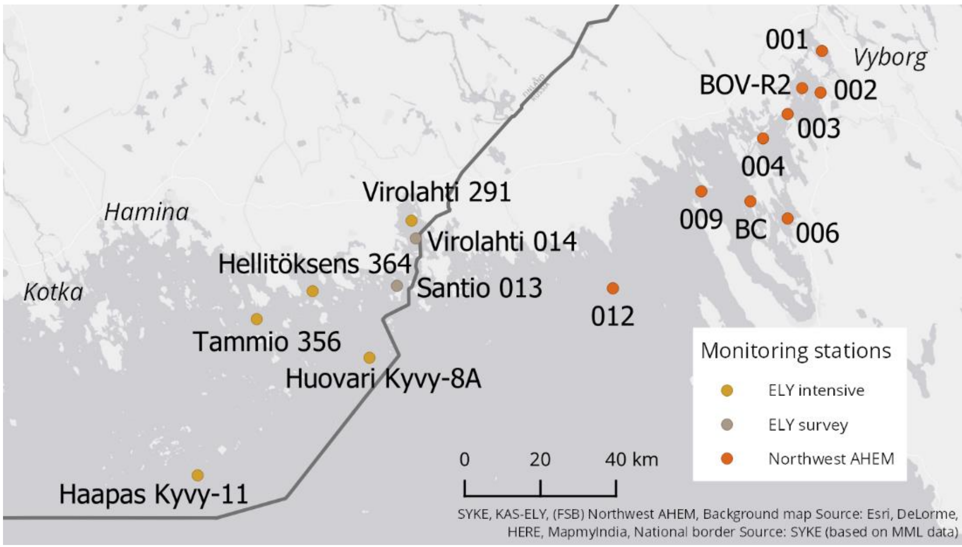



*Figure 2. SEVIRA-monitoring stations in near-border coastal region conducted in the framework of ELY's monitoring program and in the Vyborg Bay (orange dots) sampled by North-West AHEM during 2019-2021. Annual water sampling intensity in Finnish monitoring stations: survey stations (grey dots) and intensively measured stations (5 - 18 samples/year, yellow dots).*

**Table 1. Sampling depths and analysed water quality parameters from SEVIRA sampling stations in the Bay of Vyborg (by North-West AHEM) and in the coast of Finland (by ELY) in 2019–2021. Sampling: surface (1 m) and near bottom (b-1m). $a_{CDOM}$ = Absorption coefficient of CDOM.**

| Bay of Vyborg and Coast of Finland | For combined EO/satellite monitoring purposes |
|---:|---:|
| total phosphorus (µg/l) * | Secchi depth (m) |
| phosphates (on phosphorus) (µg/l) | turbidity (FNU) |
| total nitrogen (µg/l) * | total organic carbon (mg/l) |
| nitrite + nitrate nitrogen (µg/l) | $a_{CDOM}$ at 400 nm (1/m) |
| ammonium nitrogen (µg/l) | $a_{CDOM}$ at 750 nm (1/m) |
| chl-a (µg/l) ** | Surface temperature |
| water temperature (°C) | |
| pH | |
| conductivity (mS/m) | |
| salinity (‰) | |

* both filtered and non-filtered in the Bay of Vyborg
** 0−2 m in both, and Secchi depth dependent in coast of Finland

## 1.1. Available historical datasets for the analysis of long-term changes

As a background material, SEVIRA partners took advantage of the monitoring results collected during the Vyborg Bay Joint Monitoring project (1996–2006) with complementing results from North-West AHEMs monitoring (1996–2014). The Vyborg Bay Joint Monitoring was a historical co-operation project between the Russian and Finnish organisations, that regularly sampled 2–4 times a year covering winter, early summer, late summer and autumn periods in the Vyborg Bay area. For all abovementioned years, the monitoring results were available for the period of late summer, the most relevant period to the status assessment of eutrophication. In the Vyborg Bay Joint Monitoring project, water quality samples were transported to Finland for analysis and archived in water quality register maintained by SYKE (VESLA database, available in open data OIVA portal).

Alg@line is a monitoring network that collects information on the state of the Baltic Sea using continuous measuring devices on passenger and merchant ships. The network is coordinated by SYKE. In the period 2004–2012, the City of Helsinki Environment Center and the Southeast Finland ELY-Center) participated in the implementation of Alg@line project's coastal route section in the Eastern GOF. The ship routed between cities of Helsinki and Kotka and Hamina and at times all the way to Lappeenranta-Savonlinna through Saimaa channel. The Alg@line sampling system includes a flow-through chl-a fluorometer installed in the passenger ship. The system onboard contains an automated bottle sampler. These water samples, later analyzed in a laboratory, were utilized for the quality assurance and transformation of the fluorometer values to chl-a concentrations (e.g., Rantajärvi et al., 1998). Within the SEVIRA project, the Alg@line data was used as additional water quality data for the sampling stations that coincided with the ship route. On the Vyborg Bay, the observations were available for the stations describing the main part of the river influence towards the outer parts of the coastal waters (stations 004, 009 and 012, Fig. 2). On the Finnish side, the Alg@line data was available for two of the stations (Santio 013 and Tammio 356). Annual mean concentrations of chl-a summer period (July−August) were calculated from the Alg@line data and used in conjunction with station sampling results. Although there are some differences in the Alg@line flow-through observations in contrast to station sampling (e.g. obtained while the ship is on move in cruise speed), the data complements well the status assessment over the years without station sampling results available.

## 1.2. Satellite observations i.e. Earth Observations (EO)

In addition to the coastal station sampling, the SEVIRA project utilized satellites providing observations from the Eastern GOF. The great benefit of satellite observations is that during cloudless periods, the observations are available on both sides of the country border at the same time. The frequency of satellite overpass was several times per week. Satellite observations can be utilized for the days and areas that have been cloudless during the satellite overflight. We utilized mainly satellite observations provided by the European Union's flagship satellite series, the Copernicus program. This space program produces a wide range of observations suitable for environmental monitoring in various aspects. Along with Copernicus program satellites, also NASA Landsat-series satellite instrument observations were utilized in the project.

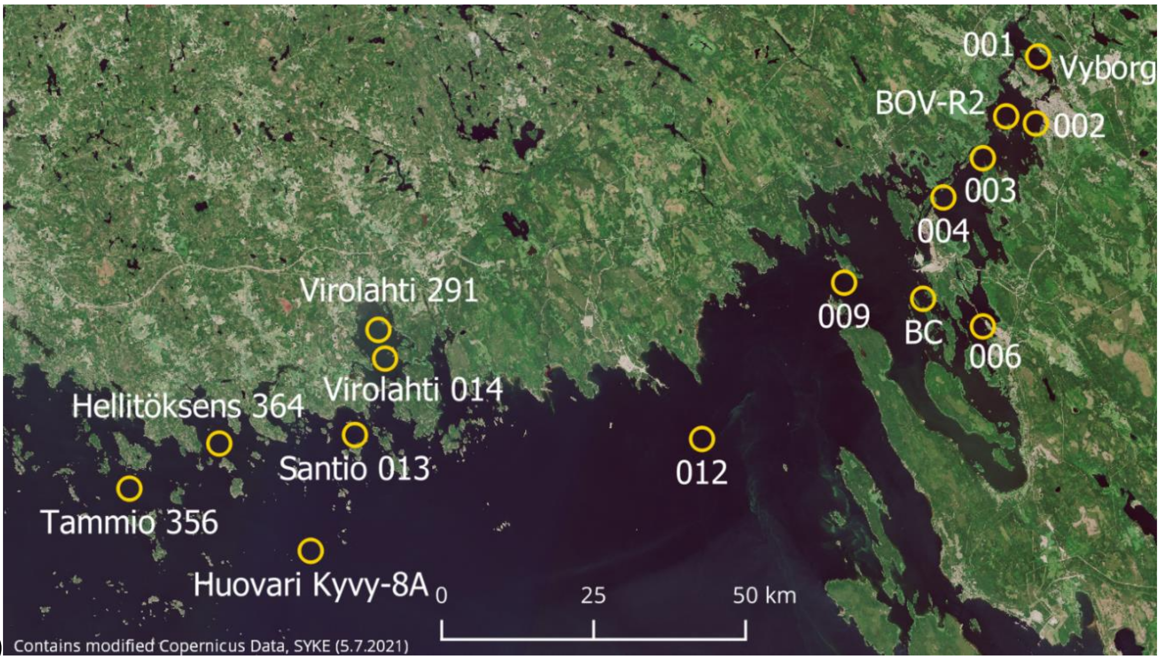
The use of satellite observations focused on determining chl-a that describes the algal abundance. The other water quality parameters that have been analyzed from satellite observations, or EO datasets, are turbidity, absorption of colored dissolved organic matter ($a_{CDOM}$) and temperature.

Satellite observations can be utilised to follow and identify interesting phenomenas on daily basis. For example, if there is an evident cyanobacteria bloom occurring in the Eastern GOF or turbidity incoming via rivers to the coastal estuary, a daily chl-a or turbidity map reveals the areal extent of the phenomenon. On the other hand, a summary, or aggregation, of the observations accounting all noncloudy satellite observations during summerly period can be calculated. These combinations of summerly observations can be used to assess the state of coastal waters and to compare with e.g., previous years or other types of monitoring methods.

Sentinel satellite series provide two types of optical instruments that are practical for monitoring water quality. Currently, OLCI (Ocean and Land Colour Instrument) instruments onboard the first two of Sentinel-3 satellites observe daily with a 300m ground observational resolution. Likewise, Sentinel-2 satellite series MSI (Multispectral Instrument) instruments are installed onboard two consecutive satellites. Their overpasses are synchronized so that typically one to three weekly observations are received from a certain area, like eastern GOF. Among the NASAs Landsat series, the project made use of both instruments OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor).

The processing of satellite observations at SYKE is highly automated. The satellite observation data handling is a stepwise process, where image pixels at various wavelengths are analyzed mainly by models. Valid observations (non-cloudy water areas) are analyzed with a bio-optical model that estimate e.g. the concentration of chl-a or the value of turbidity for each image pixel (Attila et al. 2013, Attila et al. 2018). Also, areas covered by land, islands or shallow water are excluded. The final phase of the processing, quality assurance done by an expert, ensures that uncertainty caused by coarse errors passing the automated processing chain are excluded. The uncertainty in the observations is caused mainly by occasional overestimations due to partial clouds or ice cover in coastal waters during the wintertime and spring. Other sources of uncertainty in the observations are due to occasional underestimations by cloud shadows of nearby clouds.

Main part of satellite observations was shared through SYKEs open TARKKA-service (syke.fi/TARKKA/en). During the SEVIRA project, a total of nine new ‘virtual’ satellite monitoring stations were implemented in TARKKA service to represent relevant sites in the Bay of Vyborg (Fig. 3A). The satellite observations are collected from the areas surrounding monitoring station sites. Islands and shallow areas are excluded from these station areas in the Bay of Vyborg (Fig. 3B−E) and at the Virolahti Bay (Fig. 3F−I).

A) 

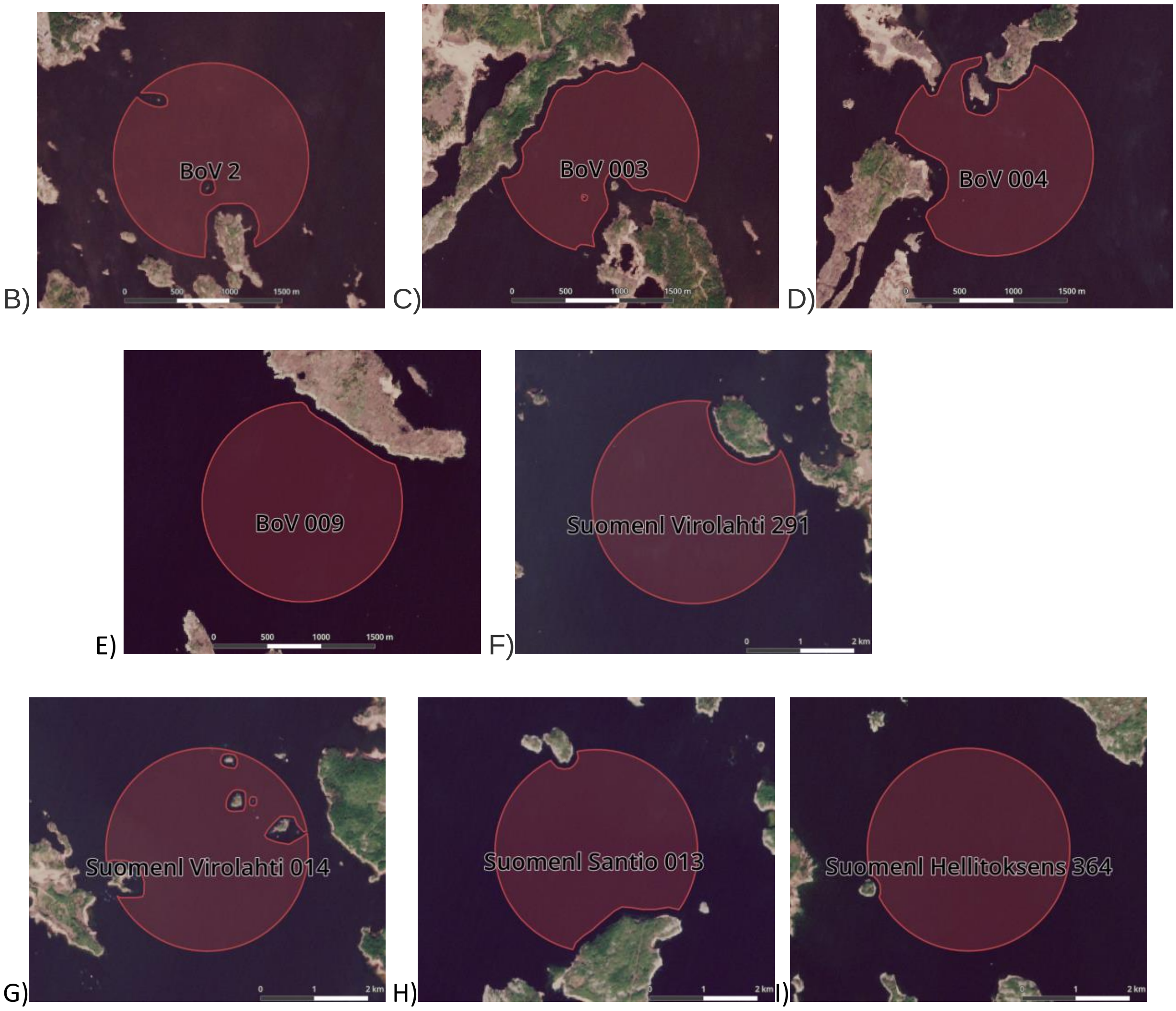



*Figure 3. A) Satellite monitoring stations were added/updated to the TARKKA (syke.fi/TARKKA/en) interface in 2021. Observations of these virtual station sites (yellow circles in the map) continue to be used to monitor fluctuations in surface water temperature, algae, and turbidity also in the future. B−E) examples of extraction areas around station sites in the Bay of Vyborg. F−I) examples of extraction areas around station sites at the Virolahti Bay. Shallow areas and areas nearby land and islands are excluded. For each virtual station, the radius around the station site central coordinate is 930m.*

# 2. Coastal monitoring results

## 2.1 Chl-a content of surface water in water quality samples

The chl-a concentration in the surface water layer varied considerably both between the stations and the years. In the innermost parts of Vyborg Bay, the chl-a concentration was typically the highest, reflecting the high eutrophic state of the area (Fig. 4). Chl-a concentration was gradually lowered towards the mouth of the Bay from ~ 30 to ~ 10 µg/l. During the sampling in 2019, the concentrations in the Vyborg Bay were unusually low compared to the previous years, or other sampling periods, or the EO-based assessment, which raised suspicion about their representativeness.

Virolahti Bay is a shallow inland bay with a high inflow via river Virojoki. In the bay, the chl-a concentrations were notably higher (~ 15 µg/l) than in the inner archipelago (~ 5 µg/l) indicating eutrophic conditions. This was expected as the bay has a limited water exchange with the offshore regions. At the station locating off the bay area (Santio 013) and in the inner archipelago stations further west (Hellitöksens 364 and Tammio 365) the chl-a concentration indicated moderate trophic state. At the outer archipelago monitoring stations (Huovari Kyvy-8a and Haapas Kyvy-11) as well as at the outermost station (012) on the Russian side, the chl-a concentrations were moderate being in accordance with the previous monitoring results. The differences in the chl-a concentrations between the analyzed outermost monitoring stations were small.

