The Hypertrophic Estuary of Mariager Fjord

Pollution of Coastal Waters

June 2015

Group 2.310 at Aalborg University

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Synopsys:

Mariager Fjord is a highly eutrophicated estuary and is considered to have a bad water quality according to the Aquatic Plan 1.3 [2011] for Mariager Fjord. This is caused by a high nitrogen and phosphorus load into the fjord from the adjacent streams. The Water Framework Directive [2000] states that all european water bodies must reach a good water quality at the end of 2015. In this report, the nutrient reduction is going to be investigated by setting up an ecological model and a hydrodynamic model. Furthermore, the behaviour of the ecological model is going to be observed in regards to the nutrient reductions. In order to improve the water quality of the fjord, a conceptual solution is going to be studied. Although nitrogen reduction can be achieved by implementing the suggested solutions, the criteria for the end of 2015 cannot be complied in time. It is possible though that a good water quality can be reached in the near future.

The content of the report is at free disposal, but a publication (with citations) must only happen with an agreement with the authors.

Danish abstract

Mariager Fjord er en meget eutrofieret fjord og anses for at have en dårlig vandkvalitet ifølge vandplanen for Mariager Fjord. Dette er forårsaget af en høj belastning af kvælstof og fosfor til fjorden fra de tilstødende vandløb. Ifølge Vandrammedirektivet skal alle Europas vandområder opnå en god tilstand inden udgangen af år 2015. I denne rapport, vil reduktionen af næringsstoffer blive undersøgt ved at udvikle en økologisk og hydrodynamisk model. Endvidere vil der blive analyseret på modellens optræden i forhold til reduktion af næringsstoffer. Udover det, vil en konceptual løsning blive undersøgt for at forbedre vandkvaliteten i fjorden. Selvom reduktion af kvælstof kan muliggøres ved at implementere de foreslåede løsninger, vil kriteriet om god vandkvalitet inden udgangen af år 2015, ikke blive opnået i tide. Det er stadigvæk muligt at en god vandkvalitet kan opnås i en nær fremtid.

Preface

This project has been written at the faculty of Engineering and Science at Aalborg University during the spring of 2015. The project has been written by Group 2.310, comprising six members that are currently studying at the 2nd semester of the Master's program Water & Environment and Environmental Engineering.

The project is a study of the water quality of Mariager Fjord with a study on its ecological state. The project builds on the lessons and literature given during the semester. The project is based on 2005 data measurements obtained by [DCE, 2012]. For making this project, a special gratitude goes to the supervisors, Torben Larsen and Thomas Ruby Bentzen, who have assisted with guidance and ideas.

Reading instructions

The report is divided into chapters that contains sections and subsections. In this way, it will be easier to refer to. For each figure, table and equation may be present in this report, these are numbered with respect to the given chapter. For instance, the first figure in chapter 3 will be Figure 3.1.

Additional calculations are placed in the appendix, which is after the bibliography list. The bibliography contains the list of literature, which is referred to through the entire report. The citations in the report are presented as author-year citations, which is the Harvard method.

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Contents

1 Introduction

Throughout the history, estuaries and coastal areas have become one of the most populated areas in the marine environment. This is due to the industrialization at the banks of estuaries, which have made transport routes, between the major cities of the world, possible. However, as the industrialization and population continued to grow, the marine environment faced some critical issues regarding degradation of the water quality. [Wolanski, 2007; Clark, 2001]

The water quality of the marine environment becomes degraded, when the input has a damaging effect. One of these type of inputs that cause this degradation of the water quality, is the nutrient over-enrichment to the marine environment, which will be the focus in this report. The excessive nutrient enrichment, mainly nitrogen (N) and phosphorus (P), can be derived from sewage systems, industrial discharges, and runoff or river inflow containing pesticides or fertilizers from agriculture. [Wolanski, 2007; Clark, 2001; Ansari and Gill, 2014]

The nutrient loads that are discharged can sometimes have damaging consequences for the marine environment. That happens when large inputs of nutrients cause a larger production of algal biomass, also known as eutrophication. The eutrophicated waters may suffer from oxygen depletion. [National Academy Press, 2000]

In order to bring the problem of eutrophication in focus, the European Union initiated a legislative framework, called Water Framework Directive [2000] along with other directives. The purpose of this directive is to ensure that each member state takes the necessary steps to protect the water bodies, which include streams, lakes, coastal waters and groundwater. In Denmark, the demands from Water Framework Directive [2000] was followed up by Aquatic Plans (danish: Vandplaner). These Aquatic Plans are applied for each river basin that accounts for how the aim of a "good quality" in the danish water bodies can be succeeded. [DEPA; Ansari and Gill, 2014]

In this report, there will be focused on the estuary of Mariager Fjord, which belongs to the river basin 1.3 (danish: Hovedvandopland 1.3). The river basin is shown in figure 1.1 on the following page. During the last decades, Mariager Fjord has suffered from massive nutrient loads, which have left the Fjord in a poor state. The fjord has been affected by oxygen depletion during the 90's in the inner part. Furthermore, in the summer of 1997, the inner part has reached anoxic conditions throughout the water column. [Markager et al., 2008; Fallesen et al., 2000]

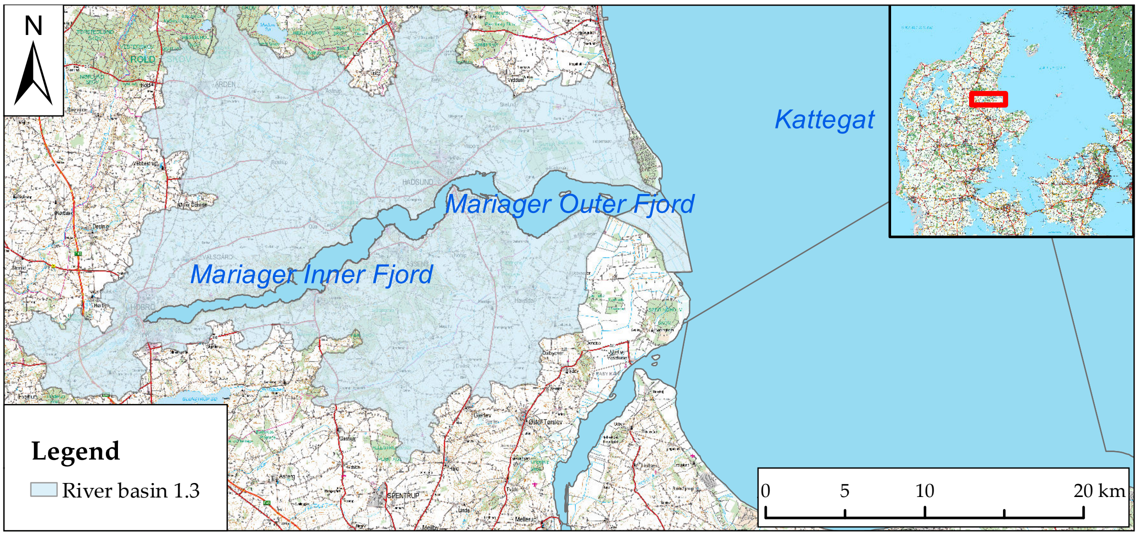


Figure 1.1: *The estuary of Mariager Fjord, showing the river basin and coastal areas.*

2 Site investigation

In this chapter, the catchment of Mariager Fjord will be described in further detail in regards to the river basin, area usage, biodiversity and geology. Furthermore, the issue of eutrophication in regards to Mariager Fjord will be described. Lastly, the stratification of Mariager Fjord will be accounted for, where the focus will be on the deeper inner part of the fjord.

2.1 Catchment description and area usage

Mariager Fjord is situated in the southern part of northern Jutland, starting from Hobro and moving towards east into Kattegat. It is the longest estuary in Denmark with a total length is around 42 km and a total surface area of approximately 47 km^2. The fjord is characterized as being shallow in the outer part and very deep in the inner part. The widest point of the fjord is of around 4.5 km and of only 250 m in the most narrow point near Hadsund. This leads to a very slow replacement of water inside the estuary, which is why the fjord can be vulnerable to eutrophication. [Mariager Fjord Guiden]

The catchment of the fjord has an area of 572 km^2 and covers around 80% of the municipal area of Mariagerfjord Kommune, shown in figure 2.1. From here, numerous streams are running into the Fjord which supplies it with freshwater.

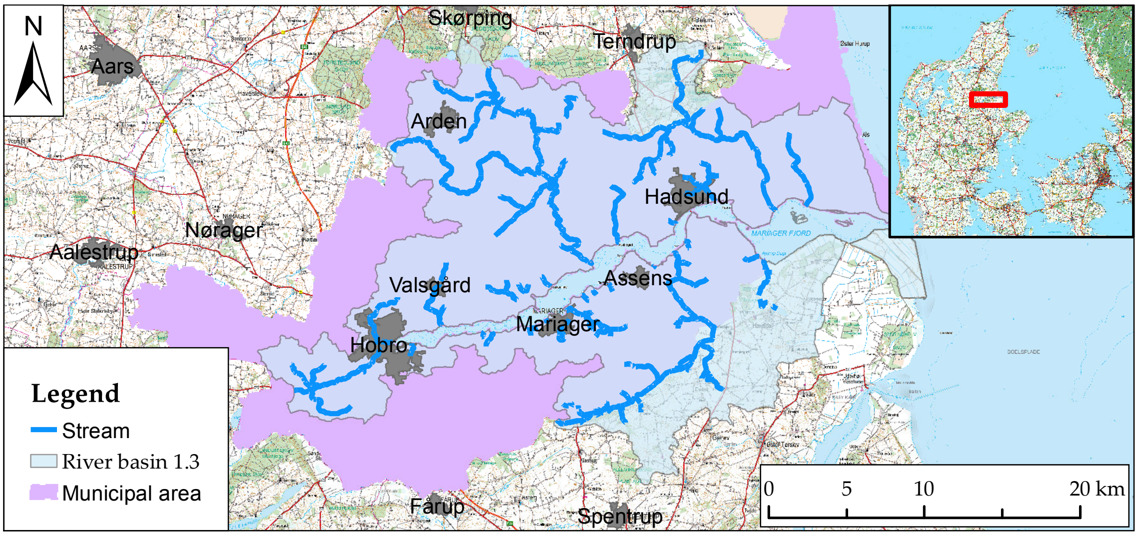


Figure 2.1: *The location of Mariager Fjord, showing the river basin in contrast to the municipal area. Also visible is the many streams that ends up in Mariager Fjord. [Aquatic Plan 1.3, 2011]*

The land use around Mariager Fjord is dominated mainly by agricultural purposes, from which high concentrations of nitrogen and phosphorus are transported into the fjord [Müller-Wohlfeil et al., 2002]. Figure 2.2 shows the area usage in contrast to the total catchment area of Mariager Fjord.

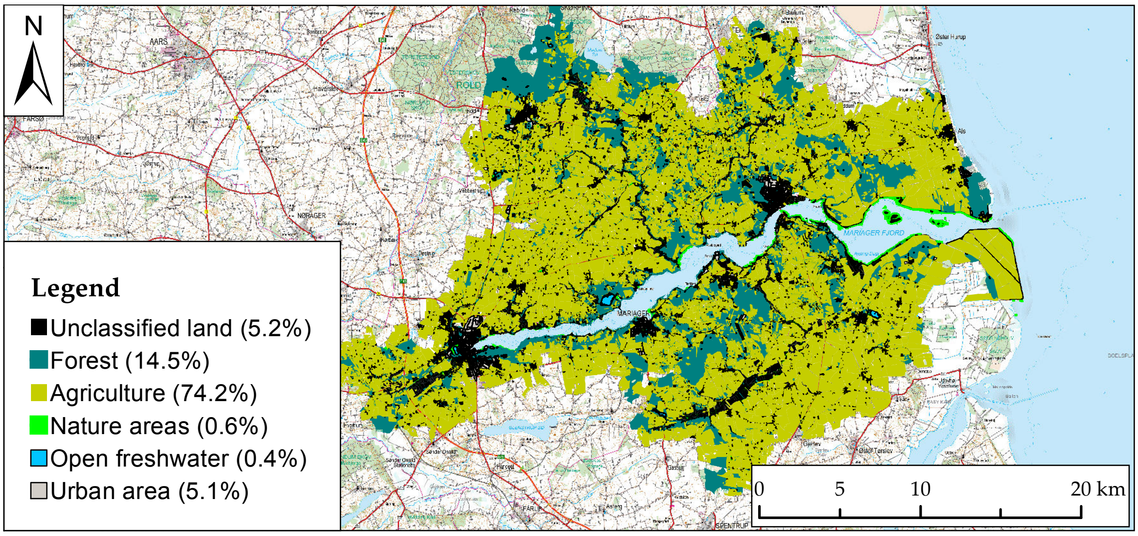


Figure 2.2: *Map showing land use around Mariager fjord [Bidstrup et al., 2010; Müller-Wohlfeil et al., 2002].*

As shown in figure 2.2, around 75% percent of the land is used for agricultural purposes. This has a deep impact, because agriculture is the largest input source of nutrients to the fjord. A significant reduction in the input is essential if a good water quality criteria is to be reached.

2.2 Biodiversity

As it is shown by numerous experiments, biodiversity is an indicator for the water quality and helps the ecosystem to withstand pressures from pollution. [Roddis, 2011]

The phytoplankton in Mariager Fjord consists of few species, but there are frequent blooms of individual species. Algae production in Mariager Fjord is 2 to 4 times greater than the production in other danish fjords and waters. In 1994, a study has been performed in a stratified basin in the inner part of Mariager Fjord, where the depth has been 30 m. It has been recorded that the lower half of the water column is anoxic and sulphidic. Also, it has been estimated that 10-15% of the net primary production is mineralized anaerobically. [Tom Fenchel, 1994]

Mariager Fjord has an impoverished zooplankton. Only a number of 81 species of protozoa were identified in the water column. From these, 37 were identified to belong to only three groups: ciliates, flagellates and rhizopods. It is supposed that this may occur due to the sulphidic water in the deep part of the fjord, which, when present, will be lethal to the sedimenting eggs. [Tom Fenchel, 1994]

Time series data about the species and concentrations that can be found in the surface water of Mariager Fjord are available from 1990 to the present. Among these species, the most abundant are the diatoms, which are a major group of algae, and are among the most common types of phytoplankton. They present a unique feature by having a cell wall made of silica. Diatoms are dependent on silica for growth, making silica a limiting factor for them. [Carstensen; Waggoner]

Another species of zooplankton found is dinoflagellate, which are flagellates that are able to survive both in marine environmental and in fresh water as well. Moreover, they are known to be photosynthetic, but a large fraction of these are in fact mixotrophic, combining photosynthesis with ingestion of prey. [STOECKER, 1999]

Other species found in Mariager Fjord include cryptophytes, litostomatea, chrysophytes, clorophytes, nostocophytes, prymnesiophytes, prasinophytes, euglenophytes and other species that have not been identified. [Carstensen]

In the late summer of 1997, the zooplankton perished due to anoxic conditions. In the following spring and summer, a sampling program at three stations in the anoxic part of the fjord has been initiated. In the beginning of April, salinity throughout the depths of the inner fjord was decreasing, thus no sign of major water intrusions from Kattegat. During the first part of May, salinity decreased even more, coinciding with a large freshwater run-off. However, in the second half of May and June, total salt content as well the salinity of the bottom water has increased. Therefore this points a salty-water intrusion from Kattegat. This has lead to a re-population of the zooplankton in the fjord.

