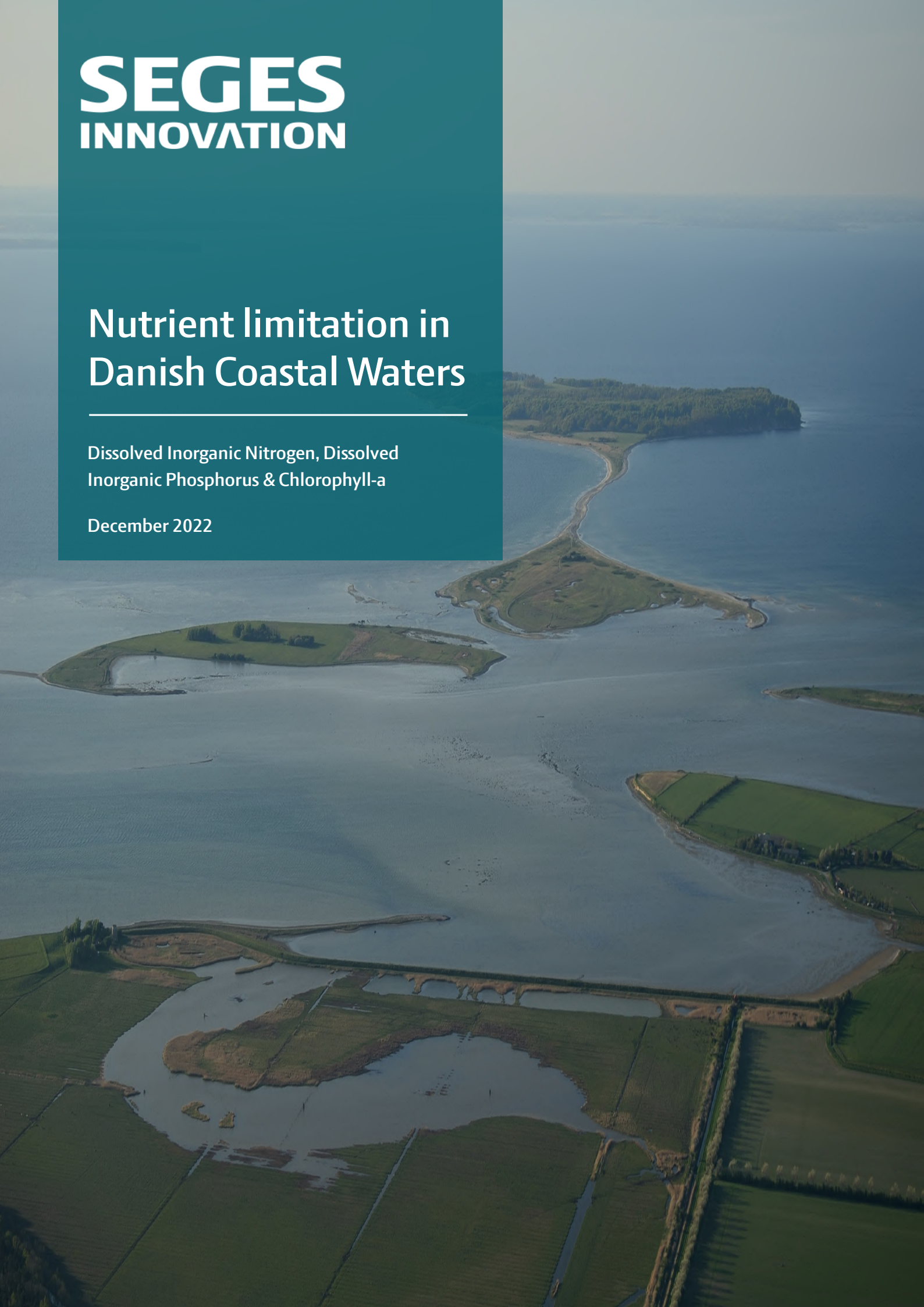
SEGES INNOVATION

Nutrient limitation in Danish Coastal Waters

Dissolved Inorganic Nitrogen, Dissolved Inorganic Phosphorus & Chlorophyll-a

December 2022



Nutrient limitation in
Danish Coastal Waters

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PLEASE CITE
Gertz F, Thostrup L K, Møller K D, 2022.
Nutrient limitation in Danish Coastal Waters
Report from SEGES Innovation

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FUNDED BY
Promilleafgiftsfonden

STØTTET AF
Promilleafgiftsfonden for landbrug

SUMMERY

This report includes 28 different coastal water locations, from very enclosed and fresh water influenced estuaries to straits and open coastal waters. 39 stations have been analysed for Dissolved Inorganic Nitrogen (DIN) Dissolved Inorganic Phosphorus (DIP) and Chlorophyll-a. Only data from stations with relatively long time series have been used. Some stations have data from 1980 and up to date while other stations have some data gaps but in general the data often covers 30-40 years. Monitoring frequency has changed over the 40 years. In the 1980s data was collected typically once a month or 10-12 times per year and this increased in the 1990s to typically 10-20 times per year and in a 10-year period from 1998 to 2007 the monitoring program peaked with typically 30 times per year or more. From 2007 and up to date it has typically been approx. 24 times a year.

Data shows in general over time a decrease in DIN, DIP and chlorophyll-a concentration and strongest in estuaries closest to fresh water source. By no surprise there is an increase in concentration in DIN, DIP and chlorophyll-a from open coastal waters towards estuaries with freshwater inflow. DIP is primarily decreased in 1980s and 1990s, which is corresponding to the major effort to reduce nutrients from point sources at this period. The decrease in DIP has led to a limitation of primary production (DIP limitation) seen as a decrease in chlorophyll-a in spring. In the estuaries DIP limitation typically starts in February and Marts and typically in April, May or June, DIN is becoming the limiting factor for primary production for the rest of the summer. The pattern for open coastal waters like Kattegat is different. DIN and DIP limitation happens here at the same time in early spring February and Marts and both DIN and DIP becomes limiting over the summer and often DIN more than DIP. DIN limitation also seems to be ongoing for a longer period into the autumn. Øresund (the strait between Denmark and Sweden) has less DIP limitation than similar waters and DIP has been increasing for the last 10 years. This could be due to relatively high input from point sources due to the population intensity (Copenhagen and Malmö). The overall conclusion is that both DIP and DIN play an important role for limiting primary production in both estuaries and open coastal waters with a very few exceptions. DIN does not play a role in Mariager Fjord and Inner part of Nissum Fjord. In Øresund DIP is playing a minor role for limiting primary production, properly due to relative high point source input. Otherwise DIP is important in estuaries for limiting primary production in typically February to May/June and DIN from May/June and the rest of the summer, while in open coastal waters both DIN and DIP are limiting the primary production from February and DIN is limiting also into autumn.

CONTENTS

PREFACE 1

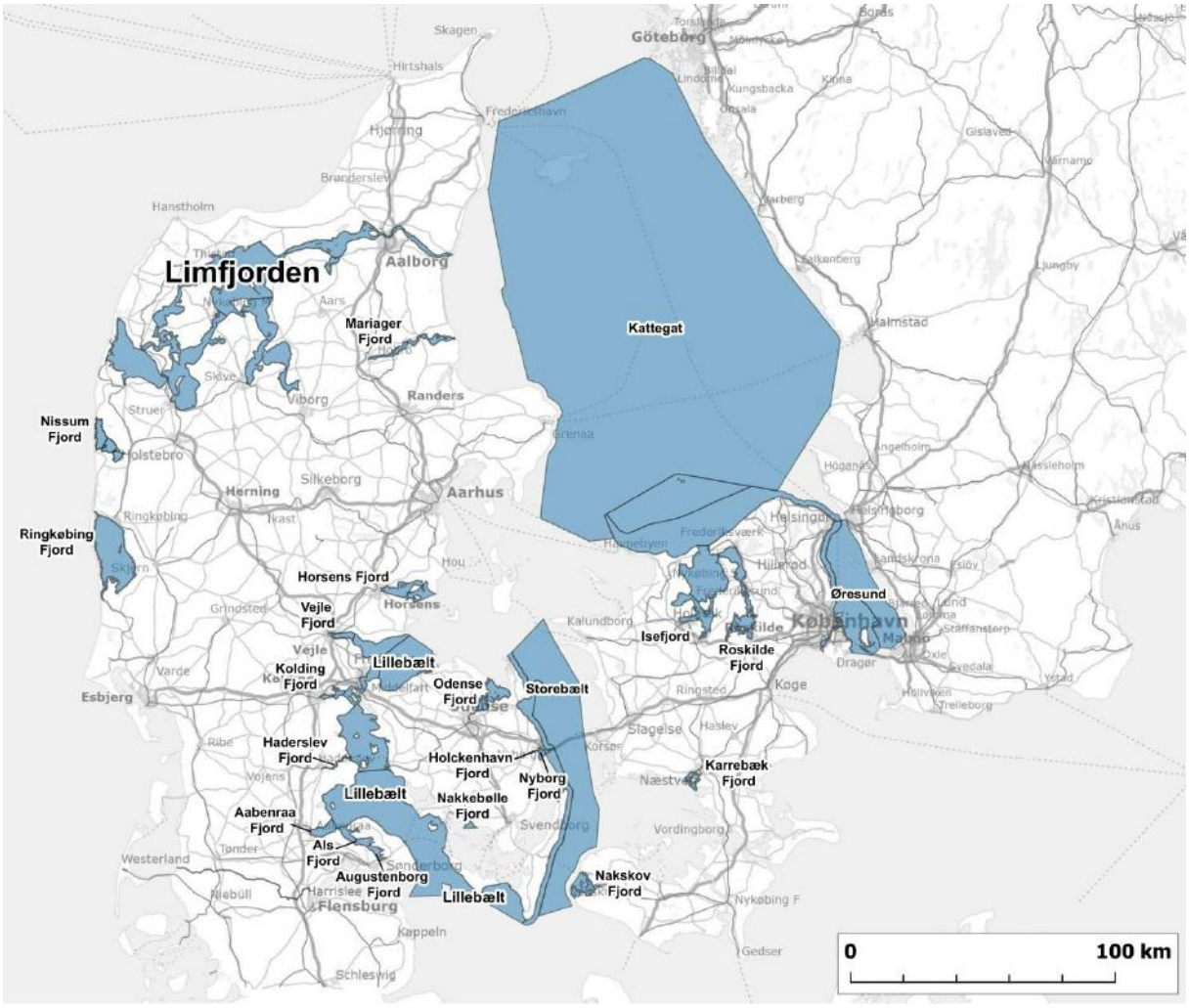
This report summarises some of the work SEGES Innovation has made since 2018 regarding Danish coastal waters. Due to the important discussion concerning the environmental conditions in the Danish coastal waters, SEGES Innovation has used the national monitoring data for coastal waters to investigate the role of nutrients in the coastal ecosystems. The monitoring goes back as far as early 1980's in some areas and it is therefore possible to carry out analyses for several important parameters and thereby gain knowledge about the role nutrients have played the last 40 years. The perspective in this report has been to tune in at specific water bodies concerning the levels of nutrients and how they have influenced the Chlorophyll-a levels (proxy for planktonic algae). The focus in the report is the levels of Dissolved Inorganic Nitrogen (DIN), Dissolved Inorganic Phosphorus (DIP) and how these levels have developed over the years and changed within a year with the perspective to understand how and when DIN or DIP are limiting the primary production. This report and another report concerning the physical oceanographic conditions in Danish coastal waters (Nielsen M.H. 2022) addresses some of the questions raised by a panel of international experts in 2017 (International evaluation 2017) concerning residence times in Danish estuaries, seasonal nutrient loadings and nutrient limitation patterns. It is our hope that both reports together will be able to shed light on both hydrodynamics / residence time and on the dynamics of DIP and DIN in relation to chlorophyll in Danish coastal waters.

DATA USED

2

2.1 Water Bodies

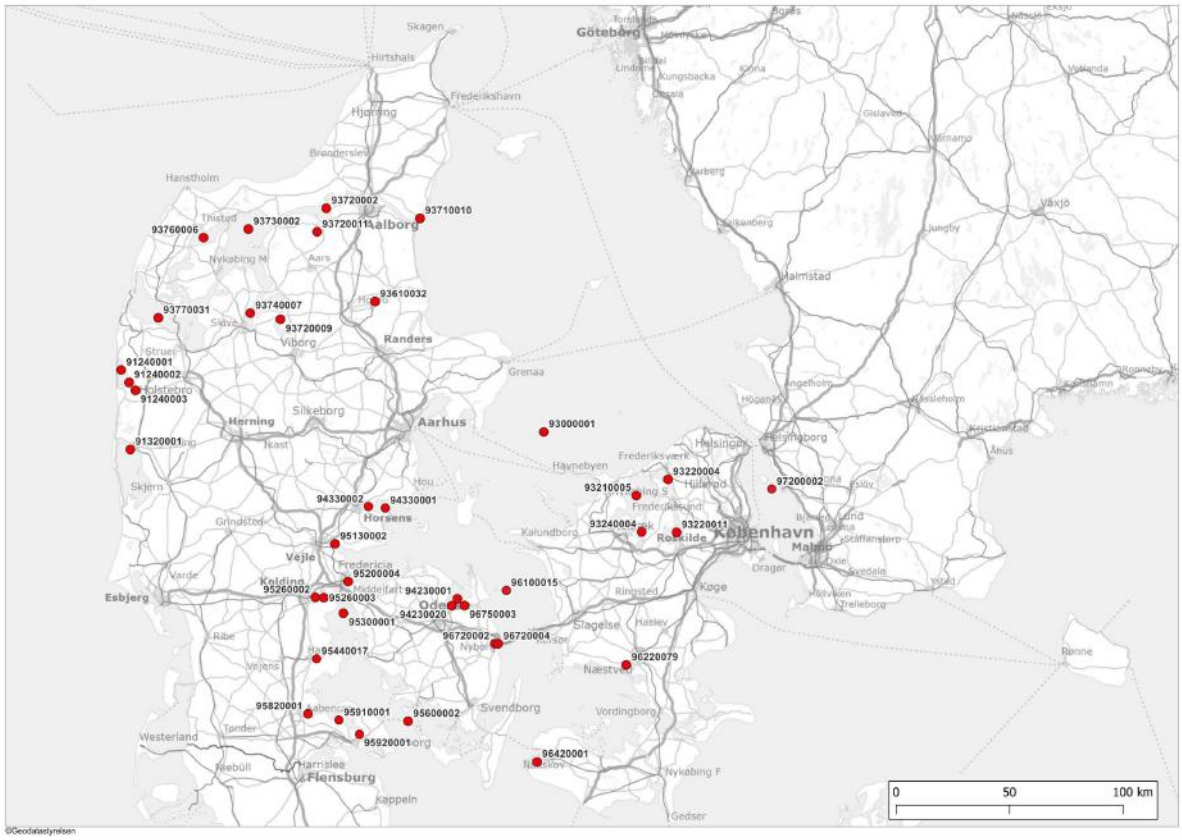
The chapters in the report refers to specific coastal water bodies (Figur 2.1). Small estuaries are in Denmark mostly referred to as a ”fjord”, even if they are shallow water lagoons (max water depth 3-4 m) as Ringkøbing Fjord and Nissum Fjord on the vest coast of Jutland or more deep and narrow water bodies like Vejle Fjord on the east coast of Jutland. Limfjorden is the largest estuary of the Danish ”fjords”, with a complex typology and therefore divided into smaller areas in the report (Figur 13.1).



Figur 2.1 Water bodies referred to as chapters in the report

2.2 Data stations

The report is based on data from the ”ODA-database”, which contains data collected within the Danish national monitoring program for water environment and nature (NOVANA). Not all stations in the monitoring program that includes data for Dissolved Inorganic Nitrogen (DIN), Dissolved Inorganic Phosphorus (DIP) and Chlorophyll-a are included in the report.



Figur 2.2 Monitoring stations included in the report.

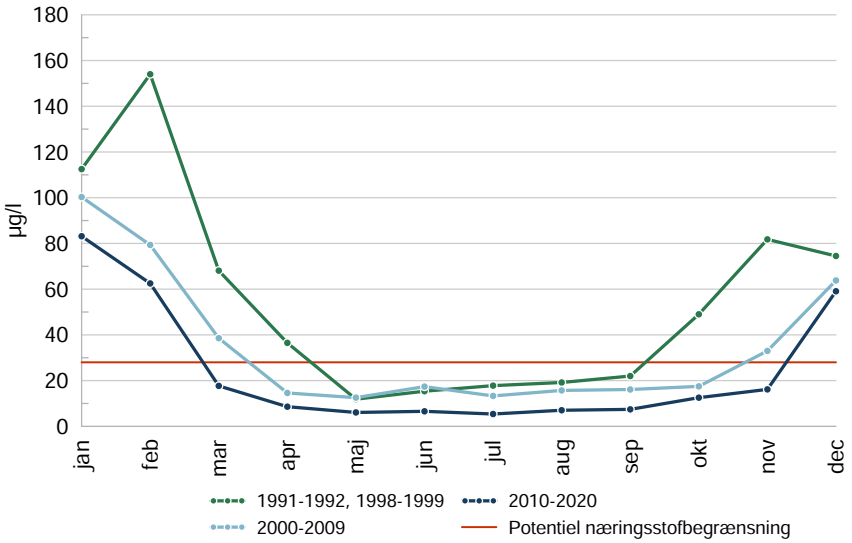
2.3 Nutrient limitation

Nutrient limitation of primary production in marine waters and estuaries has over time given raise to much scientific debate. Nitrogen is often referred as the primary limiting nutrient (Ryther 1971; Nixon 1992) but phosphorus has been argued to also play a role and be limiting at the same time as nitrogen (Paerl 2009, Riemann 2016) or that primary production can switch seasonally from being phosphorus-limited to nitrogen-limited (Malone 1996).

In this report DIN and DIP are defined as potentially limiting the primary production below concentration of 28 µg/l DIN and 6,3 µg/l DIP. These numbers contain a considerable uncertainty but are aligned with the figures reported from Aarhus University to the national authorities (Hansen 2021).

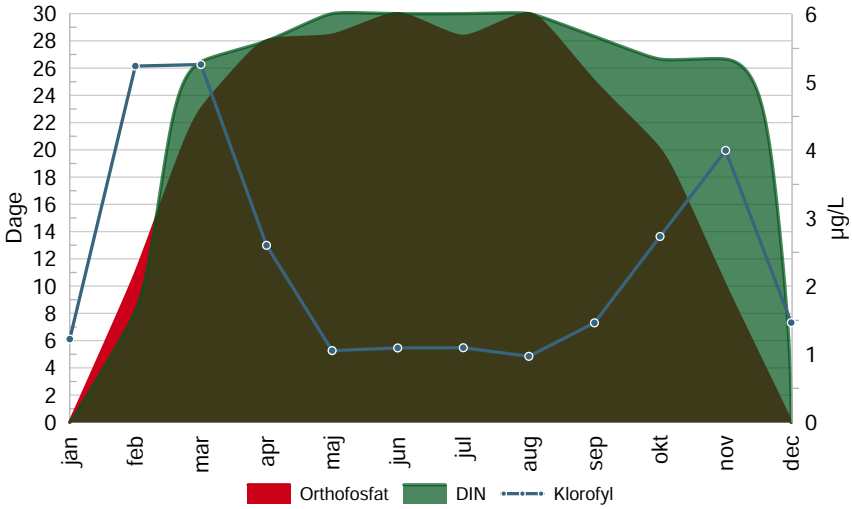
Data used in the reporting is from the upper part of the water column above the stratification. In Kattegat and other open water stations it is the upper 10 m while in the estuaries it is the upper 1-2 m.

Two different methods are used to illustrate nutrient limitation. One method is using monthly average values of DIN and DIP with 10 years average for each month. Below an example from Kattegat (Figur 2.5). The potential DIN-limitation at 28 µg/l is marked by red line. It has not always been possible to make 10 years average for each month and in these cases it is marked in the figure text as seen for the 1990s where only 4 years of data were available.



Figur 2.3 Average DIN-concentration per month (µg/l) in upper water column for periods 1991-1992/1998-1999, 2000-2009 and 2010-2020 at station 93000001 in Kattegat. Only few samples in winter month in 1991 and 1992.

The other graphic method is using number of days per month with nutrient limitation. This means number of days with levels of nutrients below the potential limitation of primary production (28 µg/l DIN and 6,3 µg/l DIP). Also as a 10 years monthly average. The water samples are taken approximately 2 times per month and therefore the monitoring is not able to represent daily or even weekly fluctuations. Therefore the method is a simple counting of samples below 28 µg/l for DIN and 6,3 µg/l for DIP per month and over 10 years (primary axis). Below same example from Kattegat (Figur 2.4). Also included is the average concentration per month of chlorophyll-a (secondary axis).

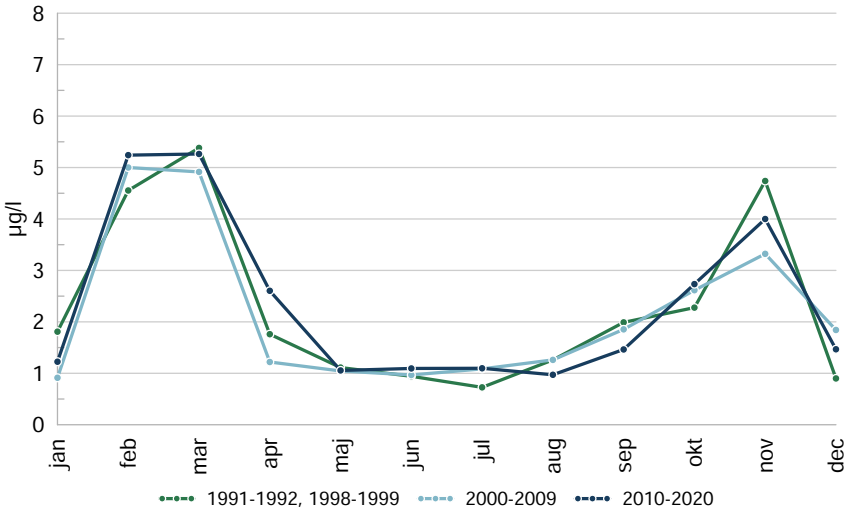


Figur 2.4 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column (psu 15-22, depth ≤ 10 meter) at station 93000001 in Kattegat.

2.4 Chlorophyll-a

Data regarding chlorophyll-a concentrations are from the same water sampling as used for nutrients. Spectrophotometer method for determining chlorophyll absorbance is used (Markager 2013). Data from the upper photic zone are used. In the estuaries it is the upper 1-2 m while in Kattegat and other open water stations it is the upper 10 m. During summer a chlorophyll-a maximum can occur in the stratified layer at 10-15 m due to the mix of bottom water, rich in nutrients, into the upper layer. This maximum is excluded on purpose in the reporting due to the dynamic nature in both time and space. Chlorophyll-a concentrations are presented as monthly average values with 10 years average for each month. It has not always been possible to make 10 years average for each month and in these

cases it is marked in the figure text as seen for the 1990s where only 4 years data where available. The boundary between good and moderate status for Chlorophyll-a concentrations related to the Danish RBMP is marked by a green straight line. Some of the figures are not updated with the latest RBMP 3 number, and the correct RBMP 3 number is noted in the text.



Figur 2.5 Average Chlorophyll-a -concentration per month (µg/l) in upper water column for periods 1991-1992/1998-1999, 2000-2009 and 2010-2020 at station 93000001 in Kattegat. No boundary for good-moderate status in RBMP3.

AABENRAA FJORD

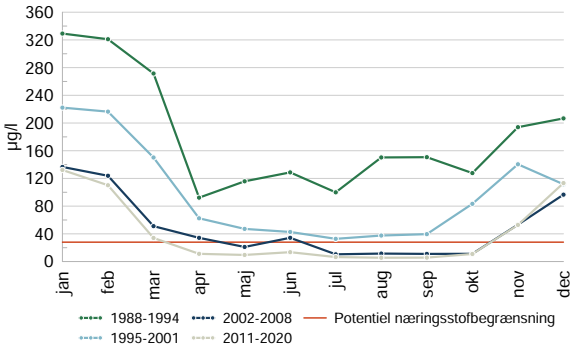
3

Aabenraa Fjord is a small estuary with a wide boundary to the Little Belt (Lillebælt), which entails a large exchange of water with the Little Belt. The catchment area for the fjord is relatively small compared to the estuary. The estuary is relatively deep, with water depths of up to approx. 35 m in the inner part, while in the outer part and in Little Belt the deepest parts are approx 25 m.

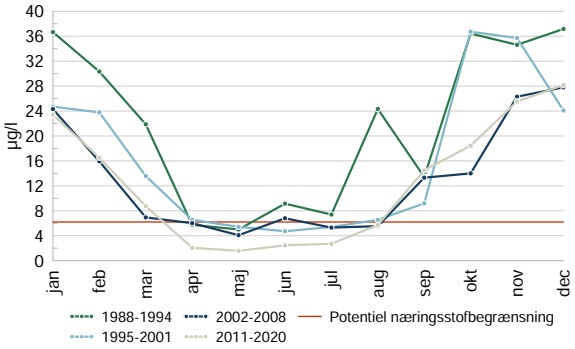
Figur 3.1 Water bodies and monitoring stations

Aabenraa Fjord	
Water body area	31 km^2
Catchment area	80 km^2
Area ratio (catchment/water body)	2.5
Water depth max.	35 m
Salinity	12-28 psu
Stratification	Periodic

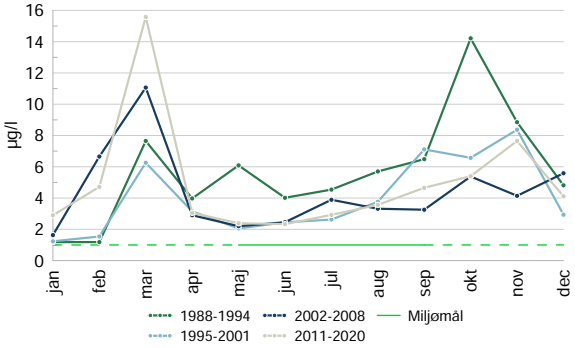
Aabenraa Fjord, station 95820001



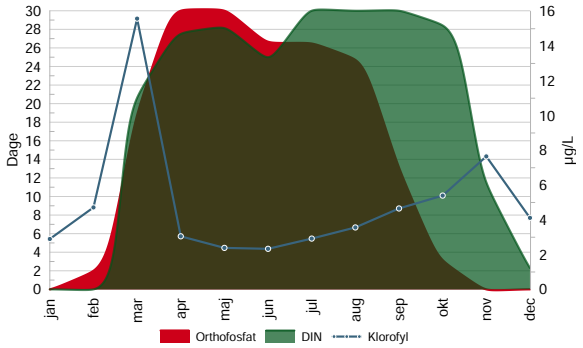
Figur 3.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1988-1994 and 1995-2001 and 2002-2008 and 2011-2020.



Figur 3.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1988-1994 and 1995-2001 and 2002-2008 and 2011-2020.



Figur 3.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1988-1994 and 1995-2001 and 2002-2008 and 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1 µg/l.