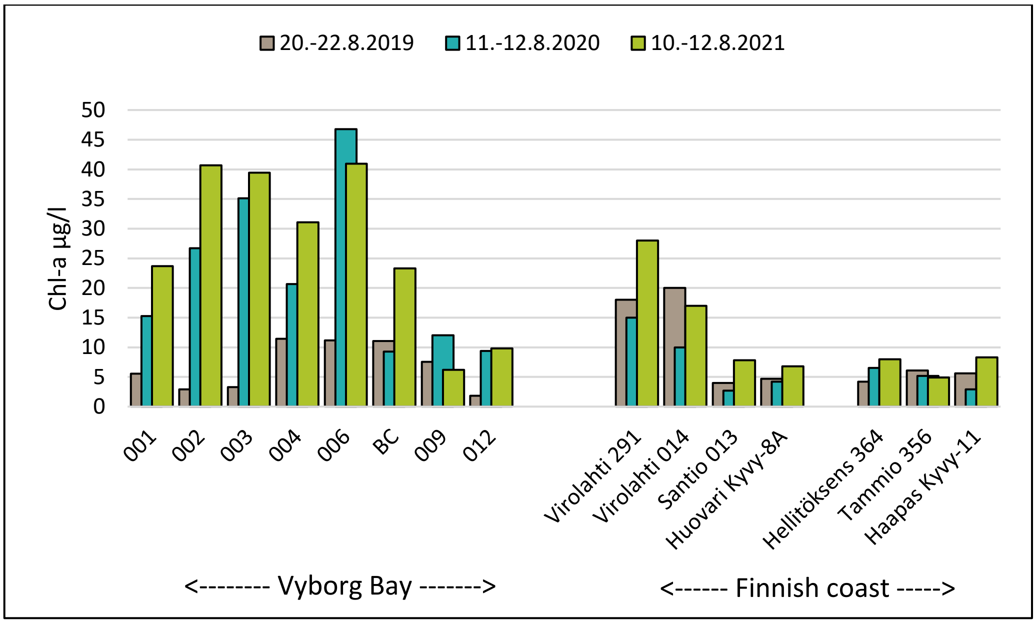



*Figure 4. Chl-a content in surface water samples (0−2 m) in Vyborg Bay and Finnish coastal stations on mid-August sampling occasions in 2019 (grey bars), 2020(cyan bars) and 2021(green bars).*

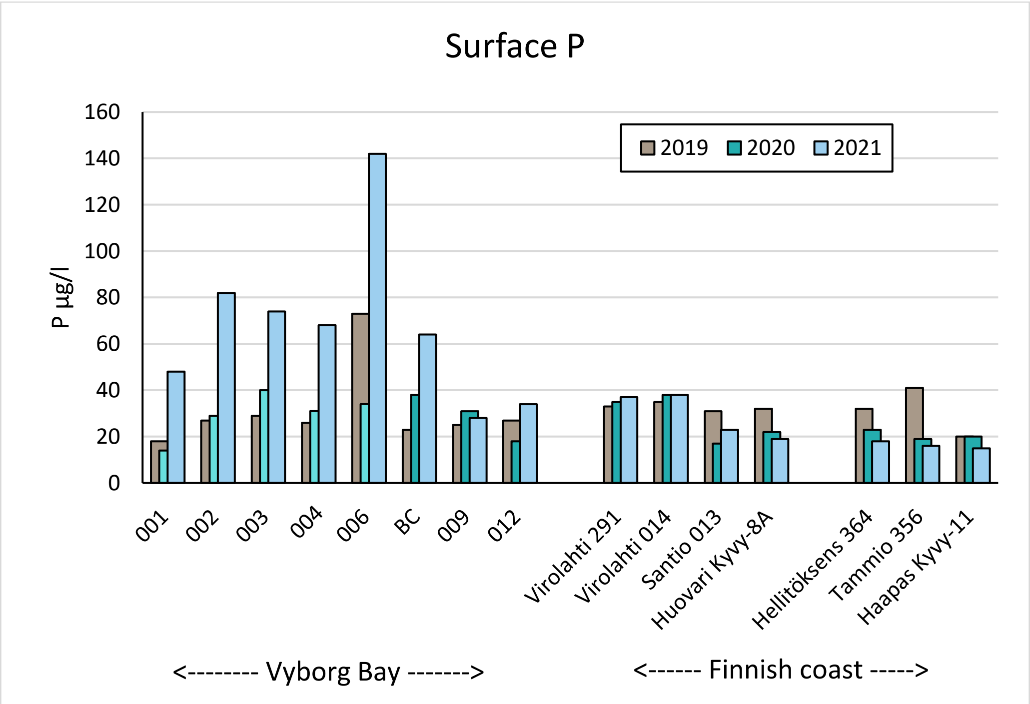
## 2.2. Nutrient concentrations in surface water and near-bottom layer

The availability of phosphorus and nitrogen ultimately regulates the algal growth. Concentrations of late summer total phosphorus (P) and total nitrogen (N) in the surface waters have been used along with the chl-a concentration as indicators of the trophic state of the water. Both P and N concentrations are commonly higher in the coastal area than in the open sea area in the GOF. Especially in estuaries, the N concentration is markedly higher than in the open sea.

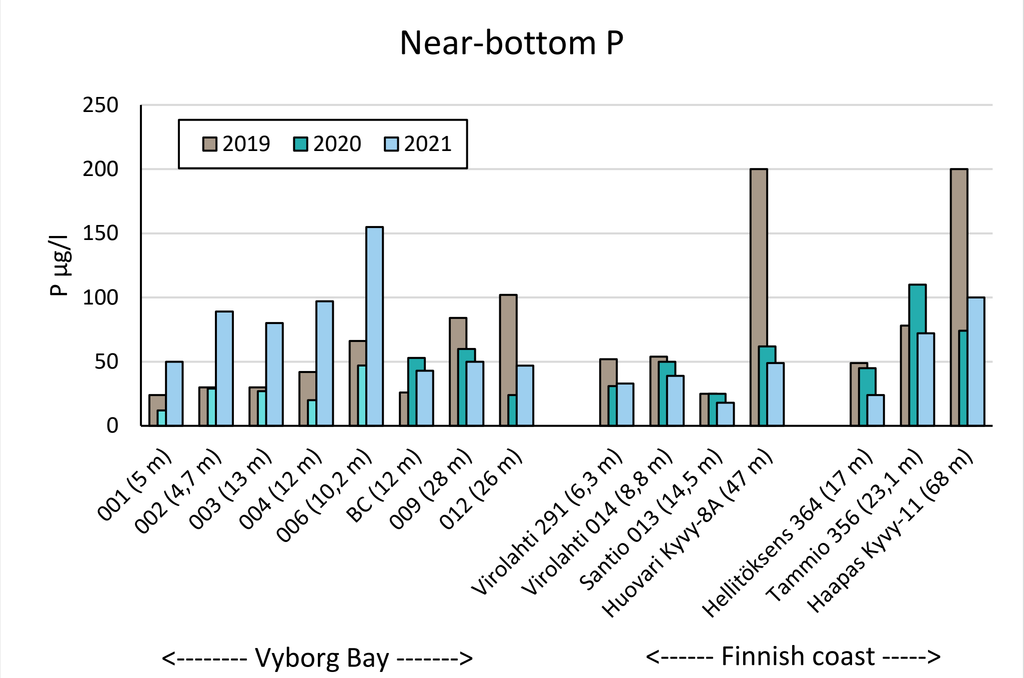
Considering the pronounced coast-offshore continuation in the study area the surface P concentration showed only a moderate variation during the studied years (Fig. 5A). Having said this, the year 2021 in the inner Vyborg Bay was distinct, having twice the concentration level observed in the other years (~ 60 vs 30 µg/l). Whether this was a manifestation of the abnormally high internal or external loading cannot be ascertained. The fact that the high P concentration levels were found near to the bottom, too, suggests for the former option.

The deep P concentrations were expectedly higher than met in the surface (Fig.5B). The abnormally high deep P concentrations at the stations Huovari Kyvy-8A and Haapasaari Kyvy-11 in 2019 (~ 200 µg/l) were associated with high near-bottom salinities, thus providing evidence for the advection of deep-water masses high in P and salinity and poor in oxygen to these sites (Fig. 8 and Figs. 9–10). It is not uncommon to see this kind of fluctuation in the GOF.

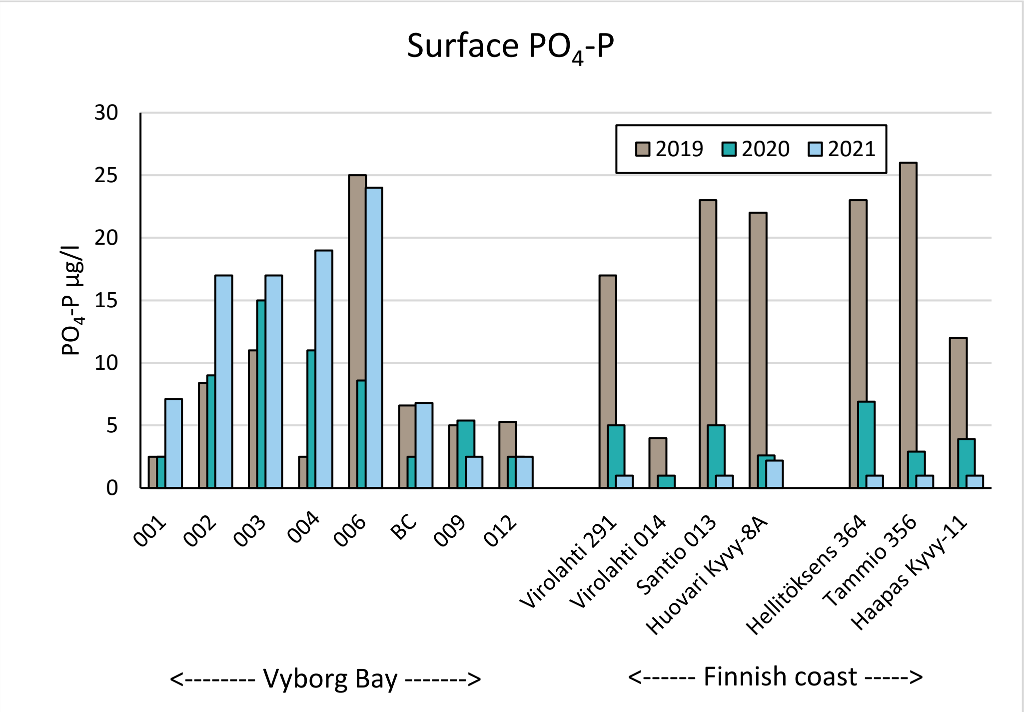
A striking feature of the phosphate-phosphorus ($PO_4$-P) field during the study was the extremely high concentration level occurring in the Finnish surface waters in 2019 (Fig.5C). This level (~ 20 µg/l) is almost comparable to the wintertime $PO_4$-P levels when the annual course of the $PO_4$-P is at its maximum. This deviation from the typical summertime nutrient setup can be explained only by upwelling event taken place in the area prior to the sampling. Upwelling - according to its name - causes deep-water masses to incline to the surface layer due to wind forcing. The deep phosphorus levels were already high due to deep-water advection (see above). On top of that the $PO_4$-P concentration exhibited a clear coast-offshore continuation especially in the Vyborg Bay from ~ 15 to ~ 5 µg/l. Further, the year 2021 set apart from the other years by its higher $PO_4$-P levels in the Vyborg Bay, as already observed with P.



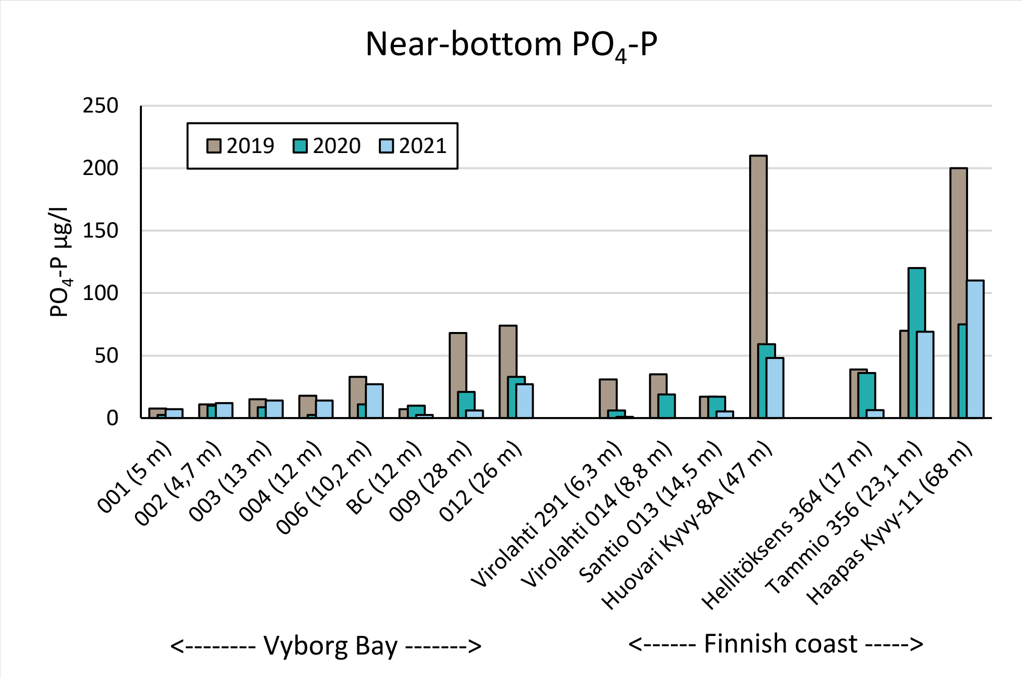

A)


Near-bottom P
2019
2020
2021
P µg/l
250
200
150
100
50
0
001 (5 m)
002 (4,7 m)
003 (13 m)
004 (12 m)
006 (10,2 m)
BC (12 m)
009 (28 m)
012 (26 m)
Virolahti 291 (6,3 m)
Virolahti 014 (8,8 m)
Santio 013 (14,5 m)
Huovari Kyvy-8A (47 m)
Hellitöksens 364 (17 m)
Tammio 356 (23,1 m)
Haapas Kyvy-11 (68 m)
<-------- Vyborg Bay ------->
<------ Finnish coast ----->

B)


Surface PO4-P
2019
2020
2021
PO4-P µg/l
30
25
20
15
10
5
0
001
002
003
004
006
BC
009
012
Virolahti 291
Virolahti 014
Santio 013
Huovari Kyvy-8A
Hellitöksens 364
Tammio 356
Haapas Kyvy-11
<-------- Vyborg Bay ------->
<------ Finnish coast ----->

C)



D)

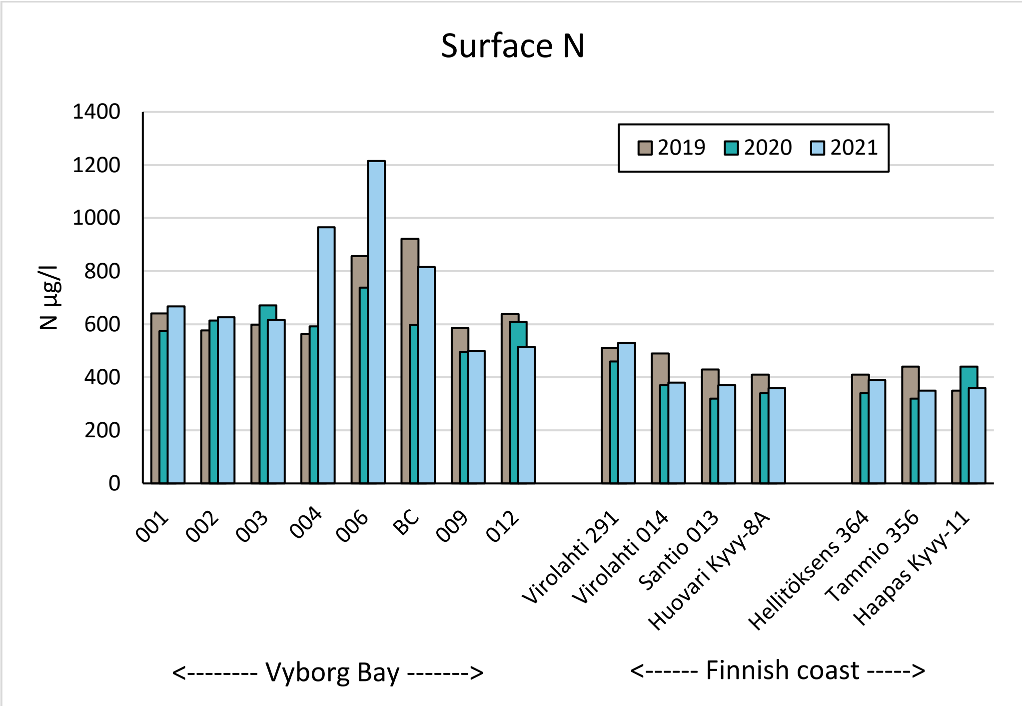
*Figure 5. A) Surface and B) near bottom total phosphorous (P, not filtered, µg/l) and C) surface and D) near bottom phosphate phosphorus ($PO_4$-P, µg/l) concentrations in water column at Vyborg Bay and Finnish coastal stations on mid-August sampling occasions in 2019 (grey bars, sampling during week 34), 2020 (green bars, week 33) and 2021 (blue bars, week 32). In 2020, P concentration was analyzed only from filtered samples at stations 001−006 (light green bars).*

Generally, N is more inert in its occurrence in the water than P. That could be observed here, too. The N concentration varied only moderately between the studied years, the studied areas and vertically (Fig. 6). The stations in the Vyborg Bay area had a higher N level (~ 600 µg/l) than was found in the Finnish side (~ 400 µg/l). Apart from that feature there wereno distinct patterns in the sampling material.

Inorganic nitrogen compounds, nitrite-nitrate nitrogen ($NO_{2+3}$-N) and ammonium nitrogen ($NH_4$-N), are in a form for planktonic algae intake and, in the case of nitrogen being limiting factor in algal growth, are rapidly depleted of surface water (Figs. 7A−C). In the Vyborg Bay, elevated levels of $NO_{2+3}$-N concentrations in surface water layer were observed during the late summer sampling occasions (Fig.7A). This seems to be a result from the absence of stratification and mixing of water layers in shalow parts of the bay (Fig. 9). Only one of the coastal stations on the Finnish side showed clearly elevated $NO_{2+3}$-N concentrations in surface water (Fig. 7A). The elevated concentrations may have been related to nearby fish farms in Virolahti. In the coastal stations that represent areas of high water depth, the near-bottom $NO_{2+3}$-N concentration level reached concentrations up to 150−200 µg/l (Fig.7B).