From the study it has been observed that the number of settled individuals has increased from May and peaked in June 1998. The water exchange rate as well as the tidal current in Mariager Fjord are modest, increased the chance of zooplankton retention and settlement, furthermore reforming the benthic fauna which plays a critical role in the functioning and maintenance of Mariager Fjord [Hansen et al., 2002].

Despite the recovery in 1998, it can be concluded that Mariager Fjord is an unstable system, characterized by high biomass, large productivity and very small species diversity. [Leonhard et al., 2010]

2.3 Geology

From figure 2.3 on the following page, in which the geology of the catchment area is presented, it is supposed that Mariager Fjord has been formed long before the Ice Age. During the Ice Age, and also after it, the glacial ice and melt-water flowing along with changes in sea level and due to the geology, have formed the fjord as it is today. [Mariager Fjord Guiden]

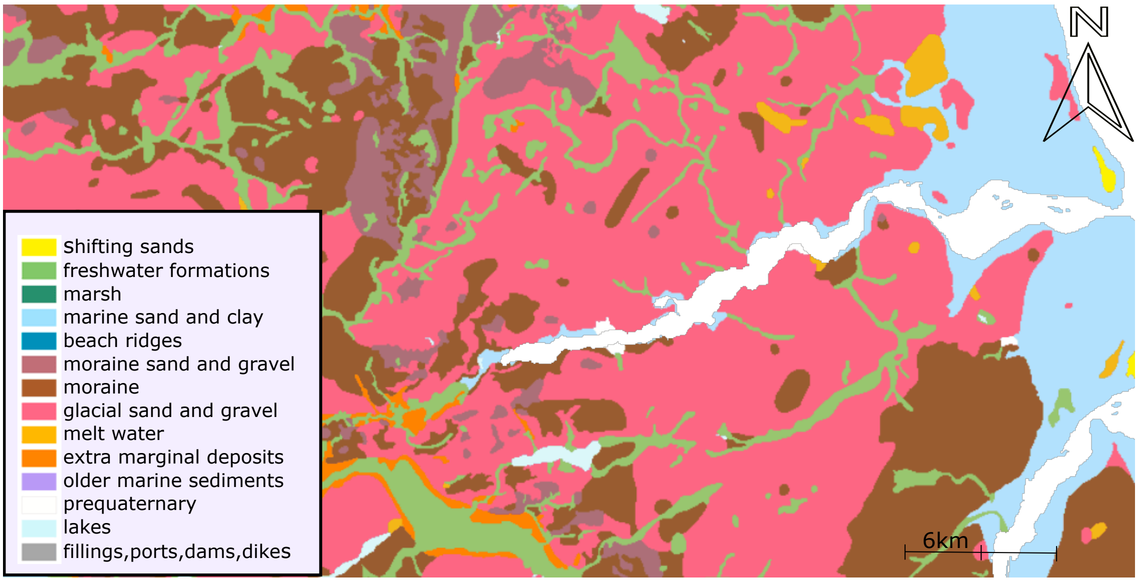


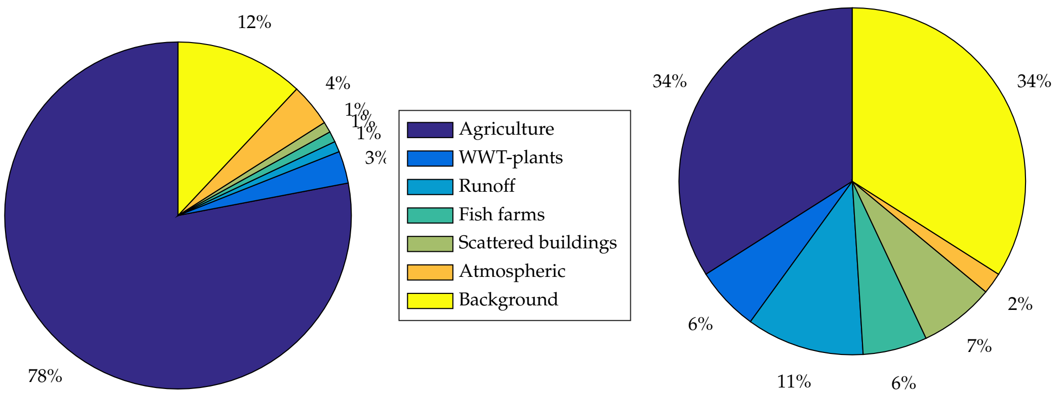
Figure 2.3: *Geological view of the area surrounding Mariager Fjord [GEUS, 2002].*

Mariager Fjord has several hills around it, which are traces of various ice ages, where glacial ice has drifted over northern Jutland. The hills consist initially of moraine clay and sand till. Furthermore, it can be seen that an ice from the Late Ice Age, which originates and have detached itself from central Sweden, has put its character in the fjord valley. The ice has shot through the Kattegat and further across the northern Jutland. The ice's direction of movement is in accordance with fjord basins longitudinal direction, suggesting that this ice has formed the inlet path. A long section of the valley consists of marine sediments as chalk and Danian chalk as the bottom layer.

2.4 Eutrophication in Mariager Fjord

Eutrophication is the process directly associated with the enrichment of limiting nutrients, commonly associated in aquatic environments with the increase of nitrogen and phosphorous amounts in the system. The base of any food chain are photosynthetic organism and in the case of aquatic environments this base is constituted by phytoplankton that use inorganic carbon and other nutrients to growth, releasing oxygen to the environment. When neither carbon, nutrients or light are limiting factors, a huge growth of the phytoplankton can occur. This so-called algae blooms can have consequences as a decrease in biodiversity, loss of habitats, and episodes of hypoxia and anoxia that can kill benthic and even pelagic communities. [National Academy Press, 2000]

Although the eutrophication of aquatic systems can occur naturally, it is usually enhanced by human activities. One of the most common source is the over-fertilization of agricultural fields that can produce an increase of the content of nutrients in the runoff water. This is the case of Mariager Fjord in where a significant part of the lands of its catchment are dedicated to agricultural purposes as explained in section 2.1. Figure 2.4 shows the distribution of nutrient sources that enter Mariager Fjord.



(a) The nitrogen load. (b) The phosphorus load.

Figure 2.4: *The distribution of the nutrient sources that enter Mariager Fjord [DEPA, 2004].*

From figure 2.4(a), it is clearly seen that agriculture is the dominating source of nitrogen discharge into Mariager Fjord in contrast to a relatively small part coming from the point and background sources, where the latter means the naturally occurring discharge. As for the discharge of phosphorus, the agriculture constitutes around one third of the total amount to the fjord. The point sources all together constitute the other third, where the the last portion is the background sources. [DEPA, 2004]

As for the nitrogen load from agriculture, there are laws in Denmark that limits the fertilization. According to §5 and §6 in the law, LBK no. 500 [2013], the agricultural firms may not exceed the nitrogen limit during the production period, calculated for each particular field. The limit is set, based on the size of the field and the usage.

Finally, the discharge of nutrients from wastewater treatment plants is being reduced as a result of ongoing centralization. The existing treatment plants with outlet to the fjord, are gradually substituted by a new larger treatment plant with outlet directly to Kattegat, sparing the load to the fjord. The new treatment plant is planned to be finished in 2018. [Leonhard et al., 2010]

Primary productivity is affected mainly by the availability of nutrients, light limitation and predation. The increase of primary productivity and the low predation rates lead to a big input of dead organic matter both in the water column and in the sediments. This dead organic matter is degraded mainly by bacterias, consuming oxygen. If this oxygen is not replaced by photosynthesis or mixing events the consequence will be oxygen depletion. During the warmer period in Mariager Fjord, when the weather is calm, the water is stratified due to no mixing so the water column cannot be re-aerated.[National Academy Press, 2000]

2.5 Stratification in Mariager fjord

Mariager Fjord is a long shallow Danish threshold fjord with a strong stratification of the water column [Ramsing et al., 1996]. The topographical characteristics control the residence time of the water and the stagnation of the bottom water in the deep basin. The water exchange with the sea is very low and it takes 17 months before half of the bottom water in the inner fjord is replaced. Whereas in the outer fjord two thirds of the water is replaced within a month, shown in figure 2.5. [Fallesen et al., 2000]

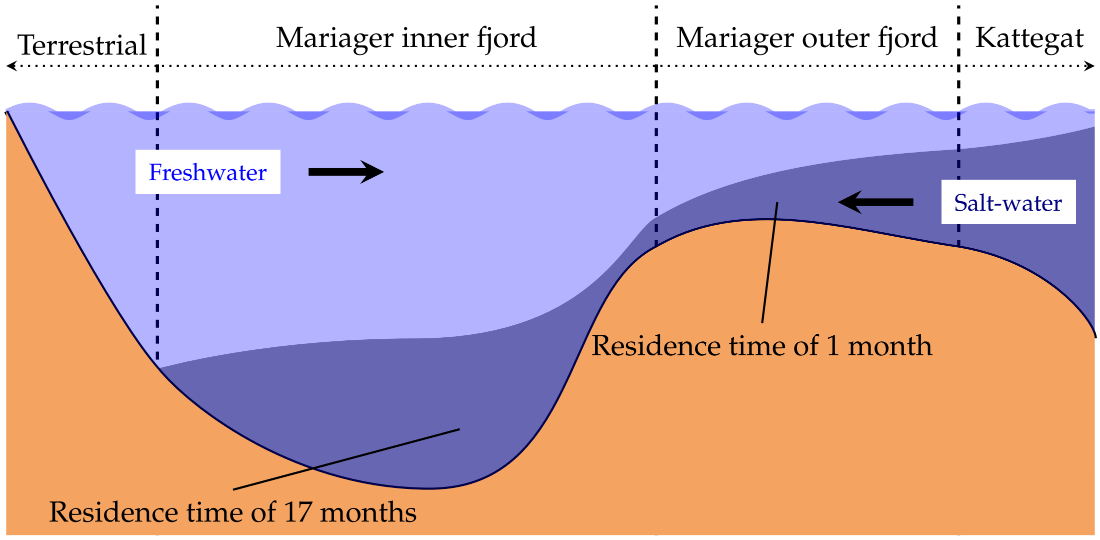


Figure 2.5: *The stratification of Mariager Fjord.*

A hypsometric curve is created in order to have an overview of the accumulative distribution of depths in the inner Fjord. In figure 2.6, it can be seen that around 80 % of the depths are below 15 meters.

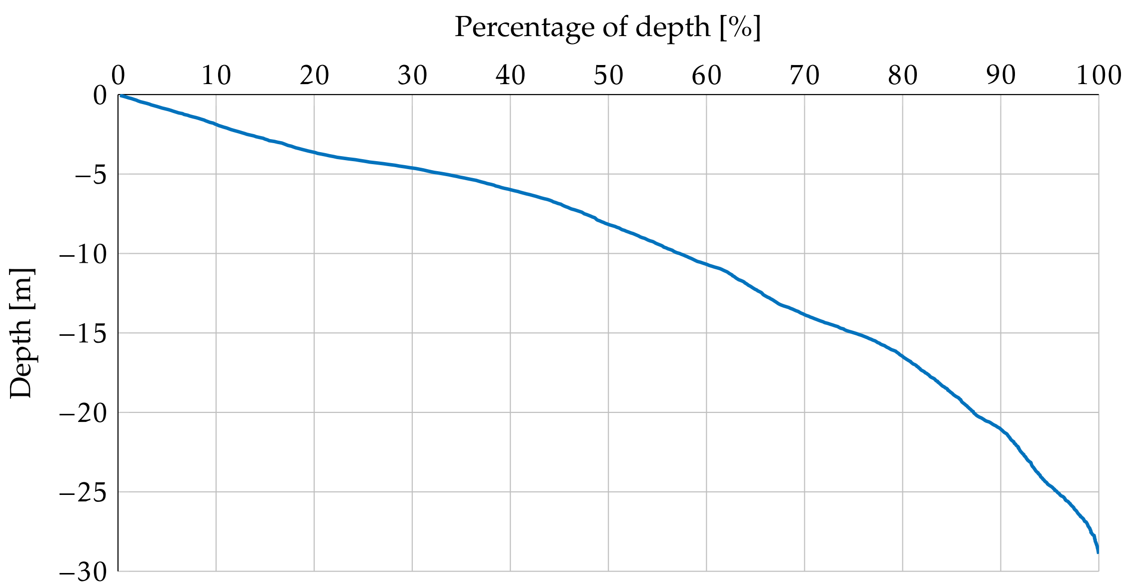
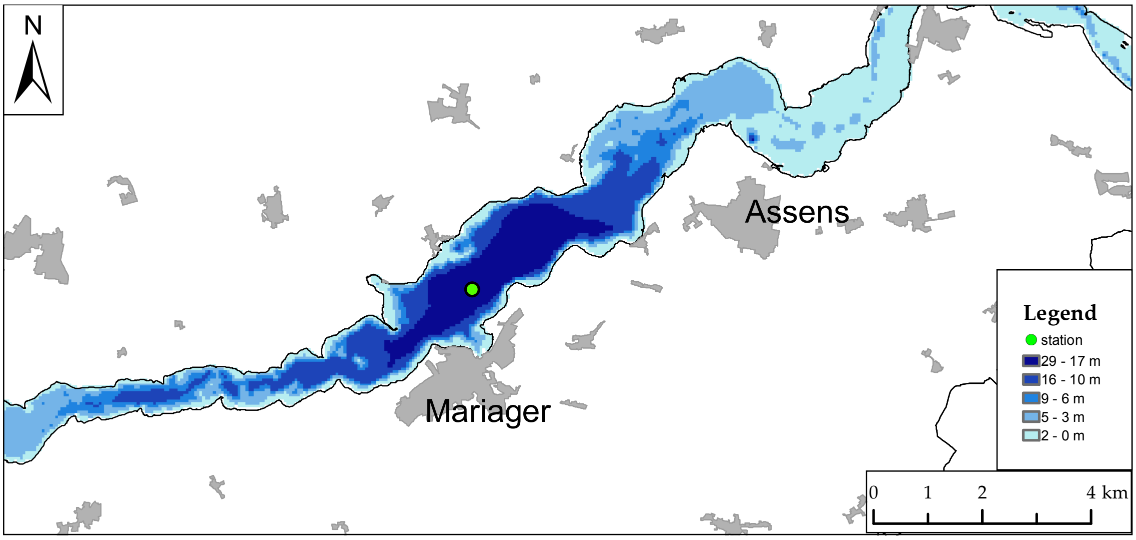
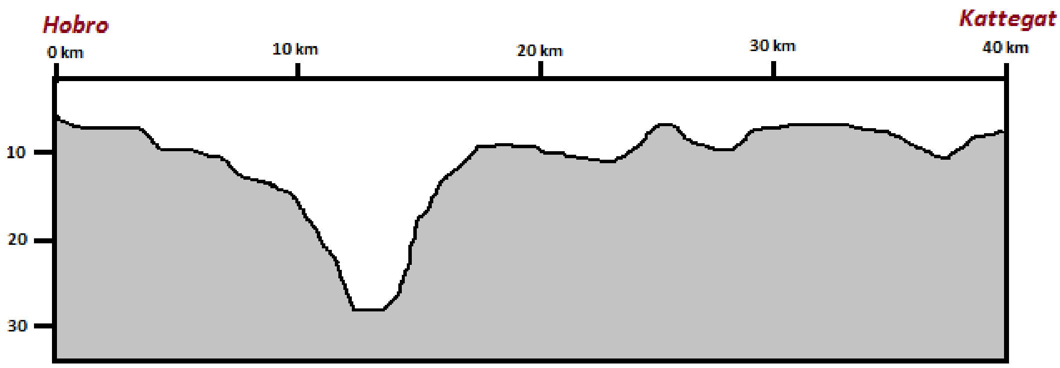


Figure 2.6: *Hypsometric graph which describes the depth distribution.*

In figure 2.7, the bathymetry of the entire fjord is shown, where the outer part is more shallow and the inner part is deeper.