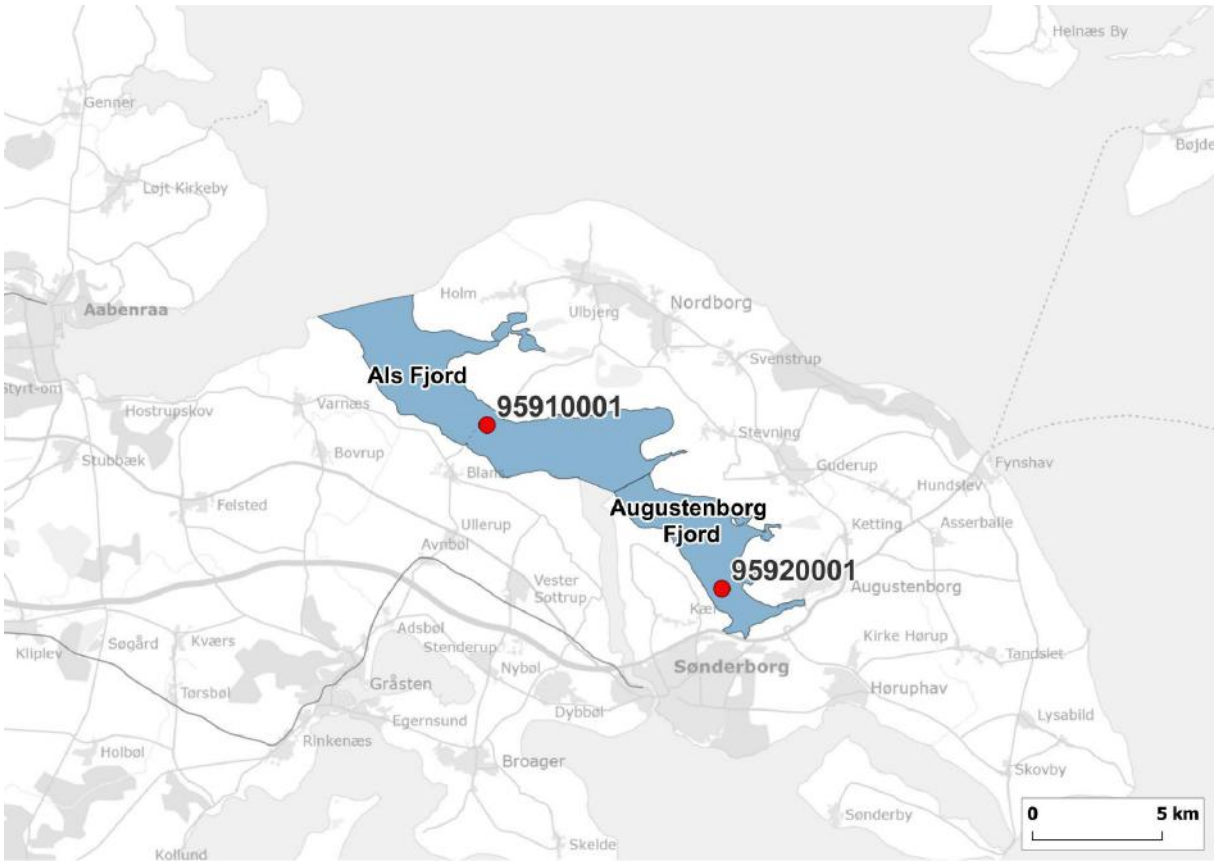


Figur 3.5 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

ALS/AUGUSTENBORG FJORD

4

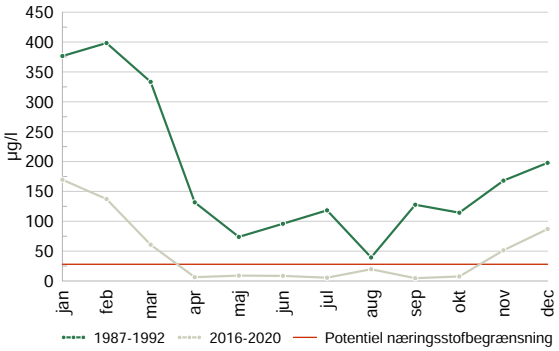
Als Fjord is an extension of Augustenborg Fjord and the total length is about 20 km. At the outer part to Aabenraa Fjord the opening is relatively wide and deep (30 m). In Als Fjord the depth decreases gradually to approx 15 m in the central part of Augustenborg Fjord. In the middle between Als Fjord and Augustenborg Fjord the narrow strait ”Als Sund” makes a connection to the water body south of Sønderborg city. The water exchange is very dynamic and influenced by flows in Lillebælt of more brackish Baltic water and more salty Kattegat water. The salinity can change very rapidly and within a few days the water column may be replaced either in the surface layer of brackish water, or in the bottom layer of heavier Kattegat water.



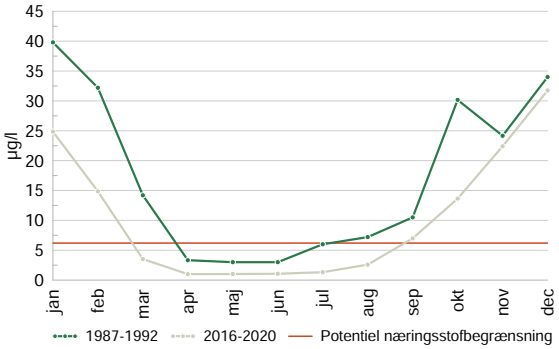
Figur 4.1 Water bodies and monitoring stations

Als/Augustenborg Fjord	
Water body area	48,5 km^2
Catchment area	194 km^2
Area ratio (catchment/water body)	4
Water depth max.	31 m
Salinity	6-25 psu
Salinity stratification	Periodic

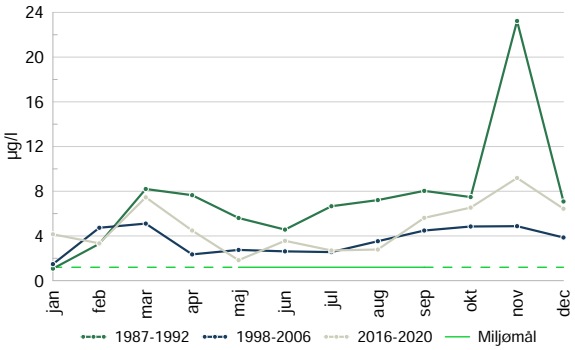
Als Fjord, station 95910001



Figur 4.2 Average **DIN**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 2016-2020.

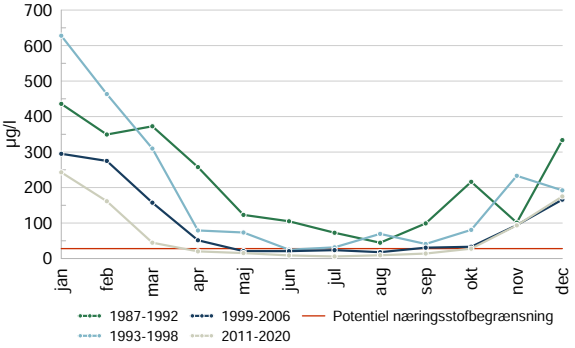


Figur 4.3 Average **DIP**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 2016-2020.

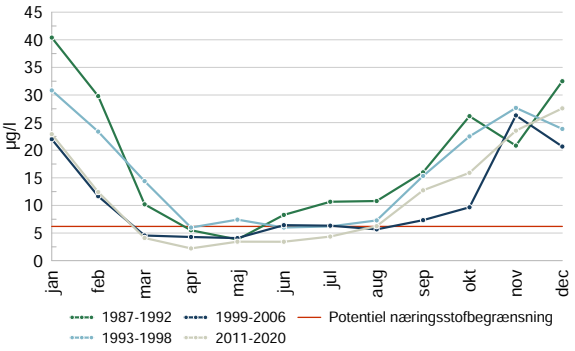


Figur 4.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 1998-2006 and 2016-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1.2 µg/l.

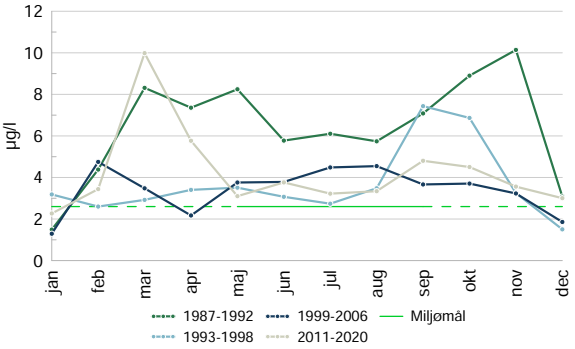
Augustenborg Fjord, station 95920001



Figur 4.5 Average **DIN**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 1993-1998 and 1999-2006 and 2011-2020.

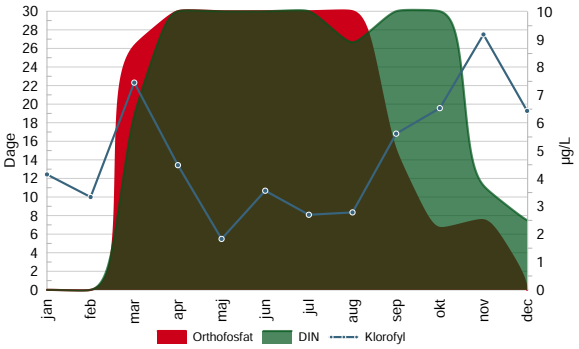


Figur 4.6 Average **DIP**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 1993-1998 and 1999-2006 and 2011-2020.



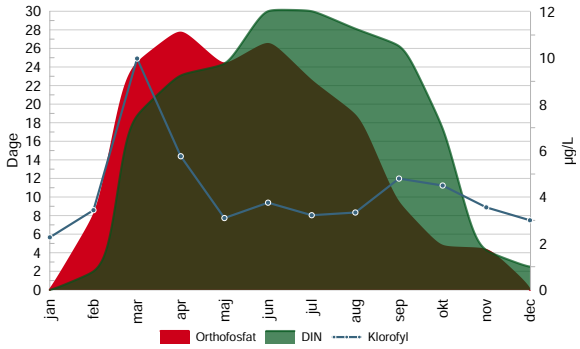
Figur 4.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for periods 1987-1992 and 1993-1998 and 1999-2006 and 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.6 µg/l.

Als Fjord, station 95910001



Figur 4.8 Number of days per month with DIP and DIN limitation as an average of the period 2016-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2016-2020 (secondary axis). Upper water column.

Augustenborg Fjord, station 95920001

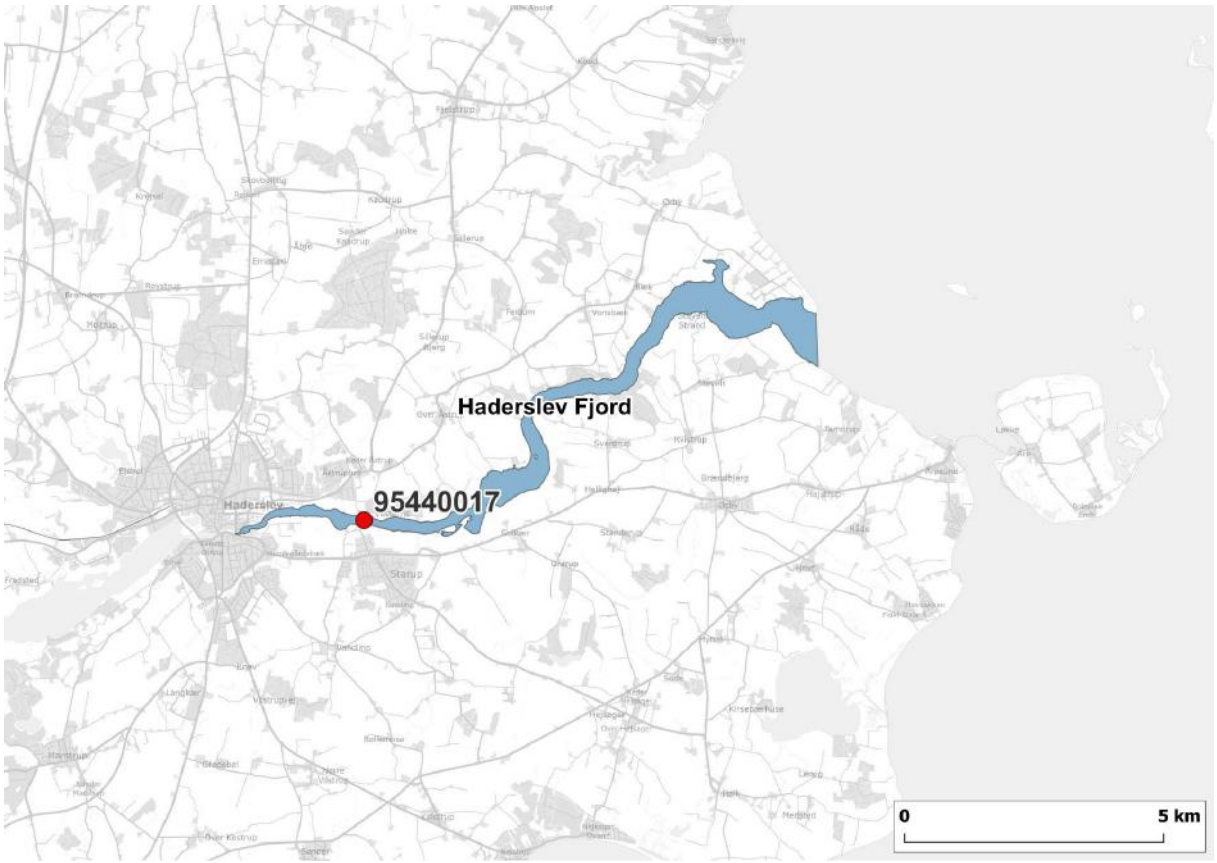


Figur 4.9 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

HADERSLEV FJORD

5

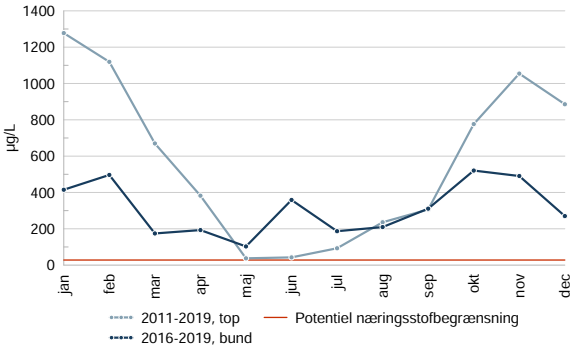
Haderslev Fjord is a long and narrow estuary (approx. 15 km long and 300 m wide) connected to Little Belt (Lillebælt) to the east. The estuary has a narrow excavated channel at approx. 6 m depth to ensure cargo transport by ships to Haderslev harbour, but the rest of the estuary is shallow at approx. 1 m water depth. Due to the channel and water depth of 6 m stratification occurs most of the year in the channel. The salinity in the inner part varies annually between 1-20 psu in the upper water column and 14-26 psu in the bottom layer, the lowest salinity in the surface layer occurs in the winter months.



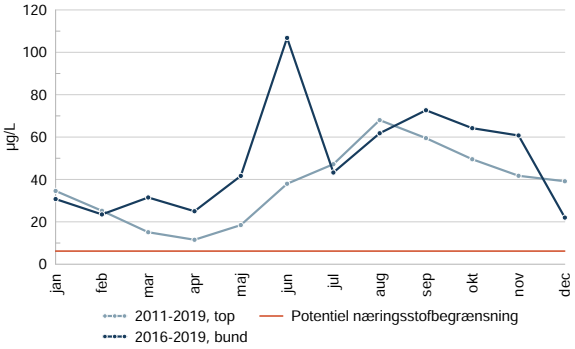
Figur 5.1 Water bodies and monitoring stations

Haderslev Fjord	
Water body area	5 km^2
Catchment area	185 km^2
Area ratio (catchment/water body)	37
Water depth max.	11 m
Salinity	1-26 psu
Stratification	Mostly

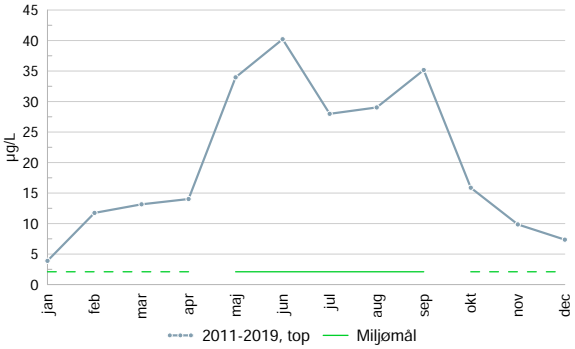
Haderslev Fjord, station 95440017



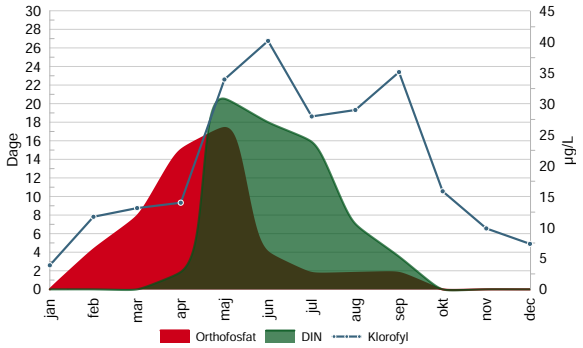
Figur 5.2 Average **DIN**-concentration per month (µg/l) in upper water column for periods 2011-2019 and in lower water column 2016-2019.



Figur 5.3 Average **DIP**-concentration per month (µg/l) in upper water column for periods 2011-2019 and in lower water column 2016-2019.



Figur 5.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for periods 2011-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 8.2 µg/l - green line not updated.

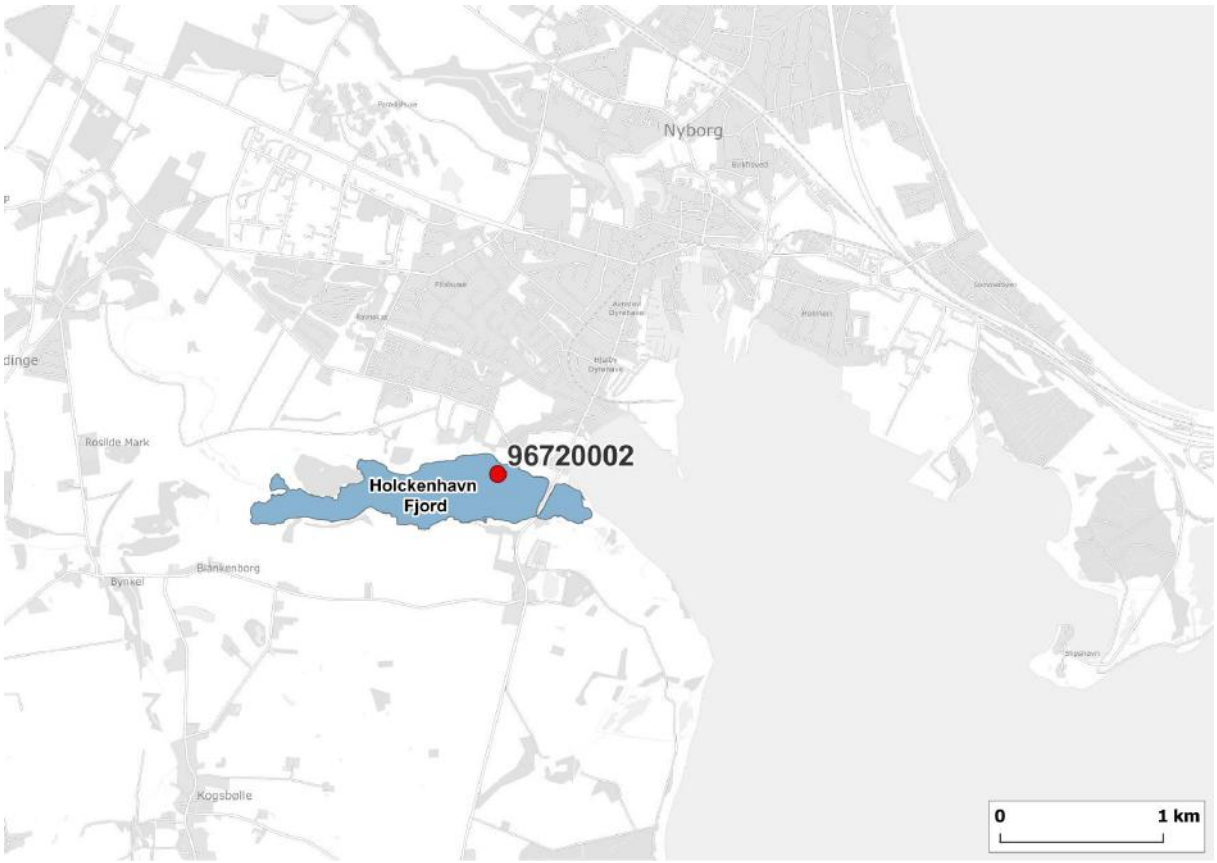


Figur 5.5 Number of days per month with DIP and DIN limitation as an average of the period 2011-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2019 (secondary axis). Upper water column.

HOLCKENHAVN FJORD

6

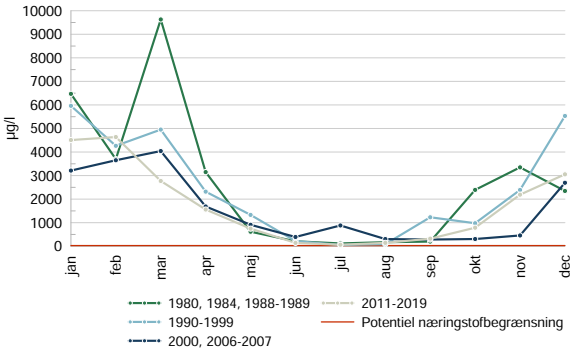
Holckenhavn Fjord is a small estuary with connection to Nyborg Fjord through a 7,5 wide passage in a dam. The estuary is shallow (no data, but presumably no more than 1.-2 m) and has a relatively large supply of fresh water. The water column is mostly stratified with up to 20 psu at the bottom and as low as 1 psu at the surface, typically in winter periods with large freshwater runoff. There is no registered oxygen depletion despite stratification, but the constant water replacement and renewal of bottom water with oxygen-rich surface water from Nyborg Fjord probably prevents oxygen depletion, however, this is somewhat uncertain.



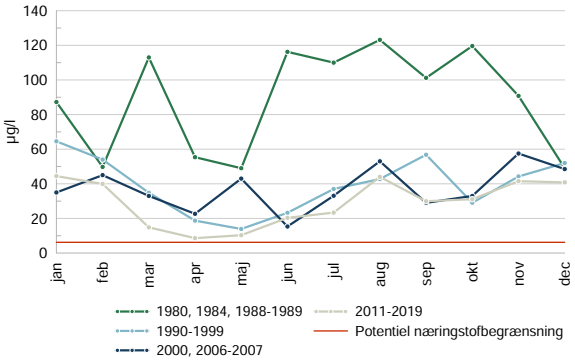
Figur 6.1 Water bodies and monitoring stations

Holckenhavn Fjord	
Water body area	0.5 km^2
Catchment area	220 km^2
Area ratio (catchment/water body)	440
Water depth max.	2 m
Salinity	1-20 psu
Stratification	Mostly

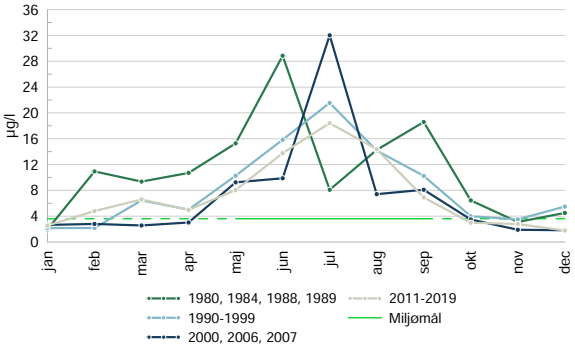
Holckenhavn Fjord, station 96720002



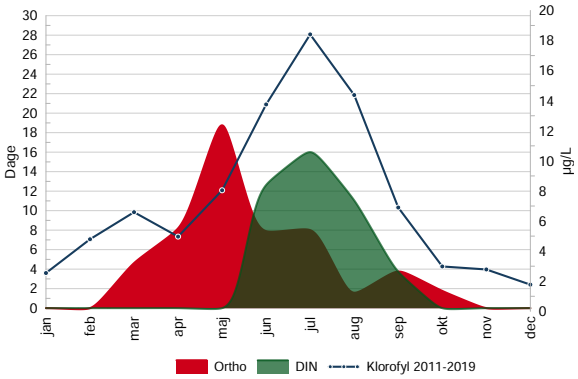
Figur 6.2 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1980, 1984, 1988, 1989 and 1990-1999 and 2000, 2006, 2007 and 2011-2019.



Figur 6.3 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1980, 1984, 1988, 1989 and 1990-1999 and 2000, 2006, 2007 and 2011-2019.



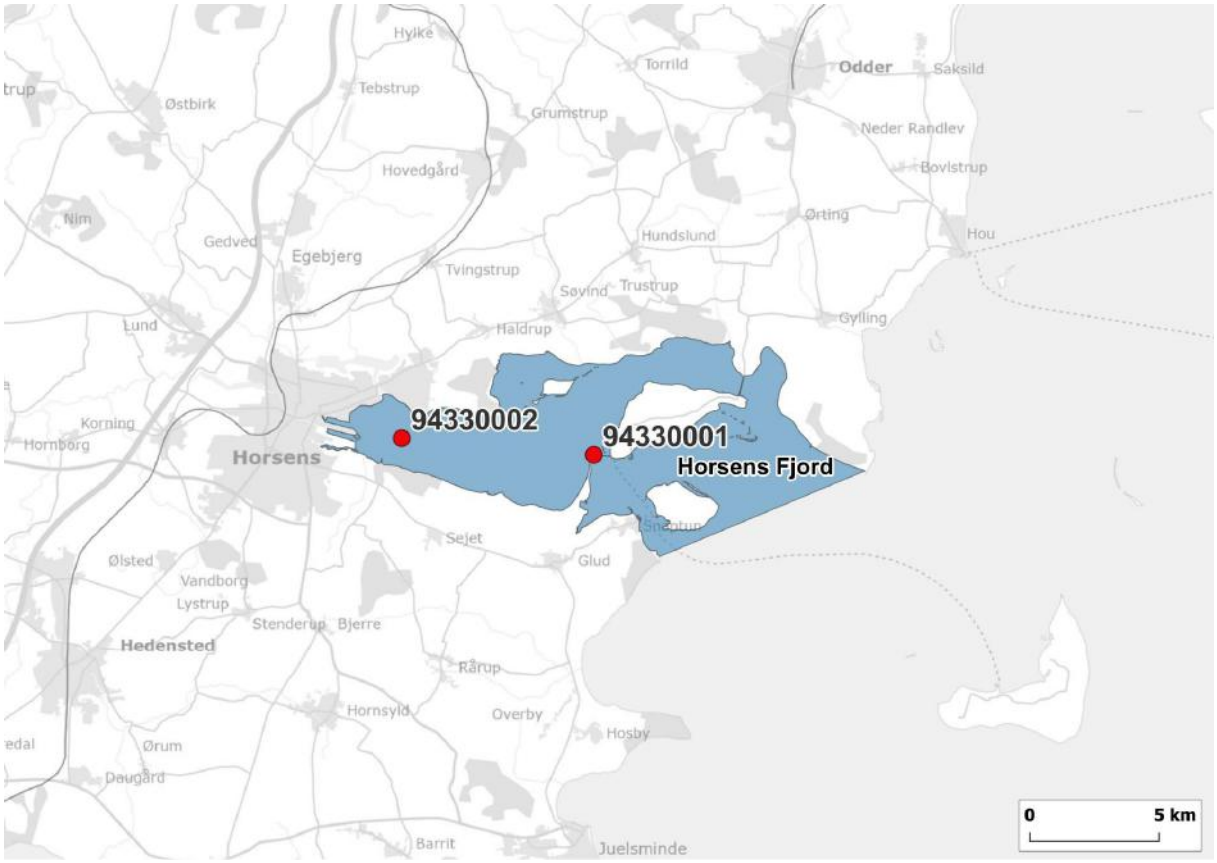
Figur 6.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for for 4 periods: 1980, 1984, 1988, 1989 and 1990-1999 and 2000, 2006, 2007 and 2011-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 4.7 µg/l - green line not updated.



Figur 6.5 Number of days per month with DIP and DIN limitation as an average of the period 2011-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2019 (secondary axis). Upper water column.

HORSENS FJORD 7

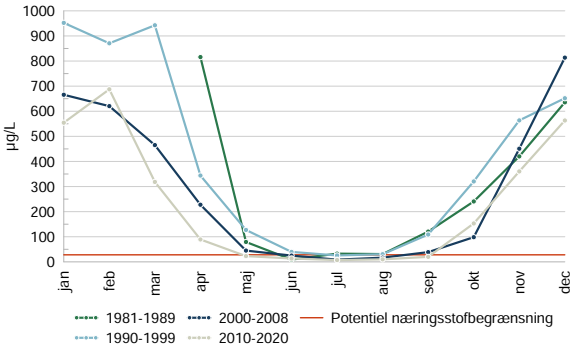
Horsens Fjord is an estuary divided into an inner part (46 km^2) and an outer part (33 km^2) with a wider boundary to the Kattegat. The inner part is relatively shallow with a depth of approx. 1-3 m in the most inner part, gradually increasing to approx. 7 m. Water passage is blocked to the north by a dam. The flow to the inner part takes place especially south of the islands through a channel with a water depth of up to 22 m. The salinity in the inner part varies annually between 6 - 28 psu in the upper water column and 13 – 32 psu in the bottom layer.