Elevated $NH_4$-N concentrations are often associated with either a close point source of load or a lack of oxygen e.g. in the near-bottom water layer. Elevated concentrations of $NH_4$-N (up to 60−170 µg/l) in the near-bottom water layer were observed especially in 2019 at some Vyborg Bay observation stations and stations in the outer archipelago that represent coastal areas with water depth more than 40 meters where also the higher salinity causes stratification in the water column (Fig.7C, Figs. 8−10). In addition, it is particularly important to note that high concentrations of ammonium in the near-bottom water layer were also observed in the bays off the coast of Finland (including Virolahti) and in the isolated and oxygen-deficient bottom areas of the inner archipelago (Tammio). This was also reflected in slightly elevated surface water layer $NH_4$-N concentrations. Otherwise, the $NH_4$-N concentrations in the surface water layer were below the limit of quantification.

A)




B)

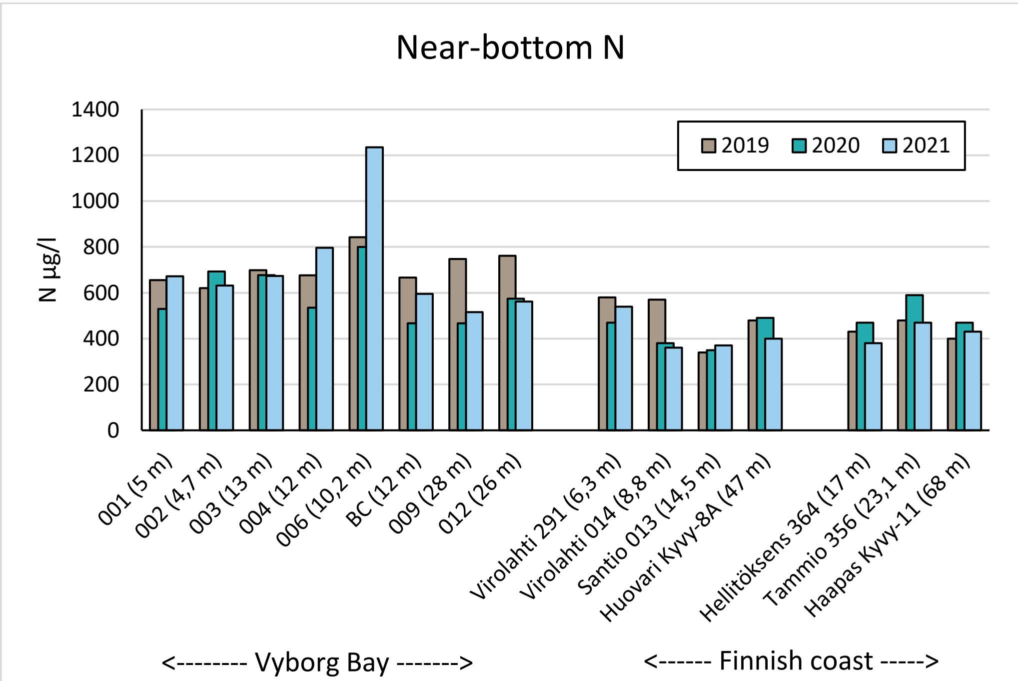
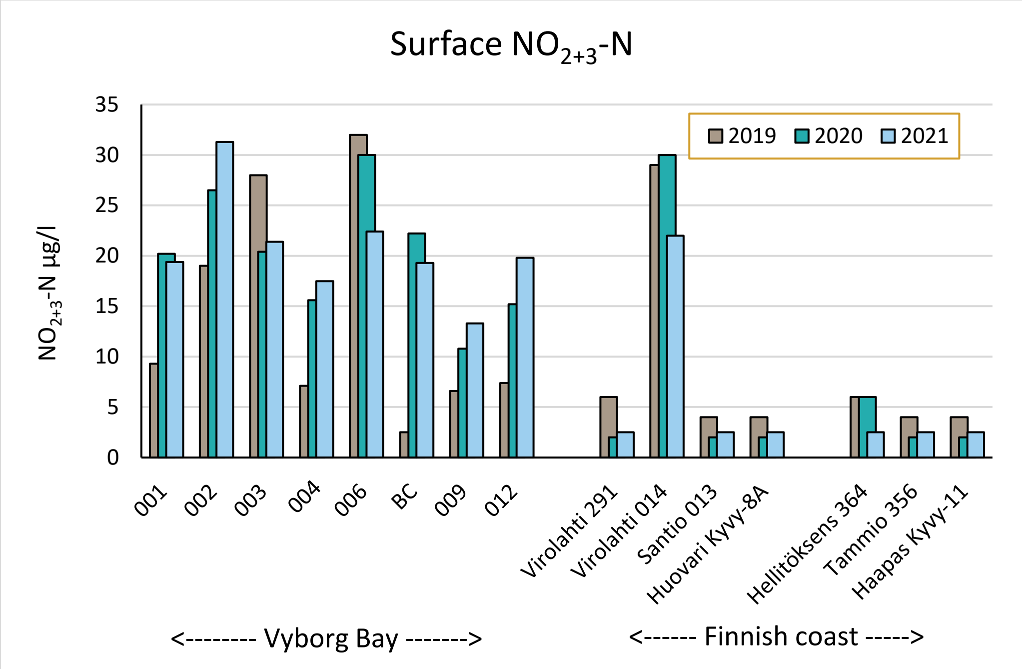
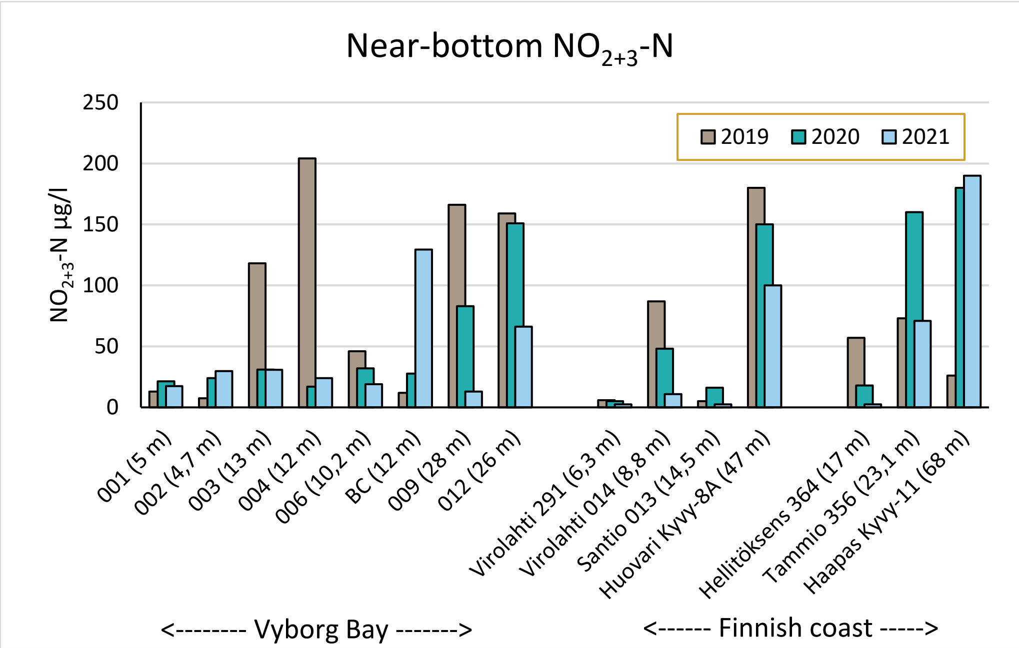



*Figure 6. Total nitrogen (N, not filtered, µg/l), concentrations in water column in A) surface and B) near bottom layer at Vyborg Bay and Finnish coastal stations on mid-August sampling occasions in 2019 (grey bars, sampling during week 34), 2020 (green bars, week 33) and 2021 (blue bars, week 32).*


Surface $NO_{2+3}$-N
35
30
25
20
15
10
5
0
$NO_{2+3}$-N µg/l
2019 2020 2021
001
002
003
004
006
BC
009
012
Virolahti 291
Virolahti 014
Santio 013
Huovari Kyvy-8A
Hellitöksens 364
Tammio 356
Haapas Kyvy-11
<-------- Vyborg Bay ------->
<------ Finnish coast ----->

A)


Near-bottom $NO_{2+3}$-N
250
200
150
100
50
0
$NO_{2+3}$-N µg/l
2019 2020 2021
001 (5 m)
002 (4,7 m)
003 (13 m)
004 (12 m)
006 (10,2 m)
BC (12 m)
009 (28 m)
012 (26 m)
Virolahti 291 (6,3 m)
Virolahti 014 (8,8 m)
Santio 013 (14,5 m)
Huovari Kyvy-8A (47 m)
Hellitöksens 364 (17 m)
Tammio 356 (23,1 m)
Haapas Kyvy-11 (68 m)
<-------- Vyborg Bay ------->
<------ Finnish coast ----->

B)

C)

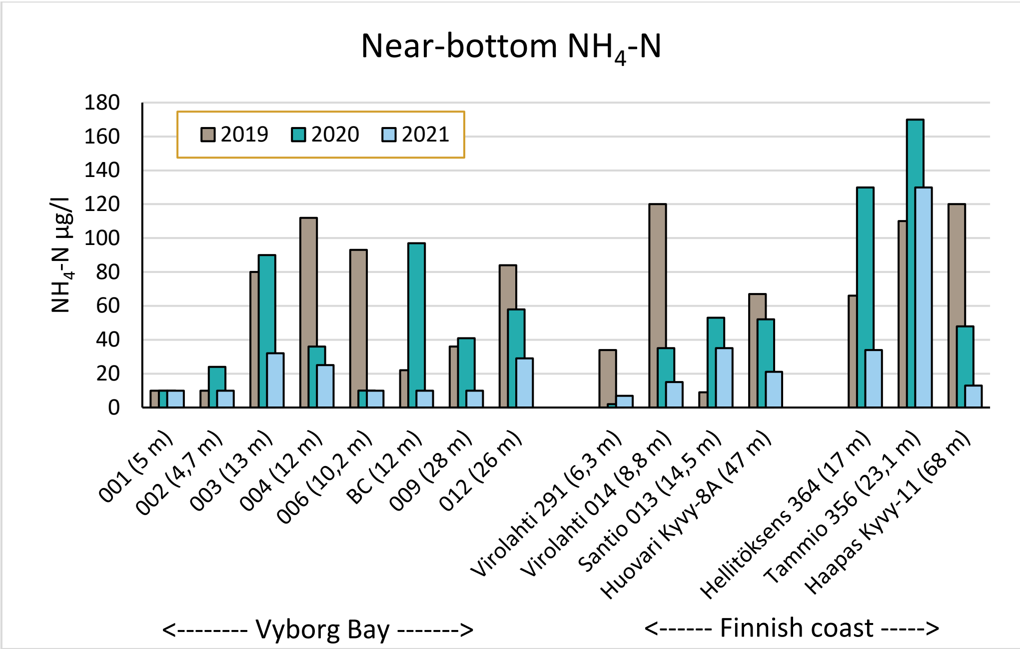



*Figure 7. Inorganic nitrite-nitrate-nitrogen ($NO_{2+3}$-N, µg/l) concentrations in water column in A) surface and B) near bottom layer and ammonium-nitrogen ($NH_4$-N, µg/l) in C) near bottom layer at Vyborg Bay and Finnish coastal stations on mid-August sampling occasions in 2019 (grey bars, sampling during week 34), 2020 (green bars, week 33) and 2021 (blue bars, week 32).*

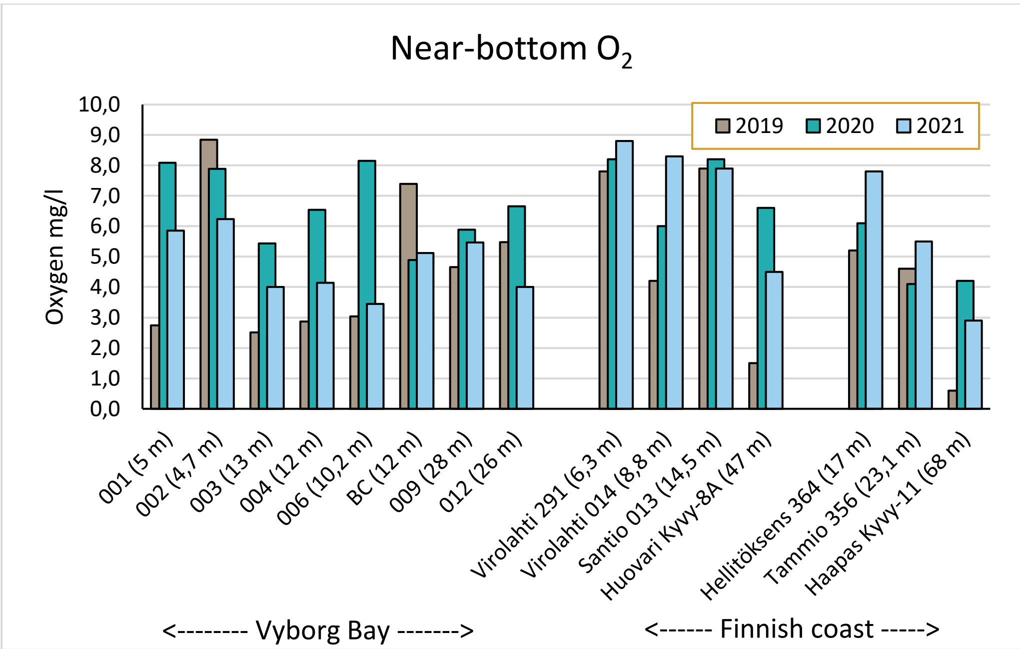



*Figure 8. Near-bottom oxygen concentration (mg/l) at Vyborg Bay and Finnish coastal stations on mid-August sampling occasions in 2019 (grey bars, sampling during week 34), 2020 (green bars, week 33) and 2021 (blue bars, week 32).*

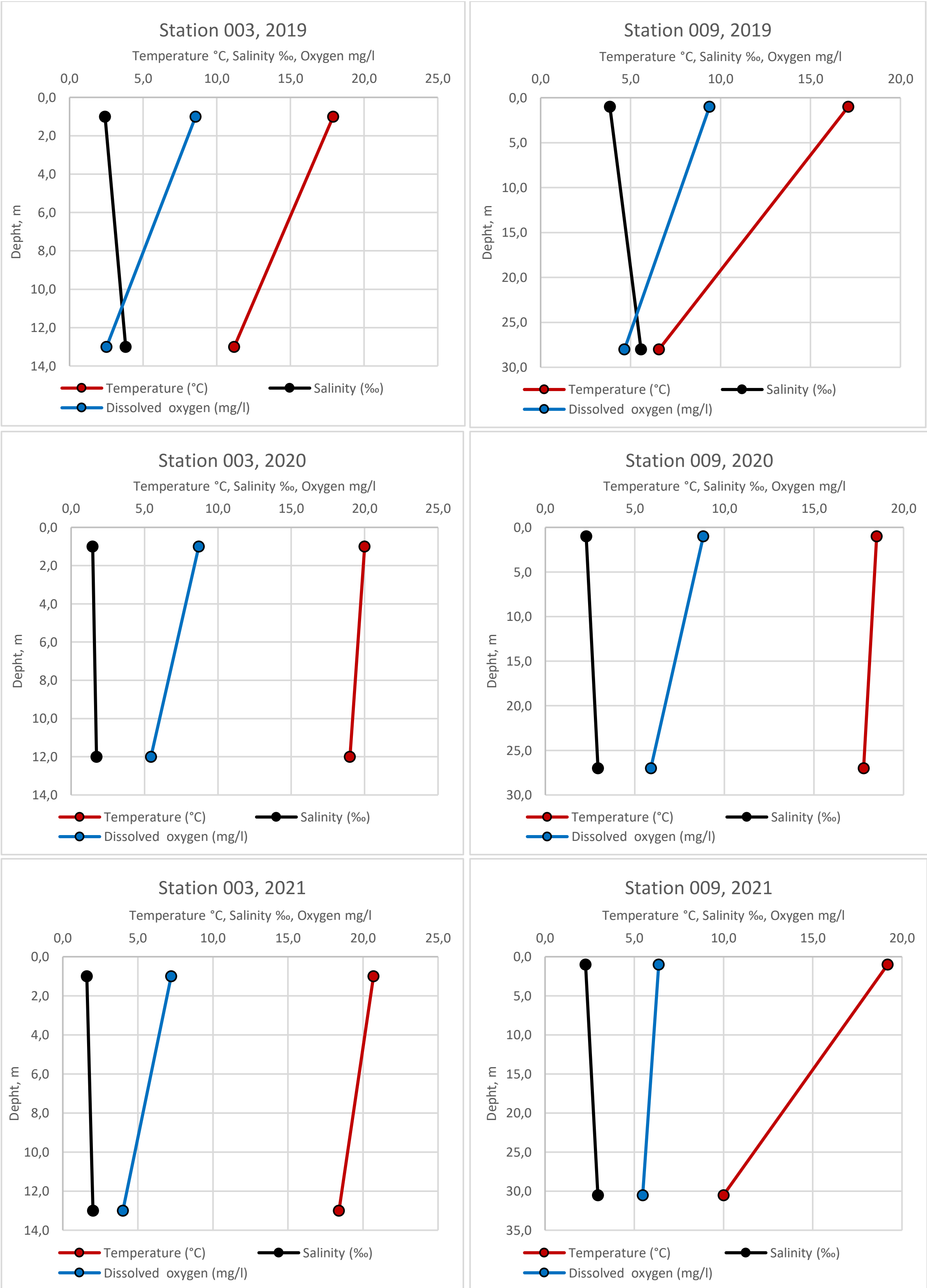



*Figure 9. Temperature, salinity and oxygen profiles at Vyborg Bay sampling stations 003 and 009 mid-August sampling occasions in 2019 (week 34), 2020 (week 33) and 2021 (week 32).*