(a) The bathymetry of Mariager Fjord and the location of the station where the measured data was taken. The UTM coordinates are: 560 095.746 E; 6 280 460.123 N.



(b) Longitudinal profile of the estuary of Mariager Fjord.

Figure 2.7: *The bathymetry of Mariager Fjord along with the longitudinal profile.*

The factors that contribute to stratification are salinity and temperature. The tidal effect in the inner part is almost negligible and does not have an influence on the stratification, since the range is significantly small, between 20-30 cm. However, in Kattegat, the tidal effect might fluctuate between 1.5 and 1 m. Salinity is increasing with depth whereas the temperature decreases with depth (the colder water is denser). [Fallesen et al., 2000]

For estuaries and fjords, a strong salinity gradient (halocline) can be found in the water column where fresh water from the terrestrial system meets the saline sea water. Due to the less dense freshwater that originates from streams and groundwater, the freshwater tends to move towards the water surface. However, the salinity gradient is seasonal dependent, leading to a higher concentration of freshwater during periods with heavier rain or ice and snow melting. In Mariager Fjord, there is a permanent halocline in 10-15 meters depth, which separates into an upper and a lower salinity layer.

In the upper layer near the surface, the salinity varies between 12 PSU to 17 PSU[1], while the lower layer towards the bottom is in the range of 18 PSU to 24 PSU. A stable salinity of 16 PSU are assumed to be present in the topwater of Mariager Fjord, while the bottom part has a salinity of 20 PSU. This is indicated by the cyan line in figure 2.8. [Fallesen et al., 2000]

As for the temperature, the seasonal variations affects the temperature gradient (thermocline) remarkably. Due to warmer climate in summer, the topwater will be warmer and thereby more dense. Furthermore, the mixing rates will be reduced in the upper layer due to the more calm weather and less wind during summer time that can cause circulation and turbulence. In Mariager Fjord during summertime, temperature goes up to 24 °C in the upper water part and about 2 °C – 6 °C in the deepest water. A stable thermocline is developed at 10 m – 16 m depth, enhancing the stability of the water column stratification. In winter, the temperatures are more uniform, mostly below 4 °C in the entire water column. The red lines in figure 2.8 mark the temperature distribution through the water column in Mariager Fjord. [Fallesen et al., 2000]

Finally, the oxygen availability in the water column, is controlled by the chemocline and divided in an anoxic and oxic zone. During summer, the anoxic zone is gradually moving upwards due to the calm and warm weather. Something similar happens sometimes in winter due to the presence of a permanent ice cover that prevents mixing of the water. In Mariager Fjord, the amount of oxygen in the upper water column is typically higher than in summer, indicated by the blue lines in figure 2.8.

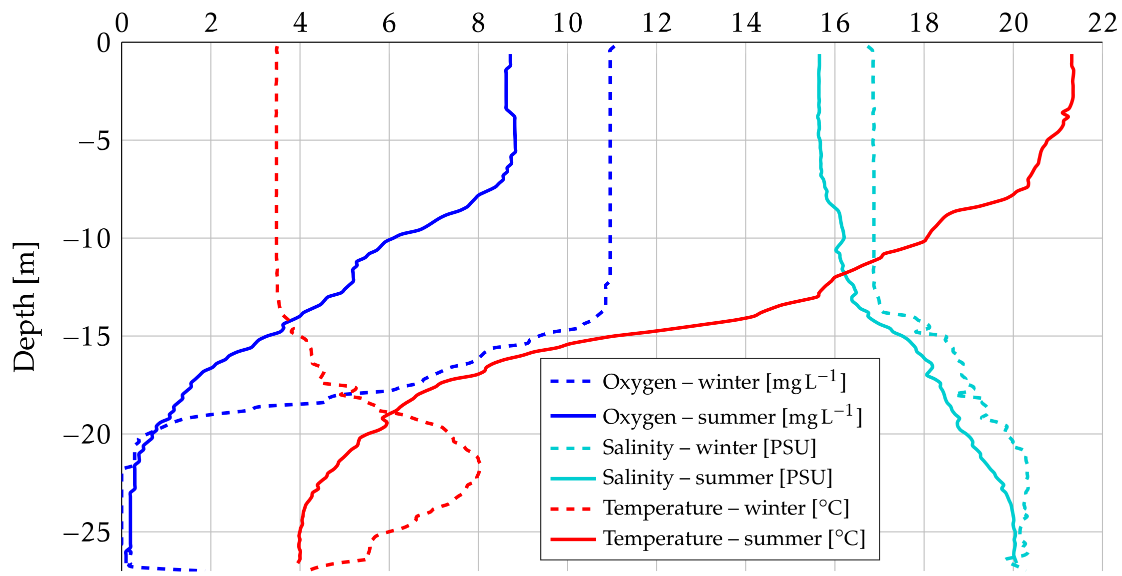


Figure 2.8: *Distribution in depth of the oxygen content, salinity and temperature values in station '5503 of Mariager Fjord. The values represent measured data obtained in January and July of 2005. [DCE, 2012]*

[1]PSU stands for Practical Salinity Unit

2.5.1 Oxygen depletion

The decrease of dissolved oxygen in the water is one, if not the most, concerns of eutrophication since larger and more frequent episodes have been observed all over the world . Aquatic fauna starts being affected when the oxygen content in water goes down below $4\,mg\,O_2\,L^{-1}$. At this point animals that can migrate away start leaving the area. Benthic animals lower their respiration and go up in the sediments to try to reach layers with higher oxygen content and head towards shallower waters if possible. Severe oxygen depletion occurs when the oxygen content goes below $2\,mg\,O_2\,L^{-1}$. Fish and non-adapted animals are killed in this condition. [National Academy Press, 2000]

Mariager Fjord has permanently natural anoxic conditions below the chemocline due to its characteristic basin and the stratification factors described above. But also the upper layer of the fjord can be exposed to oxygen depletions, especially in summer, when the chemocline start moving upward due to more stable conditions and the oxygen consumption is maximum, shown in figure 2.8 on the preceding page. Oxygen depletion can be observed at lower depths during the late summer in periods with no wind when a thermocline increases the stability of the stratification. This could continue until the point that all the water column suffers from severe oxygen depletion as it happened in 1997. [Fallesen et al., 2000]

The '97 incident

The summer of 1997 was unusually warm, sunny and calm. While the amount of phytoplankton was increasing, the oxygen demand was raising as well, due to the decomposition processes of dead phytoplankton in the bottom. Anoxic conditions started to reach the water surface and all the water column has been anoxic for 2 weeks. During those weeks a large number of dead fish, eelgrass, mussels and other benthic species were found in the ashore. A considerable formation of hydrogen sulphide was generated due to the generation of free sulfur during the decomposition of mussels, creating a stench of rotten eggs all around the fjord for a week. Figure 2.9 and 2.10 on the following page illustrates the severe oxygen depletion that occurred in the summer of 1997, where the data are obtained from DCE [2012] and can be found in appendix C.4. [Fallesen et al., 2000]

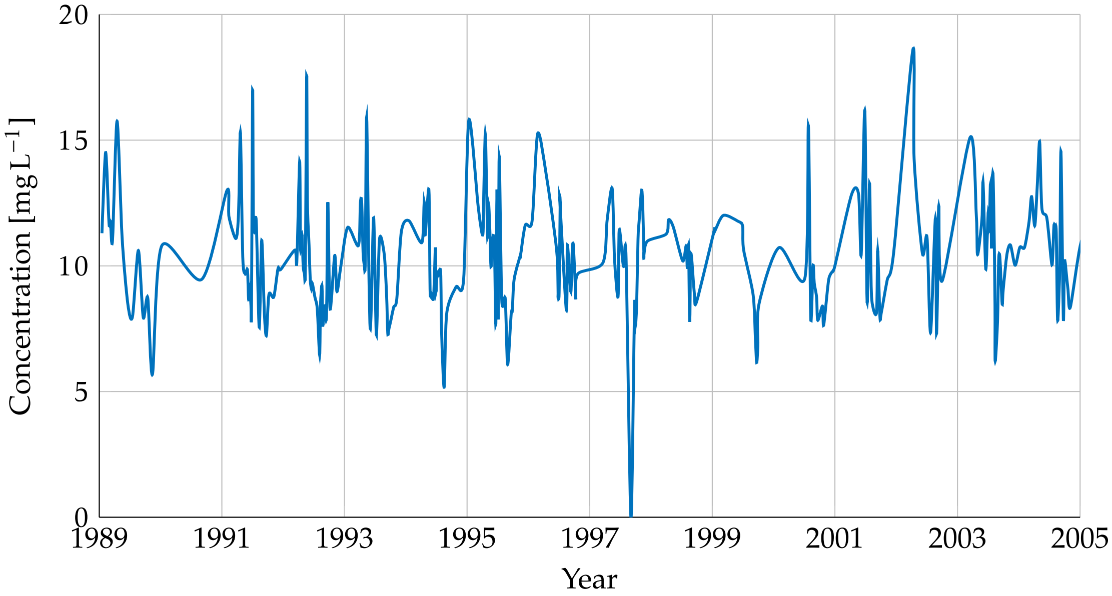


Figure 2.9: *Oxygen content in the first* 20 cm *of the water column [DCE, 2012].*

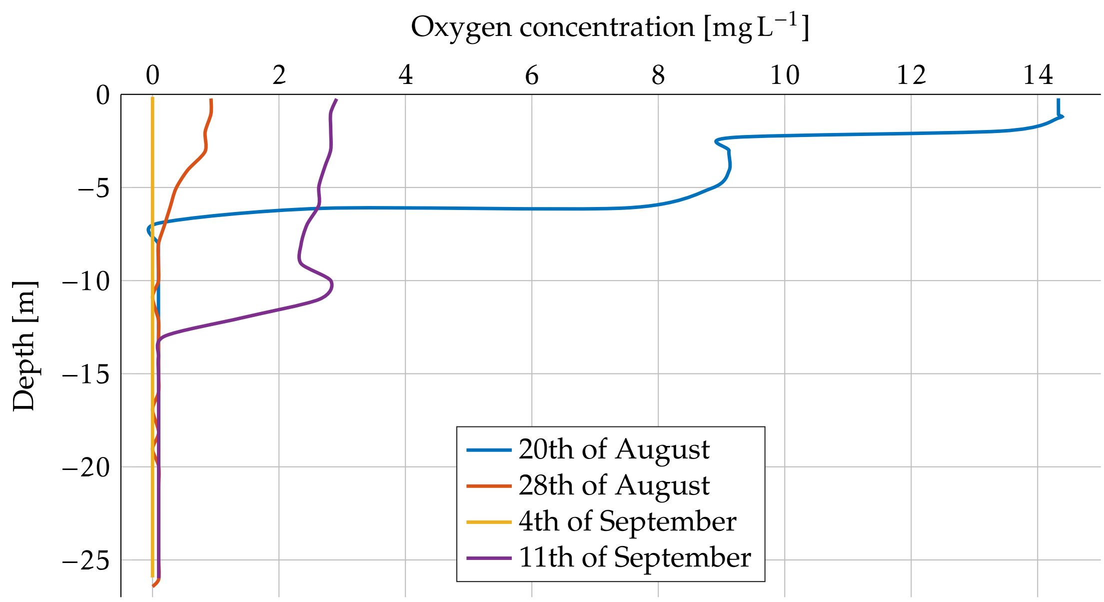


Figure 2.10: *Oxygen content in the late summer of 1997. For a week, between the 28th of August to the 4th of September, there was oxygen depletion in the whole water column [DCE, 2012].*

It is observed from the figure that the oxygen concentration is almost zero through the entire water column in the late summer of 1997. Oxygen depletions are extremely unlikely events in coastal ecosystems but they can have possible long term consequences in terms of biodiversity changes.

It can be concluded from the '97 incident that warm and calm weather can cause oxygen depletion in the whole water column, due to poor mixing. As a result of no dissolved oxygen, the flora and fauna will die.

2.6 Nutrient related ratios

Oceanographer Alfred C. Redfield has made investigations of dissolved nitrate, phosphate and oxygen concentrations in various depths of the larger oceans. He discovered an atomic ratio between nitrogen and phosphorus that is 20:1 and was later refined to 16:1. Later it has been expanded to include the carbon in regards to the existing ratio, with the observation of a ratio of 106:1 of carbon to phosphate. Thus, offering a final ratio of 106:16:1 (carbon-nitrogen-phosphorus), which has been used in the followings of this project. This ratio is known as the Redfield ratio. [Nature Geoscience, 2014]

Throughout the project instead of the molar ratio, it is chosen to use an equivalent ratio of masses. In the case of nitrogen and phosphorus the ratio is taken from the following graph in which is presented the N:P ratio in accordance to the salinity in the Baltic sea. A Redfield ratio of $5.6\,\mathrm{g\,N\,g\,P^{-1}}$ is obtained, in the inner fjord, by the relation between the N:P ratio and the salinity in the water as can be observed from figure 2.11. The data was achieved from DEPA and NERI [2002] and is shown in the electronic appendix C.1.