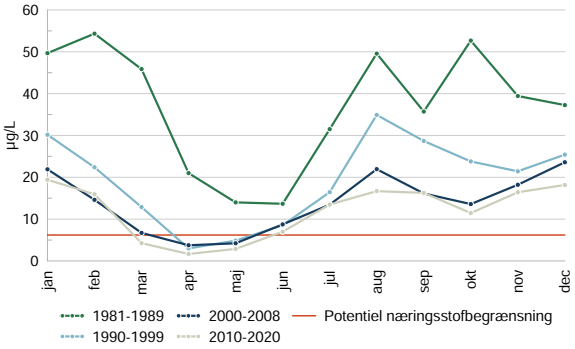
Figur 7.1 Water bodies and monitoring stations

Horsens Fjord	
Water body area (inner)	46 km^2
Catchment area (inner)	492 km^2
Area ratio (catchment/water body)	11
Water depth max.	22 m
Salinity	6-32 psu
Salinity stratification	Periodic

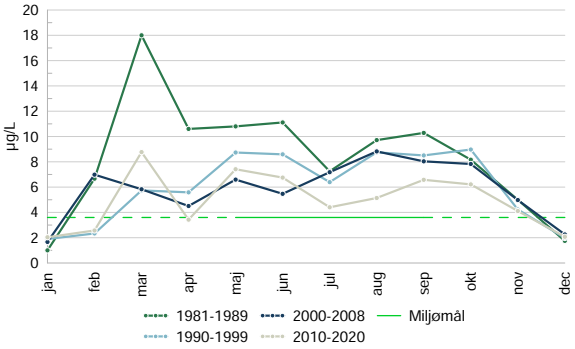
Horsens Fjord, inner part, station 94330002



Figur 7.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2008 and 2010-2020.

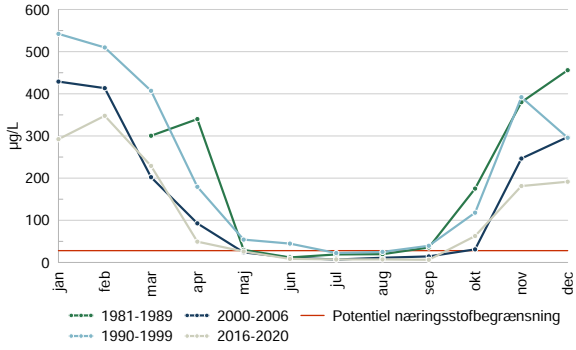


Figur 7.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2008 and 2010-2020.

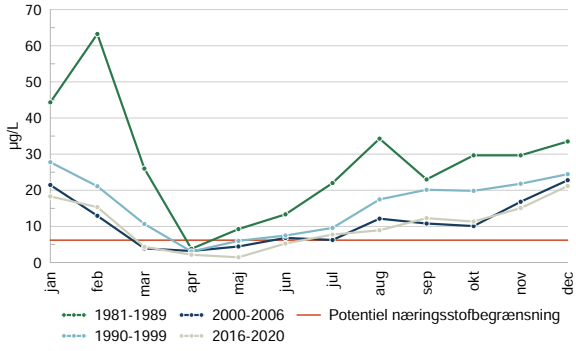


Figur 7.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2008 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.3 µg/l - green line not updated.

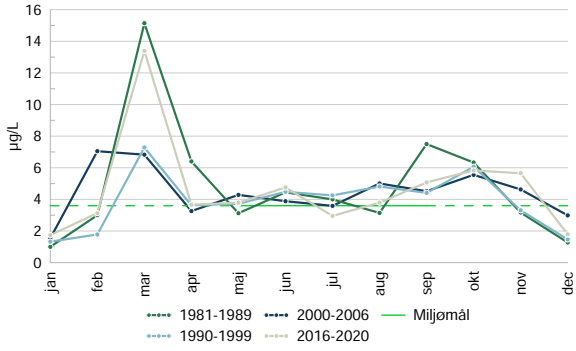
Horsens Fjord, middle part, station 94330001



Figur 7.5 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2006 and 2016-2020.

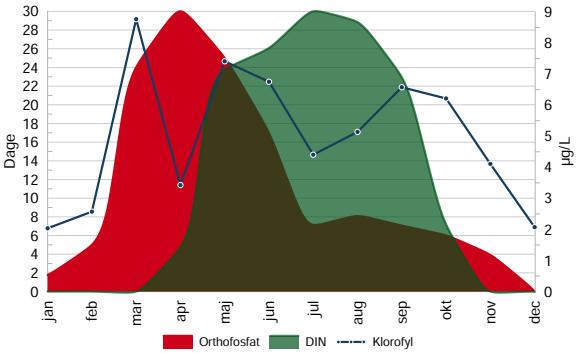


Figur 7.6 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2006 and 2016-2020.



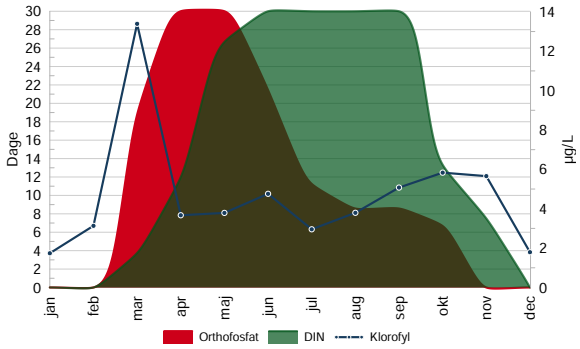
Figur 7.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1981-1989 and 1990-1999 and 2000-2006 and 2016-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1.9 µg/l - green line not updated

Horsens Fjord, Inner part, station 94330002



Figur 7.8 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

Horsens Fjord, middle part, station 94330001



Figur 7.9 Number of days per month with DIP and DIN limitation as an average of the period 2016-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2016-2020 (secondary axis). Upper water column.

ISEFJORD

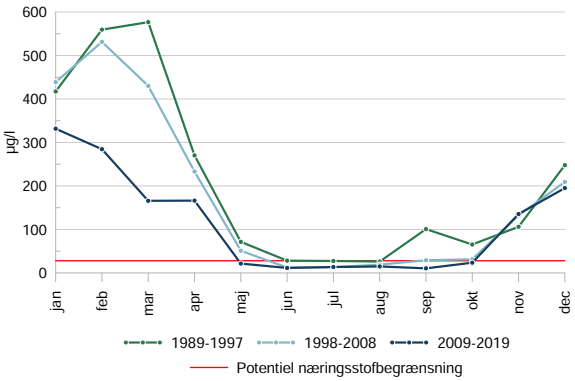
8

Isefjord consists of a larger outer part and a inner part separated by the island ”Orø” and connected via two relatively narrow straits west and east of Orø to the inner and smaller part. In the outer part, the water depth is typically 8 – 10 m. A large part of the inner part has a depth of 6 – 8 m. The salinity in different parts of the fjord has been measured at several stations during the period 1989-1997 and the data shows that the salinity is relatively similar in the different parts of the fjord and varies over the year in the same way. The observed salinities in Isefjord are all relatively high and close to the observed salinities in the southern Kattegat. The latter primarily in winter (20-25 psu), while in summer there is a difference between the Kattegat and the salinity of the fjord, in part because the salinity in the fjord decreases in the summer (15-20 psu), despite lower runoff from land. Nowhere in the Isefjord is there evidence of freshwater runoff from land in the form of stratification or upper layers with lower salinity. This shows that there is rapid mixing of the water masses and that there is a large exchange of water between the Isefjord and the southern Kattegat especially in the winter.

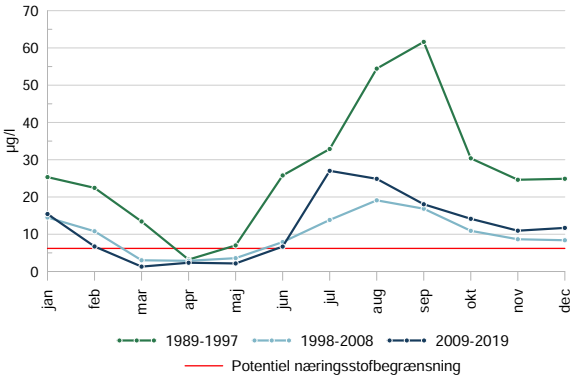
Figur 8.1 Water bodies and monitoring stations

Isefjord	
Water body area	314 km^2
Catchment area	767 km^2
Area ratio (catchment/water body)	2.4
Water depth max.	11 m
Salinity	15-25 psu
Salinity stratification	no

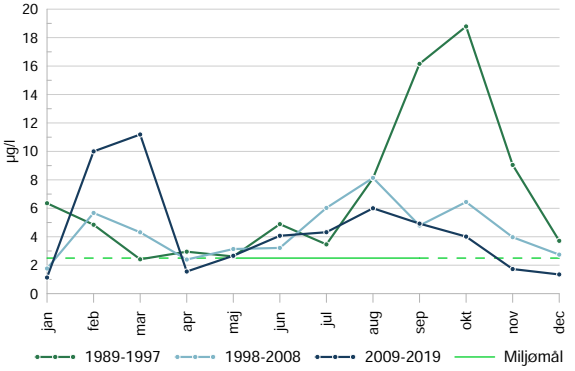
Isefjord, inner part, station 93240004



Figur 8.2 Average **DIN**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019.

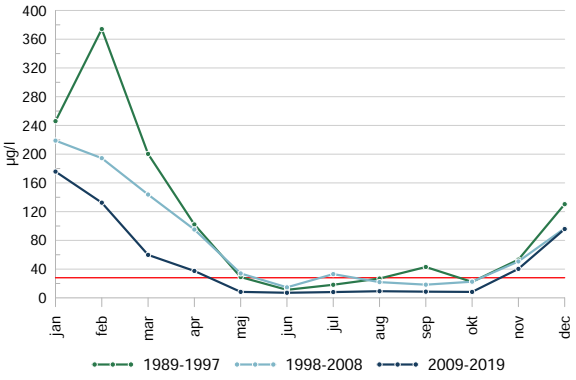


Figur 8.3 Average **DIP**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019.

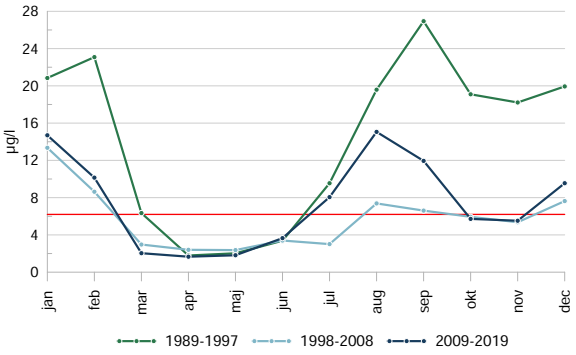


Figur 8.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 2.5 µg/l.

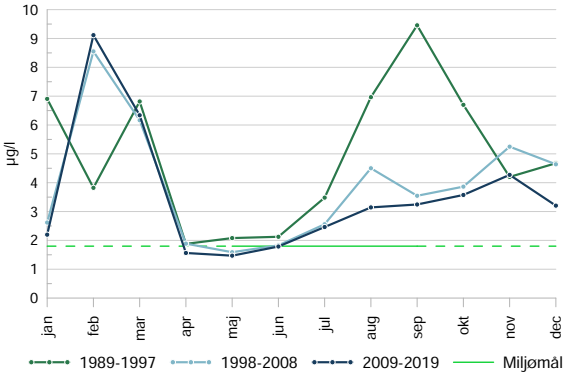
Isefjord, outer part, station 93210005



Figur 8.5 Average **DIN**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019.

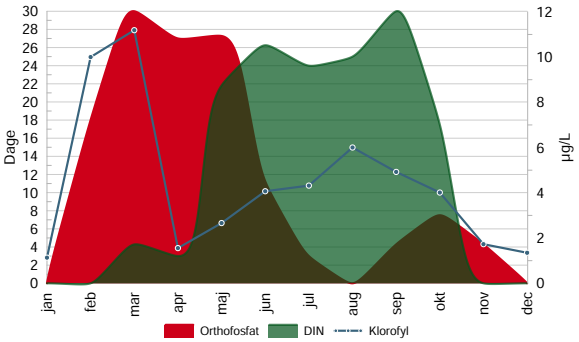


Figur 8.6 Average **DIP**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019.



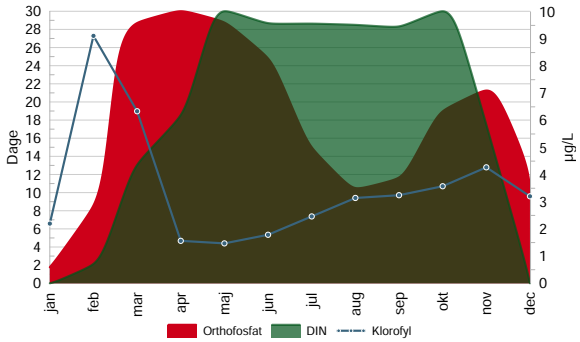
Figur 8.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods 1989-1997 and 1998-2008 and 2009-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 1.8 µg/l.

Isefjord, inner part, station 93240004



Figur 8.8 Number of days per month with DIP and DIN limitation as an average of the period 2009-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2009-2019 (secondary axis). Upper water column.

Isefjord, outer part, station 93210005

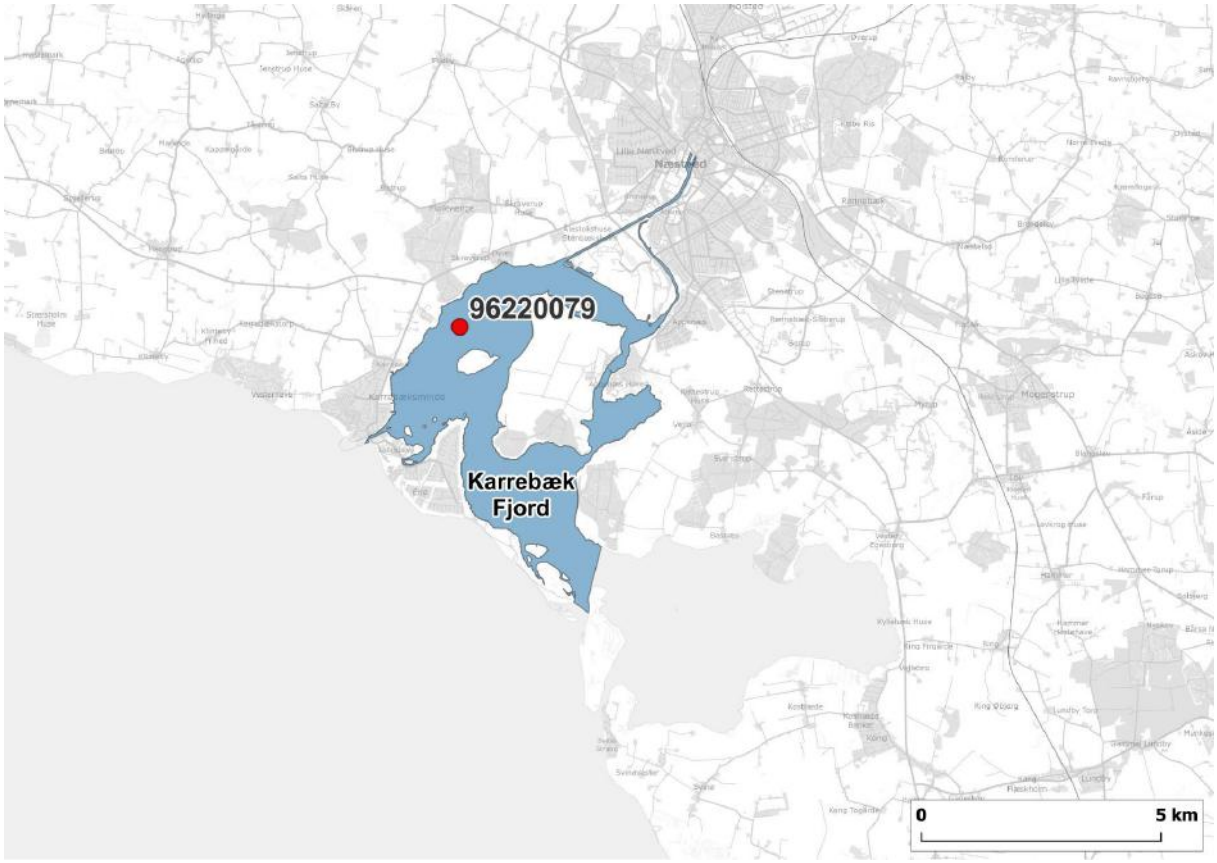


Figur 8.9 Number of days per month with DIP and DIN limitation as an average of the period 2009-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2009-2019 (secondary axis). Upper water column.

KARREBÆK FJORD

9

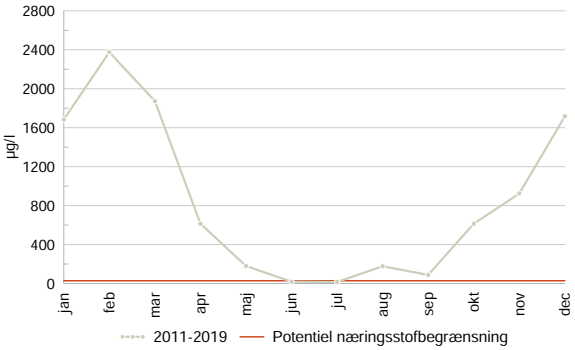
Karrebæk Fjord is a small estuary with a relatively large catchment. Karrebæk Fjord is connected to the sea (”Smålandsfarvandet”) through a 45 m wide passage at the small village ”karrebæksminde”. To the south the estuary is connected to another water body called ”Dybsø Fjord”, through a shallow (0.5 m) passage. Karrebæk Fjord is shallow with a water depth of 1-2 m in most of the estuary except for the excavated channel (6 m) made for cargo transport by ships to the town of Næstved. In winter, the average salinity at the surface is 5-10 psu, while at the bottom it is 10-15 psu. In summer, the inflow of fresh water is significantly less and the water exchange with the sea is also less and the salinity becomes more stable at 10-12 psu and with less difference between top and bottom water column. The residence time is approx 10 days in winter and 35 days in the summer (Dannisøe 2017).



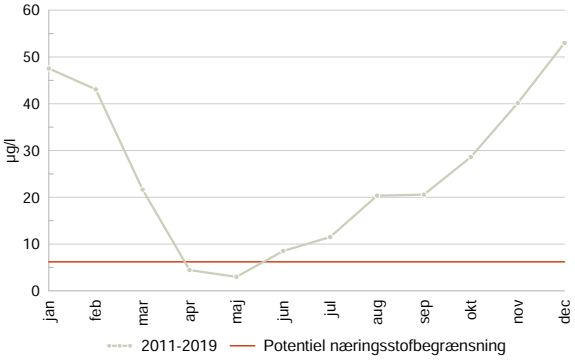
Figur 9.1 Water bodies and monitoring stations

Karrebæk Fjord	
Water body area	16 km^2
Catchment area	1105 km^2
Area ratio (catchment/water body)	69
Water depth max.	6 m
Salinity	5-15 psu
Stratification	Periodic

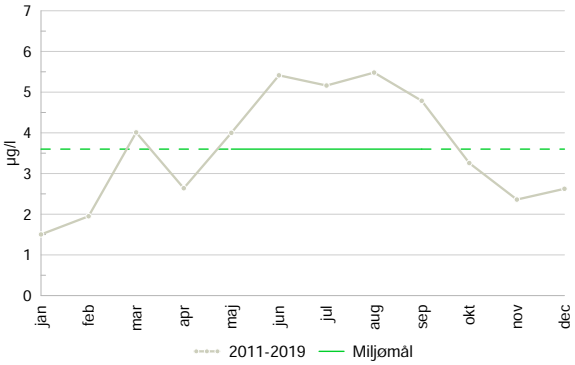
Karrebæk Fjord, station 96220079



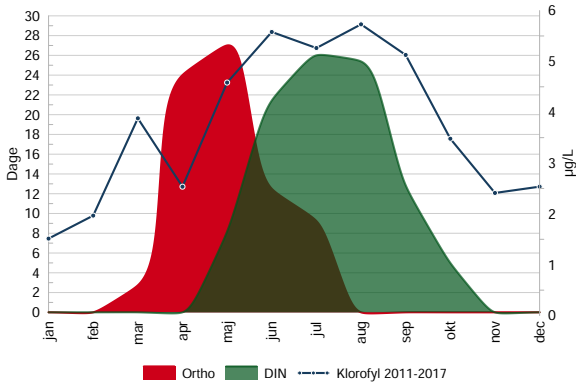
Figur 9.2 Average **DIN**-concentration per month (µg/l) in upper water column for the period 2011-2019.



Figur 9.3 Average **DIP**-concentration per month (µg/l) in upper water column for the period 2011-2019.



Figur 9.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for the period 2011-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 5.6 µg/l - green line not updated.

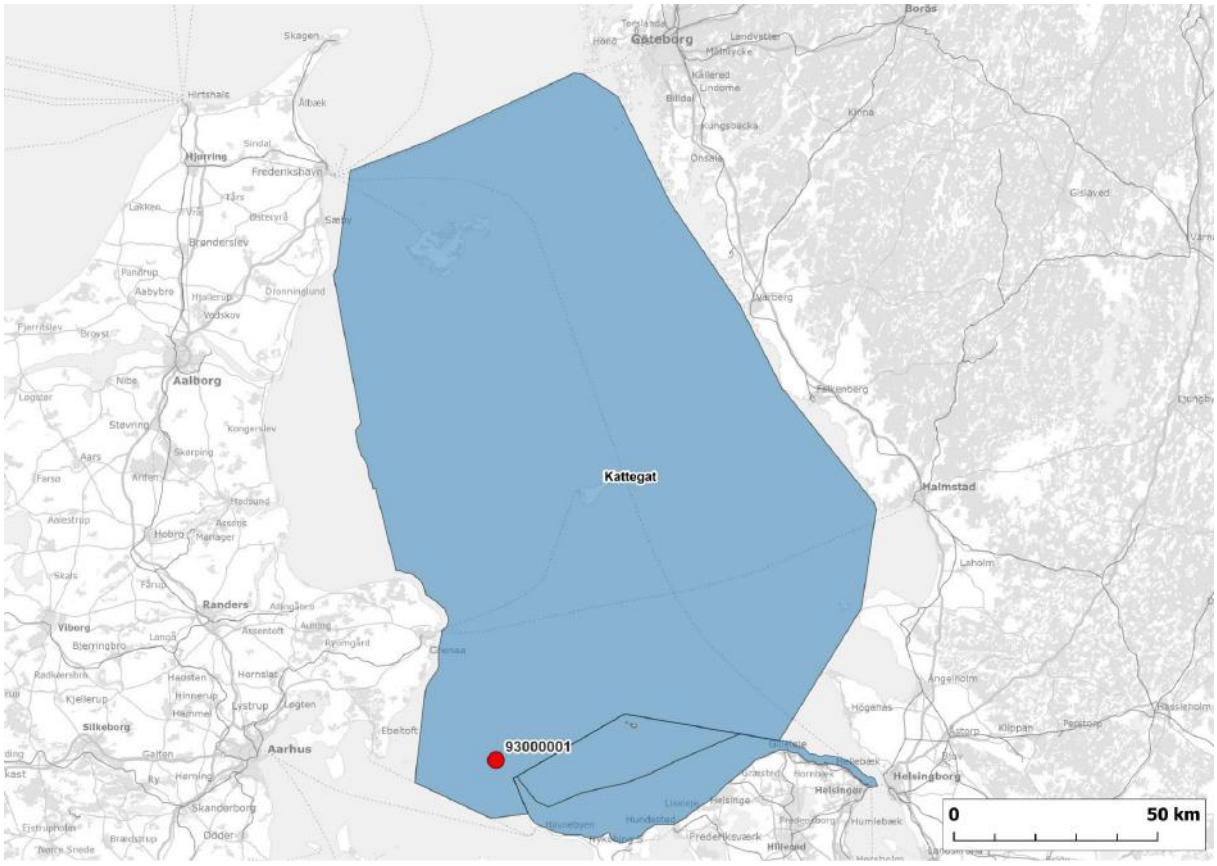


Figur 9.5 Number of days per month with DIP and DIN limitation as an average of the period 2011-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2019 (secondary axis). Upper water column.

KATTEGAT

10

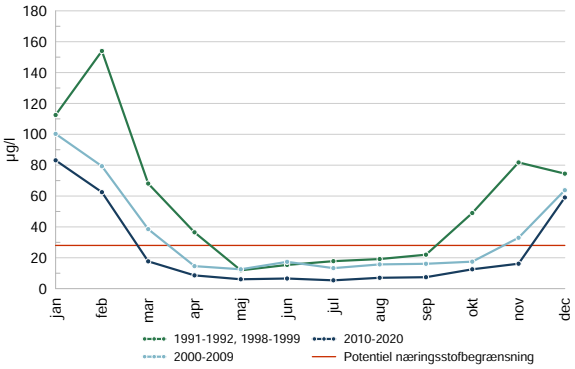
The water dynamics in Kattegat are dominated by the water exchange between the Skagerrak and the Baltic Sea. The water masses have established a relatively constant two-layer structure, where the upper layer is brackish water from the Baltic Sea, which flows north into the Skagerrak, and the lower layer consists of water that is transported in a southerly direction into in Kattegat from Skagerrak. Kattegat has a relatively large horizontal extent, which means that the currents are partly baroclinic driven by density differences, and partly influenced by the earth's rotation (Nielsen 2005 and 2022). The nutrients in the bottom water from Skagerrak contribute to the plankton growth during the summer. This growth typically occurs in the layer around 15 meters water depth during the summer. In the middle of summer, the concentration of DIN and DIP in the bottom water drops to an annual minimum, however, without reaching below the limiting level, while in the upper 10 m layer nutrients are limiting the growth during summer (Figur 12.8) and (Figur 12.9). Only one station from the Danish monitoring program in the central Kattegat have good continuous data for a longer period (Figur 12.1).



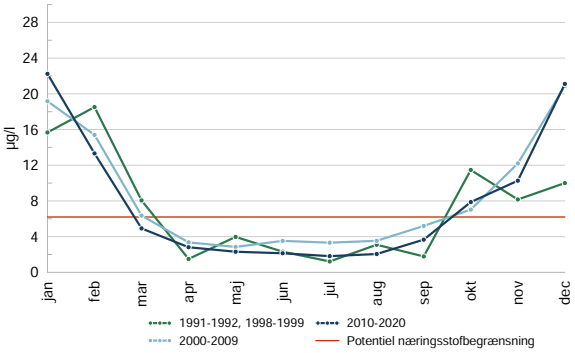
Figur 10.1 Water bodies and monitoring stations

Kattegat	
Water body area	23.000 km^2
Catchment area	- km^2
Area ratio (catchment/water body)	-
Water depth max.	100 m
Salinity	10-35 psu
Stratification	Permanent

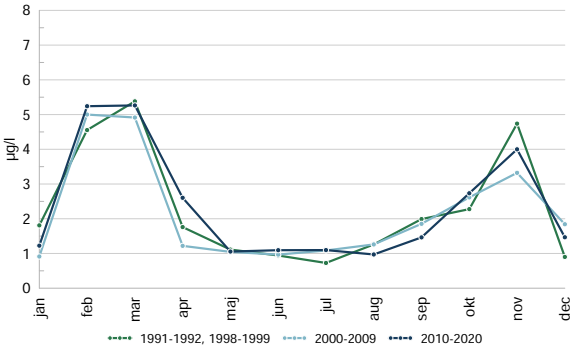
Kattegat, station 93000001



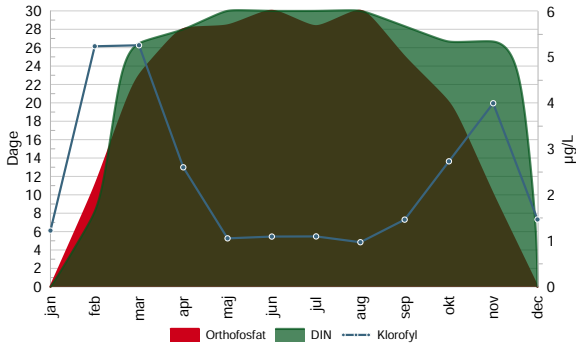
Figur 10.2 Average **DIN**-concentration per month (µg/l) in upper water column for three periods 1991-1992 + 1998-1999 and 2000-2009 and 2010-2020.