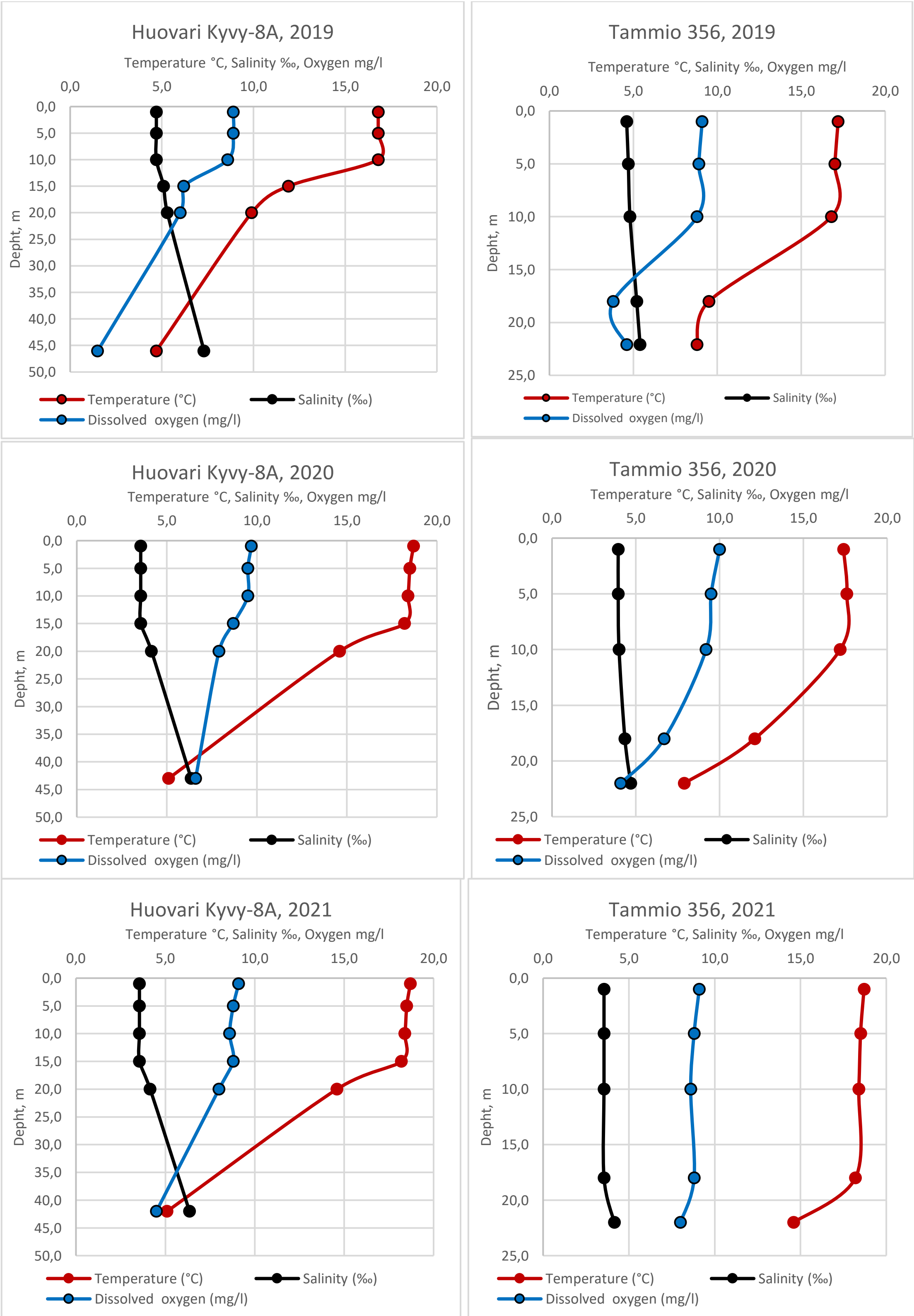
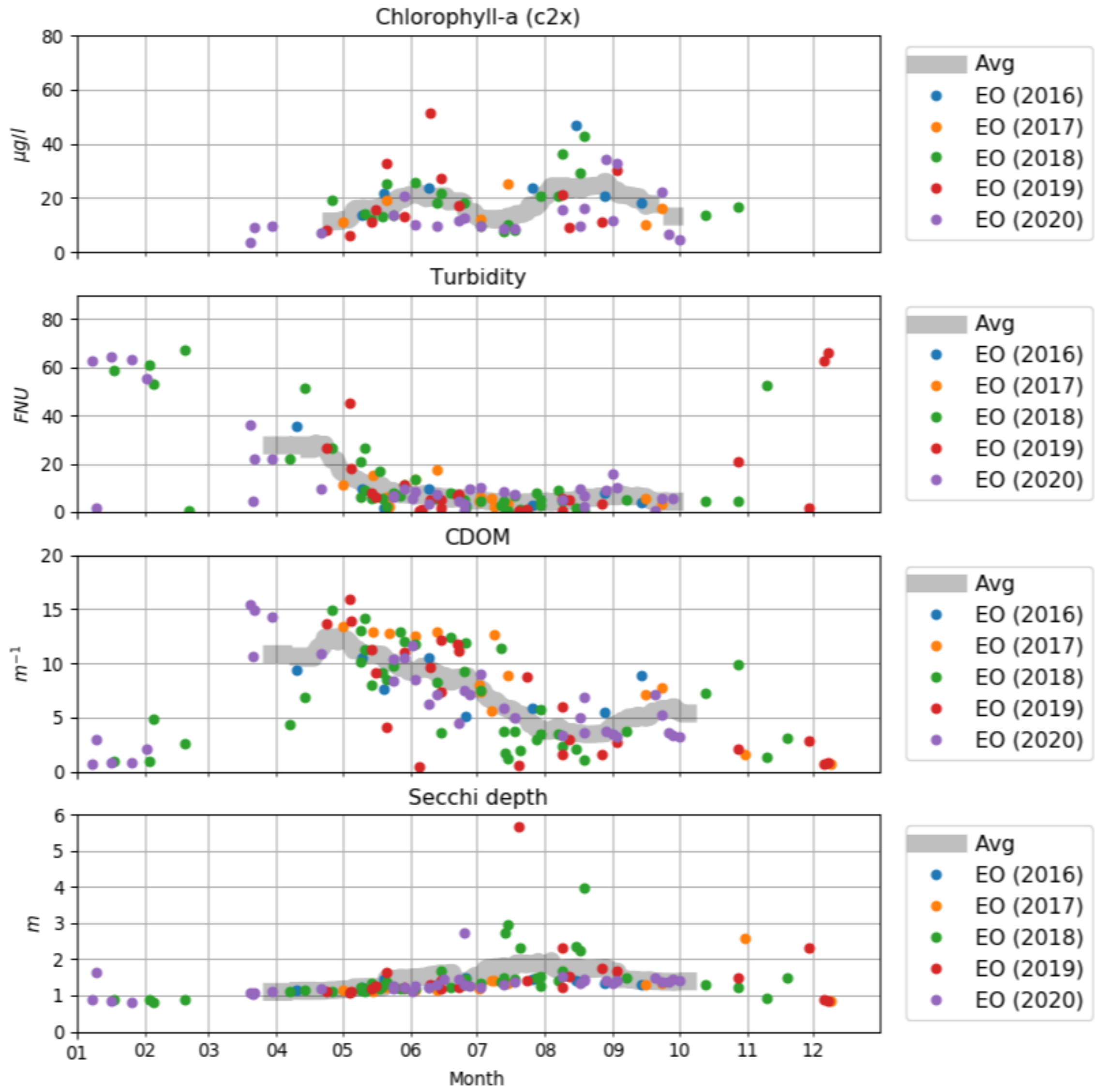


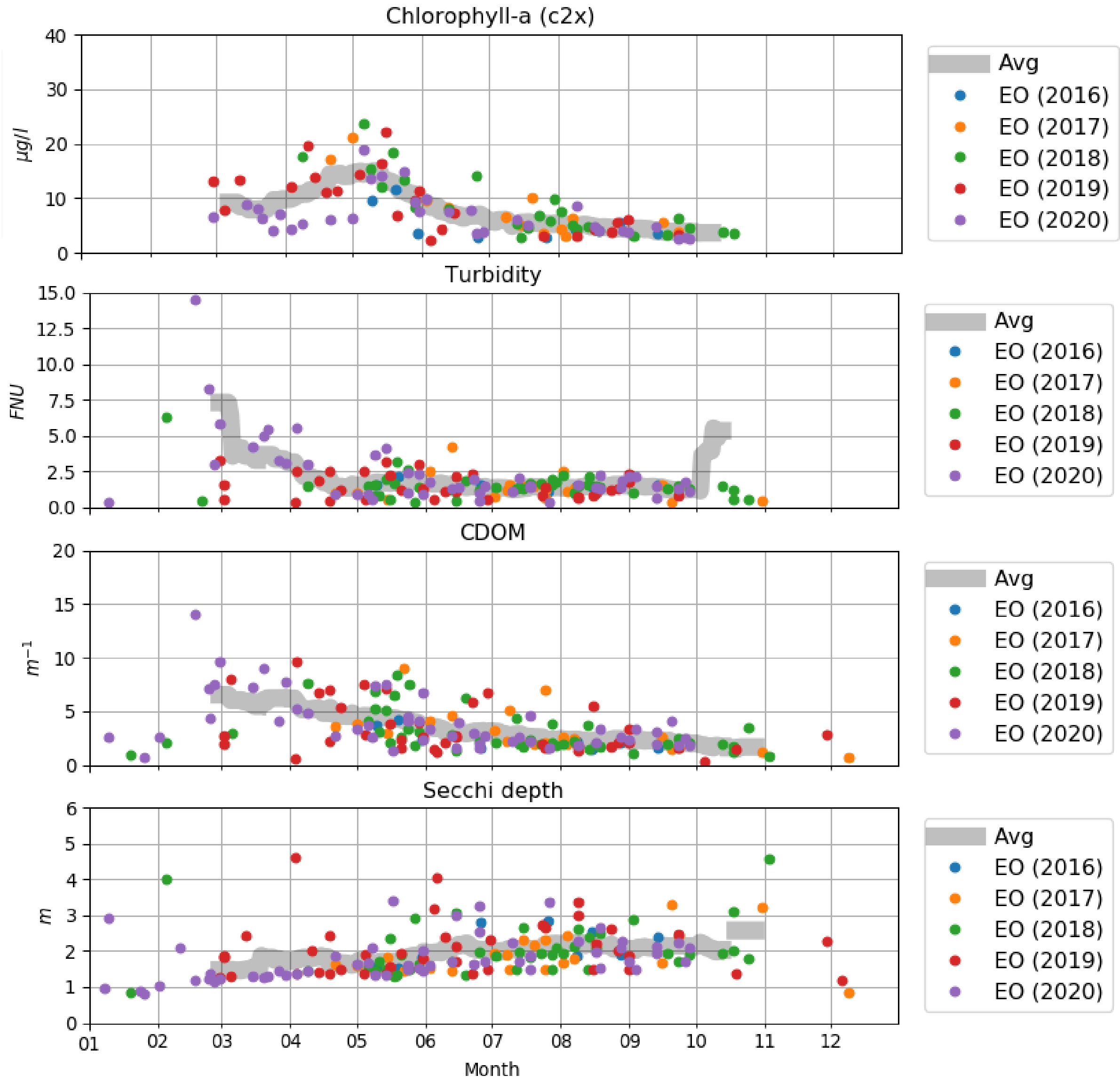

*Figure 10. Temperature, salinity and oxygen profiles at Finnish coastal stations Huovari Kyvy-8A and Tammio 356 on mid-August sampling occasions in 2019 (week 34), 2020 (week 33) and 2021 (week 32).*

## 2.3. Satellite observations results

Satellite observations (abbreviation EO in tables and figure legends hereinafter) from the station sites (Chapter 1.2.) were analyzed using time series from the coastal stations and years 2016−2020. The time series exemplify typical seasonality and range of the analyzed water quality parameters at the stations in the inner parts of the River Rakkolanjoki estuary and in the outer part of the Vyborg Bay (Fig. 11). The seasonal variation in chl-a time series reflects springtime and summerly phytoplankton bloom periods and phytoplankton bloom minimum (in June). Likewise, turbidity is high during the spring, with concurrent melting of snow, frost and ice and increased runoff from drainage basin. Mostly, when the turbidity is high in coastal waters, it originates from the drainage basin and enter to the coastal waters via rivers. During the summer, turbidity is relatively low in the most parts of the coastal waters. In estuaries, especially in enclosed bays, the turbidity can at times be high in the summertime. Mostly this due to heavy rains increased by the river runoff. Occasionally, in shallow areas, also resuspension caused by strong winds can increase the turbidity. Absorption of CDOM was high in the Bay of Vyborg, as presumed based e.g. land cover information in the drainage basin. Ice-cover season observations were excluded from the analysis.




A)




B)

*Figure 11. Time series of satellite observations (EO in legend) at A) the innermost station site at the proximity of river Rakkolanjoki estuary (BoV-R2) and B) the outermost station at the Vyborg Bay (BoV-012) for water quality parameters (from top to bottom) chl-a, turbidity, CDOM and Secchi depth, for the years 2016−2020.*

During the project, a total of nine virtual satellite observation sites were implemented in the Bay of Vyborg (Fig. 3). Likewise, six stations for the sea areas on the Finnish side were established to complement the existing ones. As a result, there are now altogether 15 sites providing satellite observations in the Eastern GOF (Fig. 12). Until the end of the project, the number of days, when satellite observations were obtained is large, but varies slightly per station and water quality parameter (Table 2). For chl-a, the observations start in 2015. Surface temperature observations are available as early as from 2004 onwards.

Comparisons between satellite observations and water sampling have been made at the sites where observations of the satellite observations and corresponding water quality sample data are available. The water samples at station and satellite observations were not observed during the same day, which hampers the possibility to make extensive statistical analysis between the two observational methods. Therefore, the good mutual correspondence between the field campaign measurements and satellite observations can be best visualized using time series (examples in Figs. 13 A and B).

**Table 2. The number of EO observation days at station sites from the river Rakkolanjoki estuary towards the open sea station (BoV−012). The number of observations is lower at stations that locate in narrow parts of the bay, like BoV−003 (map in Fig. 19). The table gives representative examples out of the 13 stations in total.**

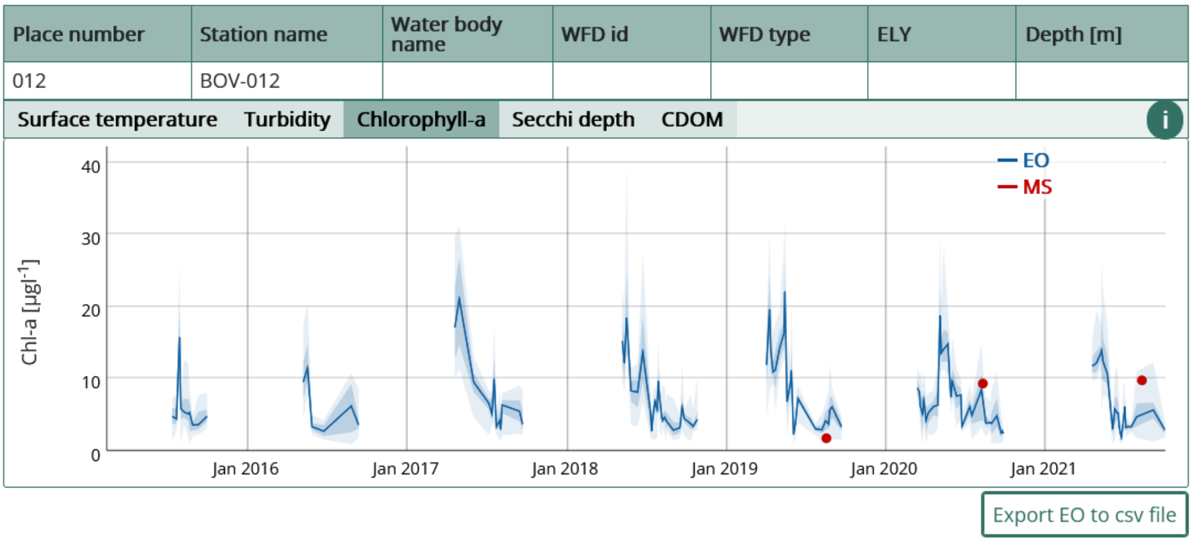
| Station | N of EO Chl-a observation days per station (2016−2021) | N of EO Turbidity observation days per station (2015−2021) | N of EO Temperature observation days per station (2004−2021) |
|---|---:|---:|---:|
| BoV R2 | 87 | 99 | 659 |
| BoV-003 | 88 | 93 | 458 |
| BoV-004 | 102 | 105 | 576 |
| BoV-009 | 116 | 128 | 687 |
| BoV-012 | 127 | 138 | 793 |

As a result of the comparisons of stations sampling monitoring and EO, new reference stations have been added to SYKE's TARKKA-web map service (syke.fi/TARKKA/en, Fig. 12). New observations are updated to the service whenever cloudless observations are available between April and October (Fig. 13). This period is typically ice-free in the area. The observations are available in TARKKA reference station time series couple of days after the satellite overpass, i.e. after the satellite observations have passed the automated processing and quality assurance phase (Chapter 1.1.2).