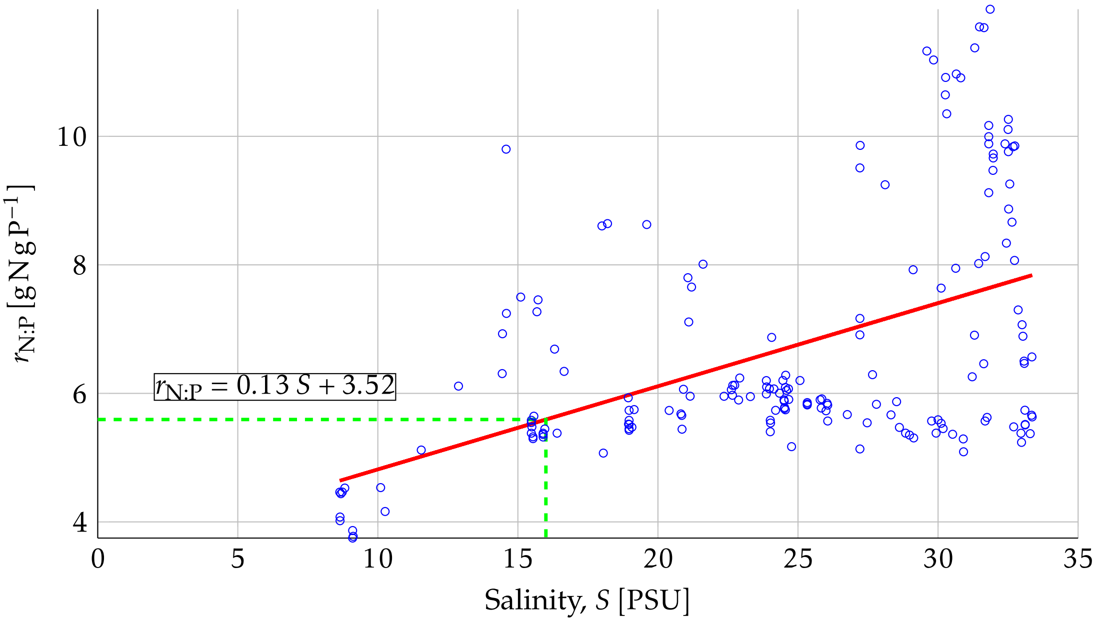


Figure 2.11: *Redfield ratio relation between nitrogen and phosphorus [DEPA and NERI, 2002].*

Another ratio that it is going to be used in combination with the Redfield ratio is the ratio between phytoplankton carbon to chlorophyll. The use of this ratio has to be taken carefully since big spatial and temporal variation can be found due to light penetration, nutrient availability and temperature differences. Phytoplankton carbon to chlorophyll ratios range from $13\,\mathrm{\mu g\,C\,\mu g\,Chl^{-1}}$ as a lower value for the East China Sea to $272\,\mathrm{\mu g\,C\,\mu g\,Chl^{-1}}$ in Kaneohe Bay in Hawaii [Lu et al., 2009]. In this project a ratio of $50\,\mathrm{\mu g\,C\,\mu g\,Chl^{-1}}$ is going to be used since is a common average result value in different investigations and also used as reference value in models as the one-box model developed for a lagoon in the Baltic sea [Humborg et al., 2000].

3 Current status of Mariager Fjord

In order to determine the current status of Mariager Fjord, it is necessary to take the environmental goals that are defined for the coastal waters of Mariager Fjord into account. Hence, the Danish Environmental Protection Agency (DEPA) has set specific goals for all danish water bodies, including coastal waters. These "goals" are described with respect to the ecological and chemical status and must be accomplished at the end of 2015. The ecological status in the coastal waters, is found by the depth limit of eelgrass growth, which is an indicator of the water clarity, where it can be expected to find eelgrass in greater depths in more clear water where the light can penetrate. The chemical status is assessed through the concentration of priority substances, specified by the Water Framework Directive [2000]. However, the chemical status in Mariager Fjord is considered as unknown due to the lack of measurements [Aquatic Plan 1.3, 2011].

The ecological status in coastal waters is derived from the ecological quality ratio (EQR). This ratio is an expression of the fraction between the reference eelgrass depth, set for the current coastal water body, and the actual depth of eelgrass growth. According to the Aquatic Plan 1.3 [2011], the ecological status for Mariager Fjord, is considered as 'bad'. This is illustrated in figure 3.1, where the depth of eelgrass has been worse with respect to the reference depth.

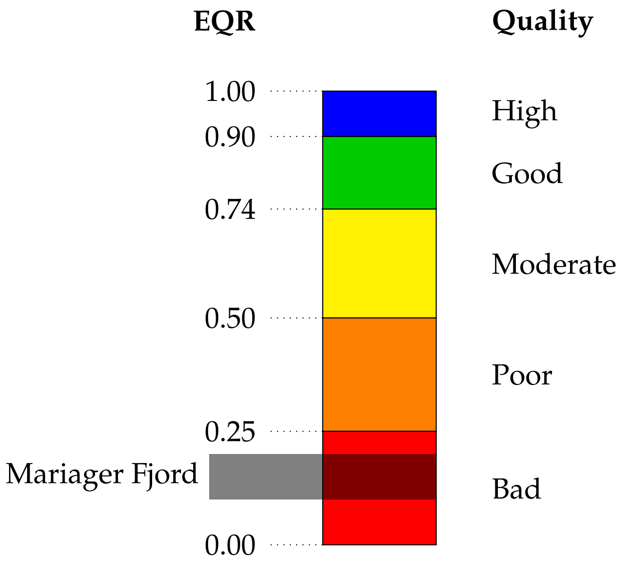
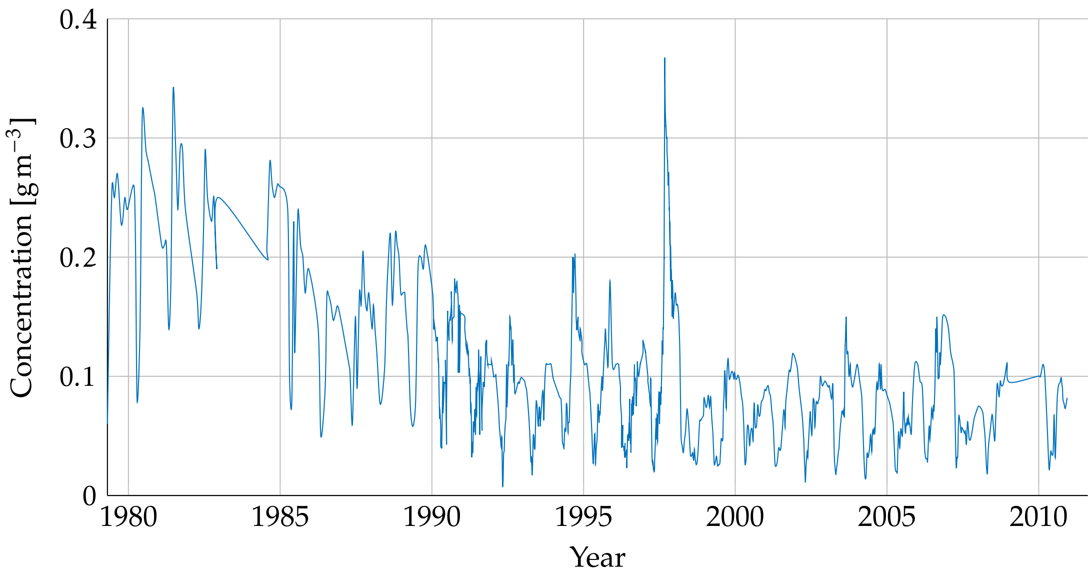


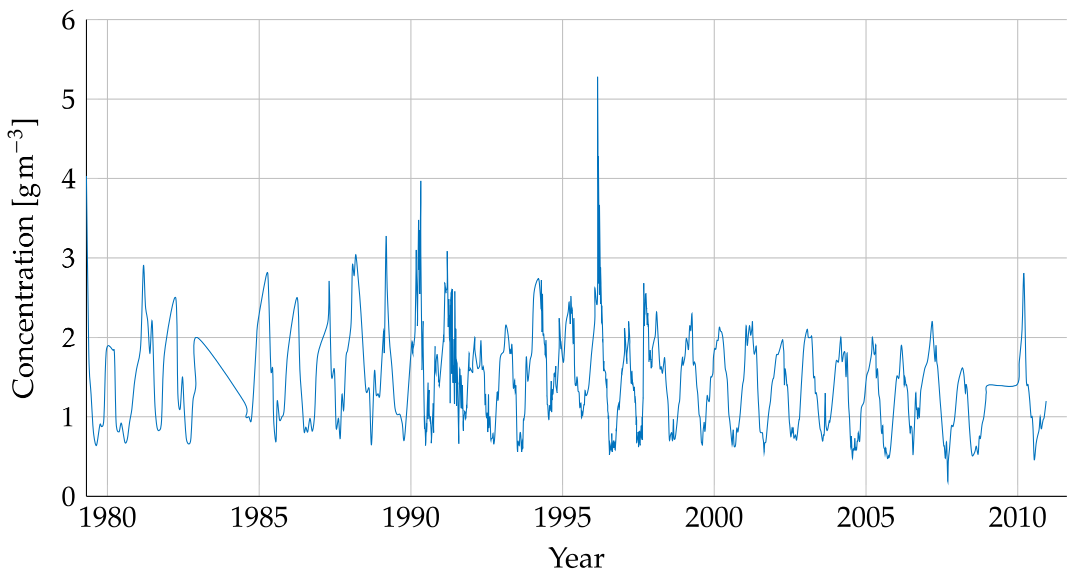
Figure 3.1: *The principle of ecological quality ratio (EQR) when measuring the quality of coastal waters, based on the eelgrass depth. Mariager Fjord is considered as bad quality and lies within the range of EQR = 0.1-0.2 [Aquatic Plan 1.3, 2011].*

The eelgrass is an indicator of the clarity of the water, because the growth of the phytoplankton blocks light penetration, which the eelgrass needs for growth. This significant growth is caused by the load of nutrients into Mariager Fjord. Nitrogen (N) and phosphorus (P) are the most critical nutrient loads. [Aquatic Plan 1.3, 2011]

As described in Markager et al. [2008], the phosphorus input to Mariager Fjord has been rapidly reduced since the late 80's. This is indicated in figure 3.2(a) on the next page that shows the trend of total phosphorus during the years in the system. The input of nitrogen on the other hand has not been significantly reduced during the same period, shown in figure 3.2(b) on the facing page. Due to the lack of water exchange in the inner part of the fjord, there is a higher concentration of nutrients, which deteriorates the ecological status of Mariager Fjord. [Fallesen et al., 2000; Markager et al., 2008; Aquatic Plan 1.3, 2011]



(a) The trend of phosphorus in the system.



(b) The trend of nitrogen in the system.

Figure 3.2: *The amount of total phosphorus and nitrogen in Mariager Fjord. The measurements are taken from Danmarks Miljøportal [2015] at the station, shown in figure 2.7(a) on page 9.*

Although there are observations of reduction in the phosphorous load, the main limiting nutrient in Kattegat and in estuaries at the west coast of Denmark is nitrogen, with periods of limitation by phosphorous during spring. In figure 3.3 on the next page the DIN/DIP ratio is plotted for 2005 to try to confirm this comportment in Mariager fjord. The large ratio in spring that is much higher than the Redfield ratio can be an indicator of the limitation of phosphorus according to DEPA and NERI [2002]. In early summer the ratio decreases and becomes lower than the Redfield ratio in late summer. This decline matches with the assumption of a limitation of nitrogen for the growth over summer.

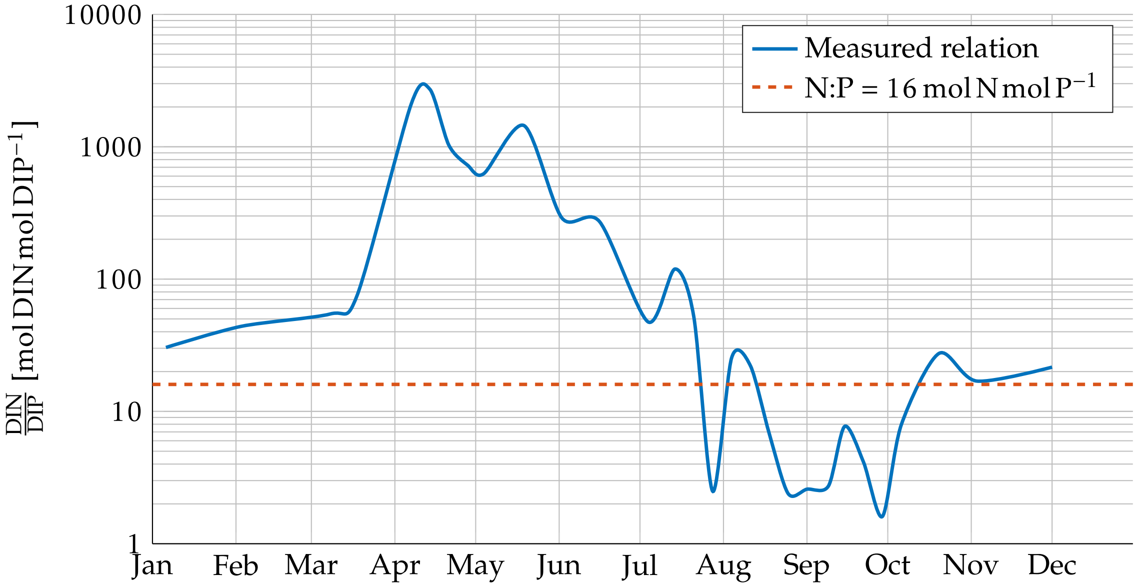


Figure 3.3: *The ratio between dissolved inorganic nitrogen (DIN) and phosphorus (DIP) for 2005 [Danmarks Miljøportal, 2015].*

In the case of silica that can be a limiting nutrient for the growth of diatoms, it seems that it is a limiting factor (< 2 µmol L^{-1}) over small periods, sporadically.

3.1 Assessment of nutrient reduction

The objective of this section is to find an upper limit for nutrient loads into Mariager Fjord, meaning the maximum amount of nutrients which can be allowed if a good quality is to be reached. Initially, an attempt has been made to relate the concentration of total nitrogen (TN) in the fjord to the depth colonization of eelgrass in order to support the information of the ecological status of Mariager Fjord. For this purpose the relations stated in Nielsen et al. [2002] can be used. These relations are derived from regression models with double logarithmic functions indicating the log-transformed maximum depth colonization of eelgrass as a function of the log transformed values of TN concentration.

In order to find the relations, local measurement data is needed for Mariager Fjord. Continuously measured data of TN concentrations is available for a time period of 36 years (1979- 2015). As for the eelgrass depth colonization, only averaged discontinuous values are available which cannot be related to the various TN concentrations.

A new parameter, secchi depth is therefore introduced to the analysis. This introduction is derived from the idea that the eelgrass depth distribution should be proportional to the secchi depth due to the fact that the plants cannot grow or survive without sunlight. Moreover the measurement times of secchi depth and TN concentrations coincide well during the 36 years long time period.