Figur 10.3 Average **DIP**-concentration per month (µg/l) in upper water column for three periods 1991-1992 + 1998-1999 and 2000-2009 and 2010-2020.



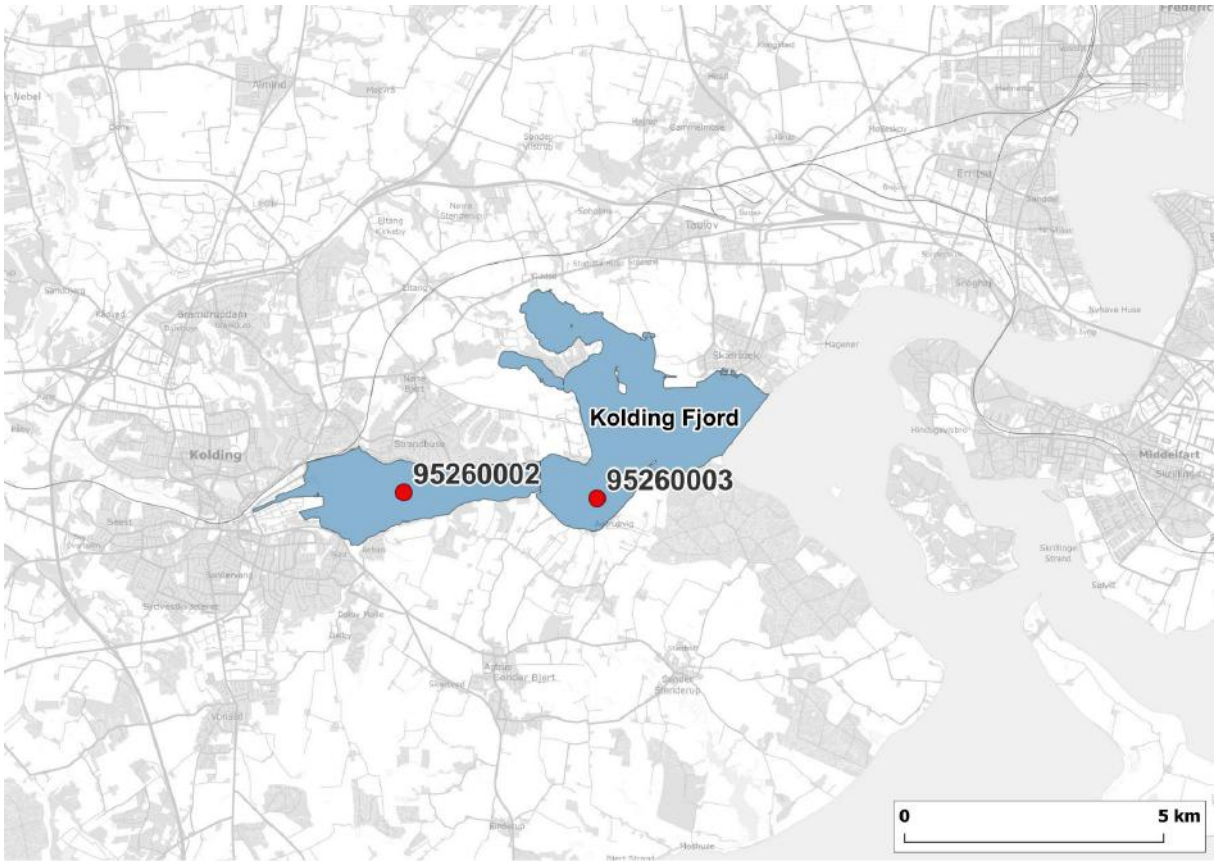
Figur 10.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods 1991-1992 + 1998-1999 and 2000-2009 and 2010-2020. No boundary for good/moderate.



Figur 10.5 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

KOLDING FJORD 11

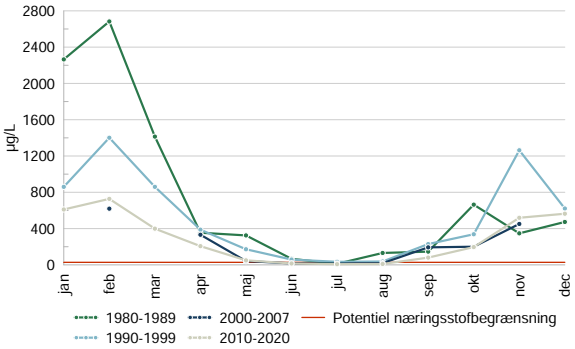
Kolding Fjord is an estuary divided into an inner part (5 km^2) and an outer part (10 km^2) with a wider boundary to the Little Belt (Lillebælt). The inner part is relatively shallow with depths of approx. 3-4 m that increases to approx. 5-7 m in the outer part and towards the boundary to the Belt, the depth is 10-15 m. Salinity fluctuates often due to the direct water exchange with the Little Belt and the freshwater runoff from the catchment area. The outer part is stratified for large parts of the year, but is regularly mixed up, which is probably due to the water exchange with the Little Belt.



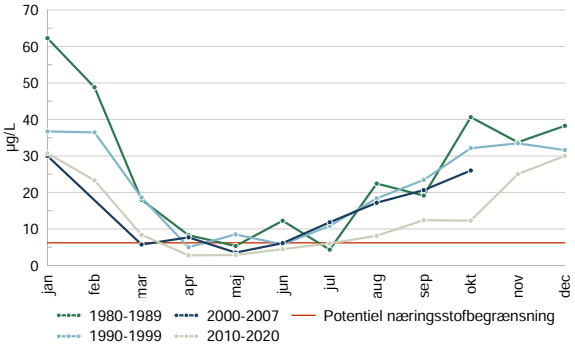
Figur 11.1 Water bodies and monitoring stations

Kolding Fjord	
Water body area (inner)	15 km^2
Catchment area (inner)	360 km^2
Area ratio (catchment/water body)	24
Water depth max.	15 m
Salinity	6-27 psu
Salinity stratification	Periodic

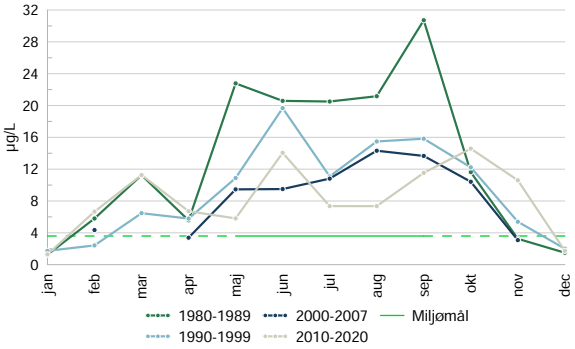
Kolding Fjord, inner part, station 95260002



Figur 11.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and 1990-1999 and 2000-2007 and 2010-2020.

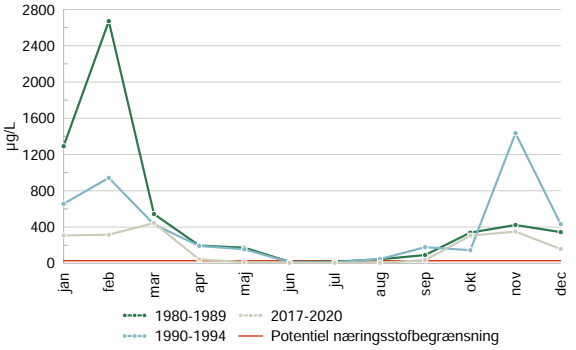


Figur 11.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and 1990-1999 and 2000-2007 and 2010-2020.

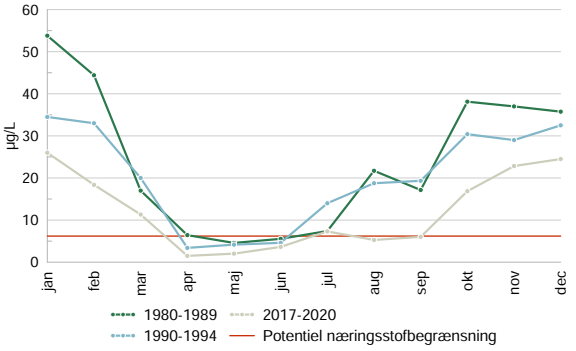


Figur 11.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and 1990-1999 and 2000-2007 and 2010-2020.Boundary good/moderate summer chlorophyll (May-Sep) is 4.8 µg/l - green line not updated.

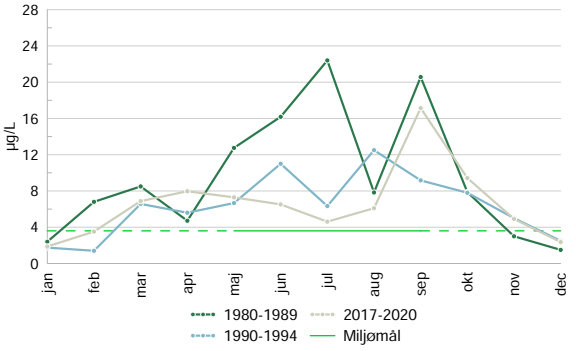
Kolding Fjord, outer part, station 95260003



Figur 11.5 Average **DIN**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1994 and 2017-2020.

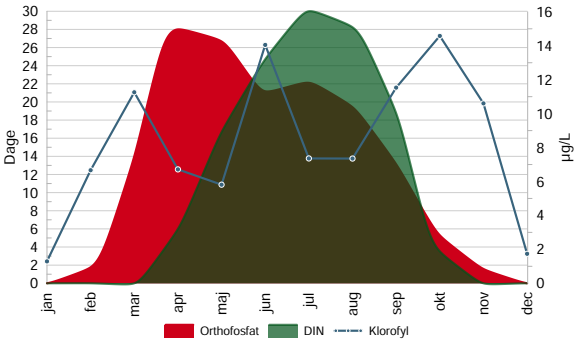


Figur 11.6 Average **DIP**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1994 and 2017-2020.



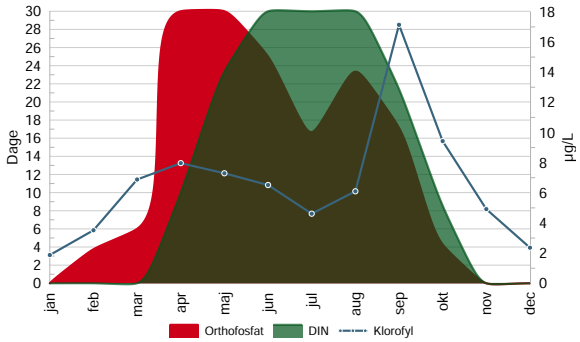
Figur 11.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1994 and 2017-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.3 µg/l - green line not updated.

Kolding Fjord, Inner part, station 95260002



Figur 11.8 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

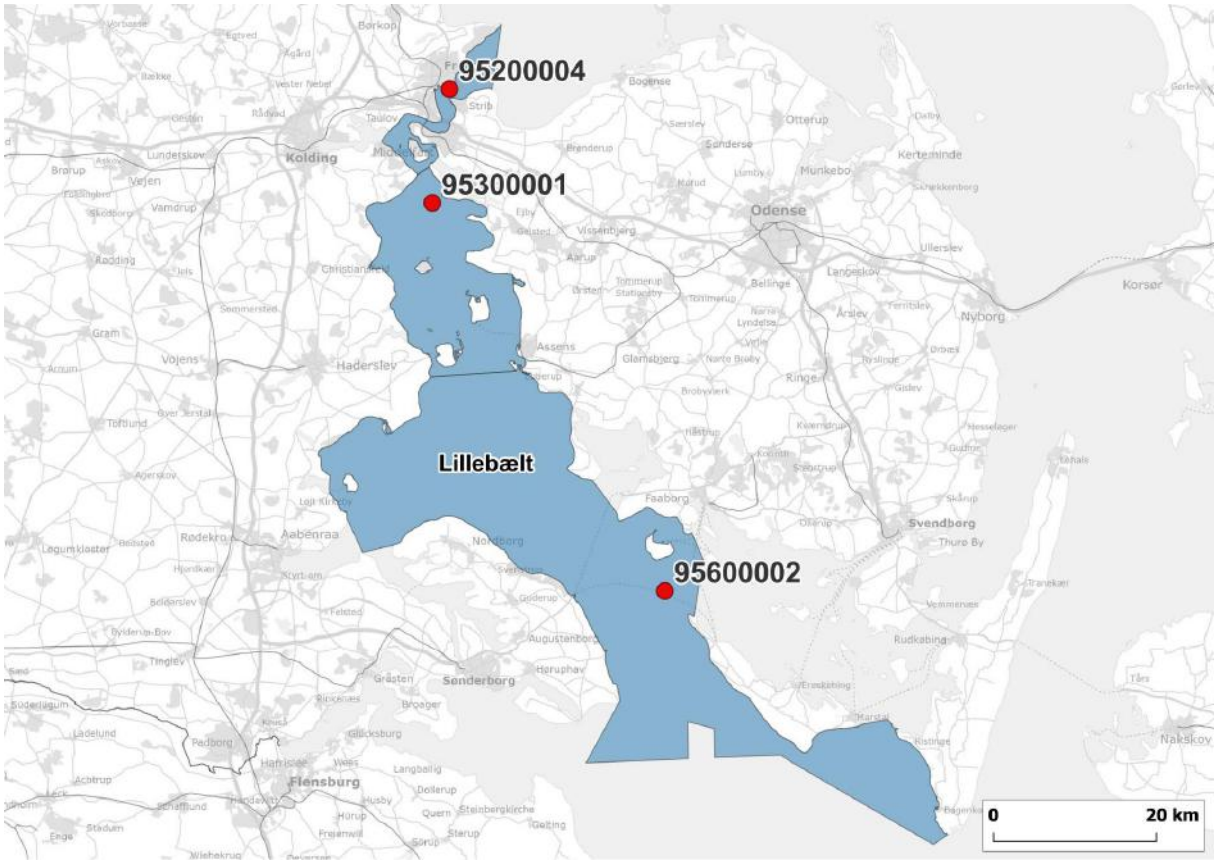
Kolding Fjord, outer part, station 95260003



Figur 11.9 Number of days per month with DIP and DIN limitation as an average of the period 2017-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2020 (secondary axis). Upper water column.

LILLEBÆLT 12

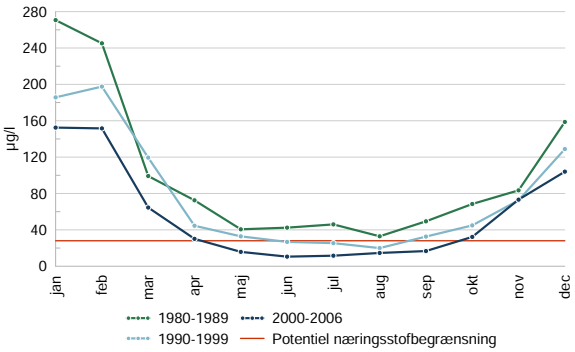
Lillebælt (Little Belt) is the strait between the peninsula Jylland (Jutland) and the island of Fyn (Funen), and is one of three straits connecting the Baltic Sea in the south with Kattegat to the North. The northern Little Belt is approx. 20 km wide with depths of approx. 10-25 metres. From the north, the belt becomes narrow (below 1 km) in a 20 km long stretch with depths of approx. 20-30 metres, but also depths down to 60 metres. When it becomes more wide again at ”Bredningen” there are depths down to 40 metres, but mostly 5-15 metres. The ”Bredningen” forms a threshold to the deeper basins in the southern Little Belt (20-35 metres deep), which extend approx. 50 km southeast towards ”Als” and ”Ærø”. The salinity in the northern Little Belt typically varies between 16-26 psu in the surface layer and between 22-30 psu in the bottom layer. In the southern Little Belt it is significantly deeper, and the salinity here varies between 10-19 psu in upper water column and 20-27 psu in the bottom layer. There is a large water transport through the Little Belt, and the narrow parts act as a bottleneck for the flow of large volumes of water, which causes turbulence and frequent mixing of surface and bottom layers - internal hydraulic control - a phenomenon important for water exchange and mixing as well as salinity and nutrient content in the top and bottom layers (Lund Hansen 2005; and Nielsen 2017). In the lower water masses in the Little Belt, there are generally significantly higher nutrient concentrations, which is why mixing of the water masses can contribute to increased plankton algae growth in the upper photic zone.



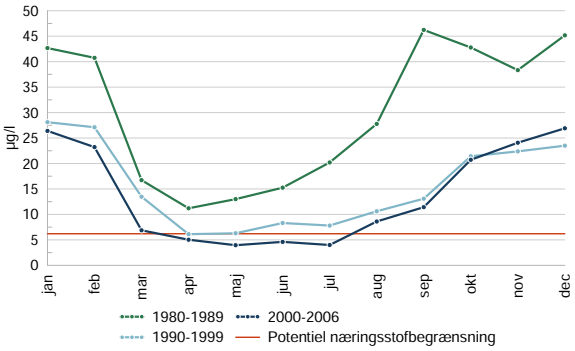
Figur 12.1 Water bodies and monitoring stations

Lillebælt	
Water body area	2.300 km^2
Catchment area	-
Area ratio (catchment/water body)	-
Water depth max.	60 m
Salinity	10-30 psu
Stratification	Periodic

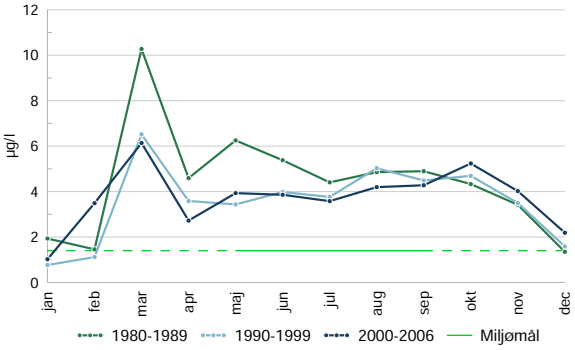
Lillebælt, North, station 95200004



Figur 12.2 Average **DIN**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1999 and 2000-2006.

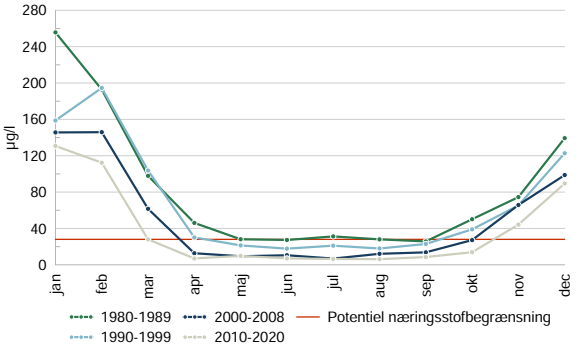


Figur 12.3 Average **DIP**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1999 and 2000-2006.

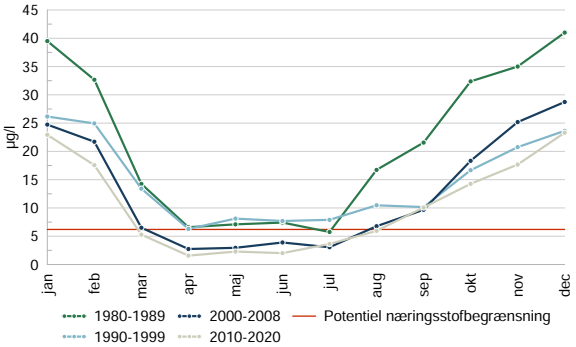


Figur 12.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods 1980-1989 and 1990-1999 and 2000-2006.Boundary good/moderate summer chlorophyll (May-Sep) is 1.3 µg/l.

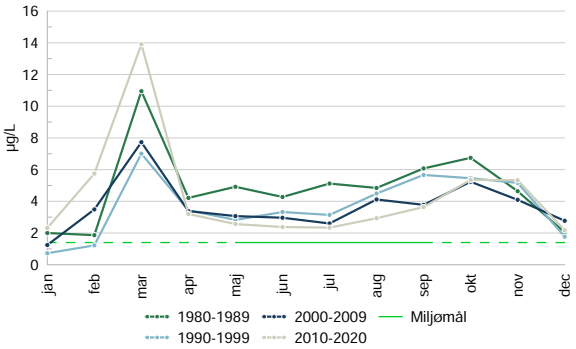
Lillebælt, Middle, station 95300001



Figur 12.5 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2008 and 2010-2020.

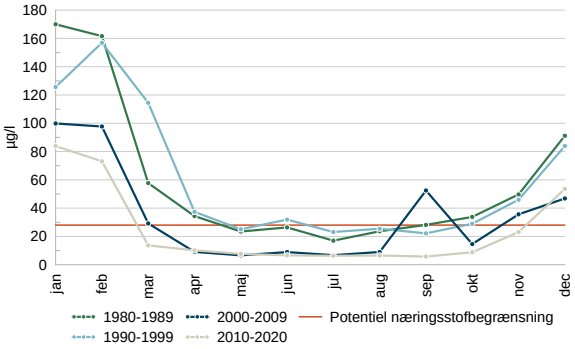


Figur 12.6 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2008 and 2010-2020.

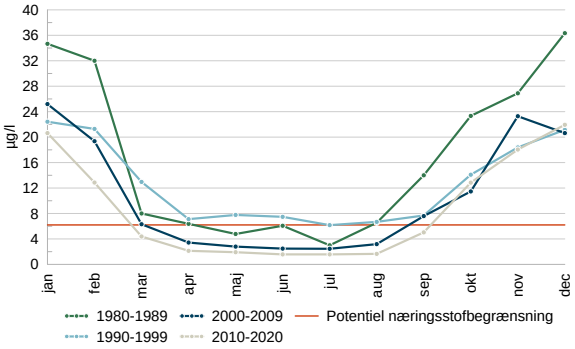


Figur 12.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1.4 µg/l.

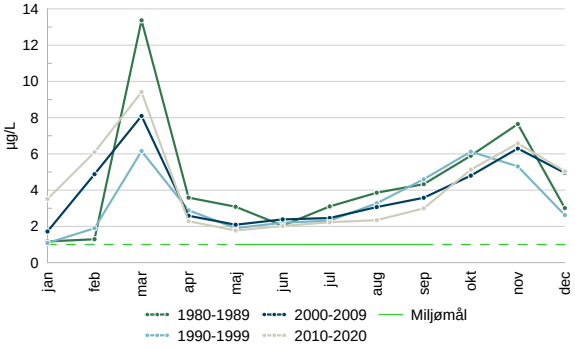
Lillebælt, south, station 95600002



Figur 12.8 Average **DIN**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2009 and 2010-2020.

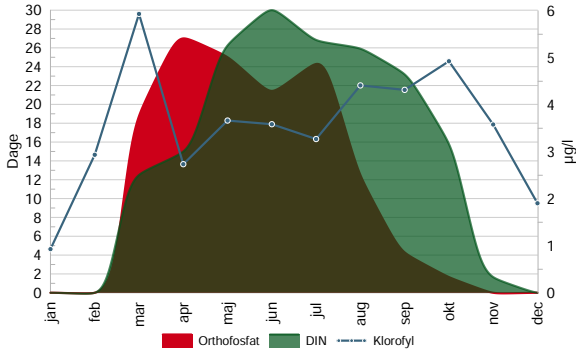


Figur 12.9 Average **DIP**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2009 and 2010-2020.



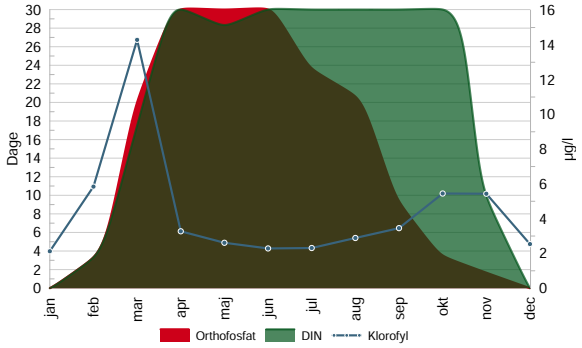
Figur 12.10 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods 1980-1989 and, 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1.0 µg/l.

Lillebælt, North, station 95200004



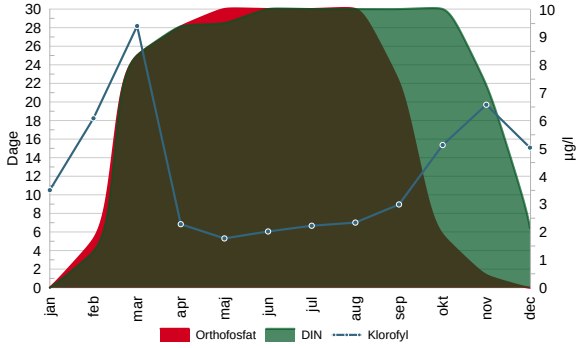
Figur 12.11 Number of days per month with DIP and DIN limitation as an average of the period 2000-2006 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2000-2006 (secondary axis). Upper water column.

Lillebælt, Middle, station 95300001



Figur 12.12 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

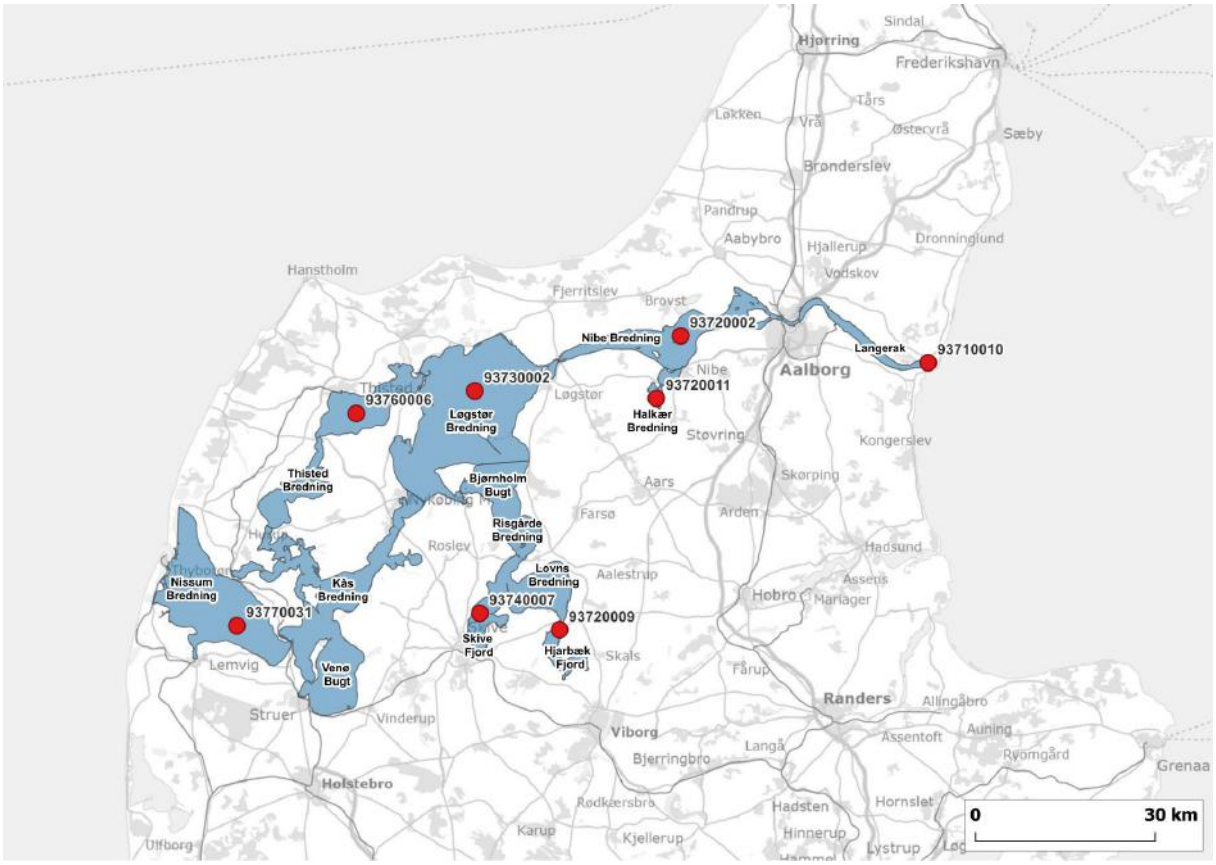
Lillebælt, south, station 95600002



Figur 12.13 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

LIMFJORDEN 13

Limfjorden is a large and complex estuary with an area of 1,500 km^2 and the catchment is approx. 7,600 km^2. Predominant wind from westerly directions causes net water flow from west to east through the estuary. Central parts of the Limfjorden, such as ”Skive Fjord”, ”Halkær Bredning”and ”Hjarbæk Fjord” easily become stratified, especially in the summer, when wind influence is less, which every year leads to oxygen depletion in the bottom layers. 3 sub-areas stand out in relation to water exchange and salinity. Nissum Bredning to the west with a large water exchange to the North Sea and a salinity of approx 30 psu. Hjarbæk Fjord and Halkær Bredning with a salinity (6-12 psu) significantly lower than the other sub-areas (20-25 psu) in the estuary.