*Figure 12. A) Map showing the permanent stations in TARKKA-interface. Station-wise satellite observations and station sampling during SEVIRA field campaigns can be accessed through TARKKA-service (syke.fi/TARKKA/en, panel on the left and icon 'Reference data'-> 'Coastal and lake reference stations'). The areas covered by the satellite observation time series can be accessed from the left panel, icon 'Additional spatial data' and activating the 'Reference station regions' material. In this example figure, the areas are shown with blue circles. The observations for each station can be reached by clicking the station site symbol.*

A)

Reference stations of coastal areas and lakes




B)

Reference stations of coastal areas and lakes

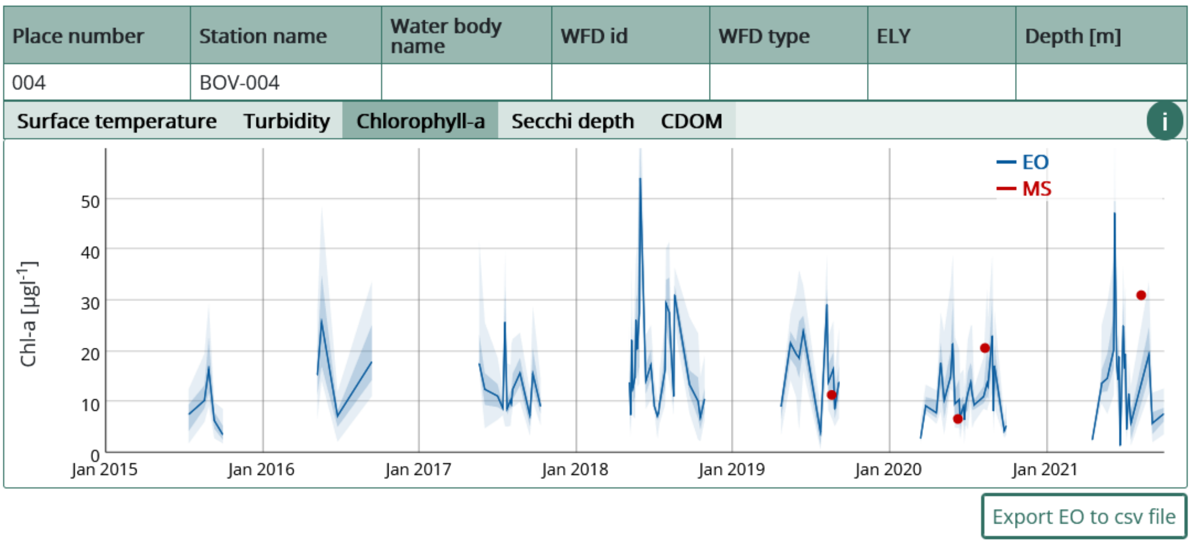
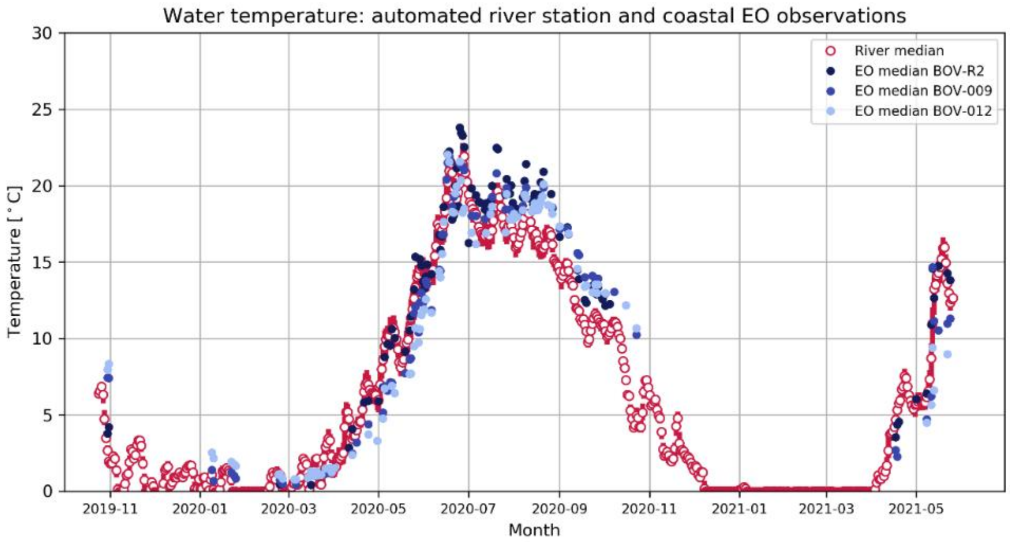


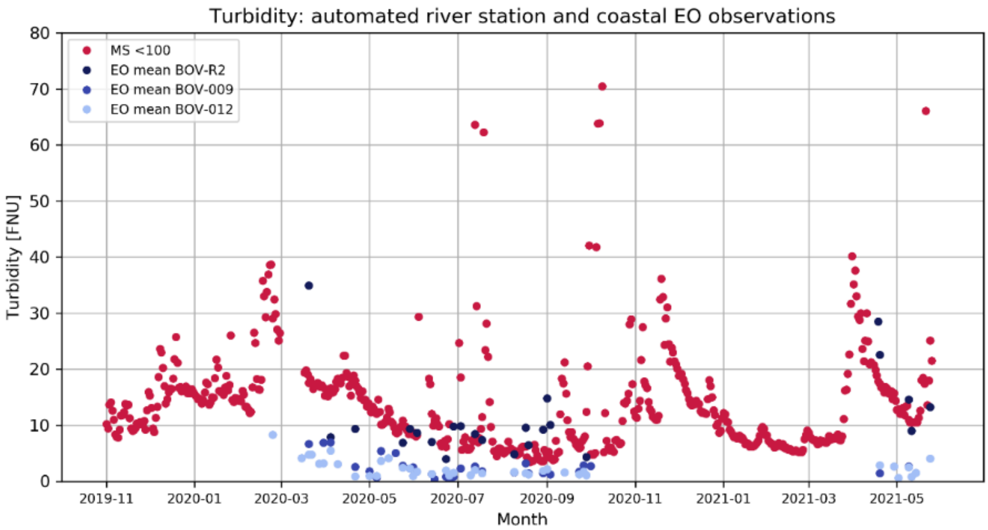

*Figure 13. Examples of satellite observations and the SEVIRA project station sampling at reference station time series in the Bay of Vyborg. Chl-a observations at stations B) BoV−012 and C) BoV−004. Numerical statistics can be exported in csv-files from the lower right corner of the time series window for surface temperature and each of the water quality parameter (chl-a, turbidity, CDOM and Secchi depth).*

### 2.3.1 Comparison of coastal satellite observations and river station measurements

In situ high-frequency river water quality data from the Seleznevka and satellite observations at the coastal waters show good mutual correspondence (Fig. 14). The satellite observations form a continuous transect from the river outlet to the open sea (stations BOV-R2, BoV-009 and BOV-012, map of station sites in Fig. 3). Satellites provide temperature observations practically daily, therefore the temporal frequency of both sea and riverine data is high (Fig. 14A). The two types of temperature observations and their mutual correspondence is an illustrative case for demonstrating the benefits of joint monitoring by modern monitoring methods, like in this case in situ river water quality sensor and satellite observations at the coastal areas of interest. Turbidity values are higher in the river and decrease towards the open sea station (BOV-012 in Fig. 11B) as the influence of river water mixes with less turbid coastal water. Combination of these two observations from two different data sources demonstrate well the spreading of the turbid riverine water to the coastal waters.




A)




B)

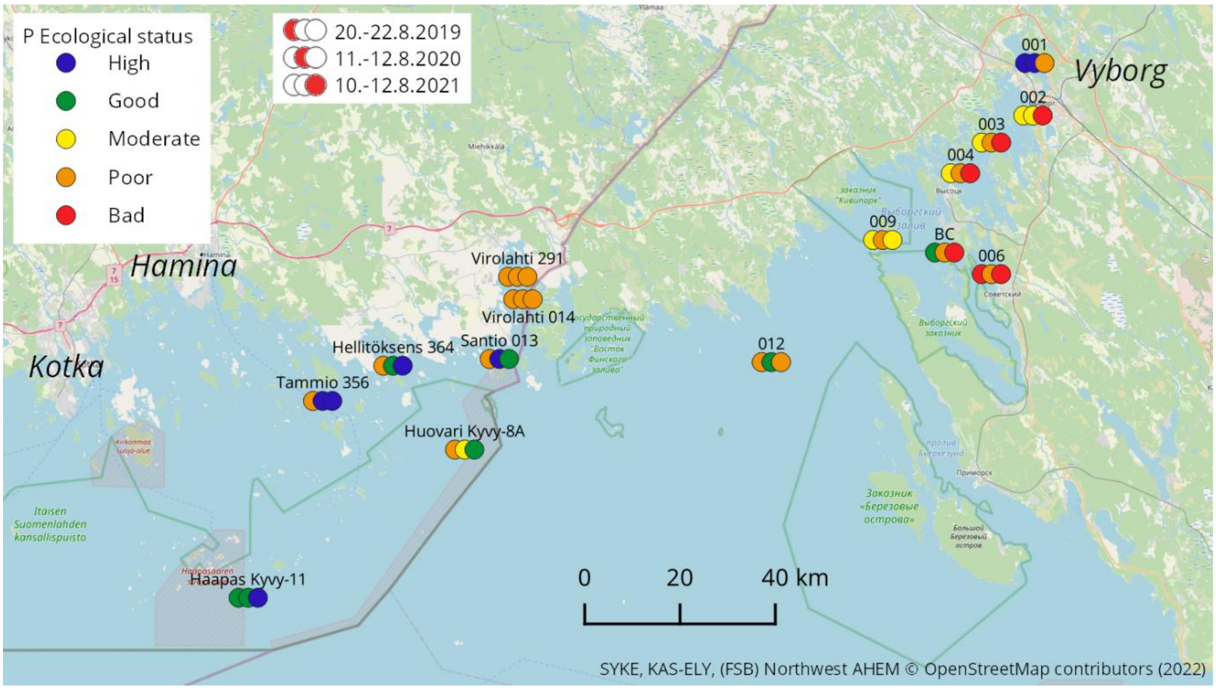
*Figure 14. Time series of A) temperature and B) turbidity measurements of the in situ high-frequency sensor in the Seleznevka river site Luzhayka (red dots) and satellite observations (EO in legend) at three coastal stations (BOV-R2, BOV-009 and BOV-012) that form a continuous transect from the river outlet to the open sea (map of the coastal station sites in Figs. 3 and 9).*

# 3. Ecological status assessment of the studied coastal waters

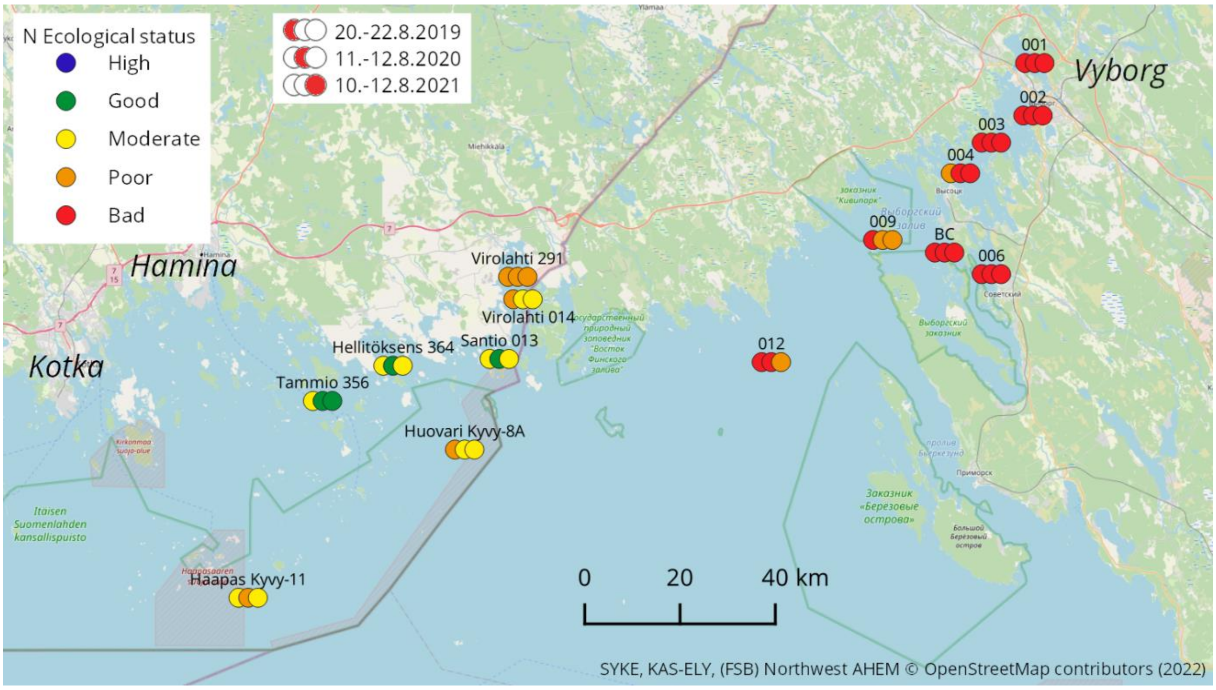
## 3.1 Annual ecological status during project years 2019−2021

Ecological status assessment and water quality classification is defined either by national or international regulations, like the directives in EU. Although the regulations may differ in detail between the water areas they apply, like lakes, coastal and open sea ares, there are similar elements in them. As for example, most regulations are based on water quality classes and boundaries between the classes that define the ecological status. Status assessment regulations typically use nutrients and chl-a as one of the classification indices. In the EU countries, these requirements are defined for the coastal water areas by the Water Framework Directive (WFD, Ferreira et al., 2007), in which the ecological classification consists of five classes (high, good, moderate, poor, and bad). In the SEVIRA project, annual classification of the coastal study areas was made based on the measured nutrients and satellite observations of chl-a concentrations in 2019−2021 (Fig.15).

A)



B)




C)

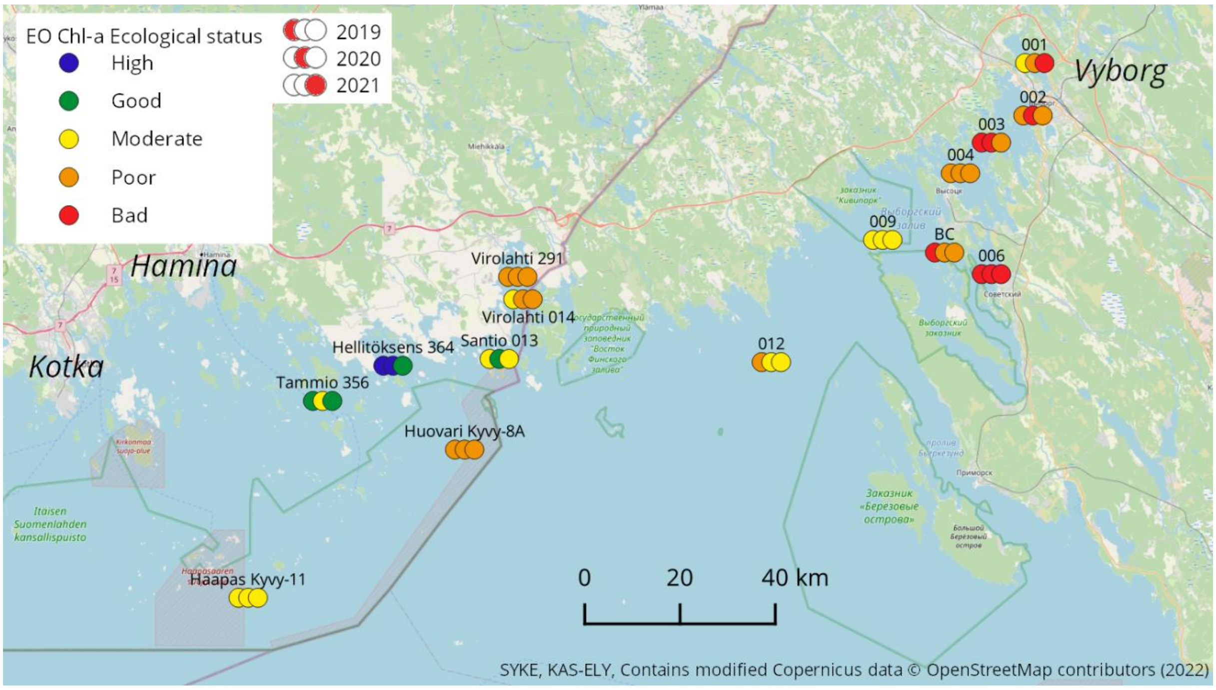



*Figure 15. Ecological status defined based on the a) P, B) N measured during the field sampling and C) aggregate of July-August satellite observations of chl-a concentrations measured during SEVIRA project years.*

In Russia, the surface water assessment is based on threshold values of the trophic state classification. The North-West AHEM has used classification according to Vinberg (1960) theory with the following criteria's for chl-a concentrations:

1. oligotrophic - less than 1 µg/l
2. mesotrophic- 1−10 µg/l

3. eutrophic- 10−100 µg/l
4. hypereutrophic - more than 100 µg/l

According to this trophic state classification, the average surface water (0−2 m) chl-a concentrations during late-summer sampling occasions suggests an eutrophic state with relatively high chl-a concentration levels. This applies to all examined years (2019−2021) and the inner parts of the Bays of Vyborg and Virolahti. Correspondingly, the outer parts of the Vyborg Bay (stations 009 and 012) and the associated areas of the inner and outer archipelago off the coast of Finland are classified as being in a mesotrophic state according to the trophic classification limits (Table 3).