However in order to find the relation between the secchi depth and the depth colonization, the light intensities in different depths are required according to Nielsen et al. [2002], which are not available.

Since it has not been possible to derive depth colonization for secchi depths and there has not been continuous data available for the eelgrass depth distribution in Mariager Fjord, it is decided to use a pre-corrected Laurentius relation. This relation is derived by several observations of eelgrass along with the TN concentrations in the coastal waters throughout whole Denmark. Figure 3.4 shows a modified graph with this relation, where the local situation of Mariager Fjord is presented for the period 2010-2015 (black line), along with the status, stated in the Aquatic Plan 1.3 [2011] for Mariager Fjord (red line). Furthermore the reference quality and good quality, stated in the Aquatic Plan 1.3 [2011], are presented with green and yellow line respectively [Carstensen and Krause-Jensen, 2009].

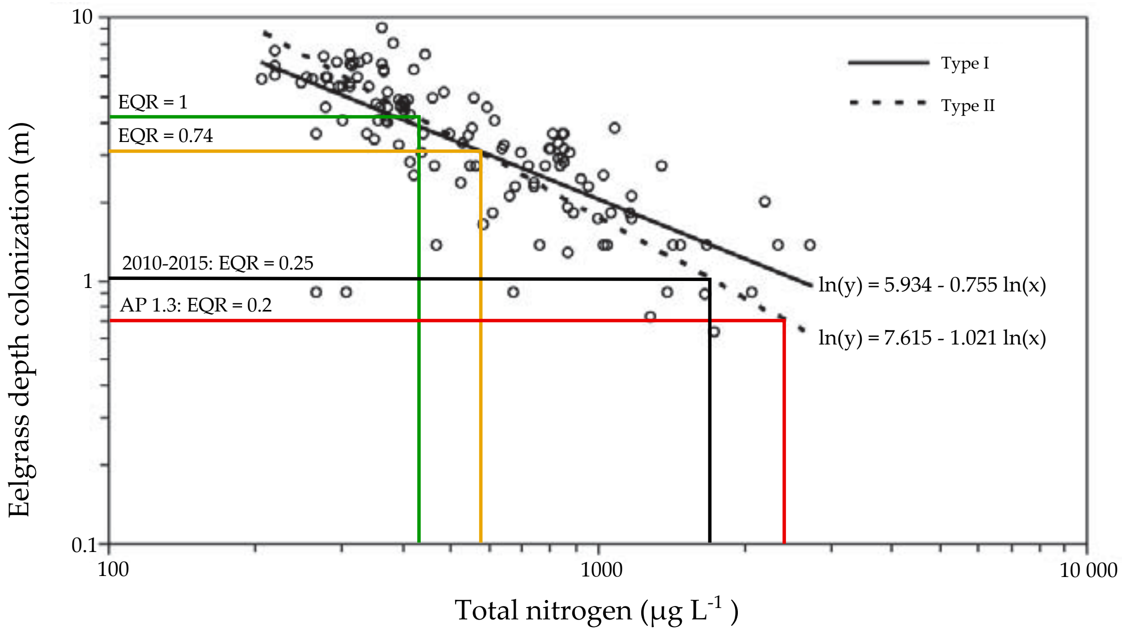


Figure 3.4: *The Laurentius relation between the nitrogen concentration and eelgrass depth colonization in Mariager Fjord. Modified after Carstensen and Krause-Jensen [2009], where the black line is analyzed from data provided by Danmarks Miljøportal [2015].*

The type II regression line is the most commonly applied relation, which is why it is chosen to use that regression line in order to find the relation. However, as it is shown in the figure, there are significant differences between the Aquatic Plan 1.3 [2011] status (red line) and the yearly measured data (black line). Hence, the upper limit for TN (yellow line that shows 570 $\mu g\,L^{-1}$) found through this regression is not sufficient and there is a need of information about limit requirements from other sources as a support.

According to an analysis, performed by Markager et al. [2008], it is recommended that the nitrogen load is reduced to between $200\,\text{ton}\,\text{N}\,\text{yr}^{-1}$ and $400\,\text{ton}\,\text{N}\,\text{yr}^{-1}$, while the phosphorus load is reduced to the range of $6\,\text{ton}\,\text{P}\,\text{yr}^{-1}$ to $8\,\text{ton}\,\text{P}\,\text{yr}^{-1}$ in order to accede the environmental goals set by the Water Framework Directive [2000]. If the nutrient load is reduced to these ranges, the growth of phytoplankton will be nutrient limited in the whole growth period. This will lead to, according to the analysis, an increase in the water clarity, which means that eelgrass will be able to grow further down. However, even though actions are made to reduce the nutrient loads, it cannot be expected that the environmental goals are accomplished at the end of 2015. [Markager et al., 2008]

4 Problem statement

In the previous chapters, Mariager Fjord has been described with respect to the site location and the current problems that appear here. The current status of Mariager Fjord has been described as 'bad' due to the overloading of nitrogen in the past years. The overload causes eutrophication, which can lead to anoxic conditions in the fjord.

In order to improve the current condition in Mariager Fjord and avoid catastrophic situations like the '97 incident, the nutrient loading must be reduced. The remaining part of the report deals with the objective of possible solutions to bring down the nutrient loading. Furthermore, the solutions will be studied with respect to their ability of improving the condition in Mariager Fjord. In order to evaluate these complex solutions two different numerical approaches are going to be used:

- First, a water quality model will be built in order to represent the nutrient cycle of the system in Mariager Fjord.
- Second, a more complex model that takes into account the physical conditions is going to be applied in order to asses the hydrodynamic processes and furthermore obtaining a more realistic representation of the actual conditions.

Hence, the key questions for the objective of this report are as following:

- Can the ecological model help to assess the necessary reduction of nutrients to comply the Water Framework directive?
- Can the hydrodynamic model be an advantage in comparison with the ecological model?
- Can the anoxic part of Mariager Fjord contribute to reduce the nitrogen?
- Is construction of wetlands a feasible solution for reducing nutrient load to Mariager Fjord?

5 Ecological system of Mariager Fjord

Due to the large input of nitrogen and the low water exchange in the inner part of Mariager Fjord, it is necessary to describe the biological processes that occur in the water phase. In order to do so, box-models can be applied for Mariager Fjord, where sinks and sources, in the form of biological processes, represent masses that are being transported in or out from the system or state variable, illustrated in figure 5.1. [Bianchi, 2007]

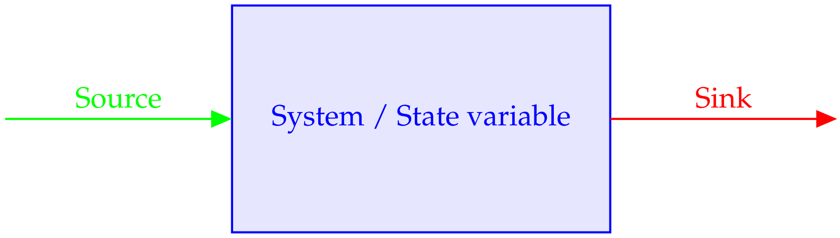


Figure 5.1: *Principle of the box model. Within the system or state variable, a mass of physical or biological properties appears, whereas the source describes the flux of some physical or biological mass that enters the box model. Finally, the sink is the mass that leaves the system. [Bianchi, 2007]*

The water quality model that is going to be developed takes nitrogen and phosphorus concentrations in the system into account. Furthermore, this model also takes the input from the terrestrial ecosystem and Kattegat into account. This is an enhancement of previous models that only take in nitrogen, along with a closed system-model, where the input was not added. Phosphorus was included, since it was observed that with only nitrogen, the model was not able to replicate the real system. The water quality model that included nitrogen can be found in appendix A.3.

The developed model that included nitrogen and phosphorus, is developed in MATLAB, from where an explanation can be found in appendix A.9. Furthermore, the calculations are included in the electronic appendix C.5.

5.1 Model setup

The model needs several input parameters in order to describe the biological processes. Since the biological processes are highly dependent on the water fluxes in and out of the system, it is crucial to determine the water balance for Mariager Fjord.

For the case of simplicity and since the anoxic bottom of the fjord only constitutes a small part of the total volume, as shown in figure 2.6 on page 8, it is chosen to apply only a single box model for the inner part of Mariager Fjord. The outer part of Mariager Fjord is neglected, since this part with a deeper channel is much more affected by physical forces like the wind and tides, which is not going to be included in the biological model.

5.1.1 Physical state

The water masses that enter Mariager Fjord can be either fresh- or salt-water. In east, the boundary represented by Kattegat is feeding Mariager Fjord with saline water, whereas the freshwater can enter in more ways. Hence, the freshwater inflow, as well as the salinity, are important parameters in order to describe the physical system. Furthermore, the flow from the streams carry nutrient concentrations along into the estuary. Figure 5.2 shows the principle sketch of Mariager Fjord.

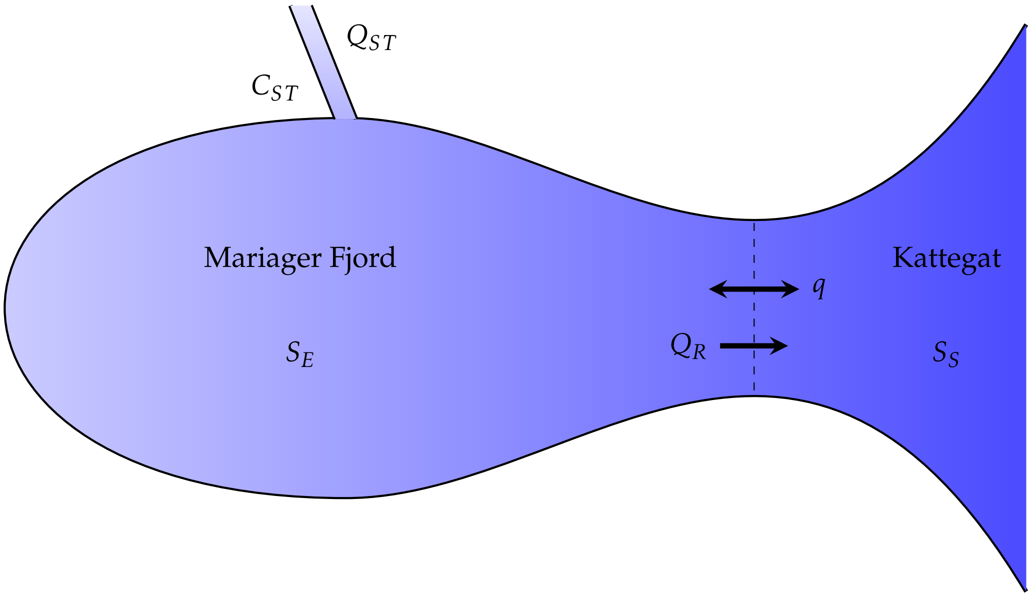


Figure 5.2: *Sketch of the physical system of Mariager Fjord. In Mariager Fjord, freshwater enters the system from streams, Q_{ST}, along with concentrations, C_{ST}. From Kattegat, salt-water enters the system and affects the salinity in Mariager Fjord, S_E.*

Freshwater budget

In an estuary, such as Mariager Fjord, there are several inputs of freshwater. The residual flow of all inputs and outputs of freshwater in a steady-state system can be defined by equation (5.1) on the facing page [Gordon et al., 1996].

$$Q_R = \text{in} - \text{out} = Q_{ST} + Q_{GW} + F\,Q_{NP} \tag{5.1}$$

Where:

Q_R	Residual flow of what is coming in and out of the system	$[\mathrm{m^3\,s^{-1}}]$
Q_{ST}	Flow from streams	$[\mathrm{m^3\,s^{-1}}]$
Q_{GW}	Groundwater discharge	$[\mathrm{m^3\,s^{-1}}]$
F	Surface area	$[\mathrm{m^2}]$
Q_{NP}	Net-precipitation	$[\mathrm{mm\,yr^{-1}}]$

All the described freshwater inputs in equation (5.1) require available data, which is not the case for groundwater. The net-precipitation is neglected, since it is small compared to the stream inflow. Thus, it is chosen only to take the freshwater input from the streams into account, which have a seasonal variation over the year. From Danmarks Miljøportal [2015] and Schmidt et al. [2005], flow measurements have been taken for the stream stations, presented in appendix A.1 and can be found in the electronic appendix C.2. From the stations, the flow is measured as a daily mean flow over year, presented in appendix A.2, which will be included in the further modelling. This flow is crucial in order to determine the water exchange between Mariager Fjord and Kattegat, described in the following.

Saltwater budget

Mariager Fjord flows into the sea of Kattegat, where the salinity of the water is higher. Due to the fact that saltwater is heavier than freshwater, an exchange flow between Mariager Fjord and Kattegat must occur. For a steady-state system, the exchange flow can be expressed as [Gordon et al., 1996; Larsen, 2015]:

$$q = \frac{Q_R\,S_E}{S_S - S_E} \tag{5.2}$$

Where:

q	Exchange flow	$[\mathrm{m^3\,s^{-1}}]$
S_S	Salinity in sea (Kattegat)	[PSU]
S_E	Salinity in estuary (Mariager Fjord)	[PSU]

In order to calculate the exchange flow, it is seen from equation (5.2) that salinity values for both Mariager Fjord and Kattegat are required. Measurements of the salinity in Mariager Fjord have been performed by DCE [2012] and are varying in time. As described in section 2.5, the salinity in the upper layer varies between 12 PSU to 17 PSU. In Kattegat, the salinity varies from day to day, but it is assumed a value of 26 PSU [DMI, 2015].

The exchange flow is needed in order to calculate the amount of nutrients that are exported into Kattegat, described in the following section.

Stream concentrations

Measurements of the stream concentrations were carried out by Danmarks Miljøportal [2015] along with the presented flow measurements. These can be found in the electronic appendix C.3.

Since no direct measurements of the dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP) concentrations are at disposal, it is assumed that the DIN concentration is the sum of nitrogen in nitrate (NO_3^-) + nitrite (NO_2^-) and ammonia (NH_3^+) + ammonium (NH_4^+) forms, whereas the DIP concentration is the orthophosphate (PO_4^{3-}) concentration.

The input concentration of DIN and DIP from the streams is considered as being monthly dependent. This is due to the fact that only few measurements of the concentrations are performed in contrast to the flow. Thus, a monthly mean concentrations is considered preferable. However, in order to do this, it is chosen to weigh the concentration from each stream with the inflow from each stream. This means that the flow must be calculated as a monthly average. Hence, with the eight streams, presented in appendix A.1, the input of DIN and DIP each month can be expressed with the following equations.