Figur 13.1 Water bodies referred to as chapters in the report

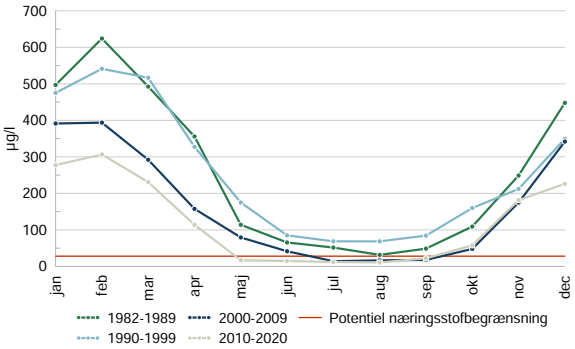
13.1 Nissum Bredning

Nissum Bredning is the westernmost part of Limfjorden with 5-6 m water depth in most parts. The water exchange to the North Sea happens via the ”Thyborøn Channel” and to the rest of the Limfjorden via ”Oddesund” a relatively narrow (500 m) strait. The salinity is 29-34 psu year-round and without any stratification. Due to the constant mixing with North Sea water no oxygen depletion is observed except for very rare occasions.

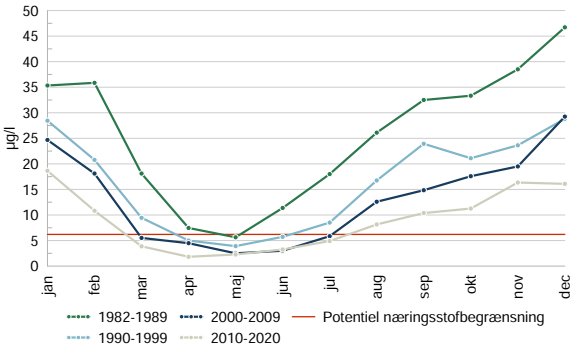
Figur 13.2 Water bodies and monitoring stations

Nissum Bredning	
Water body area	238 km^2
Catchment area	598 km^2
Area ratio (catchment/water body)	2.5
Water depth max.	6 m
Salinity	29-34 psu
Stratification	none

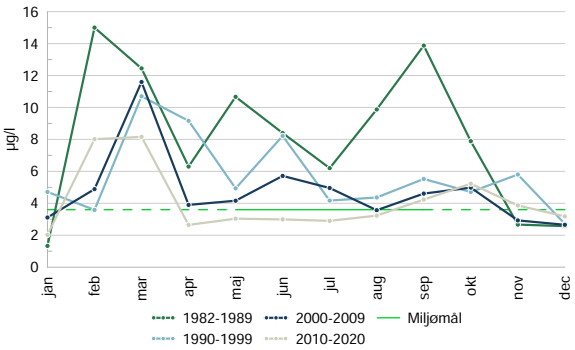
Nissum Bredning, station 93770031



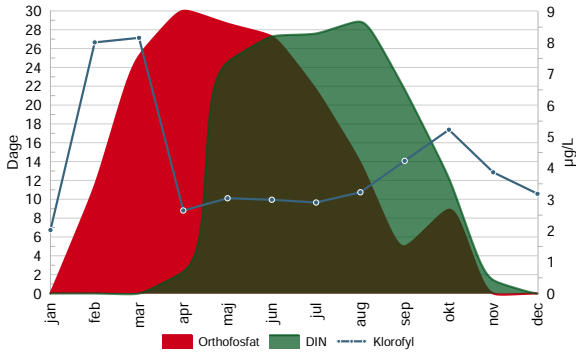
Figur 13.3 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 13.4 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 13.5 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 1.8 µg/l - green line not updated.



Figur 13.6 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

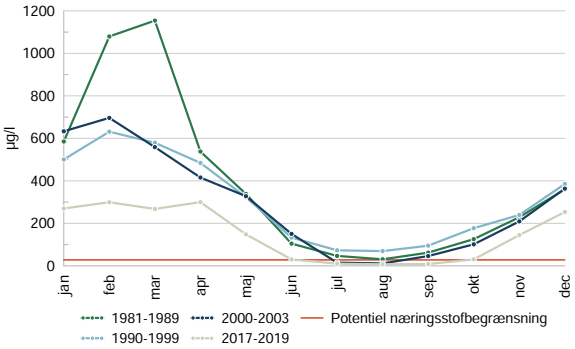
13.2 Thisted Bredning

Water depth in Thisted Bredning is in most part not exceeding 10 m except for a small area with a water depth of 18 m. Stratification is observed mainly in low wind periods in summer. This leads to oxygen depletion every year in various periods depending on the wind energy. From September 2019 to May 2020 unusually high chlorophyll-a levels of up to 40 µg/l have been observed due to an occurrence of the invasive alga Karenia mikimotoi, which therefore has influenced the average during this period. In addition, the observed DIP data from 2017-2019 seem very low. This gives rise to the suspicion that there may be errors in the data for DIP. Especially the very low winter concentrations of DIP give rise to the concern about whether the data are correct.

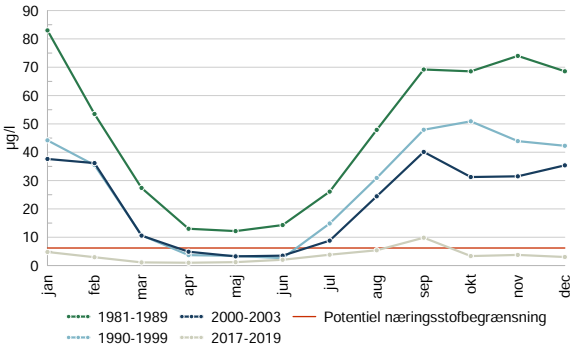
Figur 13.7 Water bodies and monitoring stations

Thisted Bredning	
Water body area	151 km^2
Catchment area	553 km^2
Area ratio (catchment/water body)	3.7
Water depth max.	18 m
Salinity	24-28 psu
Stratification	Periodic

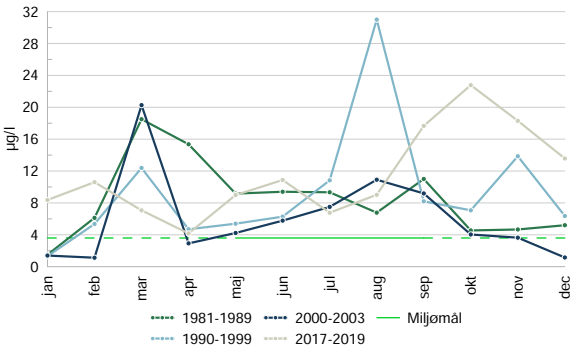
Thisted Bredning, station 93760006



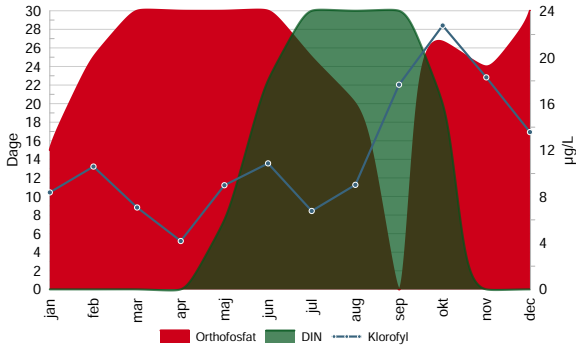
Figur 13.8 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1981-1989 and 1990-1999 and 2000-2003 and 2017-2019.



Figur 13.9 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1981-1989 and 1990-1999 and 2000-2003 and 2017-2019.



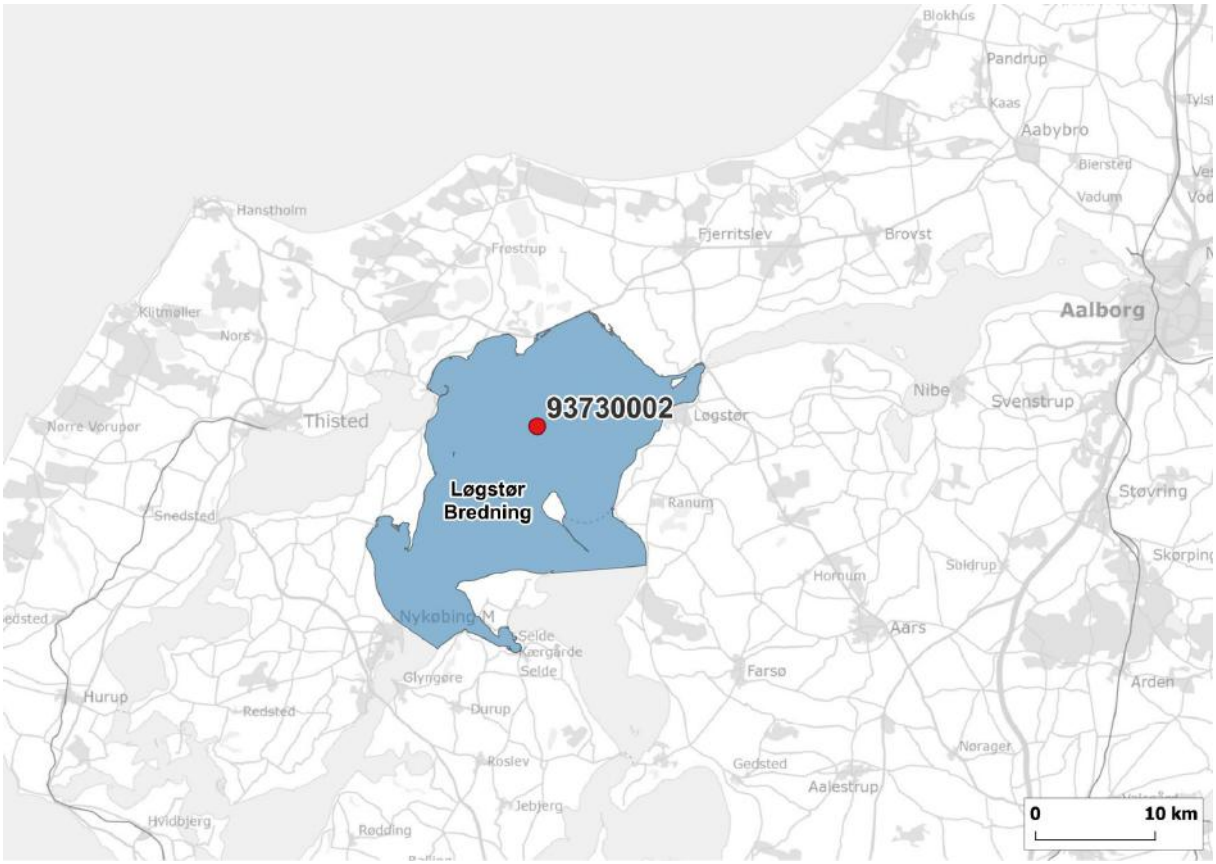
Figur 13.10 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1981-1989 and 1990-1999 and 2000-2003 and 2017-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 2.2 µg/l - green line not updated.



Figur 13.11 Number of days per month with DIP and DIN limitation as an average of the period 2017-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2019 (secondary axis). Upper water column.

13.3 Løgstør Bredning

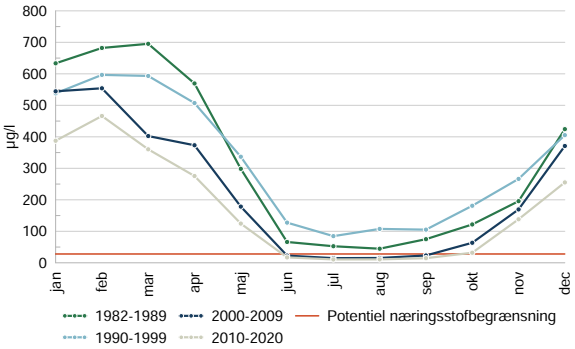
Løgstør Bredning is the most central and largest of the sub-areas in Limfjorden. Water depth is in most parts 6-8 m and up to 10 m at few locations. Stratification is observed mainly in low wind periods in summer. This leads to oxygen depletion every year in various periods depending on the wind energy.



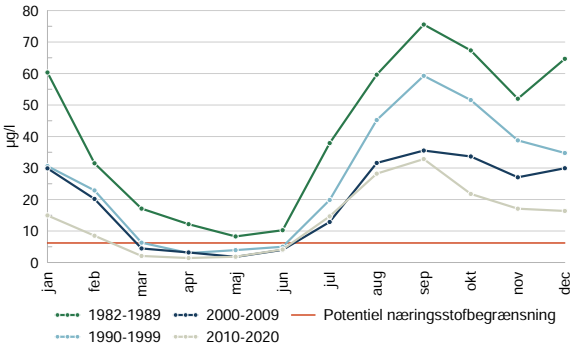
Figur 13.12 Water bodies and monitoring stations

Løgstør Bredning	
Water body area	407 km^2
Catchment area	579 km^2
Area ratio (catchment/water body)	1.4
Water depth max.	10 m
Salinity	24-29 psu
Stratification	Periodic

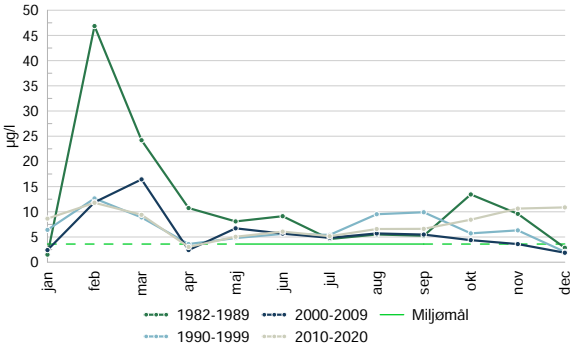
Løgstør Bredning, station 93730002



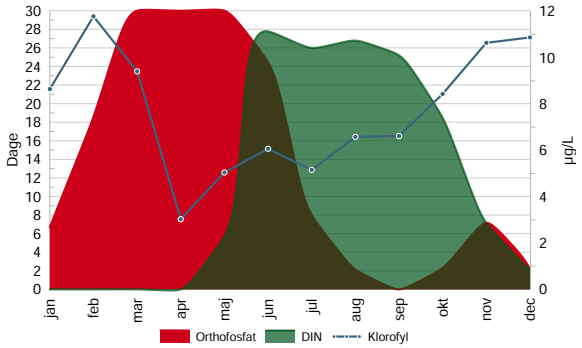
Figur 13.13 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 13.14 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020.



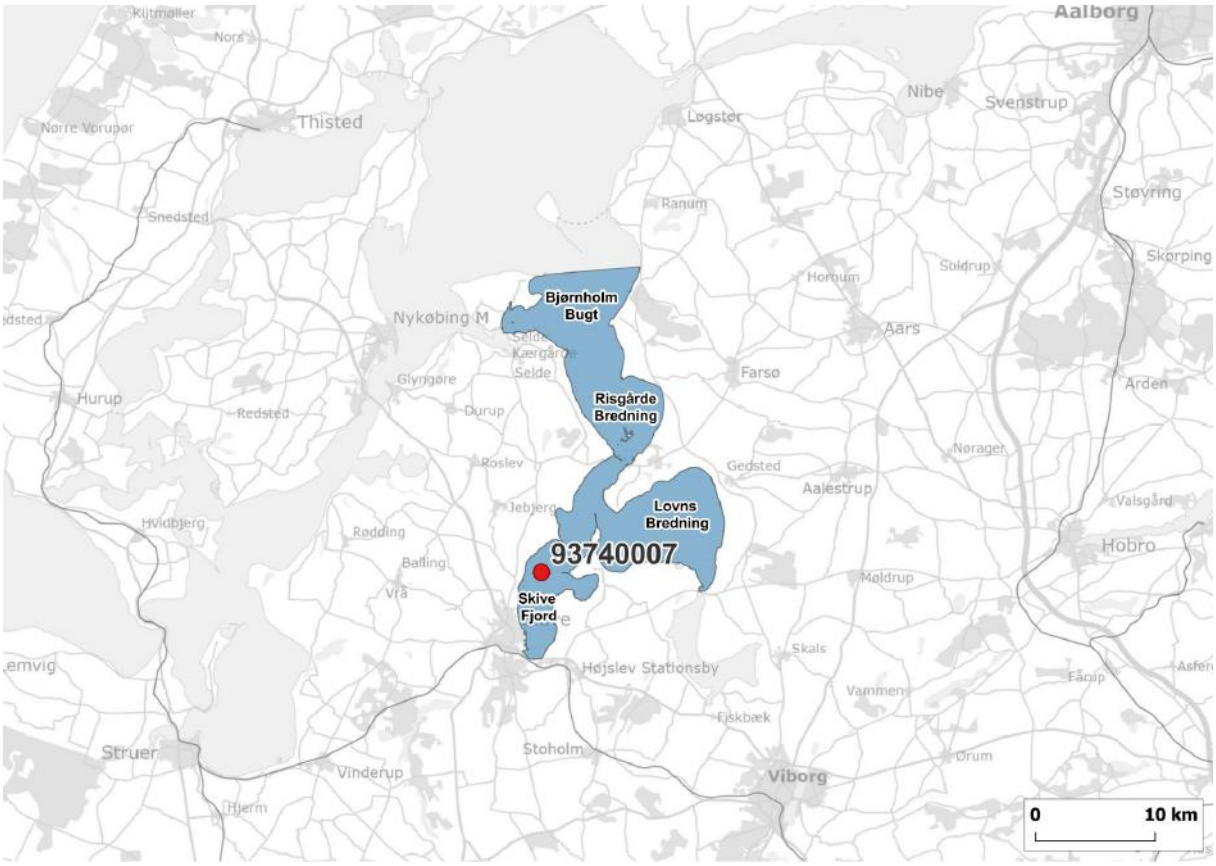
Figur 13.15 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.2 µg/l - green line not updated.



Figur 13.16 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

13.4 Skive Fjord

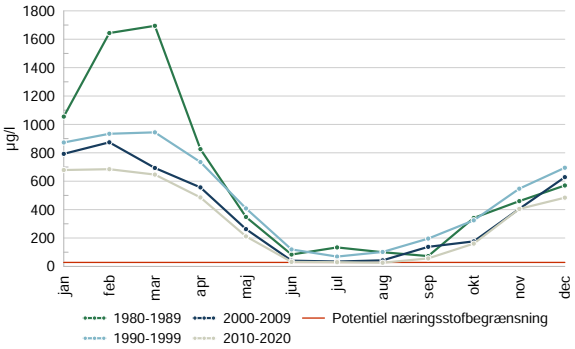
The water body ”Skive Fjord” consists of several smaller water bodies. The water depth in the northern part is mostly 10 m and in the inner southern parts 5-7 m and a central smaller part exceeding 20 m. Stratification in the inner and deepest parts is occurring more often due to the relatively high influx of fresh water but is still mainly observed in low wind periods in summer. This leads to oxygen depletion every summer in various intervals depending on the wind energy.



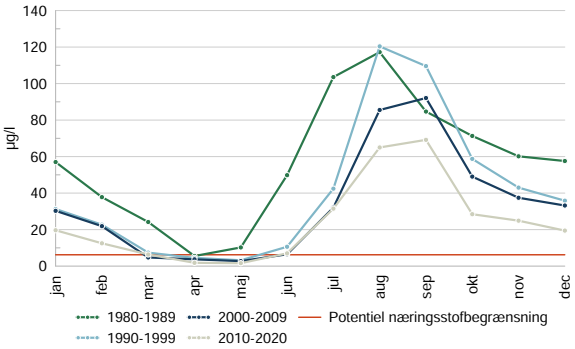
Figur 13.17 Water bodies and monitoring stations

Skive Fjord	
Water body area	222 km^2
Catchment area	1,445 km^2
Area ratio (catchment/water body)	6.5
Water depth max.	20 m
Salinity	17-28 psu
Stratification	Periodic

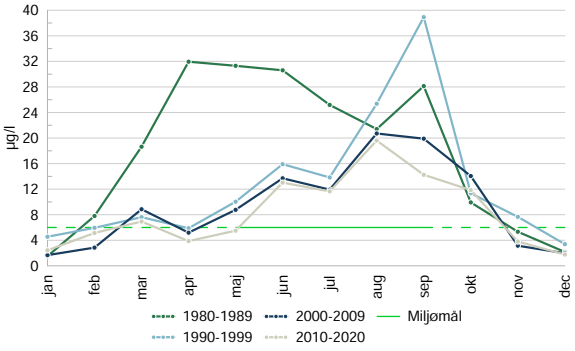
Skive Fjord, station 93730002



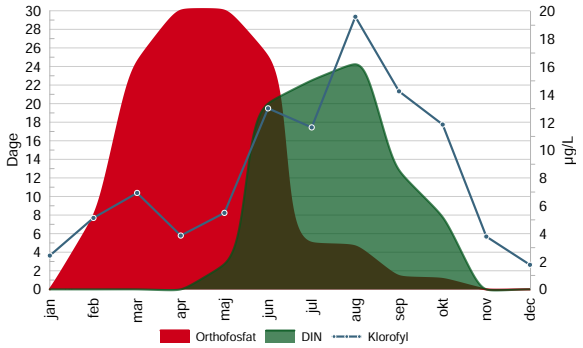
Figur 13.18 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 13.19 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 13.20 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.7 µg/l - green line not updated.



Figur 13.21 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

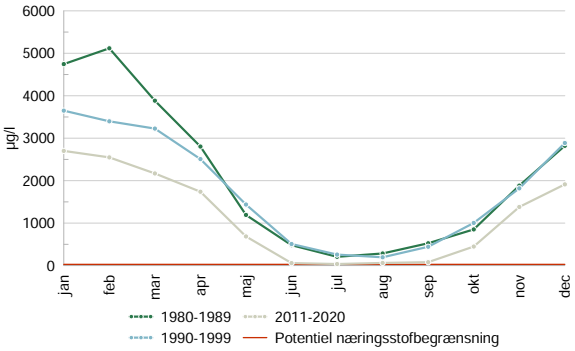
13.5 Hjarbæk Fjord

Hjarbæk Fjord is a small and shallow estuary separated from the rest of the Limfjorden by an artificial dam with a sluice and with a relatively large catchment. The water depth is 2-3 m in the central part increasing to 6 m closest to the sluice. High fresh water influx combined with influx of water with higher salinity from the Limfjorden results in almost permanent stratification most of the year. The stratification leads to oxygen depletion every summer for longer periods. The stratification is horizontal relatively homogeneous and data from other locations suggest that data from station 93720009 represent the upper layer well despite the location close to the sluice.

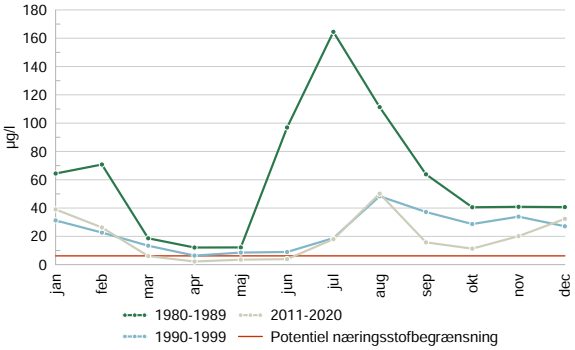
Figur 13.22 Water bodies and monitoring stations

Hjarbæk Fjord	
Water body area	24 km^2
Catchment area	1,179 km^2
Area ratio (catchment/water body)	49
Water depth max.	6 m
Salinity	3-28 psu
Stratification	Mostly

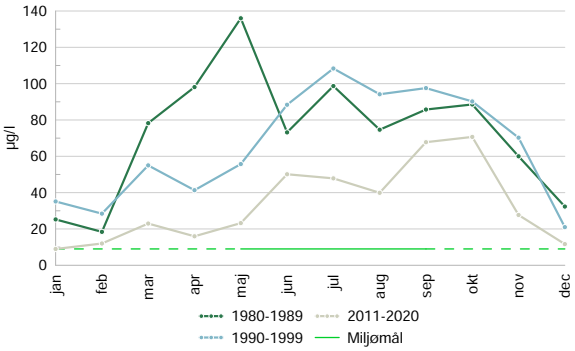
Hjarbæk Fjord, station 93730002



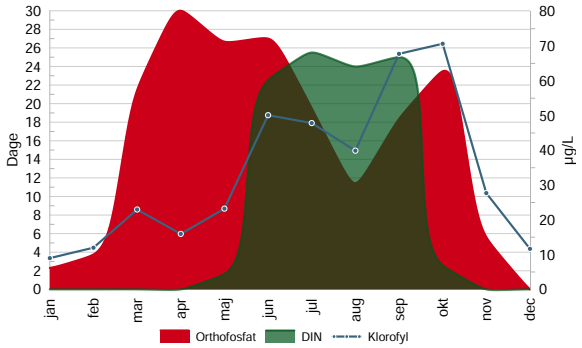
Figur 13.23 Average **DIN**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1999 and 2011-2020.



Figur 13.24 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1999 and 2011-2020.



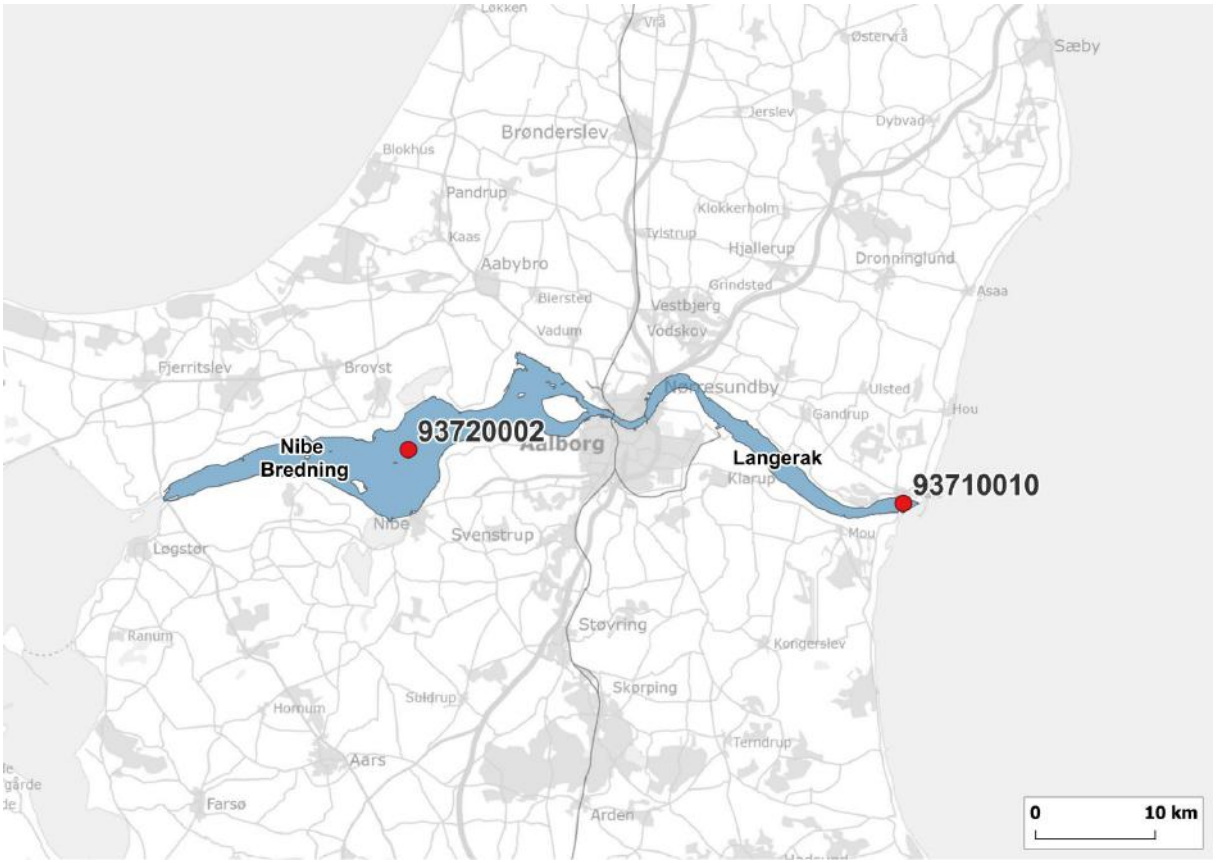
Figur 13.25 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1999 and 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 7.5 µg/l - green line not updated.