**Table 3. Trophic state classification for the coastal sampling according to the trophic classification method (Vinberg, 1960) for late summer chl-a concentrations in 2019–2021.**

| Station № | Chl-a, August 2019–2021 | |
|---|---|---|
| | Average concentration chl-a (0−2 m), µg/l | Trophic status |
| 001 | 14,8 | Eutrophic |
| 002 | 23,4 | Eutrophic |
| 003 | 26,0 | Eutrophic |
| 004 | 21,1 | Eutrophic |
| 006 | 33,0 | Eutrophic |
| BC | 14,5 | Eutrophic |
| 009 | 8,6 | Mesotrophic |
| 012 | 7,0 | Mesotrophic |
| Virolahti 291 | 20,3 | Eutrophic |
| Virolahti 014 | 15,7 | Eutrophic |
| Santio 013 | 4,8 | Mesotrophic |
| Hellitöksens 364 | 6,2 | Mesotrophic |
| Tammio 356 | 5,4 | Mesotrophic |
| Huovari Kyvy-8A | 5,2 | Mesotrophic |
| Haapas Kyvy-11 | 5,6 | Mesotrophic |

## 3.2. Long-term changes in water quality and level of eutrophication based on chl-a time series

The SEVIRA project put effort in analyzing monitoring observations from multiple data sources. Data was gathered during designated field campaigns (Chapter 1), Alg@line ferrybox observations, as well as long term monitoring station data sets by Russian and Finnish authorities (from 1996 on). Also, satellite observations of chl-a were used. The datasets, their coverage within the timeframe and their source databases are listed here:

- Results of late summer chl-a in the Vyborg Bay Joint Monitoring project (during 1996−2006, VESLA database by SYKE).
- Finnish national monitoring program for water management planning: The water quality results of the monitoring program carried out by the ELY Center in 1996−2021 and the results obtained in the obligatory monitoring of Virolahti (averages of July−August observations VESLA database, by SYKE).

- Late summer chl-a results obtained in connection with the Alg@line project for the period 2004−2012 (average results for July−August where available; three stations in the Vyborg Bay and two in the inner archipelago stations in Finland).
- Late summer chl-a results calculated from EO satellite data for 2016−2021 (mean level of aggregated results from the period of July−August (SYKE's Status database, dataset downloadable in TARKKA service).
- Results obtained during the Vyborg Bay sampling cruises carried out in August 2019−2021 during the SEVIRA project.

With respect to chl-a, these various data sources were combined, and a joint analysis of the state of easternmost coastal areas of the GOF was made. Based on the results of chl-a in the surface water, clear improvement in water quality and a decrease in eutrophication can be observed in the Vyborg Bay area during the first decades of the 21st century (Fig. 16). Based on the observations collected during the annual late summer periods, the chl-a concentration has decreased considerably in the inner part of the bay. Likewise, similar trend tendency can be seen in the mouth of the bay, although there/in that area the chl-a concentration was not high to start with. Similar development has also been observed in Finnish coastal waters (Fig. 17). The chl-a concentration in the surface water has decreased both in the outer archipelago and in the inner archipelago. In Virolahti Bay, the concentrations are still high and indicate prevalent eutrophic conditions.

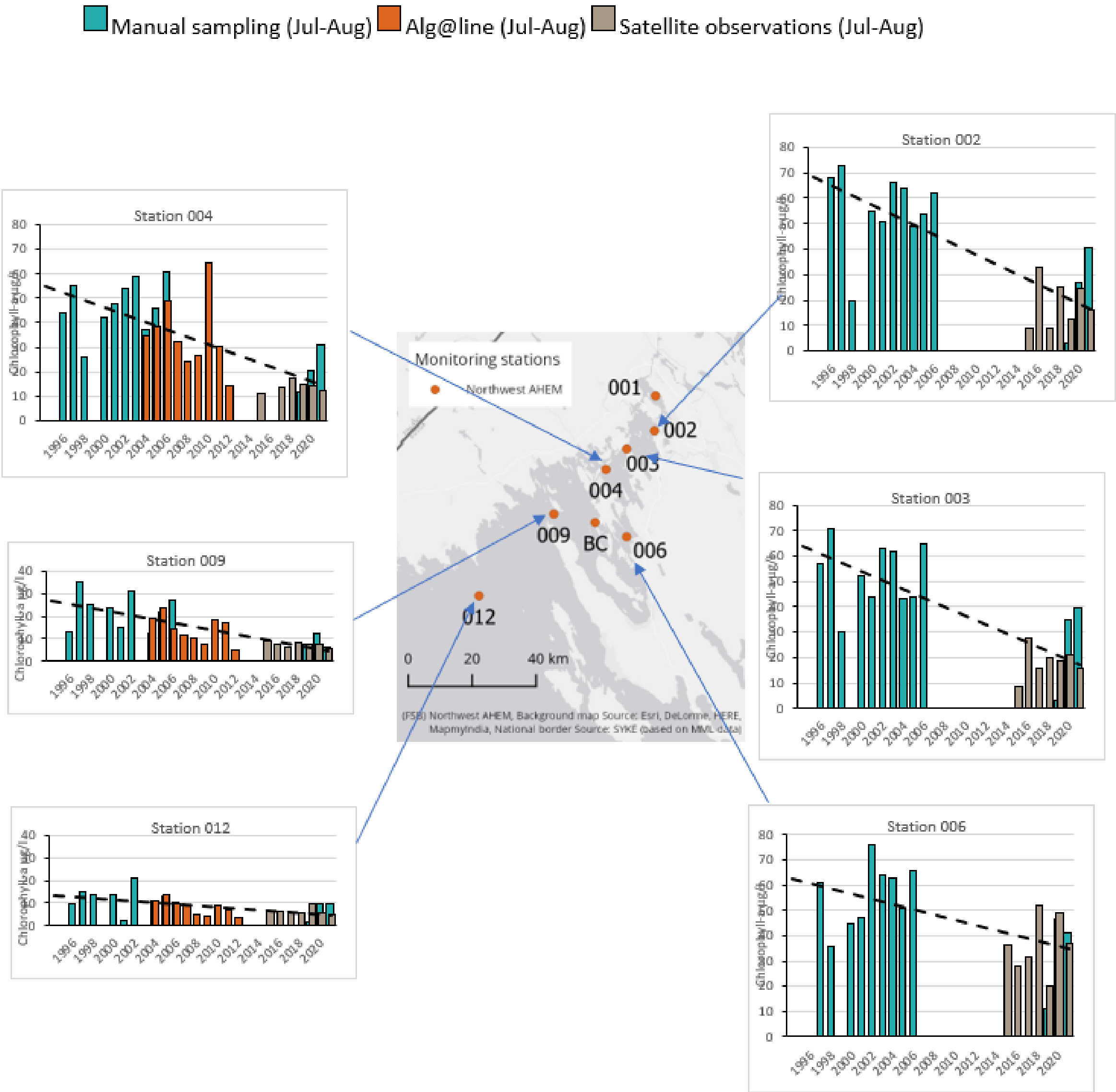



*Figure 16. Average late summer chl-a concentrations in surface water in the Vyborg Bay sampling stations starting from the year 1996. Station sites from A) to F) to represent the transect from the Rakkolanjoki estuary (A) towards the outer parts of the Vyborg Bay (F) (map of station sites in Fig. 2). Data from Vyborg Bay Joint Monitoring Program (cyan bars, 1996−2006), from Alg@line-data reconstruction (orange bars, 2004−2012) and 2015−2021, from satellite observations results (EO, 2015-2021, grey bars).*

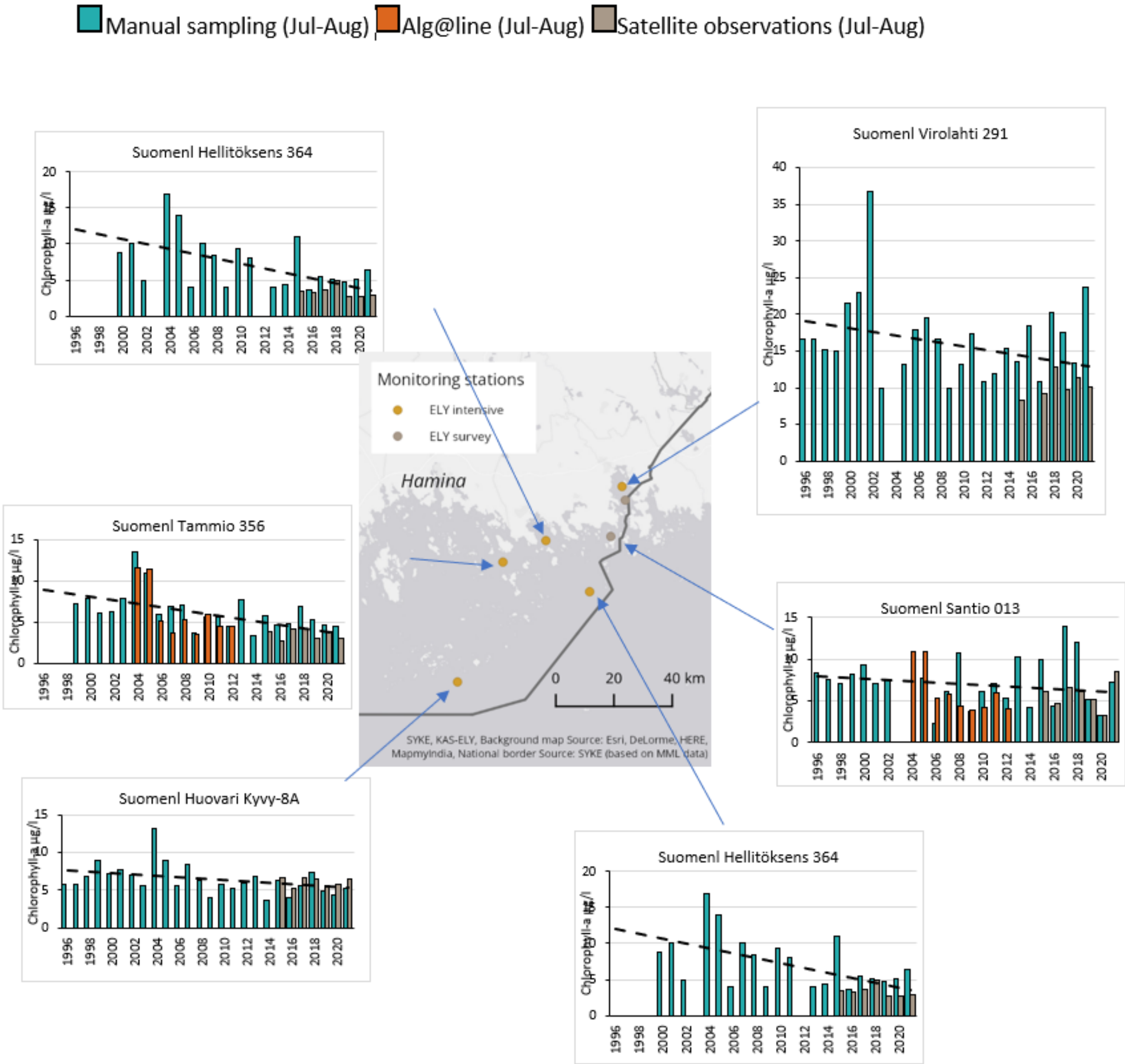
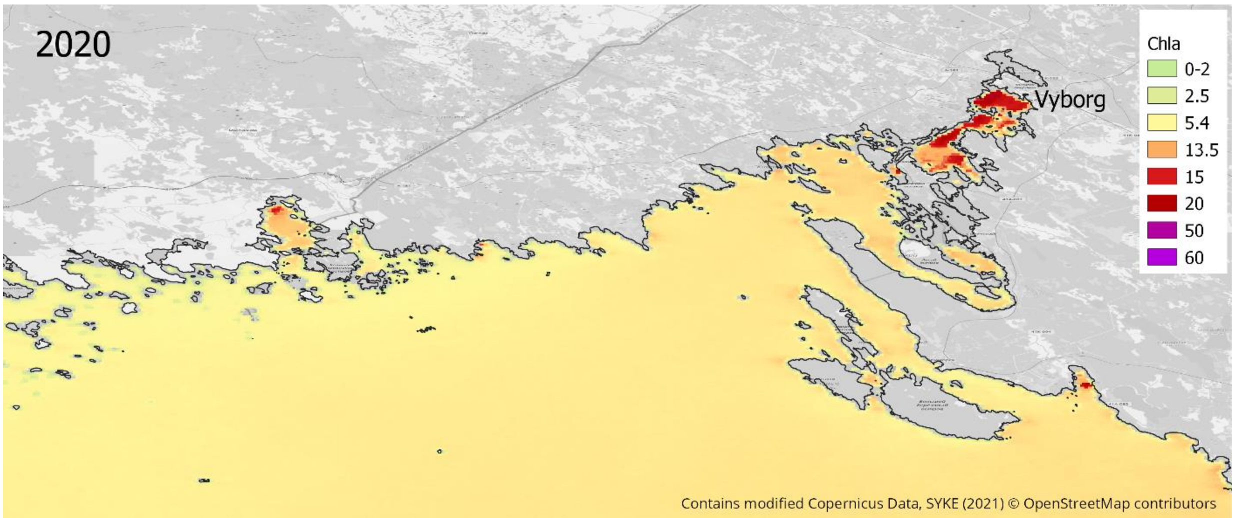


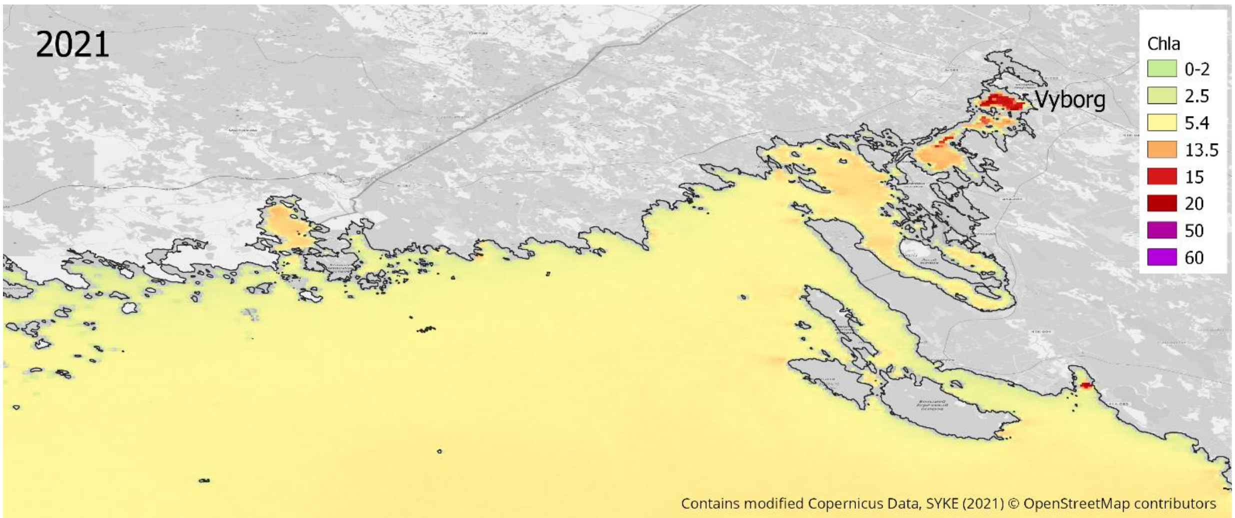

*Figure 17. Average late summer chl-a concentrations in the surface water in the Finnish coastal monitoring stations during 1996-2021 (cyan bars), from Alg@line-data reconstruction (orange bars in B and E, 2004−2012) and from satellite observations results (EO, 2015−2021, grey bars).*

Water quality maps based on satellite observations of chl-a (2003−2011 and 2016−2021) can provide a wholistic view of the study area in spatial and temporal means (Figs. 18 and 19). The use of satellite observations along with other monitoring data typically increases the reliability of the status assessment, as the number of annual observations increases from two to three station sampling cruises to statistics based on hundreds of thousands of individual measurements. Also, the spatial coverage extends from pointwise station locations and covers the coastal waters and bays, which gives more credibility to the status assessment. Annually produced maps cover the period from the beginning of July to the first week of September, which is the period applied in WFD (for the coastal waters in Finland, Figs. 18 and 19).

Annual state assessment maps of chl-a with EO observations have been calculated for years 2020 and 2021 (Fig. 18). As background information, analogous maps for the years 2003−2011 were generated (Fig. 19). The maps confirm the findings shown in station site time series (Figs. 16 and 17): the ecological condition of coastal waters has improved from what it was at the start of 21st century.