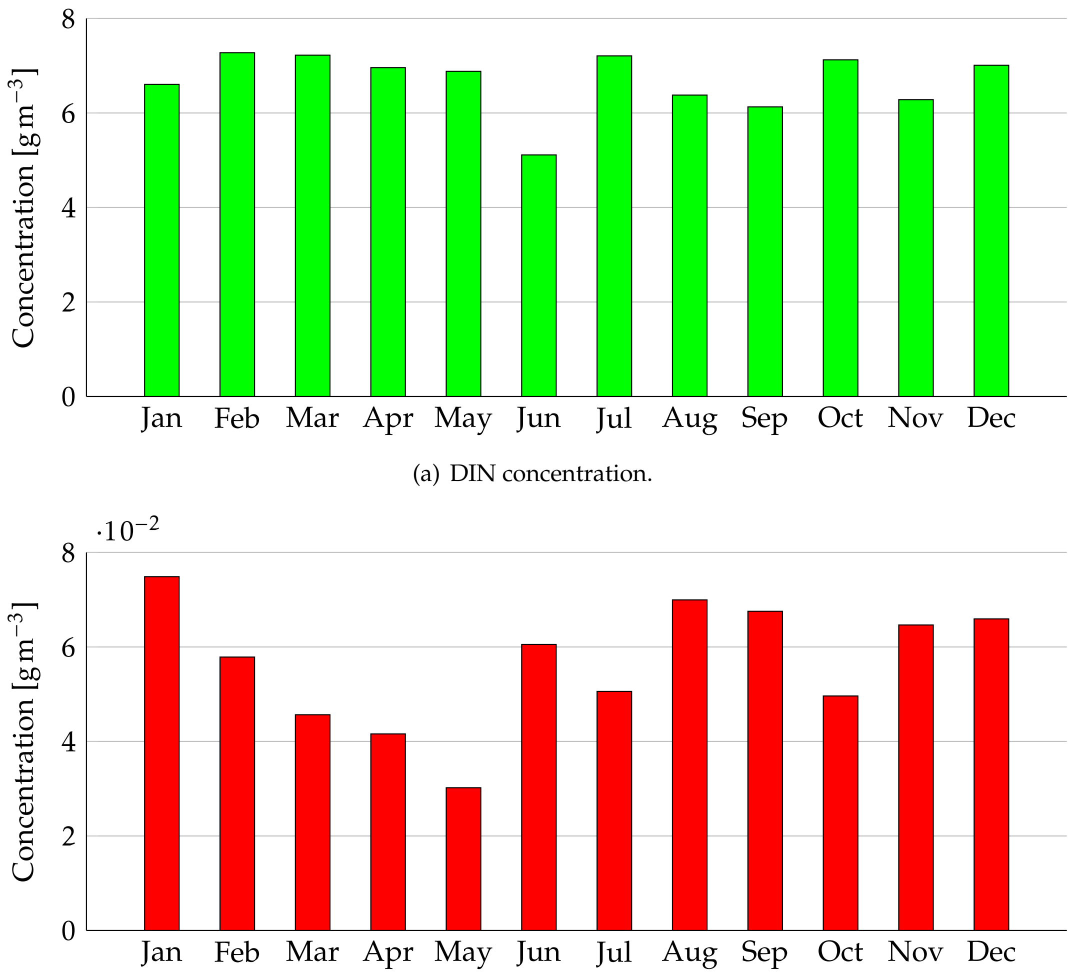
$$\mathrm{DIN_{stream}} = \frac{\sum_{i=1}^{8} Q_{\mathrm{stream},i}\, C_{\mathrm{stream},i}}{\sum_{i=1}^{8} Q_{\mathrm{stream},i}} \tag{5.3}$$

$$\mathrm{DIP_{stream}} = \frac{\sum_{i=1}^{8} Q_{\mathrm{stream},i}\, C_{\mathrm{stream},i}}{\sum_{i=1}^{8} Q_{\mathrm{stream},i}} \tag{5.4}$$

Where:

$\mathrm{DIN/DIP_{stream}}$	Average input DIN or DIP concentration from streams	$[\mathrm{g\,m^{-3}}]$
$Q_{\mathrm{stream},i}$	Inflow from the i'th stream	$[\mathrm{m^3\,s^{-1}}]$
$C_{\mathrm{stream},i}$	Concentration of DIN or DIP from the i'th stream	$[\mathrm{g\,m^{-3}}]$

In figure 5.3 on the next page, the input concentration of both the DIN and DIP is shown for 2005, which is monthly dependent.



(b) DIP concentration

Figure 5.3: *Month dependent DIN and DIP concentration in 2005. The concentrations is a weighted mean concentration for all the streams. [Danmarks Miljøportal, 2015]*

The values of the DIN and DIP input concentration from the streams are then applied for each day of the corresponding month over the year.

5.1.2 Biological state

A simplified one-box model is applied in order to represent the biological nutrient processes in the water phase. One of the goals is to see the variation of concentrations by the chosen state variables over time.

State variables

Figure 5.4 shows Mariager Fjord as the simplified ecological system, where different sources and sinks interact between the state variables in the two horizontal layers (water and sediment phase). The chosen state variables for the model are:

- dissolved inorganic nitrogen (DIN),
- dissolved inorganic phosphorus (DIP),
- phytoplankton concentration (Phy),
- the accumulation of the nitrogen in the sediment (SED_N) and
- the accumulation of the phosphorus in the sediment (SED_P).

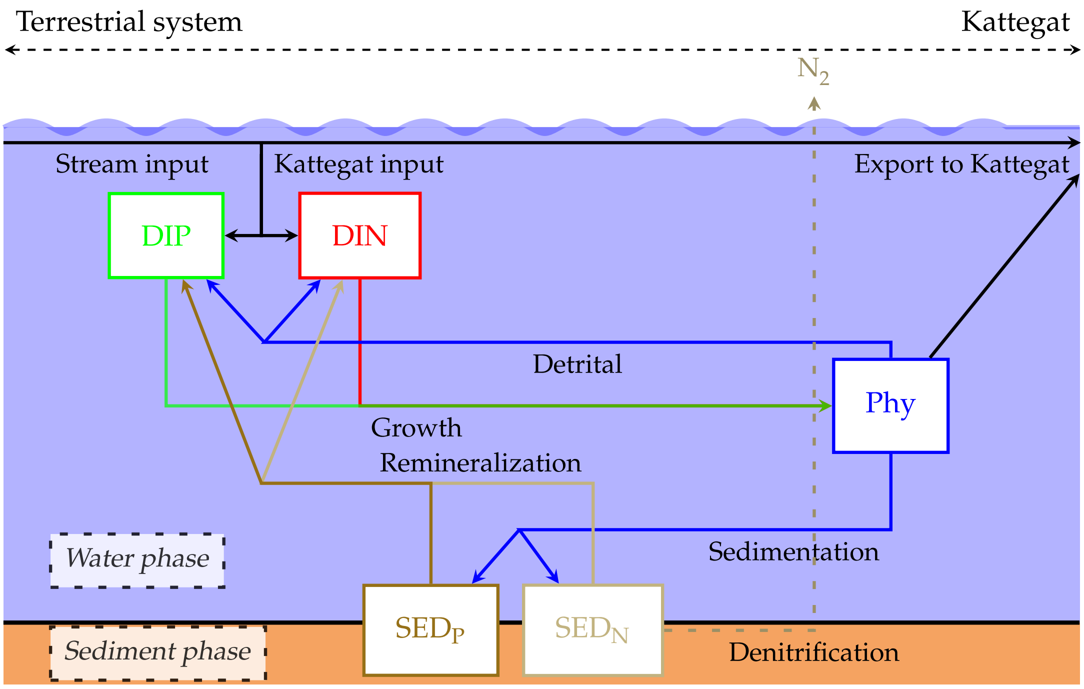


Figure 5.4: *The simplified ecosystem of Mariager Fjord with five state variables and five sources and sinks that interacts between them.*

All five state variables are in the units of $g\,m^{-3}$, where the governing equations for each of them are shown below.

$$\frac{d\,\mathrm{Phy}}{d\,t} = G - RW - S - \mathrm{Phy}_{\mathrm{export}} \tag{5.5}$$

$$\frac{d\,\mathrm{DIN}}{d\,t} = -G + RW + RS_N + \mathrm{DIN}_{\mathrm{input}} - \mathrm{DIN}_{\mathrm{export}} \tag{5.6}$$

$$\frac{d\,\mathrm{DIP}}{d\,t} = \frac{-G + RW}{r_{\mathrm{N:P}}} + RS_P + \mathrm{DIP}_{\mathrm{input}} - \mathrm{DIP}_{\mathrm{export}} \tag{5.7}$$

$$\frac{d\,\mathrm{SED_N}}{d\,t} = S - RS_N - D \tag{5.8}$$

$$\frac{d\,\mathrm{SED_P}}{d\,t} = \frac{S}{r_{\mathrm{N:P}}} - RS_P \tag{5.9}$$

Where:

G	Growth of phytoplankton	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
RW	Remineralization in the water phase (detrital)	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
S	Sedimentation of Phy	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
$\mathrm{Phy_{export}}$	Export of Phy to Kattegat	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
RS_N	Remineralization of nitrogen in the sediments	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
$\mathrm{DIN_{input}}$	Input of DIN from streams and Kattegat	$[\mathrm{g\,day^{-1}}]$
$\mathrm{DIN_{export}}$	Export of DIN to Kattegat	$[\mathrm{g\,day^{-1}}]$
$r_{\mathrm{N:P}}$	Redfield ratio between nitrogen and phosphorus	$[\mathrm{g\,N\,g\,P^{-1}}]$
RS_P	Remineralization of phosphorus in the sediments	$[\mathrm{g\,day^{-1}\,m^{-3}}]$
$\mathrm{DIP_{input}}$	Input of DIP from streams and Kattegat	$[\mathrm{g\,day^{-1}}]$
$\mathrm{DIP_{export}}$	Export of DIP to Kattegat	$[\mathrm{g\,day^{-1}}]$
D	Denitrification into atmospheric nitrogen	$[\mathrm{g\,day^{-1}\,m^{-3}}]$

The five presented state variables follow a yearly cycle of 365 days.

The amount of nitrogen and phosphorus in the system, indicated by the two state variables DIN and DIP, is controlled by how much that is entering and leaving. The input of water is the average daily freshwater runoff from the streams, shown in appendix A.2, as well as the water exchange with Kattegat. The amount of nitrogen and phosphorus that is released to Kattegat is controlled by the freshwater flow and exchange rate.

Apart from the physical processes between the terrestrial ecosystem and Kattegat, the biological processes in terms of growth and remineralization in the water and sediment phase also affects the amount of DIN and DIP in the system. Since the phytoplankton needs DIN or DIP for the growth process, there will be a loss of dissolved nutrients. The phytoplankton use chlorophyll and require light energy from the sun for photosynthesis, in order to live and grow. Furthermore, the phytoplankton generates oxygen by consuming CO_2 from the atmosphere. Meanwhile, the phytoplankton will die eventually, and DIN and DIP will be restored from phytoplankton through remineralization.

The increase of nutrients corresponds to an increase of phytoplankton in terms of growth. In addition, an increase of phytoplankton supposes an enrichment for sediments due to sedimentation processes, which is accompanied by anoxia [Humborg et al., 2000]. It happens due to eutrophication, where an augmentation of organic matter in the sediment will appear [Humborg et al., 2000].

The organic matter in the sediments affects the seasonal oxygen balance of the bottom waters, where the nutrients are released to the water column as remineralized DIN or DIP, which also affects the seasonal phytoplankton production [Jørgensen, 1996]. As for the nitrogen in the sediments, an important process is the denitrification, where a release of atmospheric nitrogen in the sediments occurs.

The remineralization of nutrients from the sediments is divided into two processes, which are for nitrogen and phosphorus, respectively.

Processes

The processes that interacts between the state variables, shown in the equations, are summarized in table 5.1.

Table 5.1: *Processes that interacts between the state variables, shown in the equations (5.5)- (5.9) on page 28.*

Process equation	
$G = \mu_{\max}\,\mathrm{PAR}\,\min\left(\frac{\mathrm{DIN}^t}{k_n + \mathrm{DIN}^t}, \frac{\mathrm{DIP}^t}{k_p + \mathrm{DIP}^t}\right)\mathrm{Phy}^t$	(5.10)
$RW = k_1\,\mathrm{Phy}^t$	(5.11)
$S = k_2\,\mathrm{Phy}^t$	(5.12)
$RS_N = k_3\,\mathrm{SED}^t_{\mathrm{N}}$	(5.13)
$RS_P = k_5\,\mathrm{SED}^t_{\mathrm{P}}$	(5.14)
$D = k_4\,\mathrm{SED}^t$	(5.15)
$\mathrm{Phy}_{\mathrm{export}} = \mathrm{Phy}^t\left(Q^t + q^t\right)$	(5.16)
$\mathrm{DIN}_{\mathrm{input}} = Q^t\,\mathrm{DIN}^t_{\mathrm{streams}} + q^t\,\mathrm{DIN}_{\mathrm{Kat}}$	(5.17)
$\mathrm{DIP}_{\mathrm{input}} = Q^t\,\mathrm{DIP}^t_{\mathrm{streams}} + q^t\,\mathrm{DIP}_{\mathrm{Kat}}$	(5.18)
$\mathrm{DIN}_{\mathrm{export}} = \mathrm{DIN}^t\left(Q^t + q^t\right)$	(5.19)
$\mathrm{DIP}_{\mathrm{export}} = \mathrm{DIP}^t\left(Q^t + q^t\right)$	(5.20)

The growth of phytoplankton is highly dependent on the light that is needed for the photosynthesis. This is controlled by the photosynthetically available radiation (PAR), which takes the latitude and the sun declination into account. From late autumn to early spring, the PAR parameter is set to 0, which means that no light is available for the phytoplankton to grow. From spring to autumn where the PAR-value is 1, the phytoplankton will grow with a maximum rate of $\mu_{\max}$.

Furthermore the growth will depend on the limiting nutrient factor analyzed for the results of the model in appendix A.6, which is either nitrogen or phosphorus. In equation (5.10), the limiting function for nitrogen and phosphorus is dependent on the half-saturation coefficient, k_n and k_p, respectively. The difference between the half-saturation coefficient for nitrogen and phosphorus is obtained by the Redfield ratio. Thus a value of k_p is a factor $r_{\mathrm{N:P}}$ lower than k_n.

The phytoplankton will be either sedimented or remineralized as DIN when it dies. The remineralization process makes the phytoplankton a source for nutrients, with a defined rate, k_1. For the sediment burial, the detrital material from phytoplankton in the overlying layer will be subject to organic matter and buried in the sediments. The sedimented organic material is mineralized by aerobic microorganisms and animals on the sea floor. The rate at which this sedimentation takes place is denoted as the sedimentation rate, k_2.

The nutrients that are stored in the sediment pool will also remineralize to the water phase as DIN with a defined rate, k_3. The bacteria use oxygen in order to convert the organic matter into inorganic form, which will cause an increase in oxygen demand. The nitrogen in the sediment pool can be converted to atmospheric nitrogen, N_2, by heterotrophic bacterias through denitrification, which again will happen with a defined rate constant, k_4. In the case of phosphorus, it will be stored in the sediment and the only output is through the exchange with Kattegat of DIP and Phy.