Figur 13.26 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

13.6 Nibe Bredning

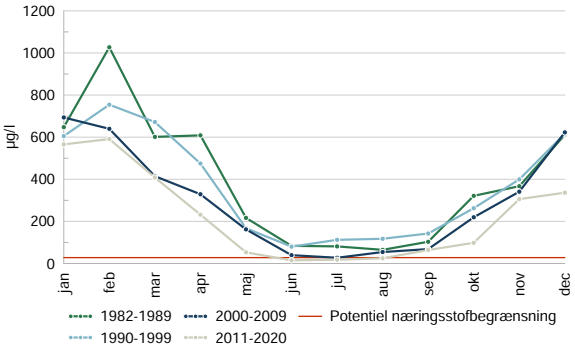
Nibe Bredning and Langerak is regarded as one water body in the RBMP 3 with an area of 174 km^2, and with the total catchment of 2,262 km^2. Nibe Bredning is the area west of Aalborg city. Most of the water body is very shallow with water depth of approx 1 m, but with a channel through the area with water depth of approx 6-10 m. From September 2019 to May 2020 unusually high chlorophyll-a levels have been observed due to an occurrence of the invasive alga Karenia mikimotoi, which therefore has influenced the average during this period



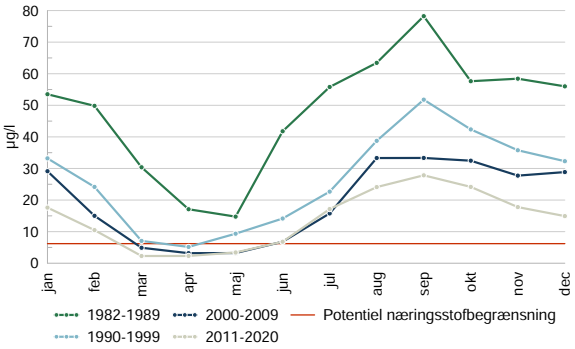
Figur 13.27 Water bodies and monitoring stations

Nibe Bredning	
Water body area	174 km^2
Catchment area	2,262 km^2
Area ratio (catchment/water body)	13
Water depth max.	10 m
Salinity	20-27 psu
Stratification	Rarely

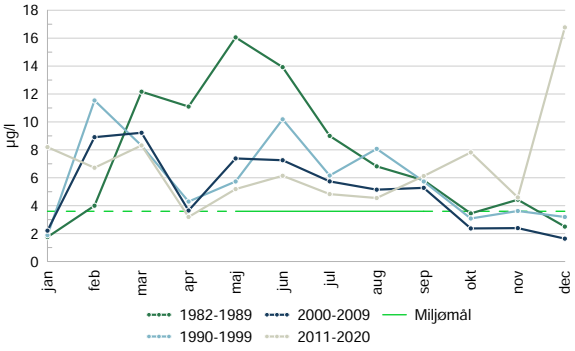
Nibe Bredning, station 93720002



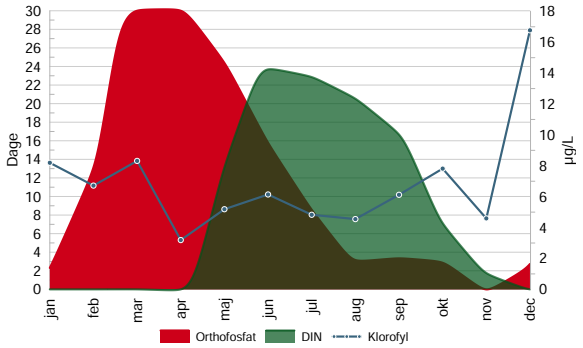
Figur 13.28 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2011-2020.



Figur 13.29 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2011-2020.



Figur 13.30 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1982-1989 and 1990-1999 and 2000-2009 and 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 3.2 µg/l - green line not updated.



Figur 13.31 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

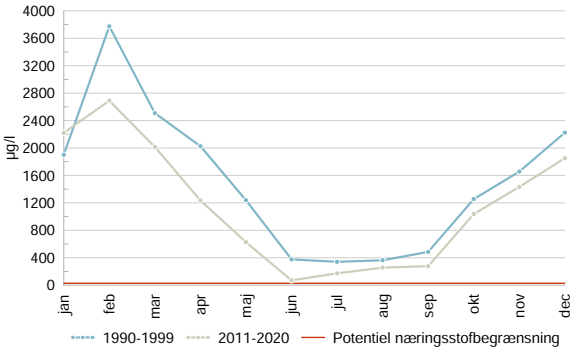
13.7 Halkær Bredning

Halkær Bredning is a small (6 km^2) and shallow estuary separated from the rest of the Limfjorden by an artificial dam with a 40 m wide open passage. In the official water body in RBMP 3 an area outside the dam is included. The water depth is approx 2 m in the central part. High fresh water influx combined with influx of water with higher salinity from the Limfjorden results in fluctuating salinities from 10-24 psu. Due to wind exposure and shallow water the water column is mostly well mixed, but in summer periods stratification can occur which leads to oxygen depletion.

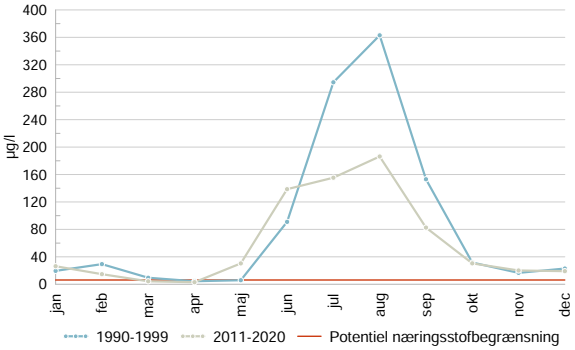
Figur 13.32 Water bodies and monitoring stations

Halkær Bredning	
Water body area	6 km^2
Catchment area	260 km^2
Area ratio (catchment/water body)	43
Water depth max.	2 m
Salinity	10-24 psu
Stratification	Periodic

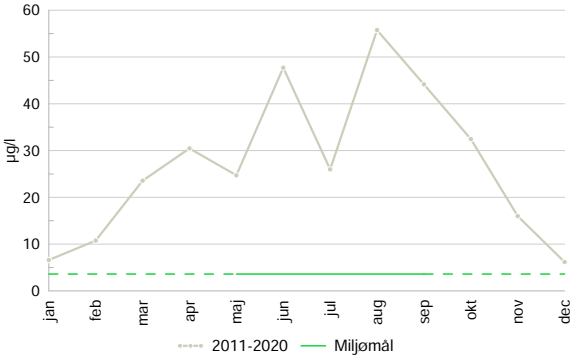
Halkær Bredning, station 93720011



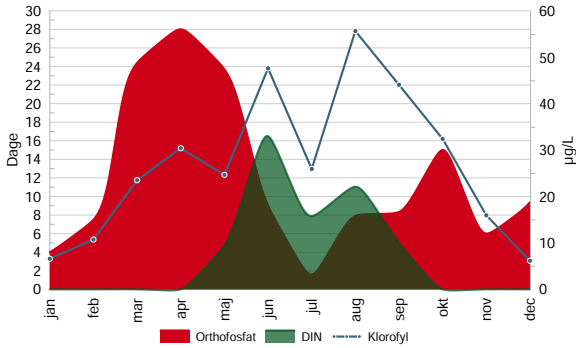
Figur 13.33 Average **DIN**-concentration per month (µg/l) in upper water column for 2 periods: 1990-1999 and 2011-2020.



Figur 13.34 Average **DIP**-concentration per month (µg/l) in upper water column for 2 periods: 1990-1999 and 2011-2020.



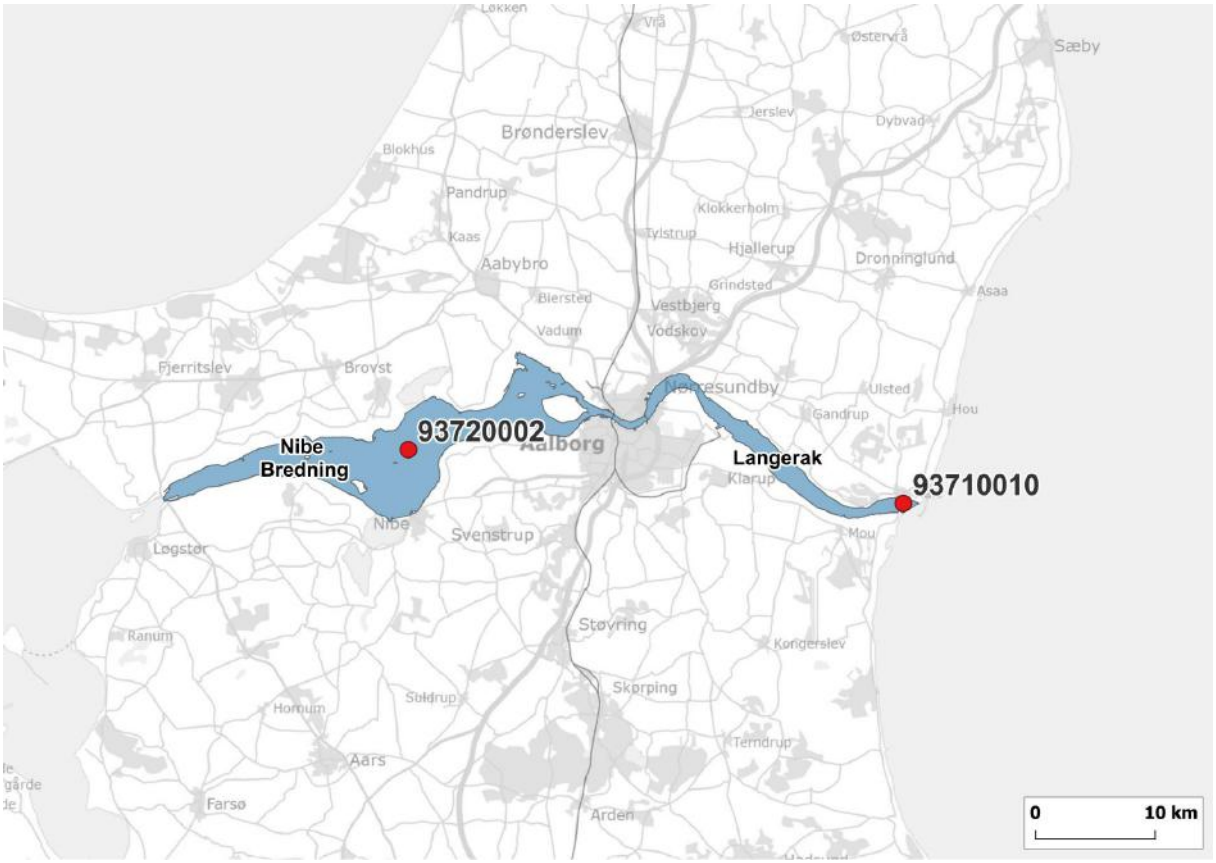
Figur 13.35 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 1 period: 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 7.4 µg/l - green line not updated.



Figur 13.36 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

13.8 Langerak

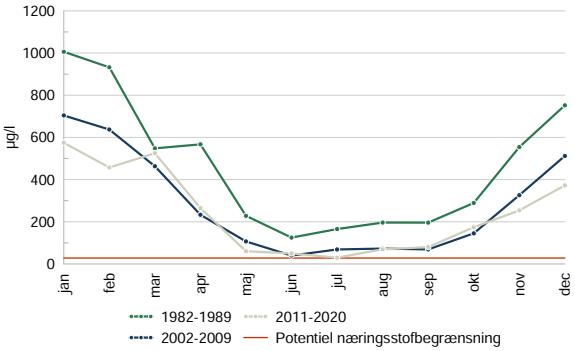
Nibe Bredning and Langerak is regarded as one water body in the RBMP 3 with an area of 174 km^2, and with the total catchment of 2,262 km^2. Langerak is the most eastern part of the Limfjorden. 30 km long and 1.5 km wide and with a 10 m deep channel approx 500 m wide. Salinity is fluctuating from 20-30 psu depending on direction of water transport. From September 2019 to May 2020 unusually high chlorophyll-a levels have been observed due to an occurrence of the invasive alga Karenia mikimotoi, which therefore has influenced the average during this period



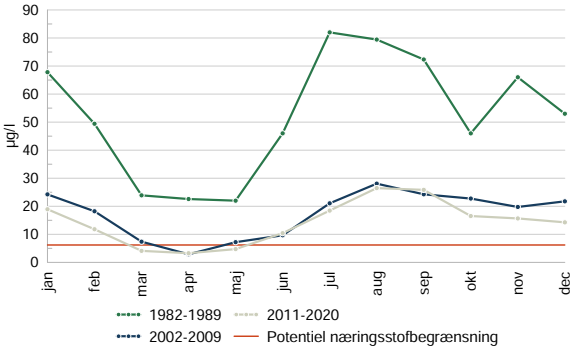
Figur 13.37 Water bodies and monitoring stations

Langerak	
Water body area	174 km^2
Catchment area	2,262 km^2
Area ratio (catchment/water body)	13
Water depth max.	10 m
Salinity	20-30 psu
Stratification	Periodic

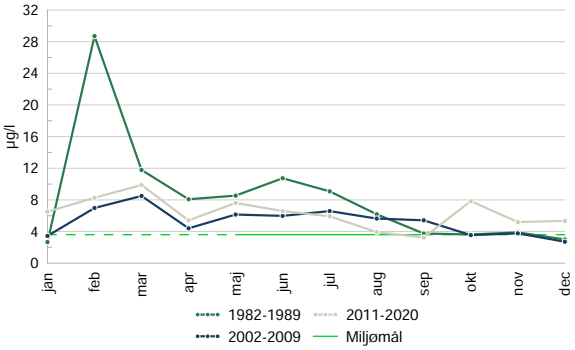
Langerak, station 93710010



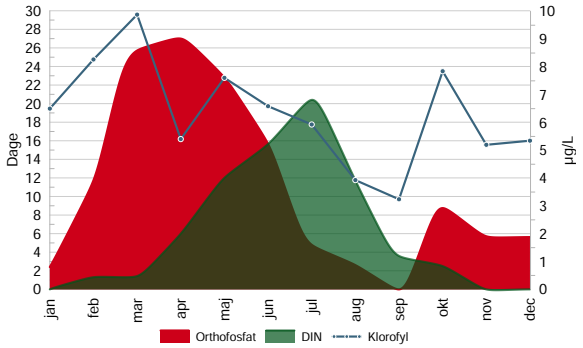
Figur 13.38 Average **DIN**-concentration per month (µg/l) in upper water column for 3 periods: 1982-1989 and 2002-2009 and 2011-2020.



Figur 13.39 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 1982-1989 and 2002-2009 and 2011-2020.



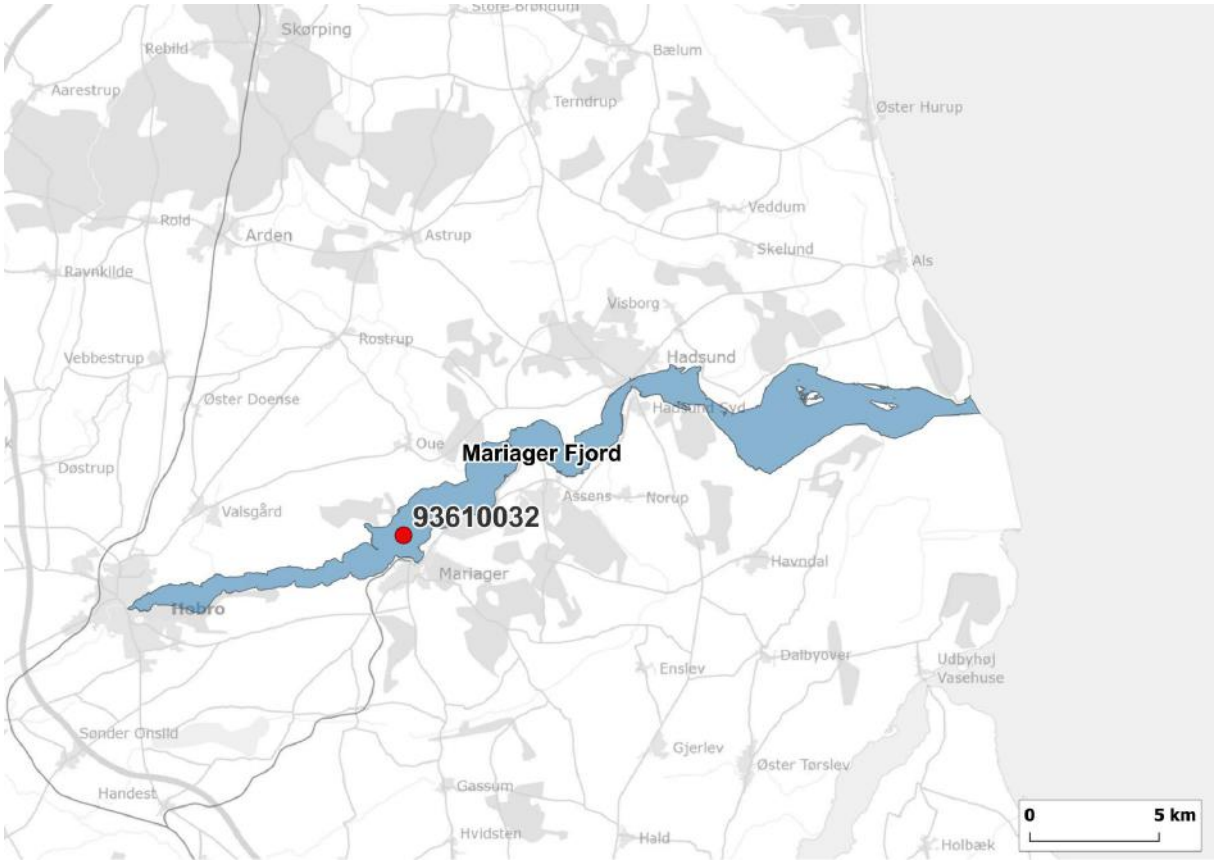
Figur 13.40 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 3 periods: 1982-1989 and 2002-2009 and 2011-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 3.2 µg/l - green line not updated.



Figur 13.41 Number of days per month with DIP and DIN limitation as an average of the period 2011-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2011-2020 (secondary axis). Upper water column.

MARIAGER FJORD 14

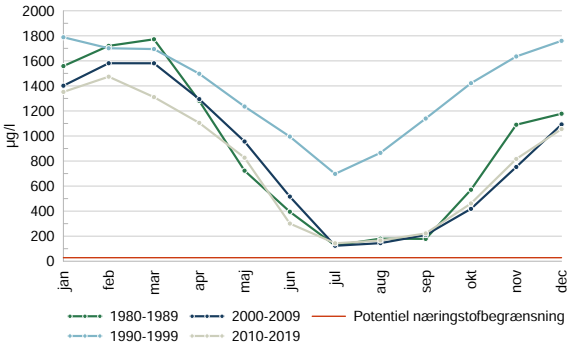
Mariager Fjord is an estuary characterised by a deep inner part and a shallow outer part. The outer part is the 20 km eastern part of the fjord with water depth of approx 0.5-1 m but with a narrow channel with depth of 5 m. The water exchange is limited by the shallow outer part. The deepest area, 30 metres, is north of Mariager village at station 93610032. There is a permanently stratification at a depth of 10-15 meters and no oxygen in the bottom layer. There has been no improvement in the environmental condition since 1980 - this is indicated by no improvement in the secchi depth. Data for chlorophyll-a do not go back that far due to errors in the data.



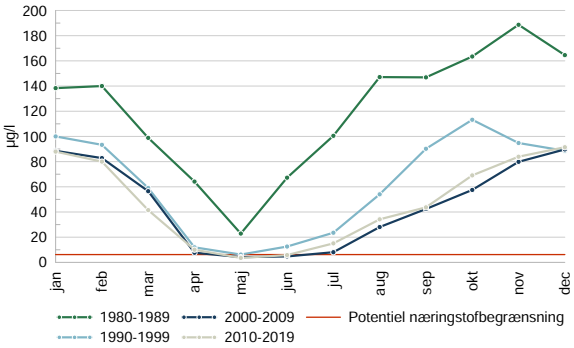
Figur 14.1 Water bodies and monitoring stations

Mariager Fjord	
Water body area	46 km^2
Catchment area	572 km^2
Area ratio (catchment/water body)	12
Water depth max.	30 m
Salinity	15-22 psu
Stratification	Permanent

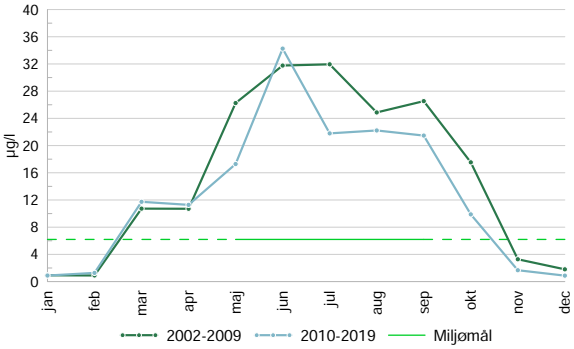
Mariager Fjord, station 93610032



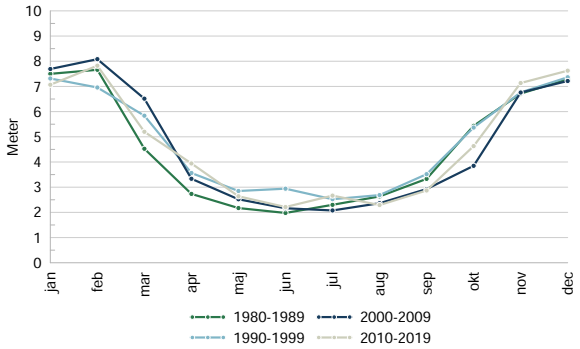
Figur 14.2 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2019.



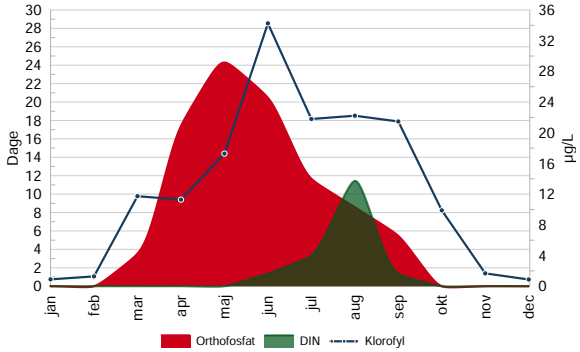
Figur 14.3 Average **DIP**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2019.



Figur 14.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 2 periods: 2002-2009 and 2010-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 3.1 µg/l - green line not updated.



Figur 14.5 Average **secchi depth** per month (m) for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2019.



Figur 14.6 Number of days per month with DIP and DIN limitation as an average of the period 2010-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2019 (secondary axis). Upper water column.

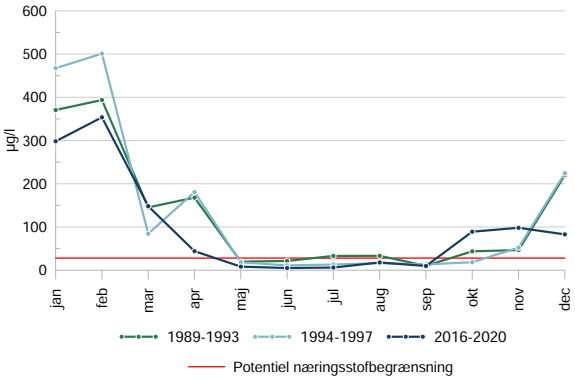
NAKSKOV FJORD 15

Nakskov Fjord is a shallow estuary with water depths of less than 2 m and only deeper water in the outer part at the wider border to the belt sea. The estuary has a narrow excavated channel at approx. 7 m depth to ensure cargo transport by ships to Nakskov harbour. Due to the shallow water, wind plays a significant role for mixing water. The water exchange is driven partly by water level variation and partly by changes in the characteristics of the water masses in the belt sea.

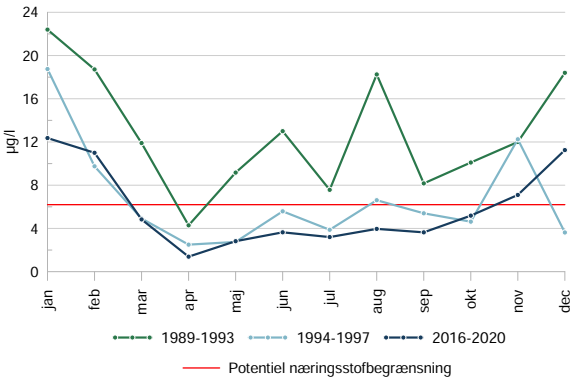
Figur 15.1 Water bodies and monitoring stations

Nakskov Fjord	
Water body area	50 km^2
Catchment area	246 km^2
Area ratio (catchment/water body)	5
Water depth max.	8 m
Salinity	10-20 psu
Stratification	None

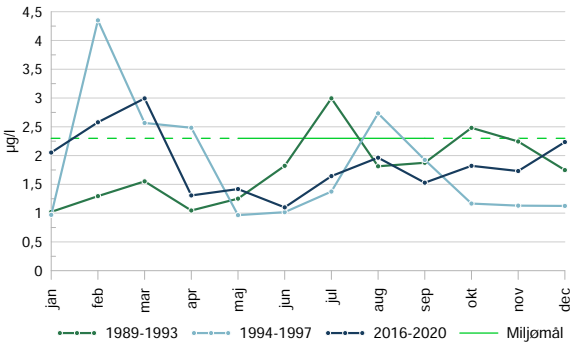
Nakskov Fjord, station 93610032



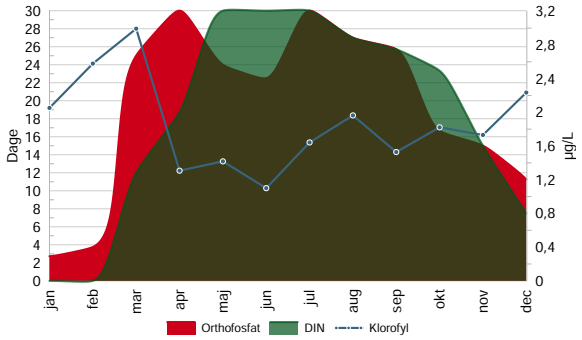
Figur 15.2 Average **DIN**-concentration per month (µg/l) in upper water column for 3 periods: 1989-1993 and 1994-1997 and 2016-2020.



Figur 15.3 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 1989-1993 and 1994-1997 and 2016-2020.



Figur 15.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 3 periods: 1989-1993 and 1994-1997 and 2016-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.3 µg/l - green line not updated.



Figur 15.5 Number of days per month with DIP and DIN limitation as an average of the period 2016-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2016-2020 (secondary axis). Upper water column.

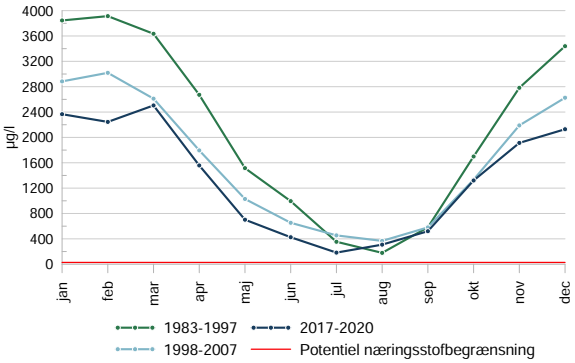
NISSUM FJORD 16

Nissum Fjord is a shallow water estuary or lagoon with an opening to the North Sea via a sluice at Thorsminde, which was put into use in 1931. The lagoon is approx. 65 km^2 and consists of three basins with a maximum depth of 2-2.5 m and in a few places approx 3 m. The three basins are separated by narrow passages, which determines that the salinity is different for most of the year in the three sub-areas. The lagoon is periodically stratified due to inflow of North sea water and water exchange between the three basins. The outer part with the direct contact to the North Sea has the highest salinity. In the upper water 1-14 psu and with inflow of water from the North Sea 32 psu at the bottom. The salinity decreases in the middle part (1-10 psu) and is lowest in the inner part (0-4 psu), which has the largest catchment at 1100 km^2, which makes up 70 % of the catchment to the lagoon. The concentration of bioavailable phosphate in the water samples is probably underestimated (Rasmussen 2006) due to the fact that bioavailable phosphate is absorbed to resuspended particles with iron content. Therefore DIP as a proxy for limitation of primary production is probably overestimated.