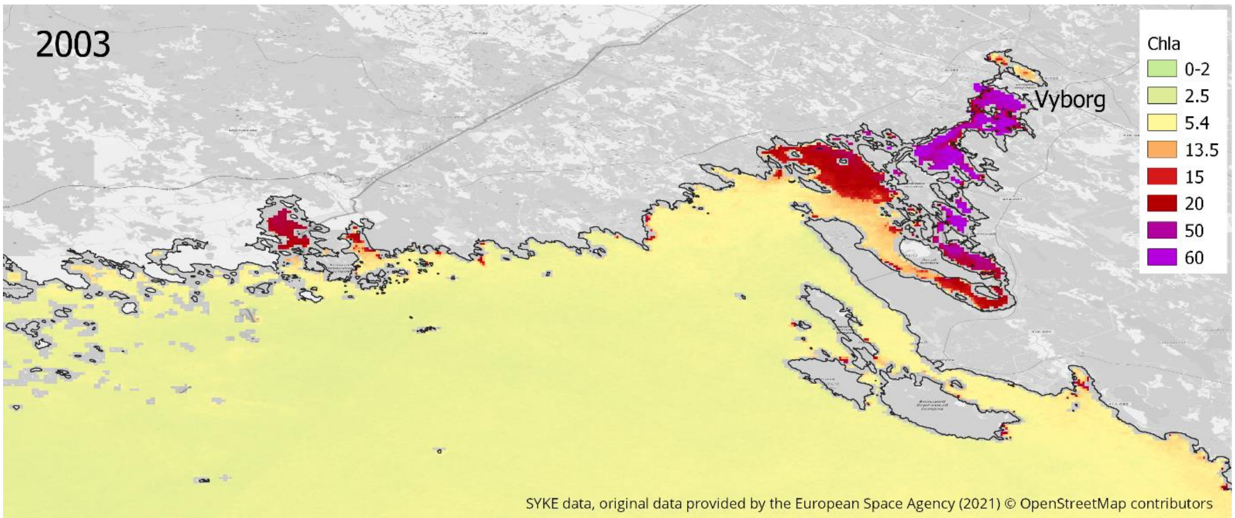

*A)*




*B)*

*Figure 18. Water quality maps for status assessment purposes are based on summerly aggregate of chl-a observations of OLCI instrument onboard Sentinel-3 satellites A) in 2020 and B) in 2021.*

*A)*




*B)*

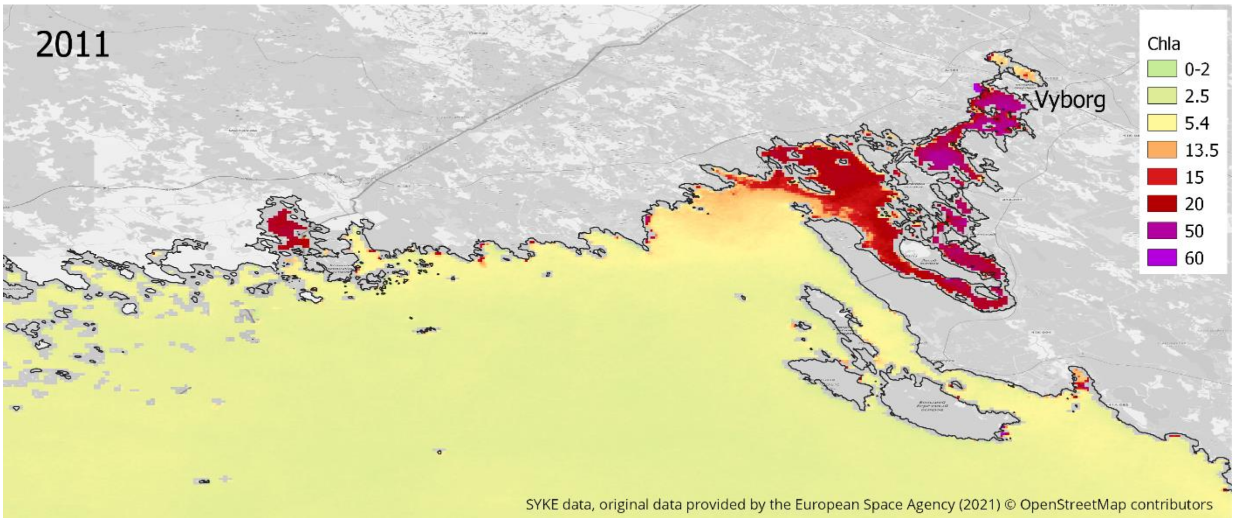



*Figure 19. Water quality maps for status assessment purposes are based on summerly aggregate of chl-a observations A) at the beginning of 2000's in 2003 and halfway of the 25-year period B) in 2011. Years 2003 and 2011 represent typical average of the period within the timeframe 2003−2011. For these years, the chl-a maps are based on ENVISAT MERIS satellite instrument observations and methods described in Attila et al. (2018).*

# 4. Conclusions based on long term analysis of water quality observations

The water quality data collected in SEVIRA cover the last 25 years and indicate the changes taken place in water quality and the level of eutrophication. We can conclude that there is a long-term positive trend in the status of coastal water areas of the Bays of Vyborg and Virolahti (as well as adjacent inner and outer archipelago region). Water quality and environmental condition in these coastal areas have improved over the last decade. An environmentally positive trend can be retrieved from all analyzed water quality parameters, each of which act as an indicator of eutrophication. The trend is clear both in terms of the reduction of nutrients and a decreasing chl-a concentration (as a proxy for the abundance of phytoplankton). Furthermore, in the coastal waters of the eastern GOF, both the cyanobacteria prevalence and the extent of verified cyanobacterial blooms have decreased, and the water has got clearer.

Despite of these positive changes in water quality, eutrophication is still a prevailing problem in large parts of the study area. This applies to the coastal estuaries and bays where the influence from the drainage basin is the most relevant through river inflow. At Virolahti Bay, another source of nutrients is aquaculture, i.e., local fish farms at the mouth of the bay. Furthermore, the magnitude of the internal load as a source of phosphorus and this load's effect on the eutrophication of the coastal and bay areas are largely unknown.

The occurred reduction in the land-based nutrient load is reflected in the quality of the coastal waters only after a long delay. Still, the changes can be observed when the cut in the load is sufficient. The improved and currently efficient wastewater treatment of St. Petersburg have had a marked effect on the water quality in the eastern GOF. A change for the better was first observed in the outer archipelago in the easternmost part of the Finnish coast but in recent years also in the inner archipelago due to local mitigation measures of eutrophication.

Monitoring of the coastal waters are needed so that the changes in water quality can be verified in the forthcoming years. This applies both to the Bay of Vyborg and the easternmost coastal waters of Finland. In the coastal area of south-eastern Finland, monitoring under the EU water management is a regular feature and implemented comprehensively. However, there is variation in the spatiotemporal coverage of water quality parameter observations bringing uncertainty to the analysis of long-term changes. The use of satellite observations has brought new opportunities for utilizing spatially and temporally comprehensive water quality observations. This is important for the areas and periods that are not currently covered well or at all by the national monitoring programs in station sampling. Within this project, new autonomous stations providing satellite observations were added to SYKEs TARKKA-service. These will continue providing observations of water quality and temperature after the project.

To gain a better status of water quality in the inland bays (e.g., Virolahti) the nutrient loads from the drainage basin should be reduced. Furthermore, an effective water management requires addressing the role of the internal loading of nutrients. In the Vyborg Bay, a further study identifying the relative amounts of varying sources of pollution is still needed. This is important for establishing effective water protection measures and continued mitigating of the effects of eutrophication in the bay. A further challenge is to estimate the influence of the main basin of the Baltic Sea, which at times extends as far as to the eastern part of the GOF. It is not just the local nutrient loads we must look at when assessing the state of the open sea and the outer archipelago region. On top of these, the climate change will shape the future of the eastern GOF.

There has been a long-term positive trend in water quality the Bays of Vyborg and Vironlahti during the last past years. The positive trend is clear both in the reduction of nutrients and as a decreasing trend in chl-*a* concentrations. In the coastal waters of the eastern Gulf of Finland, the effects of cyanobacteria blooms have decreased significantly, and the water has clarified. For the future improvements on coastal water quality, reducing the impact of riverine loads on the sea is important (diffuse pollution from agriculture and forestry). The use of satellite observations has brought new opportunities for spatially and temporally comprehensive collection of water quality observations. Within this project, new autonomous stations providing daily statistics on EO observations were added to the TARKKA-service. These automated stations will continue providing observations after the SEVIRA project on both countries.

- ⇨ As a relevant nutrient point source in the area is aquaculture, the location of the farms should be planned accurately.
- ⇨ It is important follow the changes in the quality of coastal waters in the future. In particular, actions should be taken to continue monitoring the water quality in the Vyborg Bay that currently does not have regular monitoring programme.
- ⇨ An additional challenge is to quantify the effects from the main basin of the Baltic Sea, which at times extend as far as to the eastern part of Gulf of Finland. Therefore, it is not just the local pressures to be considered when looking at the open sea and the outer archipelago region. Furthermore, for the future of eastern Gulf of Finland, also the effects of climate change will have to be paid attention.

# Lexicon

**ADCP** Acoustic Doppler Current Profiler

**Alg@line** a ferrybox system for automated measurements, operates on merchant ships

**BMP** Best Management Practice

**BSAP** Baltic Sea Action Plan

**CDOM** Coloured Dissolved Organic Matter

**CORINE** Coordination of Information on the Environment

**CUP** Calibration Uncertainty Program

**Chlorophyll-a (Chl-a)** Determines the algae abundance in the water. Monitoring of Chl-a provides information on the effects and state of eutrophication in the water.

**DEM** Digital elevation map

**ELY Centre** The Centre for Economic Development, Transport and the Environment

**EU** European Union

**EO** Earth Observations, satellite observations

**ESA** European Space Agency

**GOF** Gulf of Finland

**HELCOM** Baltic Marine Environment Protection Commission

**HRU** Hydrological Response Unit

**ILHM** Institute of Limnology Hydrological Model

**ILLM** Institute of Limnology Load Model

**ILRAS** Institute of Limnology at Russian Academy of Sciences

**IPSL** Institute Pierre-Simon Laplace

**MSI** Multi-Spectral Instrument onboard Sentinel-2 satellite series

**NASA** National Aeronautics and Space Administration (US)

**Nitrogen (N)** Nitrogen in waters originates from point and diffuse sources from catchment areas. Nitrogen deposition from air is an additional source of nitrogen in surface waters. Nitrogen is typically a limiting nutrient of algae growth during the summer period in the Baltic Sea. Spring bloom may consume algae-available nitrogen from the sea surface waters. This makes conditions favourable for nitrogen-fixing cyanobacterial blooms in case phosphorus is still available.

**North-West AHEM** North-Westt Administration for Hydrometeorology and Environmental Monitoring

**NS** Nash-Sutcliffe model efficiency coefficient

**OIVA** Open data portal by SYKE

**OLCI** Ocean and Land Colour Instrument onboard Sentinel-3 satellite series

**OLI** Operational Land Imager

**Phosphorus (P)** Phosphorus concentration in the Earth's crust is about one gram per kilogram. Weathering of phosphorus naturally from primary minerals is slow and of importance compared to phosphorus mobilisation and leaching to water bodies due to human activites. Phosphorus is an essential plant nutrient. Excess phosphorus in surface water originates typically from municipal waste water treatments plants and from diffuse sources, particularly from agriculture.

**QGIS** A Free and Open Source Geographic Information System

**RCP** Representative Concentration Pathways

**RSHU** Russian State Hydrometeorological University

**Sentinel-2** Satellite series by European Space Agency

**Sentinel-3** Satellite series by European Space Agency

**Suspended solids (SS)** Solid materials, including organic and inorganic materials, that are suspended in the water. Determination of suspended solids concentration requires filtration of water samples.

**SYKE** Finnish Environment Institute

**SWAT** Soil & Water Assessment Tool

**TARKKA** Web map service for satellite observations by SYKE (syke.fi/TARKKA/en).

**TIRS** Thermal Infrared Sensor

**Turbidity** Turbidity is measured optically. It can measured directly in a stream, lake or sea water with an in situ turbidity sensors or from water samples with laboratory devices. The scattering of light from material in water by clay, silt, inorganic and organic matter, algae, soluble coloured organic compounds, plankton and other microscopic organisms causes water to be turbid. Turbidity is commonly used as a proxy for estimating suspended solids content of water.

**WFD** Water Framework Directive by the EU

**WCRP CMIP5** World Climate Research Program Coupled Model Intercomparison Project Phase 5

**WGEN** Weather generator of SWAT model

**VEMALA** A national-scale nutrient loading model for Finnish watersheds

**VESLA** A database for surface water monitoring station observation in Finland

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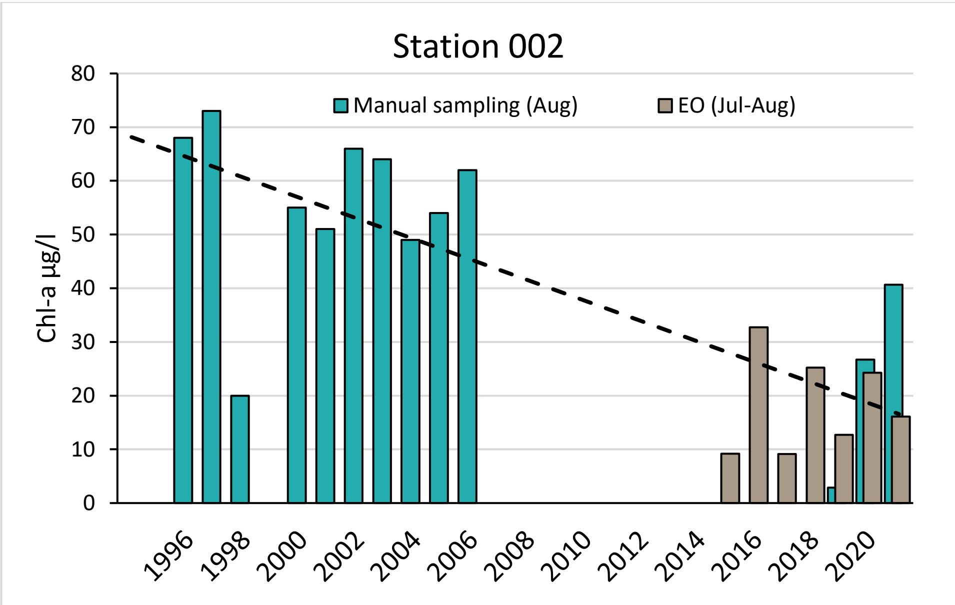
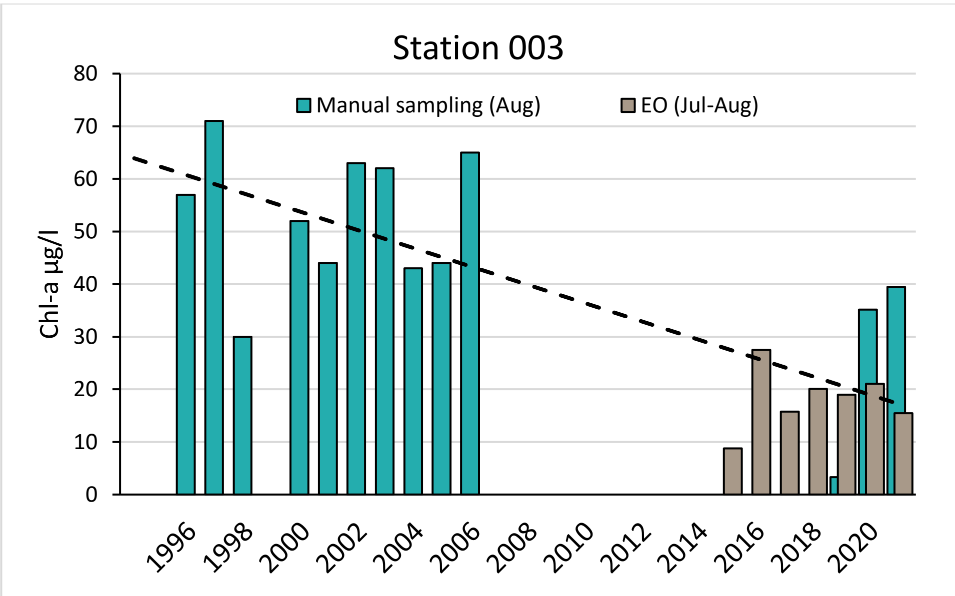
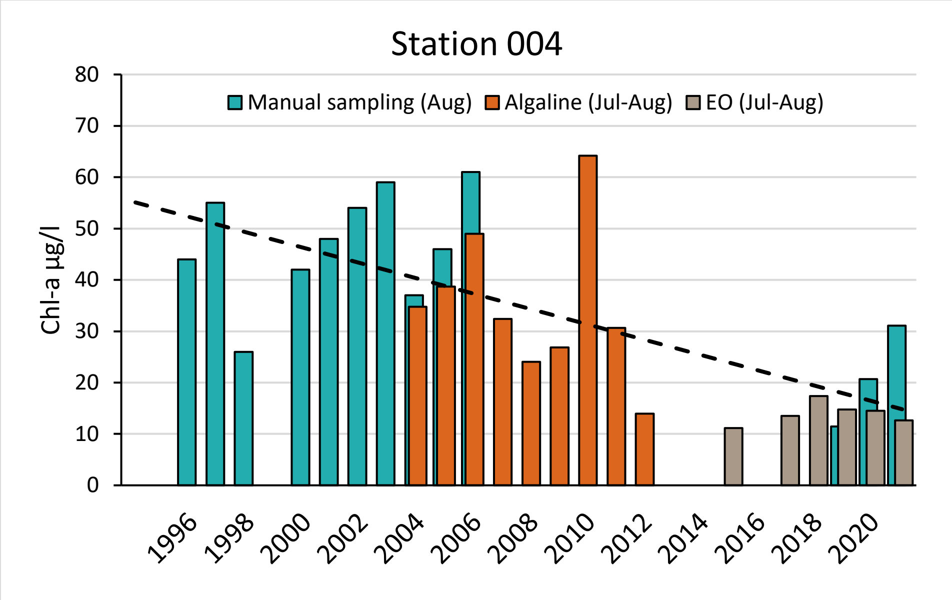
# Appendix.