Finally, the input and export processes, which take the concentrations in the streams and Kattegat are taken into account. As it is expressed in equation (5.17) and (5.18), it is chosen to hold the background concentration in Kattegat constant in contrast to the stream concentration that varies for each month.

5.1.3 Model parameters

In this section, the input parameters will be explained with respect to the processes and state variables. Thus, a summarized model input can be found in the end, in table A.3 on page 78.

Volume of the inner part of the fjord

The volume of Mariager inner fjord is obtained from the bathymetry that contains depth values for each cell. Each cell has an area of $50 \times 50\,\mathrm{m}$, from which the depth can be multiplied to, in order to obtain a cell-volume. Hence, the total volume is the sum of all cell-volumes.

Availability of light

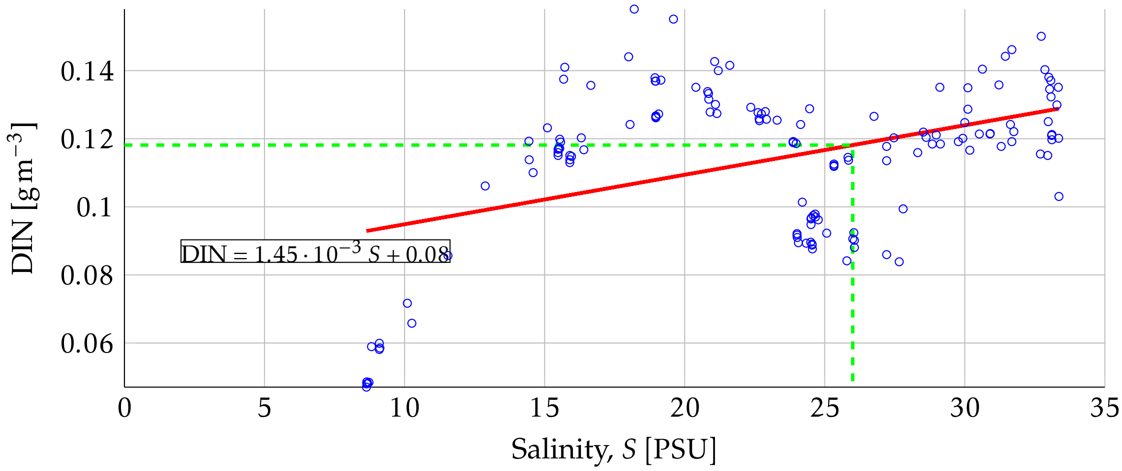
The light, which is introduced by the PAR-parameter, can be controlled by a simple step function, $y(t)$. This enables or disables the PAR-value to a value of either 0 or 1 over the yearly cycle of $T = 365\,\mathrm{days}$ [Fennel, 1995]:

$$y(t) = \sin\left(\frac{2\,\pi\,t}{T} - \frac{\pi}{2}\right) \tag{5.21}$$

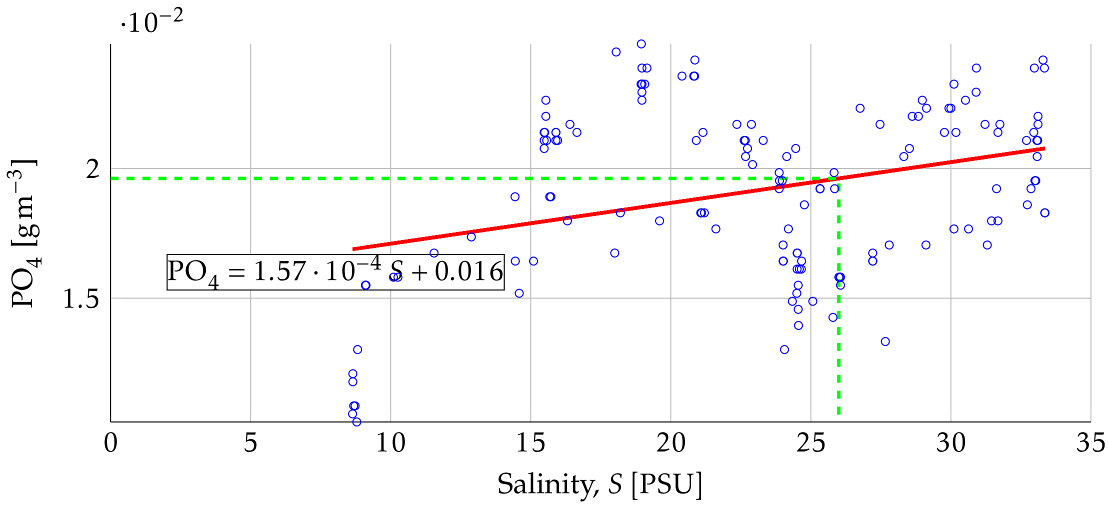
Where t is the current day of the year, ranging from 1 to 365 days. The value of $y(t)$ will either be below or above 0. Thus, when $y(t) < 0$, the PAR-value is 0, which will happen from late autumn to early spring [Fennel, 1995]. The description of the sine function can be found in appendix A.4.

Background concentration in Kattegat

The values for the background concentration for DIN and DIP in Kattegat is assumed to be obtained by linear relations with respect to the salinity. This positive linear relation in Kattegat of the measurements can be explained because of the lower nutrient concentrations of the upper layer of the baltic sea with lower salinities in comparison with the lower layer with higher salinity content and nutrient concentrations. In figure 5.5, the relations between salinity and the respective values are shown, which is based on measurements. The measured values are converted from units of $\mu\text{mol}\,\text{L}^{-1}$ into $\text{g}\,\text{m}^{-3}$ by the use of molar weight for nitrogen and phosphorus. These data are included in the electronic appendix C.1. [DEPA and NERI, 2002]



(a) DIN relation.



(b) DIP relation.

Figure 5.5: *The correlation between salinity and the DIN and DIP concentration. The scatter points are measured values, the solid red line is a regression line and the dashed green line is the optimal value. [DEPA and NERI, 2002]*

From figure 5.5(a) and 5.5(b), it is shown that the regression line returns an optimal value for the DIN and DIP concentration of approximately $0.12\,\text{g}\,\text{m}^{-3}$ and $0.02\,\text{g}\,\text{m}^{-3}$, respectively, using the assumed sea salinity of 26 PSU.

Initial concentrations of the state variables

The initial concentrations for the state variables, DIN and DIP, are taken from measured values at the beginning of the year. The initial concentration for the Phy is only included to enable the phytoplankton growth [Fennel, 1995].

Switch of the sediment pool of phosphorus

The effect of phosphorus release from the sediments is going to be modelled by applying a switch in the remineralization from the sediments process that turns it on in the summer months and off the rest of the year. In addition, the pool of phosphorus in the state variable SED_P is renewed to an initial concentration at the start of the year, calculated with the approach described in appendix A.5. [DEPA and NERI, 2002]

5.1.4 Model presentation

In figure 5.6, the model with the input parameters, presented in appendix A.7 are considered against the measured values of three modelled concentrations. The graphs shows the modelled concentration of the state variables for the 10th year where the state variables are stabilized.

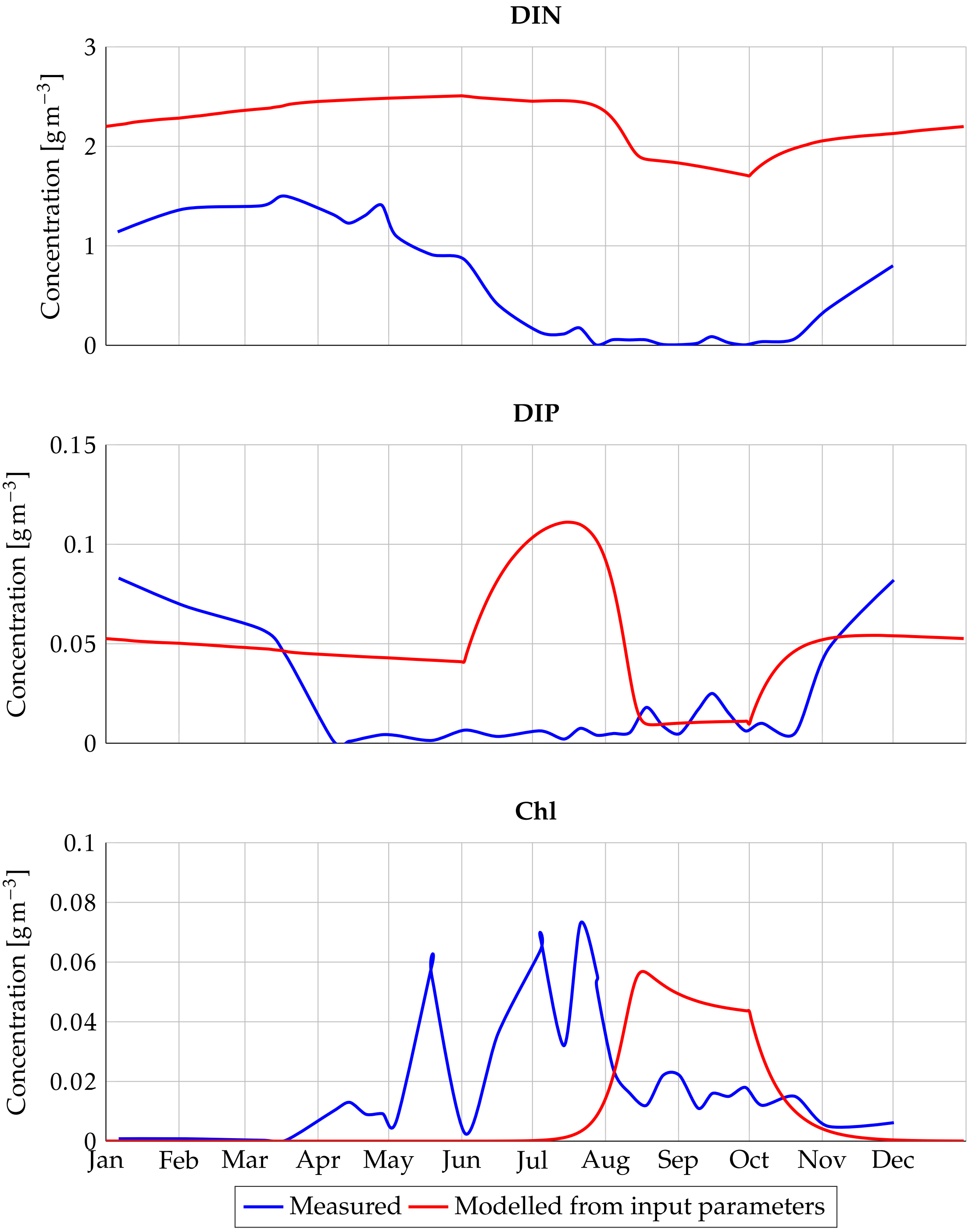


Figure 5.6: *The measured values in the first layer of the water column* (1 m) *against the modelled from input parameters.*

The measured phytoplankton concentration is the DIN concentration subtracted from the total nitrogen. However, this concentration shows a constant amount during the yearly cycle. Thus, it can be concluded that the assumed measured values of the Phy concentration is a poor comparison with the modelled ones. Instead of using these values, it would be more preferable to compare with the measured chlorophyll concentrations. Hence, the modelled phytoplankton is "converted" into carbon concentration and further on to chlorophyll concentration, with the use of the ratio between carbon and nitrogen, and carbon and chlorophyll, respectively, described in section 2.6.

Since it is chosen to disable the growth from late autumn to early spring, it would be expected that the modelled Phy concentration is close to zero during this period.

Like the input of nitrogen for the streams, there is only measurements of nitrate, nitrite and ammonia, where the sum of these three is assumed to be the DIN concentration. For the DIP concentration, the measured values are assumed to be the available data of orthophosphate, which is a dissolved product of phosphorus.

The modelled DIN concentration is much higher in the yearly cycle in contrast to the measured, but may seem to follow the cycle. The modelled algae bloom is giving a late response in comparison with the measured values. The duration of the higher algae concentrations is similar with the measured values but as expected the model is not being able to reply the peaks since daily radiation variations are not included. When the algae bloom appears in late July, there is a short period with a low DIN concentration before it goes back to the original. The modelled DIP concentration is, like the DIN concentration, higher than the measured. Until May, it follows the yearly cycle to a certain degree, until it increases to a maximum and decreases again in late summer.

5.2 Model calibration

In order to obtain a representable model that can reflect the reality to some degree, it is necessary to calibrate the parameters. The measurements, from which the calibration will take basis in, are taken from the location shown in figure 2.7(a) on page 9 in the depth of 1 m. It is chosen to calibrate the three state variables from which measurements are available, DIN, DIP and Phy, with respect to the measured values. Thus, the rate constants, presented in table A.3 on page 78 along with the initial concentration of phosphorus, presented in appendix A.5, are changed until the model fits. Hence, the calibrated model is presented in figure 5.7 on the next page.