Figur 16.1 Water bodies and monitoring stations

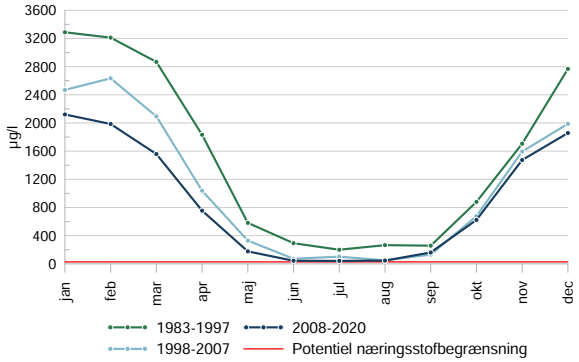
Nissum Fjord	
Water body area (inner)	65 km^2
Catchment area (inner)	1,615 km^2
Area ratio (catchment/water body)	24
Water depth max.	3 m
Salinity	0-32 psu
Salinity stratification	Periodic

Nissum Fjord, inner part, station 91240003

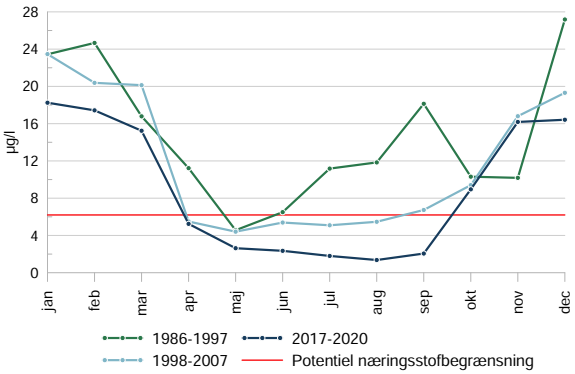


Figur 16.2 Average **DIN**-concentration per month (µg/l) in upper water column for three periods: 1983-1997 and 1998-2007 and 2017-2020.

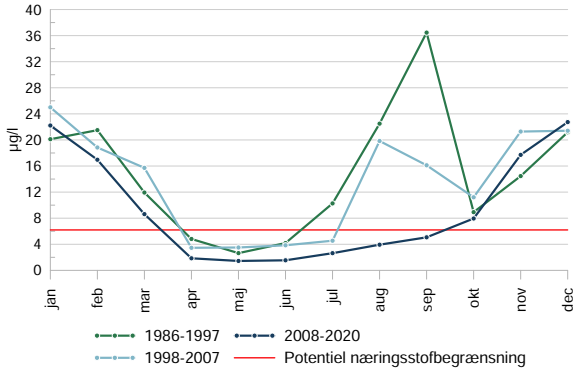
Nissum Fjord, middle part, station 91240002



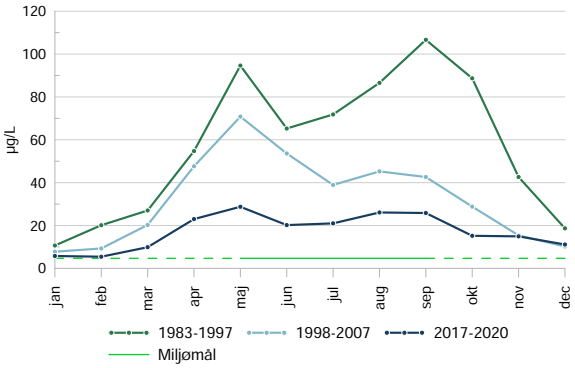
Figur 16.5 Average **DIN**-concentration per month (µg/l) in upper water column for three periods: 1983-1997 and 1998-2007 and 2008-2020.



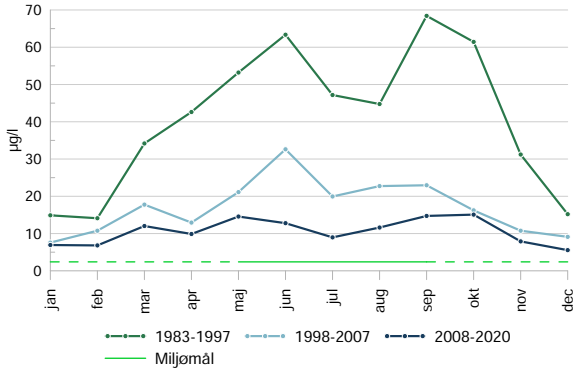
Figur 16.3 Average **DIP**-concentration per month (µg/l) in upper water column for three periods: 1986-1997 and 1998-2007 and 2017-2020.



Figur 16.6 Average **DIP**-concentration per month (µg/l) in upper water column for three periods: 1986-1997 and 1998-2007 and 2008-2020.

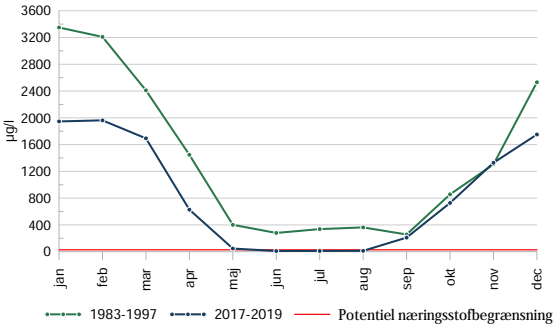


Figur 16.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods: 1983-1997 and 1998-2007 and 2017-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 4.7 µg/l.

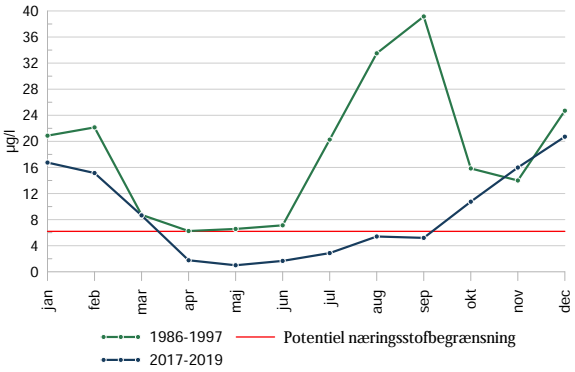


Figur 16.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods: 1983-1997 and 1998-2007 and 2008-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.4 µg/l.

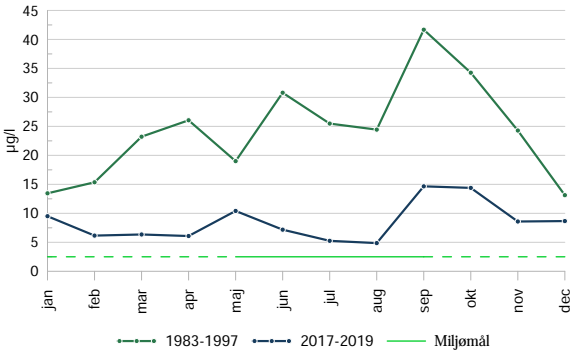
Nissum Fjord, outer part, station 91240001



Figur 16.8 Average **DIN**-concentration per month (µg/l) in upper water column for 2 periods: 1983-1997 and 2017-2019.

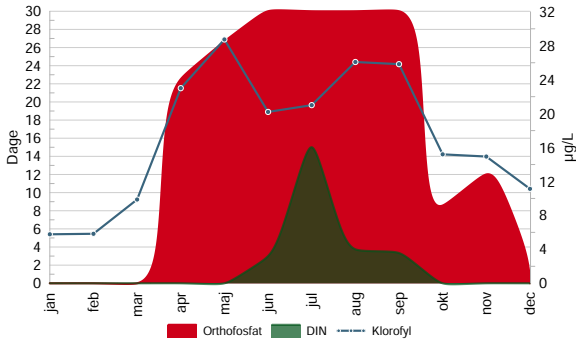


Figur 16.9 Average **DIP**-concentration per month (µg/l) in upper water column for 2 periods: 1986-1997 and 2017-2019.



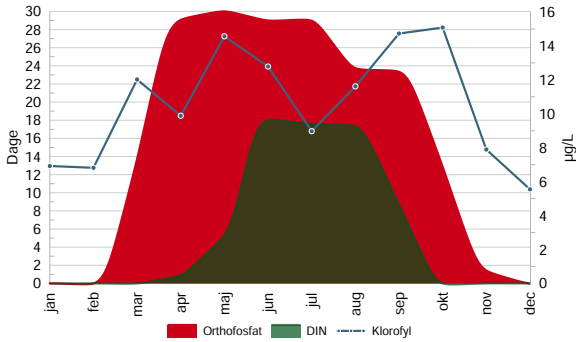
Figur 16.10 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 2 periods: 1983-1997 and 2017-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 2.5 µg/l.

Nissum Fjord, inner part, station 91240003



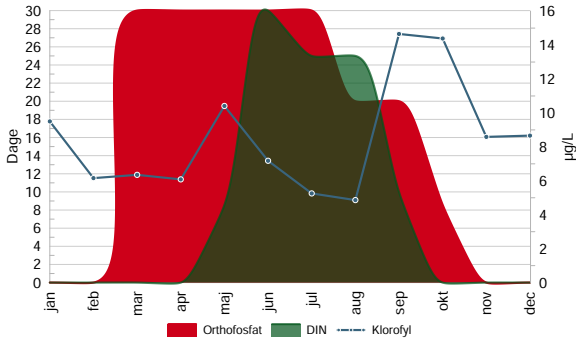
Figur 16.11 Number of days per month with DIP and DIN limitation as an average of the period 2017-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2020 (secondary axis). Upper water column.

Nissum Fjord, middle part, station 91240002



Figur 16.12 Number of days per month with DIP and DIN limitation as an average of the period 2008-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2008-2020 (secondary axis). Upper water column.

Nissum Fjord, outer part, station 91240001



Figur 16.13 Number of days per month with DIP and DIN limitation as an average of the period 2017-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2019 (secondary axis). Upper water column.

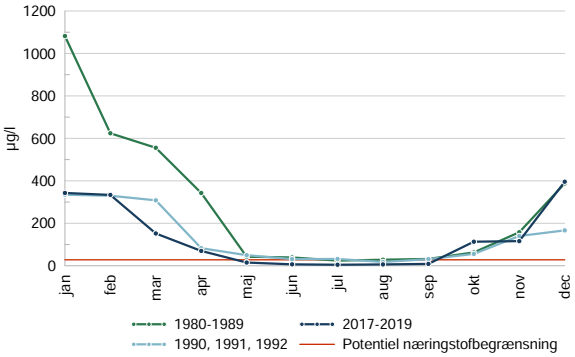
NYBORG FJORD 17

Nyborg Fjord is an estuary with a wide boundary to the Great Belt. The water depth is 10 m in the central part of the estuary and is periodicly stratified. Due to the constant water exchange with the Great Belt oxygen depletion occurs rarely. The estuary has only a small direct catchment of 30 km^2 but also receives water from the Holckenhavn Fjord with larger catchment of 220 km^2. The salinity at the monitoring station is typically 20-25 psu at the bottom and 15-20 psu at the surface.

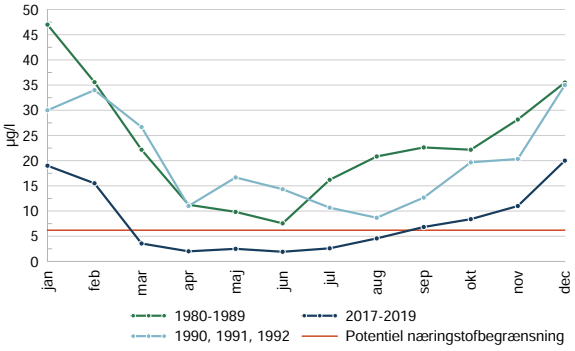
Figur 17.1 Water bodies and monitoring stations

Nyborg Fjord	
Water body area	8 km^2
Catchment area	250 km^2
Area ratio (catchment/water body)	31
Water depth max.	13 m
Salinity	15-25 psu
Stratification	Periodic

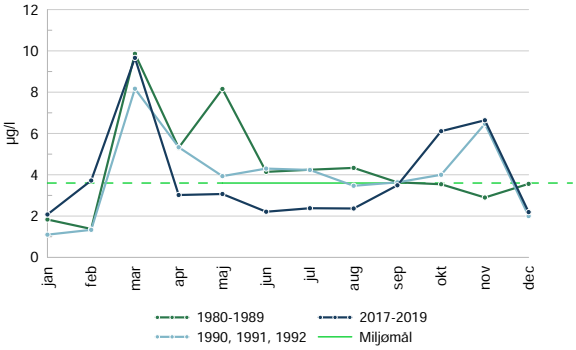
Nyborg Fjord, station 96720004



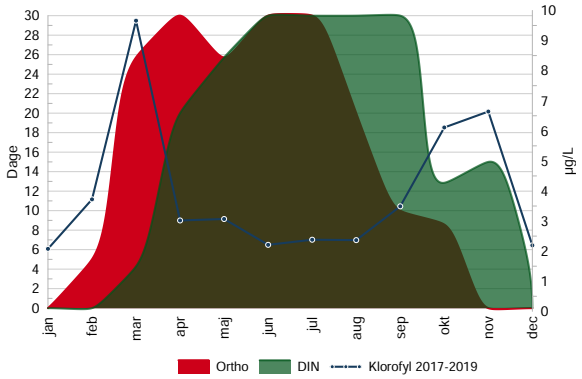
Figur 17.2 Average **DIN**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1992 and 2017-2019.



Figur 17.3 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1992 and 2017-2019.



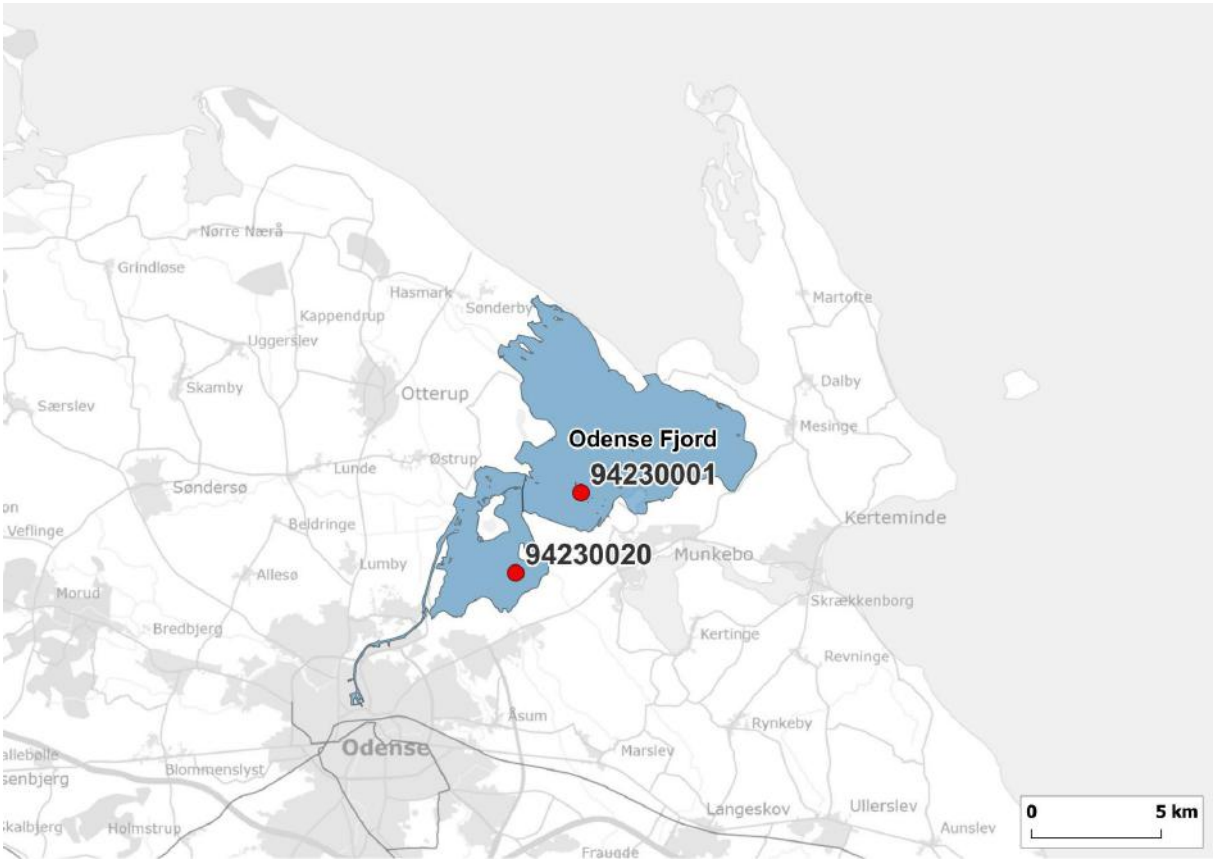
Figur 17.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 3 periods: 1980-1989 and 1990-1992 and 2017-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 1.6 µg/l - green line not updated.



Figur 17.5 Number of days per month with DIP and DIN limitation as an average of the period 2017-2019 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2019 (secondary axis). Upper water column.

ODENSE FJORD 18

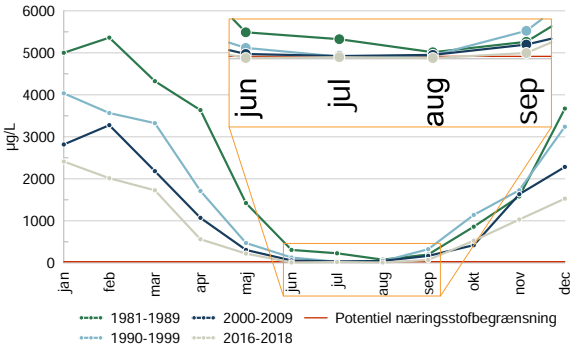
Odense Fjord is an estuary divided into an inner part (15 km^2) and an outer part (46 km^2) with a boundary to the Kattegat. The Inner part is shallow, with a water depth of approx. 0.5-1 meter in most parts. In the inner western part there are areas which are somewhat deeper (3-5 m), and there is a channel (7,5 m), all the way into Odense City. The salinity fluctuates between 8-17 psu. The outer part has a water depth of approx. 3-6 m in most parts, but in the northwestern part there is more shallow water (1-2 m) and in the central part the water depth is up to 11 m. The salinity of the outer part fluctuates between 15-21 psu throughout the year in the upper water column and approx. 18-23 psu at the bottom. The estuary is stratified for most of the year, but due to constant inflow of water from Kattegat oxygen depletion is rare.



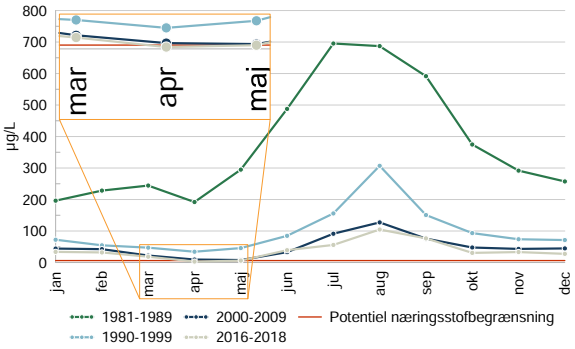
Figur 18.1 Water bodies and monitoring stations

Odense Fjord	
Water body area (inner)	61 km^2
Catchment area (inner)	1060 km^2
Area ratio (catchment/water body)	17
Water depth max.	11 m
Salinity	8-23 psu
Salinity stratification	Mostly

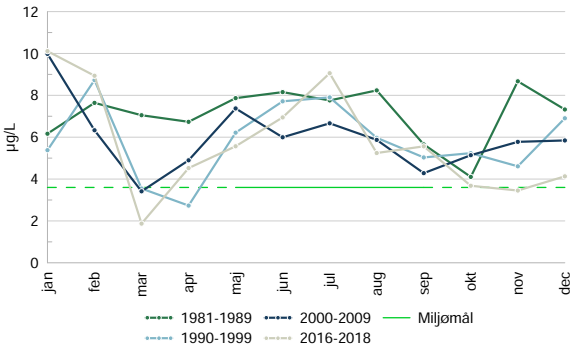
Odense Fjord, inner part, station 94230020



Figur 18.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods: 1981-1989 and 1990-1999 and 2000-2009 and 2016-2018.

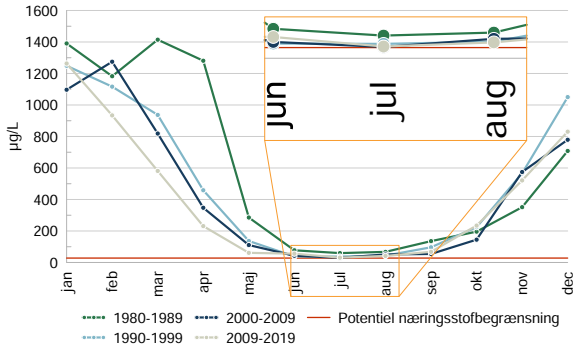


Figur 18.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods: 1981-1989 and 1990-1999 and 2000-2009 and 2016-2018.

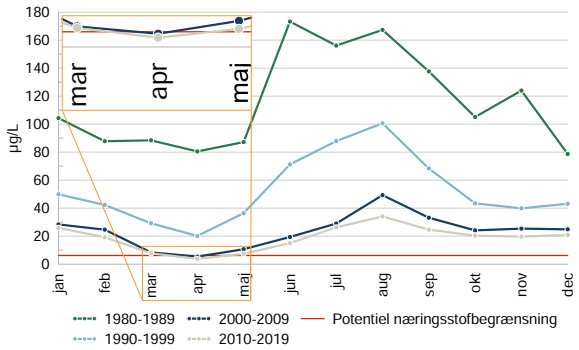


Figur 18.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods: 1981-1989 and 1990-1999 and 2000-2009 and 2016-2018. Boundary good/moderate summer chlorophyll (May-Sep) is 7.0 µg/l - green line not updated.

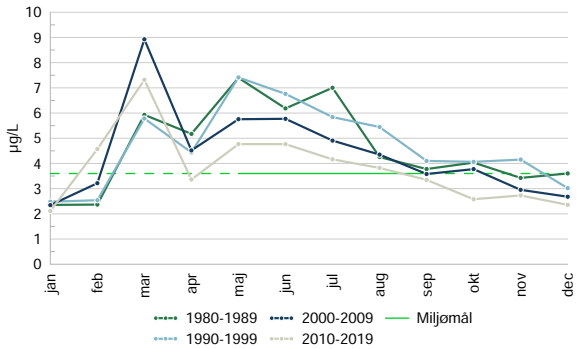
Odense Fjord, middle part, station 94230001



Figur 18.5 Average **DIN**-concentration per month (µg/l) in upper water column for four periods: 1980-1989 and 1990-1999 and 2000-2009 and 2009-2019.

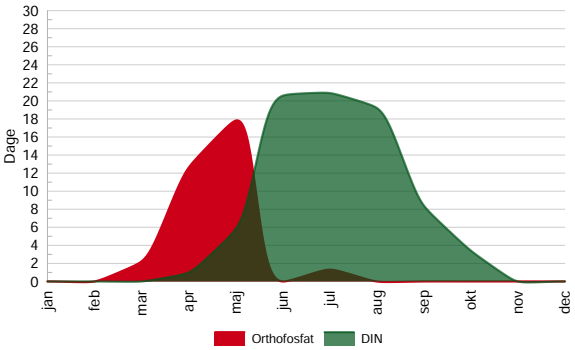


Figur 18.6 Average **DIP**-concentration per month (µg/l) in upper water column for four periods: 1981-1989 and 1990-1999 and 2000-2009 and 2010-2019.



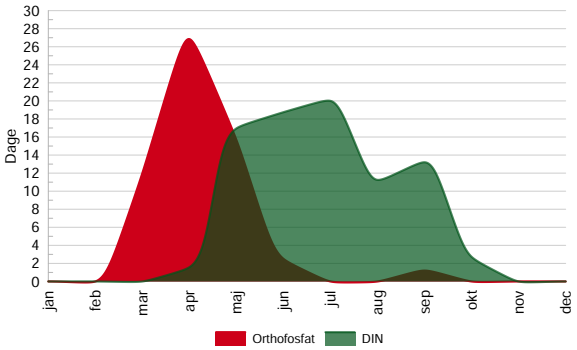
Figur 18.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2019. Boundary good/moderate summer chlorophyll (May-Sep) is 3.2 µg/l - green line not updated.

Odense Fjord, Inner part, station 94230020



Figur 18.8 Number of days per month with DIP and DIN limitation as an average of the period 2016-2018. Upper water column.

Odense Fjord, middle part, station 94230001



Figur 18.9 Number of days per month with DIP and DIN limitation as an average of the period 2010-2019. Upper water column.

RINGKØBING FJORD 19

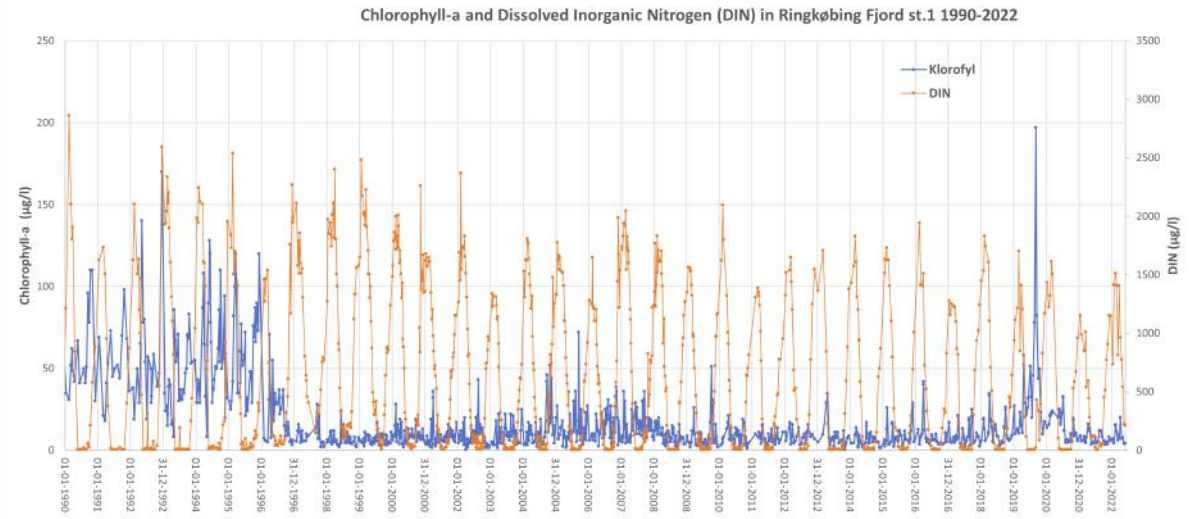
Due to a rather large influence of the clam Mya Arenaria the limitation patterns of DIN and DIP are quite different from other Danish coastal systems.

Ringkøbing Fjord is a 300 km^2 lagoon with a sluice to the North Sea located at the west coast of Jutland and with a catchment of 3.470 km^2 of mainly sandy soils. Water levels and salinity in the lagoon is controlled as far as possible by management at the sluice. The aim is to keep the salinity constant in the summer in the range 12 psu to 14 psu and in winter months above 6 psu to maintain the population of Mya Arenaria. Inflow from the North Sea in summer is only allowed when the wind speed is above 8 m/sec to ensure a mixing between the brackish water in the lagoon and the high salinity water (33 psu) from the North Sea, as quickly as possible to avoid stratification and oxygen depletion.