Station 002
Manual sampling (Aug)
EO (Jul-Aug)
Chl-a µg/l
80
70
60
50
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

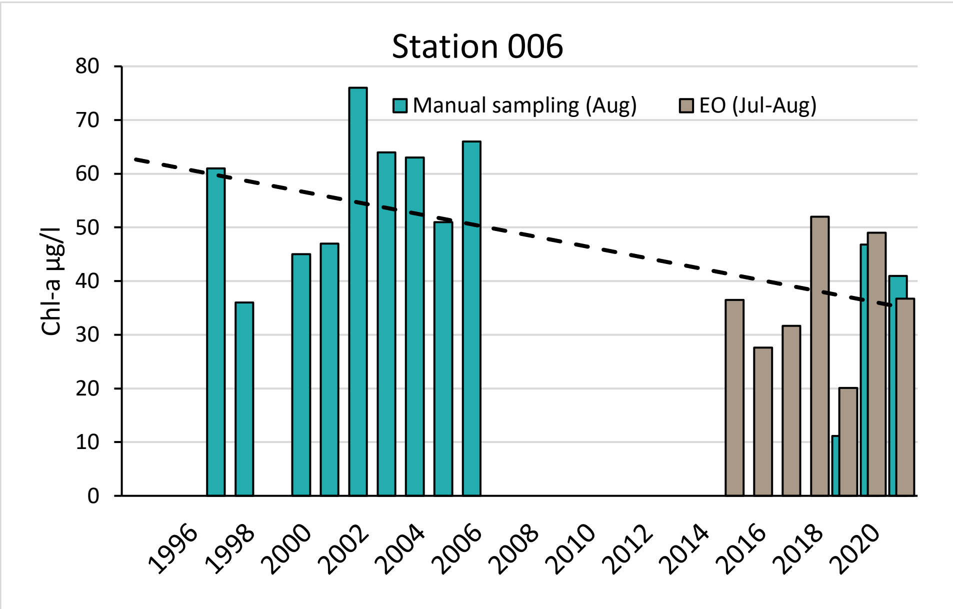
A)


Station 003
Manual sampling (Aug)
EO (Jul-Aug)
Chl-a µg/l
80
70
60
50
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

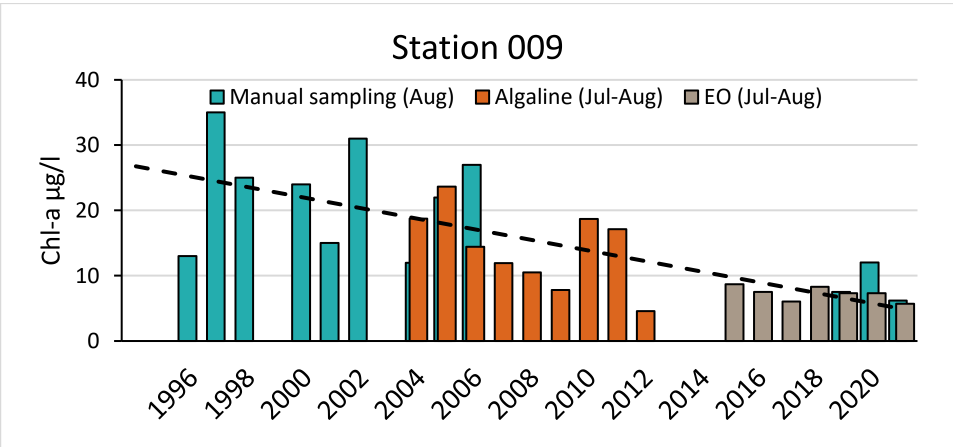
B)


Station 004
Manual sampling (Aug)
Algaline (Jul-Aug)
EO (Jul-Aug)
Chl-a µg/l
80
70
60
50
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

C)


Station 006
Manual sampling (Aug)
EO (Jul-Aug)
Chl-a µg/l
80
70
60
50
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

D)


Station 009
Manual sampling (Aug)
Algaline (Jul-Aug)
EO (Jul-Aug)
Chl-a µg/l
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

E)

F)

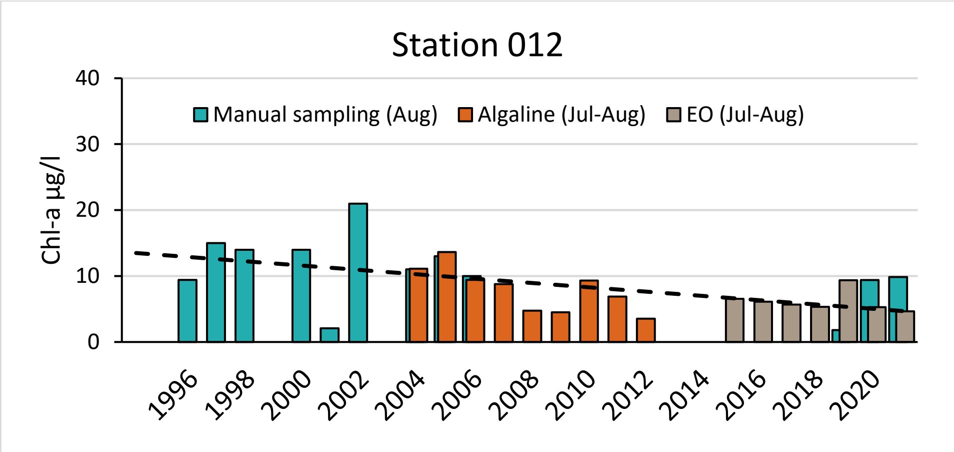
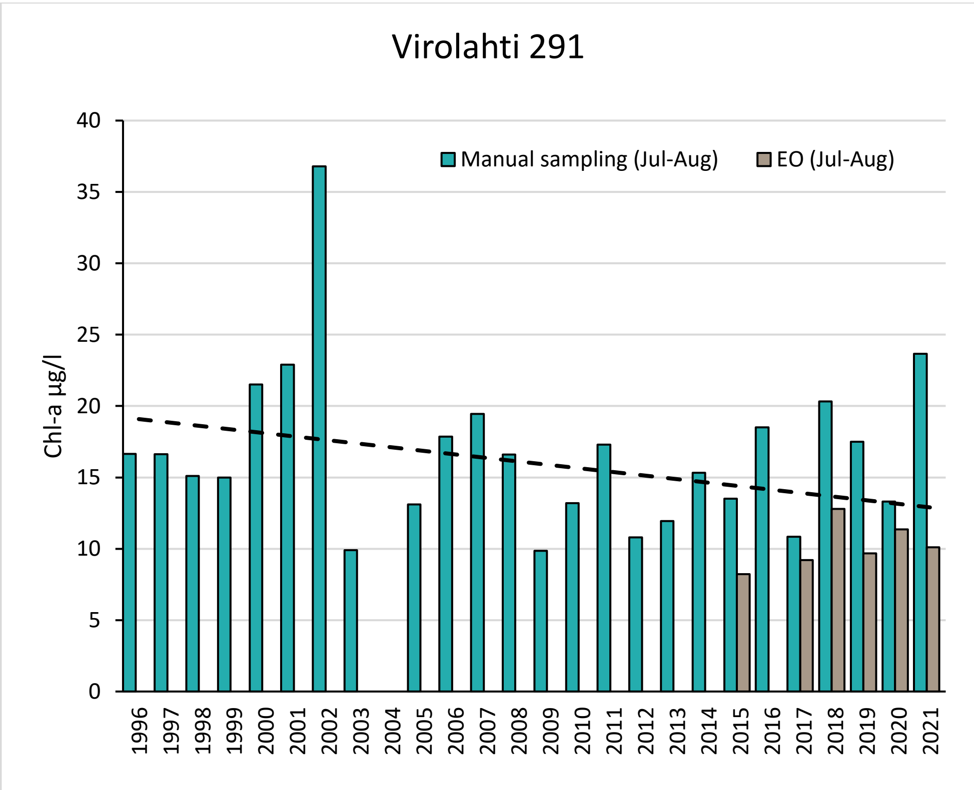
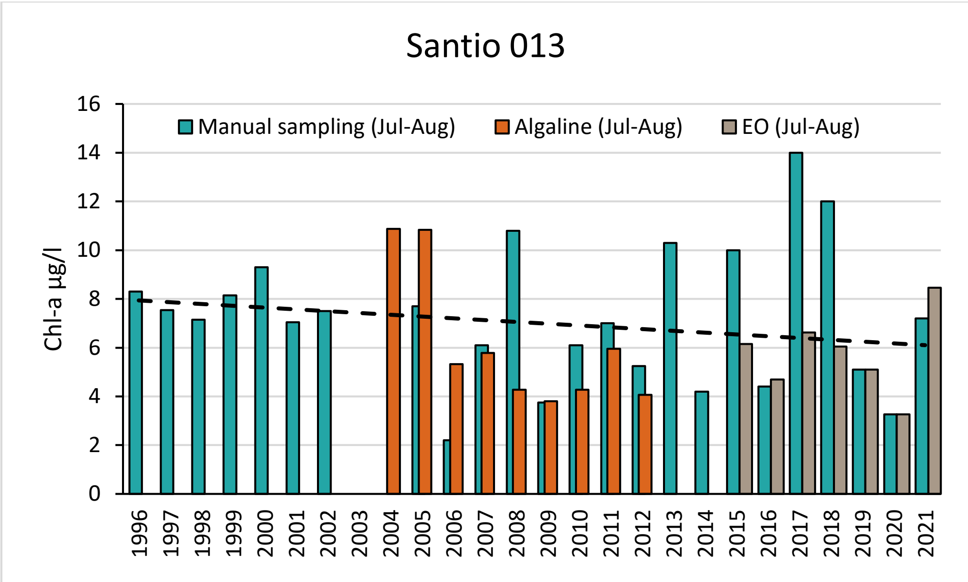


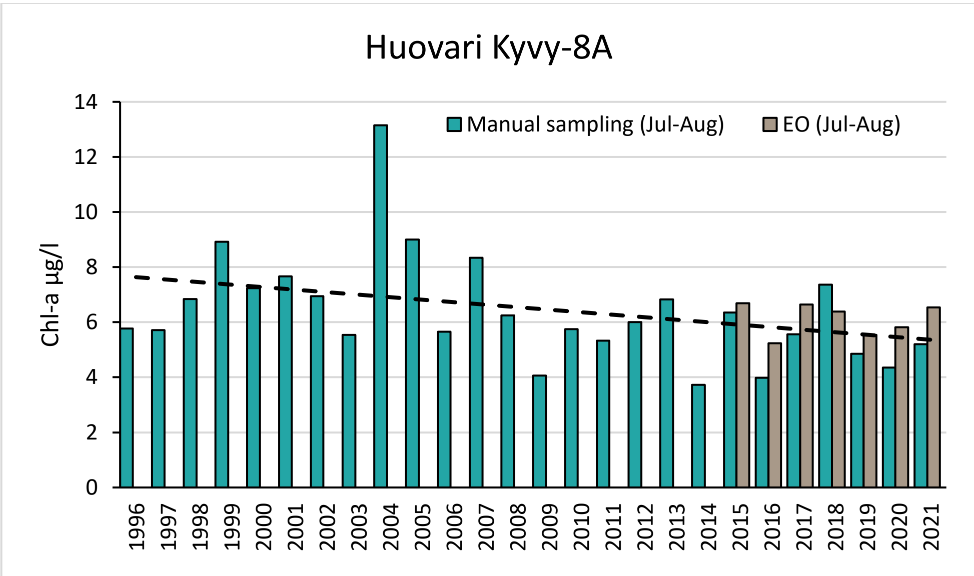

*Figure Appendix 1. Average late summer chl-a concentrations in surface water in the Vyborg Bay sampling stations starting from the year 1996. Station sites from A) to F) to represent the transect from the Rakkolanjoki estuary (A) towards the outer parts of the Vyborg Bay (F) (map of station sites in Fig. 18). Data from Vyborg Bay Joint Monitoring Program (cyan bars, 1996−2006), from Alg@line-data reconstruction (orange bars, 2004−2012) and 2015−2021, from satellite observations results (EO, 2015-2021, grey bars).*



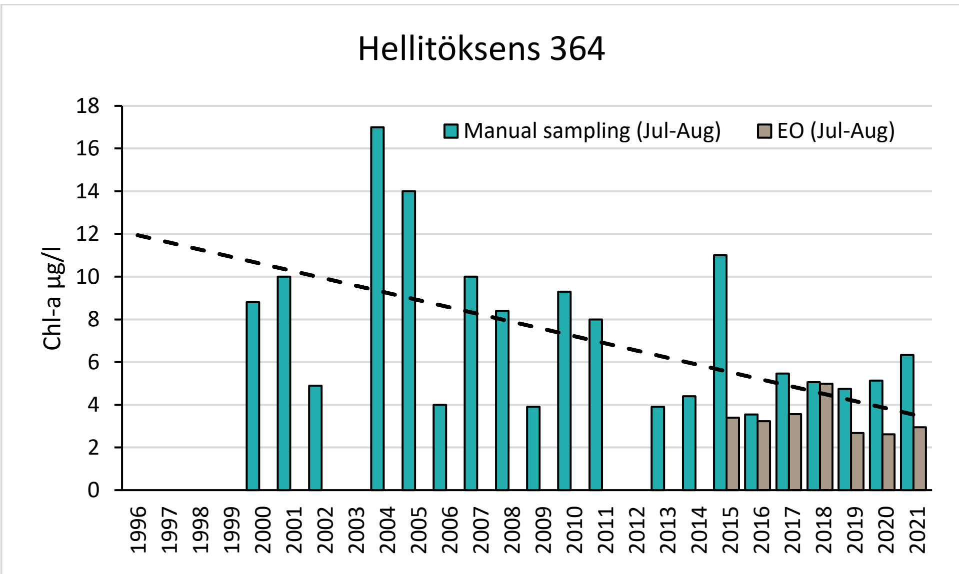

*A)*


Santio 013
Manual sampling (Jul-Aug)
Algaline (Jul-Aug)
EO (Jul-Aug)
Chl-a µg/l
0
2
4
6
8
10
12
14
16
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

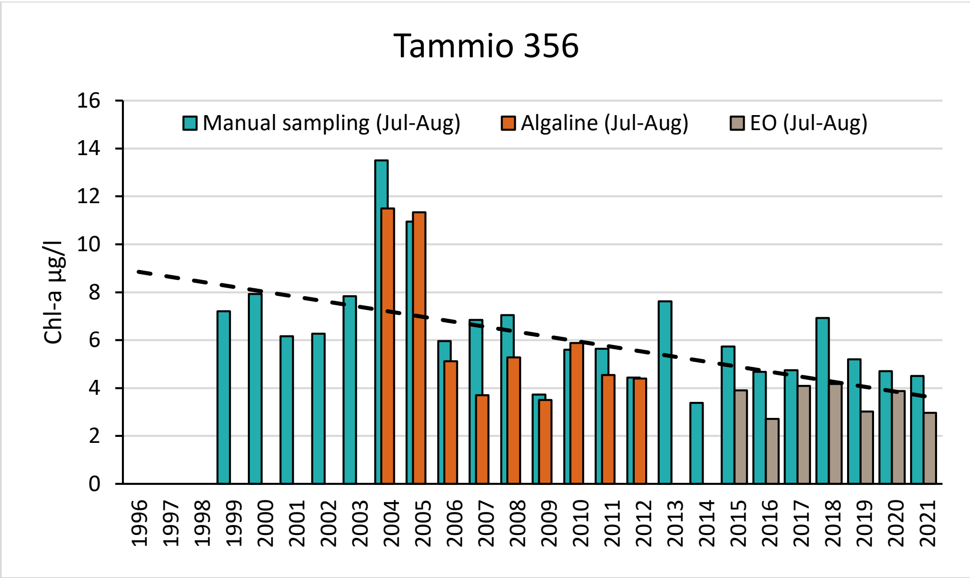
*B)*


Huovari Kyvy-8A
Manual sampling (Jul-Aug)
EO (Jul-Aug)
Chl-a µg/l
0
2
4
6
8
10
12
14
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

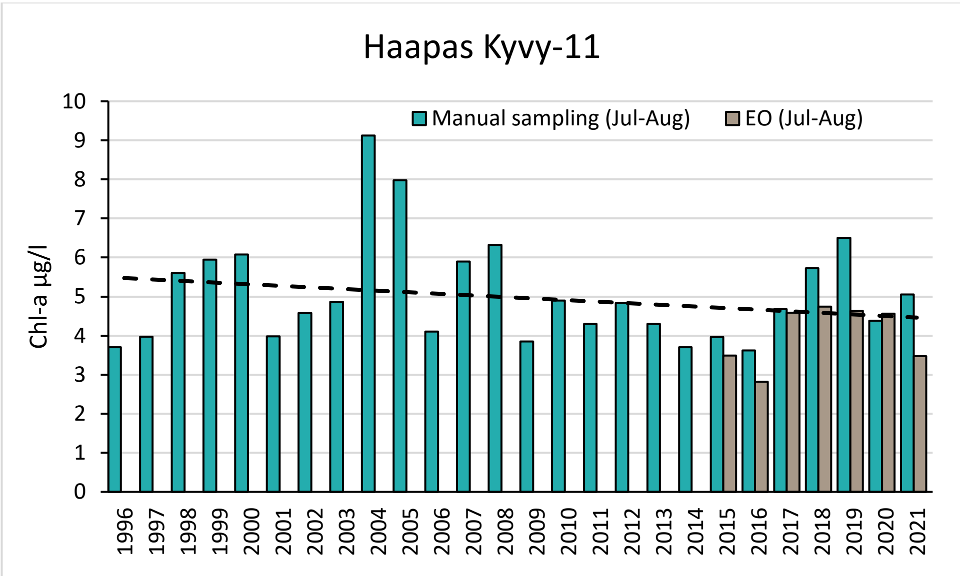
*C)*


Hellitöksens 364
Manual sampling (Jul-Aug)
EO (Jul-Aug)
Chl-a µg/l
0
2
4
6
8
10
12
14
16
18
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

*D)*




*E)*




*F)*

*Figure Appendix 2. Average late summer chl-a concentrations in the surface water in the Finnish coastal monitoring stations during 1996-2021 (cyan bars), from Alg@line-data reconstruction (orange bars in B and E, 2004-2012) and from satellite observations results (EO, 2015-2021, grey bars).*