Figur 19.1 Water bodies and monitoring stations

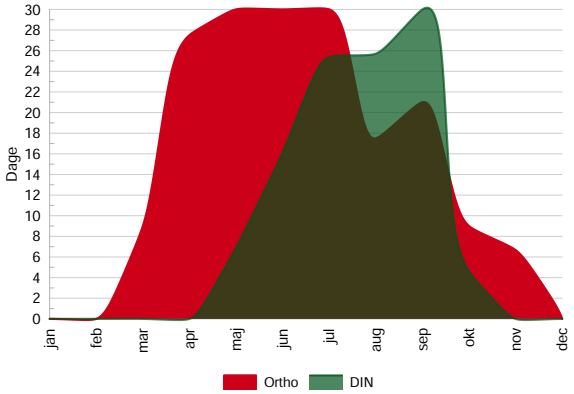
The ecosystem of the lagoon collapsed in the late 1970's introducing high algae biomasses and low secchi depth values (0.5 m). In the middle of the 1990's it was decided to obtain a higher salinity and with this decision the clam Mya Arenaria invaded the lagoon in large numbers with high filtrating rates and effectively controlling the plankton algae biomass and followed by an increase in the secchi depth to around 2 m (Petersen 2008). Due to the effective filtration, the concentration of DIN was relatively high in the summer months the first years after the regime shift in 1996 (Figur 19.2). Indicating that DIN is not controlling the chlorophyll-a concentration. The first years after the regime shift Ulva was not found in any significant numbers but that changed gradually, and Ulva became widely

distributed in the lagoon due to good light conditions and sufficient summer DIN and DIP concentrations. Since the regime shift, Ulva has been main indicator for eutrophication since chlorophyll-a most of the time is controlled by filtration. In a period in 2019 and 2020 the salinity in the lagoon was too low to support the existence of Mya Arenaria which affected the filtration capacity and the chlorophyll-a increased in that period (Figur 19.2). DIP and DIN role as limiting the Ulva biomass has been reported (Krause-Jensen 2002) but the concentration of bioavailable phosphate in the water samples is probably underestimated (Rasmussen 2003) due to the fact that bioavailable phosphate is absorbed to resuspended particles with iron content. Therefore DIP as a proxy for limitation of primary production is probably overestimated. (Figur 19.3).



Figur 19.2 Chlorophyll-a concentration and DIN concentration in upper water column for the period 1990-2022 in Ringkøbing Fjord. All data available used for plot.

Ringkøbing Fjord	
Water body area	300 km^2
Catchment area	3.470 km^2
Area ratio (catchment/water body)	11.6
Water depth max.	4.5 m
Salinity	4-14 psu
Stratification	Momentary when inflow



Figur 19.3 Number of days per month with DIP and DIN limitation as an average of the period 2013-2018. Upper water column.

ROSKILDE FJORD

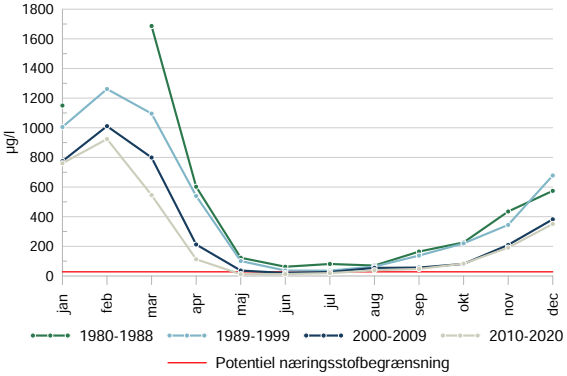
20

Roskilde Fjord is an estuary and part of a larger estuary including Isefjord with connection to Kattegat. The estuary is relatively narrow and long with an inner part (52 km^2) and outer part (71 km^2). Water depth is 2-6 m in most parts but in central parts and outer part up to 10 m and in the inner parts a few small locations with water depth up to 30 m. The salinity is highest in the outer part with a salinity of 15-20 psu and slightly lower in the inner part at 10-15 psu. At the narrowest and longest part, there are several natural and human-made constrictions, e.g. Kronprins Frederiks Bridge at Frederikssund. The constrictions must be assumed to minimise the water exchange. The average resident time for Roskilde Fjord has been reported to be 90 days in Staehr et al 2016 but they refer to Josefson and Rasmussen 2000 and this reference is a personal comment. In a new study by Nielsen M.H 2022 it is reported that the residence time is 3-4 weeks and much lower than earlier reported.

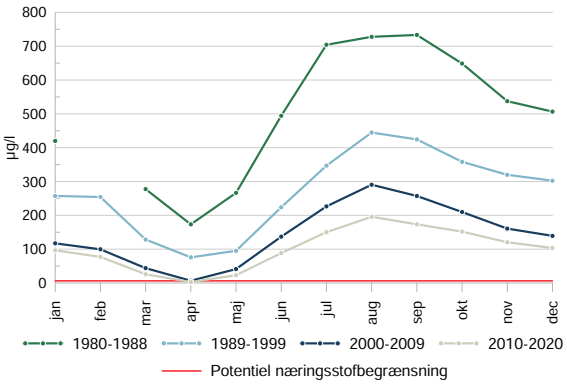
Figur 20.1 Water bodies and monitoring stations

Roskilde Fjord	
Water body area (inner)	123 km^2
Catchment area (inner)	730 km^2
Area ratio (catchment/water body)	6
Water depth max.	11 m
Salinity	8-23 psu
Salinity stratification	Periodic

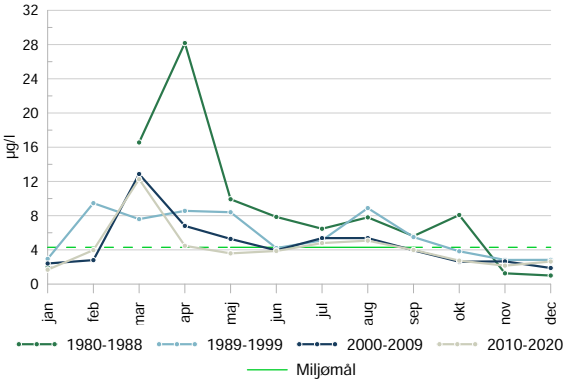
Roskilde Fjord, inner part, station 93220011



Figur 20.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods: 1980-1988 and 1989-1999 and 2000-2009 and 2010-2020.

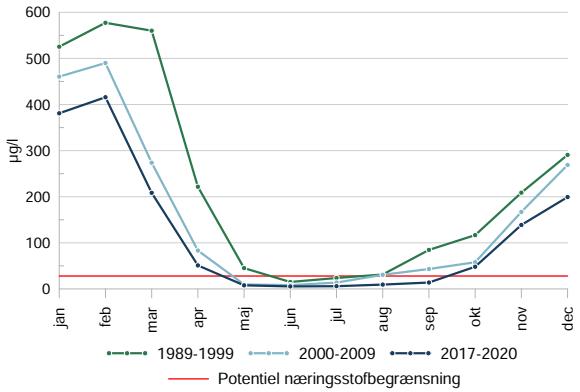


Figur 20.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods: 1980-1988 and 1989-1999 and 2000-2009 and 2010-2020.

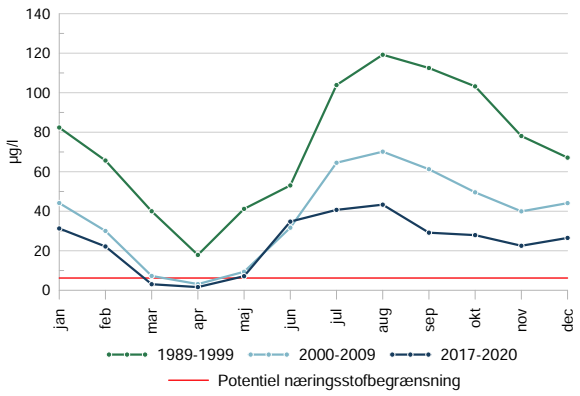


Figur 20.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods: 1980-1988 and 1989-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 4.3 µg/l - green line not updated.

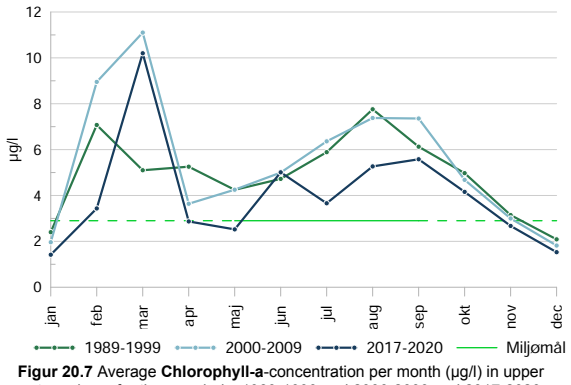
Roskilde Fjord, outer part, station 93220004



Figur 20.5 Average **DIN**-concentration per month (µg/l) in upper water column for three periods: 1989-1999 and 2000-2009 and 2017-2020.

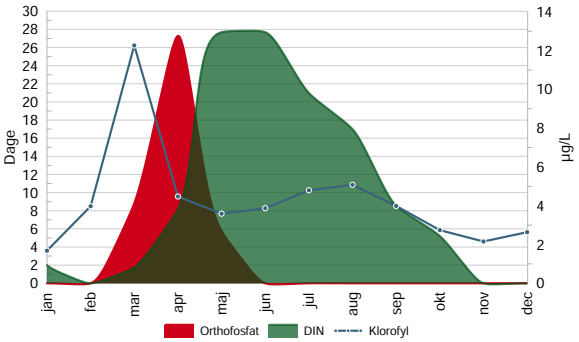


Figur 20.6 Average **DIP**-concentration per month (µg/l) in upper water column for three periods: 1989-1999 and 2000-2009 and 2017-2020.



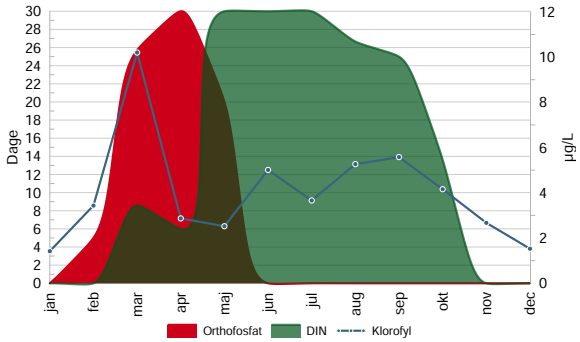
Figur 20.7 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for three periods: 1989-1999 and 2000-2009 and 2017-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 2.9 µg/l.

Roskilde Fjord, inner part, station 93220011



Figur 20.8 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

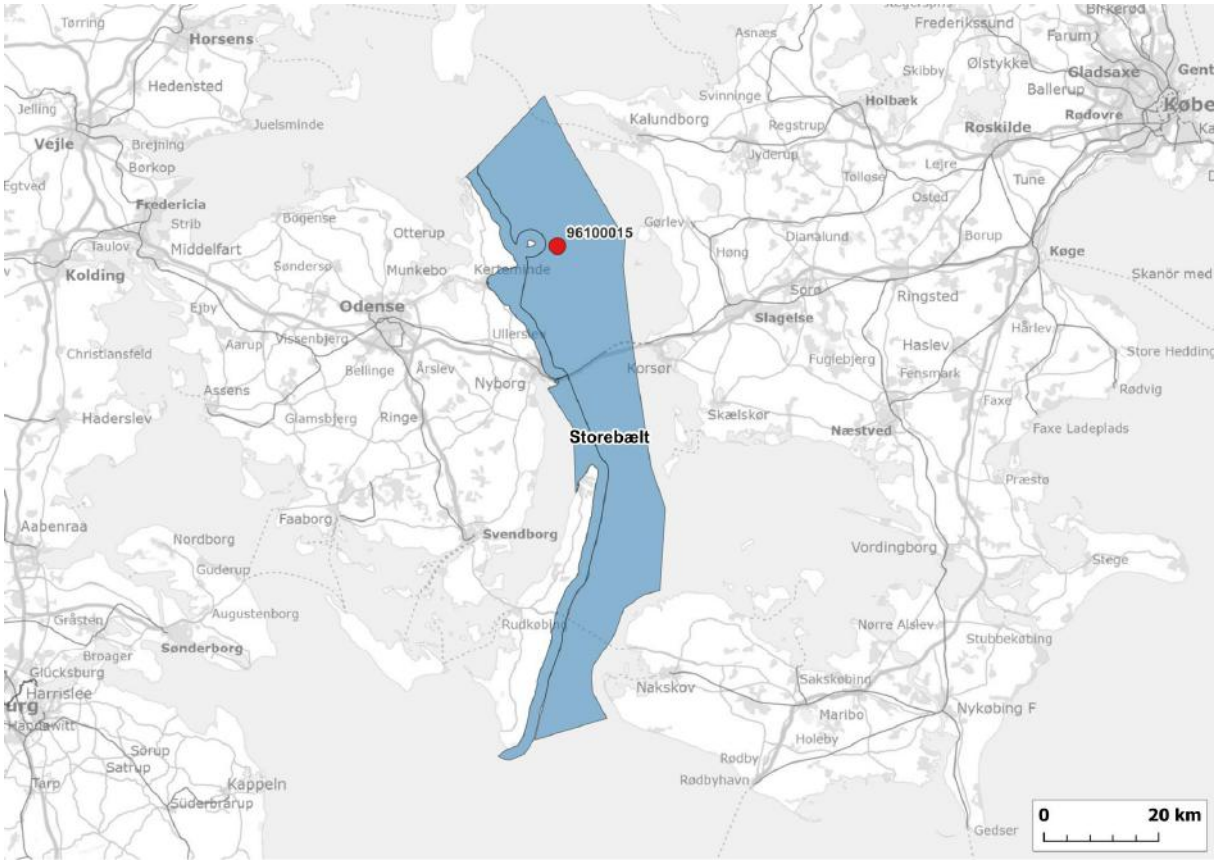
Roskilde Fjord, outer part, station 93220004



Figur 20.9 Number of days per month with DIP and DIN limitation as an average of the period 2017-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2017-2020 (secondary axis). Upper water column.

STOREBÆLT 21

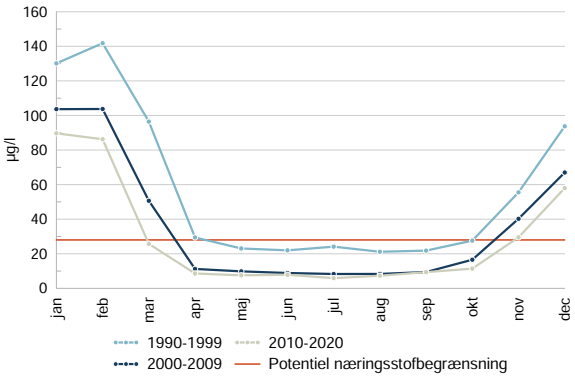
Storebælt (Great Belt) is the strait between the island of Funen and the island of Zealand and biggest of three straits connecting the Baltic Sea in the south with Kattegat to the North. In general there is a north going transport of Baltic Sea water in the upper layer and a south going transport of more saline water at the bottom but often very complex currents with high velocities at times.



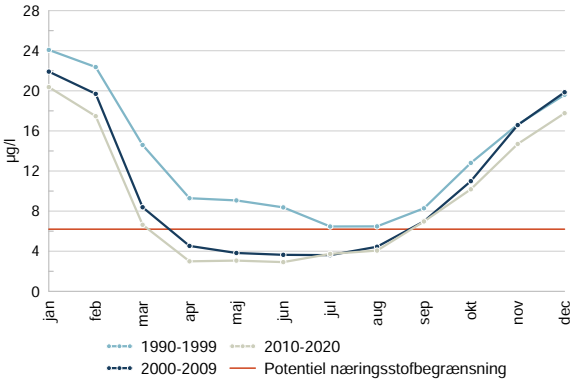
Figur 21.1 Water bodies and monitoring stations

Storebælt	
Water body area	- 1450 km^2
Catchment area	-
Area ratio (catchment/water body)	-
Water depth max.	50 m
Salinity	10-30 psu
Stratification	Permanent

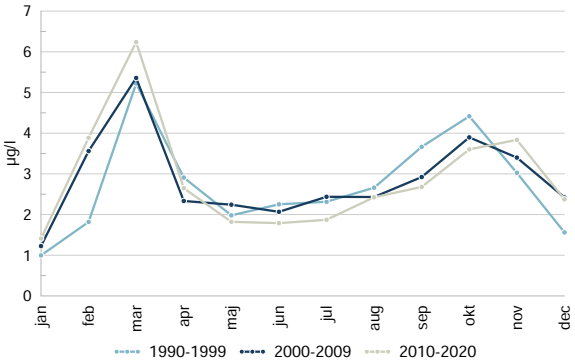
Storebælt, station 97200002



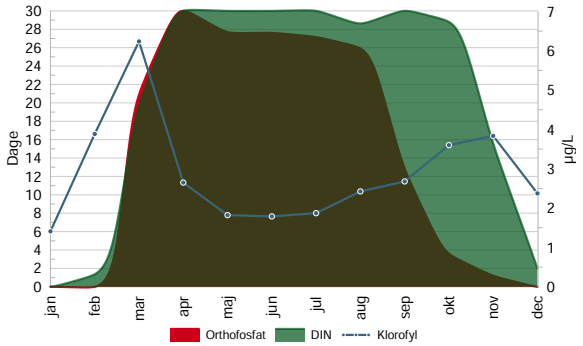
Figur 21.2 Average **DIN**-concentration per month (µg/l) in upper water column for 3 periods: 1990-1999 and 2000-2009 and 2010-2020.



Figur 21.3 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 1990-1999 and 2000-2009 and 2010-2020.



Figur 21.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 3 periods: 1990-1999 and 2000-2009 and 2010-2020. No boundary for good/moderate.

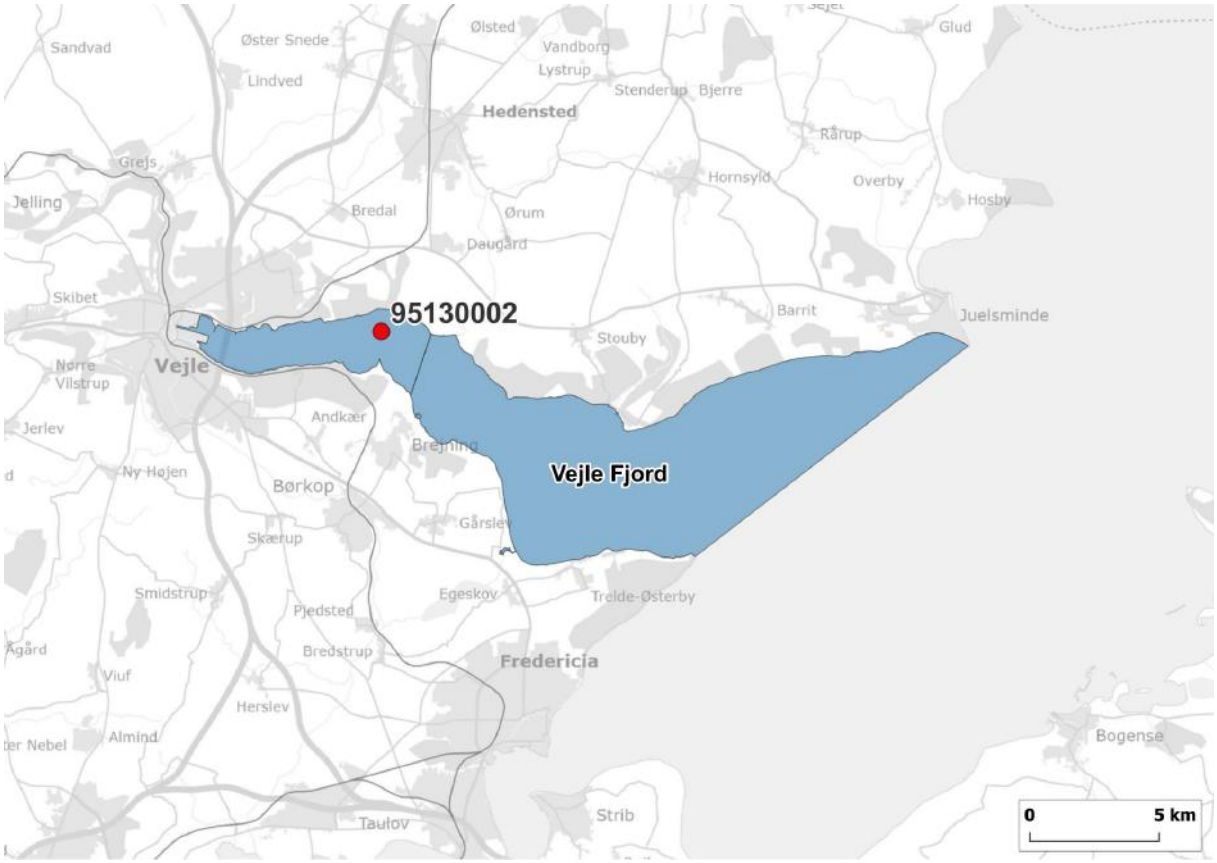


Figur 21.5 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

VEJLE FJORD

22

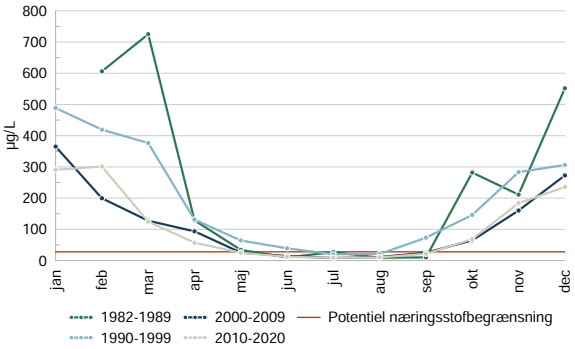
Vejle Fjord is an estuary with a wide boundary with the Little Belt. Water depth is 10-16 m in the outer part and decreasing to below 10 m in the inner part. Due to the wide boundary with Little Belt the salinity in the estuary is fluctuating in the same cycles as in Little Belt and the water volume in the estuary can within relatively few days be exchanged with water from the Little Belt.



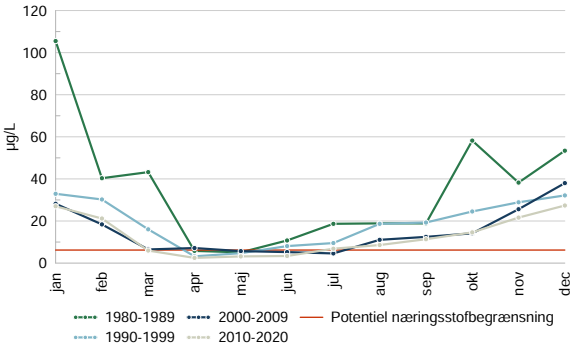
Figur 22.1 Water bodies and monitoring stations

Vejle Fjord	
Water body area (inner)	108 km^2
Catchment area (inner)	730 km^2
Area ratio (catchment/water body)	7
Water depth max.	16 m
Salinity	12-30 psu
Salinity stratification	Periodic

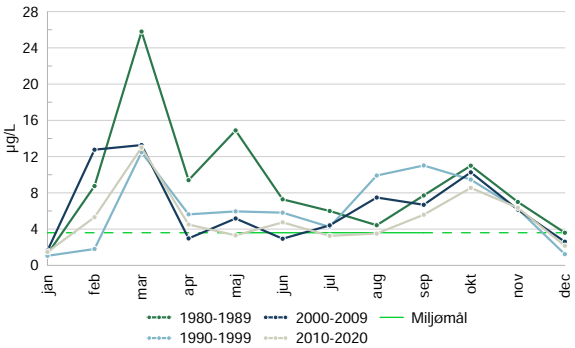
Vejle Fjord, station 95130002



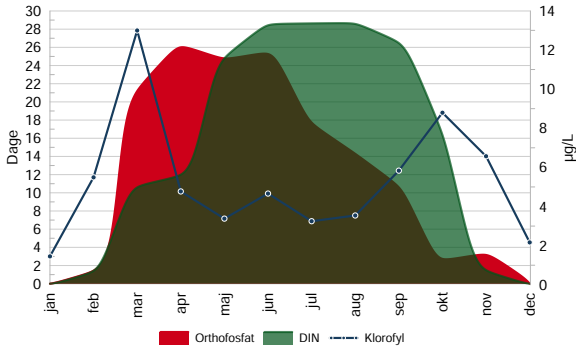
Figur 22.2 Average **DIN**-concentration per month (µg/l) in upper water column for four periods: 1982-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 22.3 Average **DIP**-concentration per month (µg/l) in upper water column for four periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 22.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for four periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020. Boundary good/moderate summer chlorophyll (May-Sep) is 3.6 µg/l - green line not updated.



Figur 22.5 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

ØRESUND

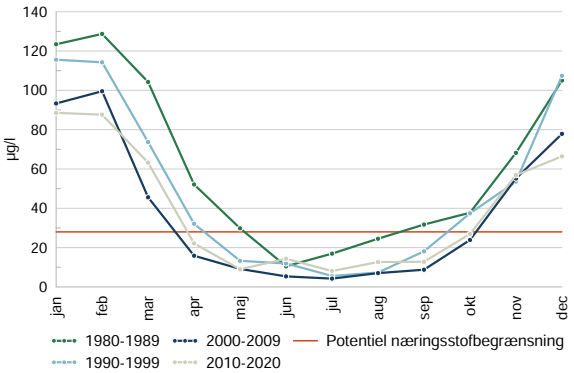
23

Øresund is the strait between Denmark and Sweden and one of three straits connecting the Baltic Sea in the south with Kattegat to the North. Øresund is deeper to the north up to 35 m but narrow between the two cities of Helsingør and Helsingborg. At this narrow part it is suggested that there is ”internal hydraulic control” (Nielsen 2001). Øresund becomes more shallow to the south and at the bridge and tunnel connection between Copenhagen and Malmo, water depth is less than 10 m resulting in a threshold for the inflow of high saline water to the Baltic. In general there is a north going transport of Baltic Sea water in the upper layer (5-10 psu) and a south going transport of more saline water at the bottom (15-30 psu) but often very complex currents with high velocities at times. The DIP level seems to have increased in Øresund (Figur 23.3) - this is aligned with other reporting (Carlsson 2019).

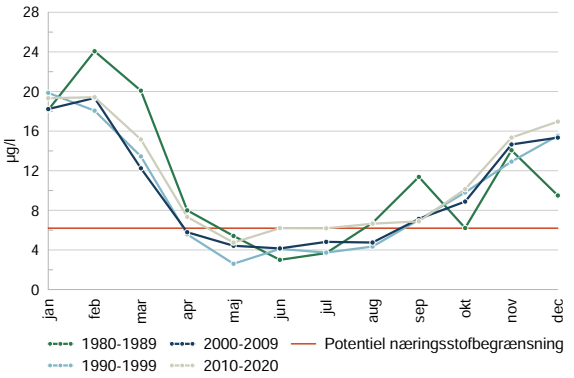
Figur 23.1 Water bodies and monitoring stations

Øresund	
Water body area	- 1400 km^2
Catchment area	-
Area ratio (catchment/water body)	-
Water depth max.	35 m
Salinity	5-30 psu
Stratification	Permanent

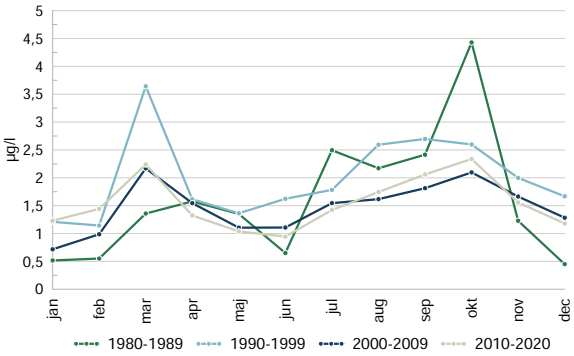
Øresund, station 97200002



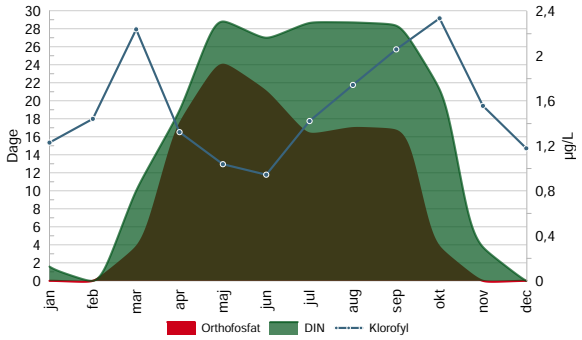
Figur 23.2 Average **DIN**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 23.3 Average **DIP**-concentration per month (µg/l) in upper water column for 3 periods: 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020.



Figur 23.4 Average **Chlorophyll-a**-concentration per month (µg/l) in upper water column for 4 periods: 1980-1989 and 1990-1999 and 2000-2009 and 2010-2020. No boundary for good/moderate.



Figur 23.5 Number of days per month with DIP and DIN limitation as an average of the period 2010-2020 (primary axis) and the average concentration per month of chlorophyll (µg/l) for the period 2010-2020 (secondary axis). Upper water column.

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