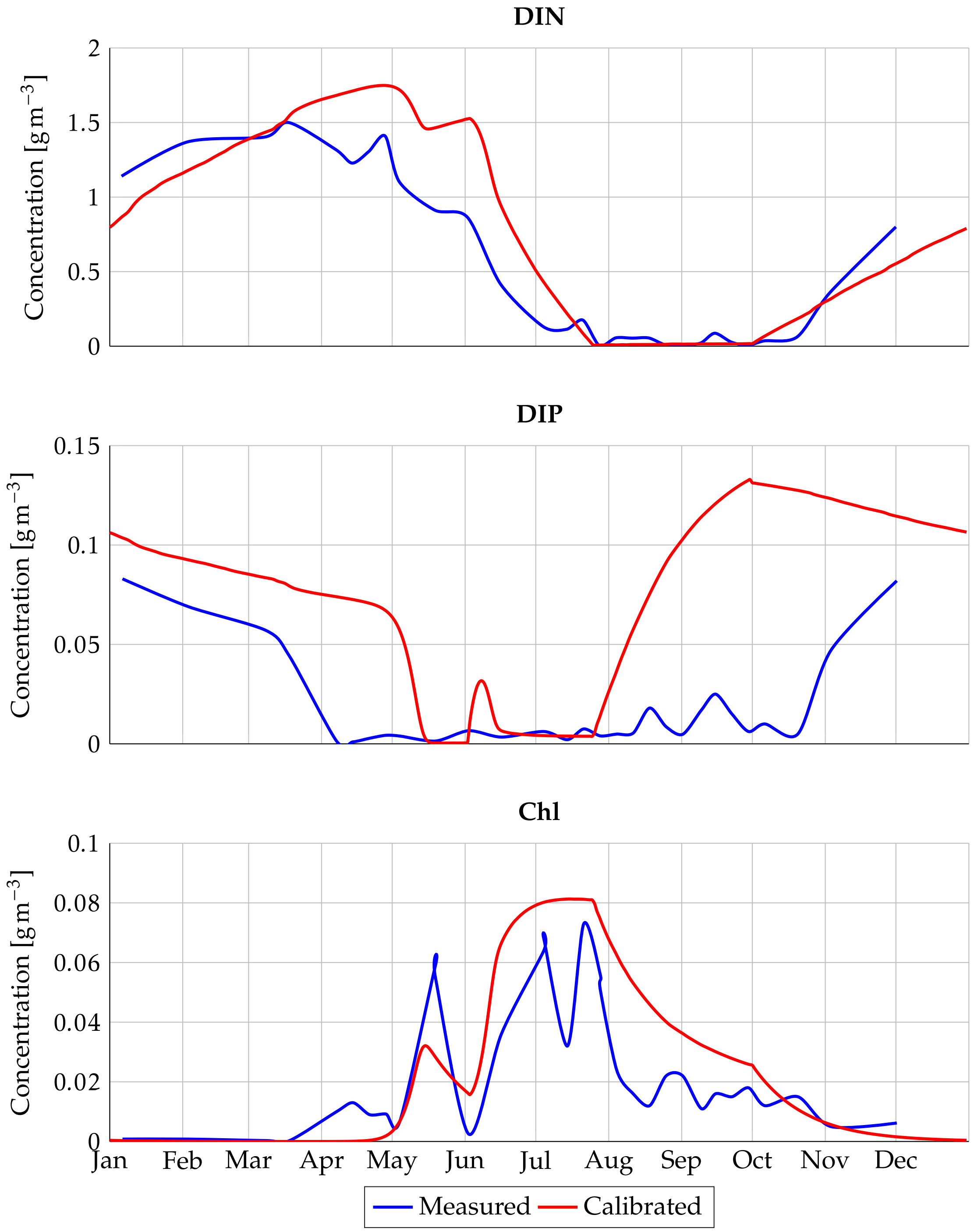


Figure 5.7: *The calibrated state variables against the measured concentrations.*

With the new set of parameters, the model is able to represent the system more accurately. The comparison between the measured and calibrated DIN concentration is well fitted, however, some differences can be found at the start of the year. This difference was not considered important, since the goal of the model was to simulate the conditions during the months where algae blooms appear. It is more important to accomplish that the model fits more accurately during these months, rather than in the winter months.

As for the DIP concentration, the same thing can be expressed as for the DIN concentration. When the algae bloom sets in, the model represents the reality better than in the beginning and the end of the year. In the months of March and April, the difference between the modelled and measured DIP concentration is due to the switch of the PAR-value that is applied in early April. In reality, the phytoplankton starts growing in early March. It was not chosen to calibrate the switch, since it was considered to be more important to model the peaks correctly.

After the calibration, the spring and summer peaks of the modelled algal bloom are fitting well in contrast to the measured values. Even though the model seems quite representable compared with the measured chlorophyll concentration, it is not possible to model the lower points. The lower peaks of the measured values may represent lower radiation periods, where the phytoplankton grow at lower rates.

The calibrated rate constants of the model are shown in table 5.2.

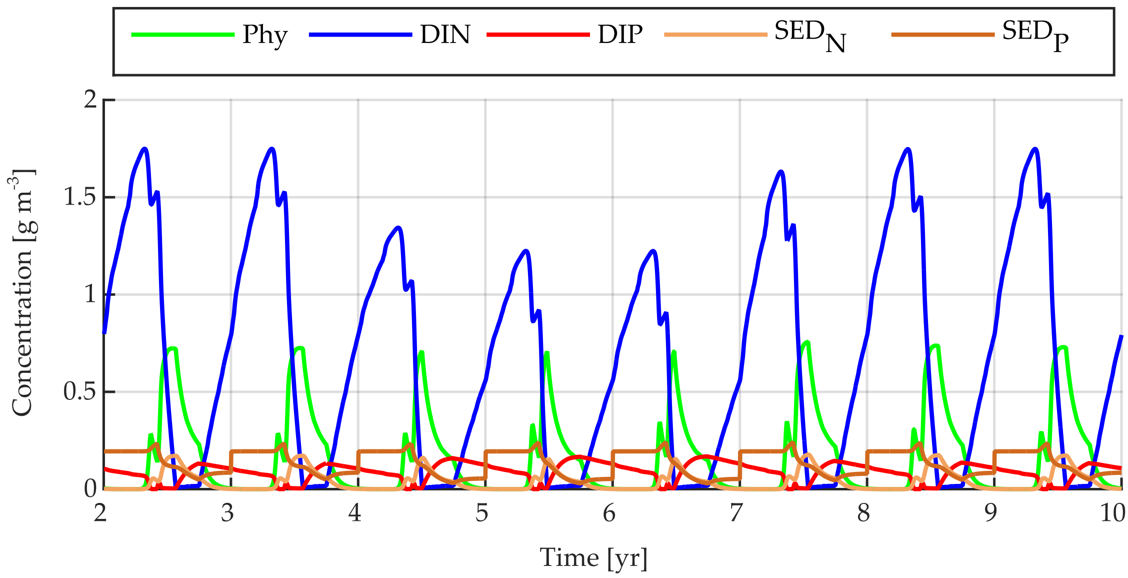
Table 5.2: *Calibrated rate constants of the model.*

Rate constant	**Symbol**	**Value** [day^{-1}]
Maximum growth rate	μ_{max}	0.45
Remineralization rate in the water phase	k_1	0.003
Sedimentation rate	k_2	0.038
Remineralization rate of nitrogen in the sediments	k_3	0.01
Denitrification rate	k_4	0.15
Remineralization rate of phosphorus in the sediments	k_5	0.045

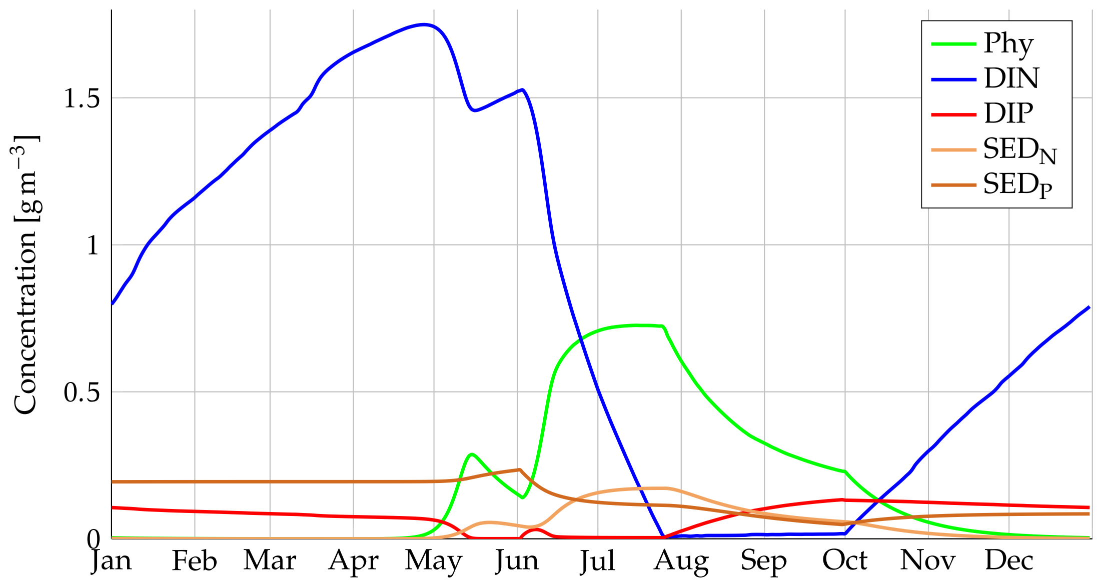
The sediment release of phosphorus has been calibrated to the highest range of $0.5 mmol\, m^{-2}\, day^{-1}$.

5.3 Model behaviour

After performing the calibration of the model it is important to study the behaviour of the model in different situations, in order to assess if the model is capable to replicate natural responses. In figure 5.8(a) is shown the model response to a reduction of a 30 % in nitrogen input of three years.



(a) The model behaviour showing the response, when reducing the amount of nitrogen by 30% in the 4th year and add it again in the 7th year.



(b) Model showing the yearly cycle for the last year.

Figure 5.8: *The model behaviour along with the yearly cycle for the last year.*

It can be observed how the model takes two years to reach a new equilibrium and how the phytoplankton bloom of late summer is reduced, as expected, while in the first year the spring peak is not affected, since in this period the limiting nutrient is phosphorous and not nitrogen. The reduction of the inputs of nitrogen also lead to an increase in the DIP concentration, that could be explained due to the lower intake of the phytoplankton in the growth process. A direct consequence of this increase of concentration after two years of reduction, is a rise in the spring peak of phytoplankton.

The model returns gradually to previous concentrations when the limitation of nitrogen input is taken out. The peaks of DIN in winter and Phy in late summer return fast to the previous concentrations after two years. The slightly increase in the peak of late summer in comparison with the peaks from before including the reduction can be explained because of the higher spring concentrations from which the growth in late summer came. The more gradually recovery of the spring peaks are due to the lower decrease in DIP concentrations, which in turn can be explained due to the attenuation factor of the switch included in the SED_P.

With this analysis of the model behavior ahead of the validation, it can be concluded that the model can be used to assess changes in the nitrogen loads.

5.4 Model validation

In order to assess the applicability of the model in different situations, a validation of the model has been performed. It has been chosen to validate the model comparing the measured concentrations of DIN, DIP and chlorophyll, against the modelled concentrations, using input flows and concentration from another year. The year that has been used is 2004. Unfortunately, due to the lack of measurements in regards of the flow from two streams used in the model, which is Hodal Bæk and Vive Møllebæk, values from 2005 have been used for these streams. It is estimated from the analysis made in appendix A.8 that there is around 38% more runoff in 2004 than in 2005. Therefore, it is chosen to add the extra runoff to the two streams, Hodal Bæk and Vive Møllebæk.

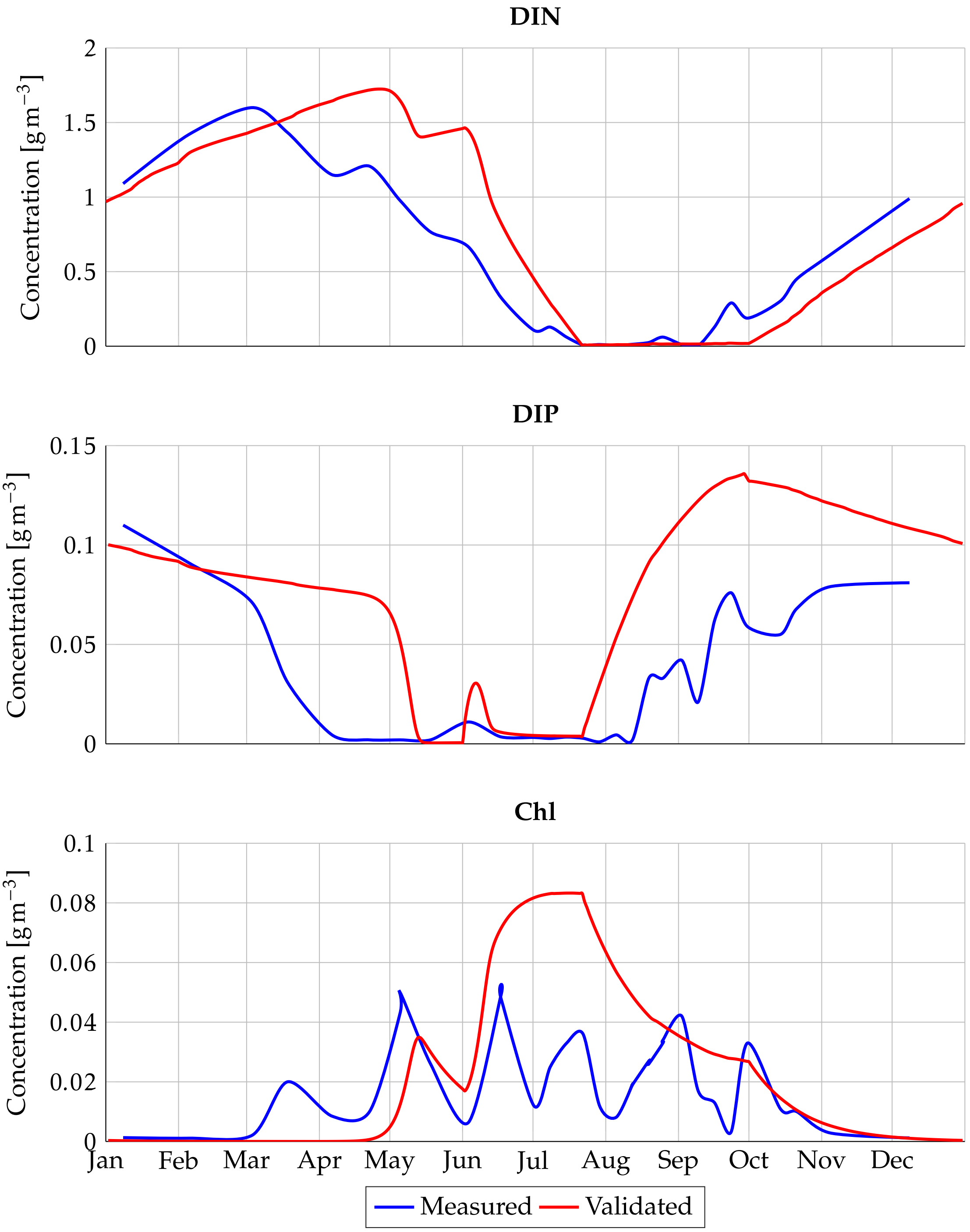


Figure 5.9: *The validated model in contrast to measured values for 2004.*

In the graph it can be observed that the model works relatively well in replicating the system for the year of 2004 in terms of DIP and DIN concentration. This could be to the similarities in the inflow between 2004 and 2005. Although the model did not work perfectly in simulating the algae peaks for 2004, giving more or less the same results as for the calibrated model from 2005. Since the model is not going to be used to model yearly variations, but for general trends in the nutrient input, it can be considered validated.

5.5 Uncertainties

The developed model that describes the processes that are supposed to occur in Mariager Fjord, comes with a number of uncertainties.

First of all the mass balance is roughly estimated. It is assumed that the only contribution of freshwater is the inflow from the streams. That is not entirely the fact, since a part of it can come from groundwater and net-precipitation.

The second uncertainty is that in the developed model there have been neglected few minor streams, this is due to the lack of measurements in these streams. Although it is expected that the error given by this fact will be low, as in the model there have been included the streams that have the highest flow and nutrients input into the fjord.

Third uncertainty stands for the measurements of the flows in some of the streams as the points in which they have been taken may have a slight difference from the real flow velocity of the streams at their mouth into the fjord. This is presented in appendix A.1, where the stations from which the flow measurements are collected. Furthermore, in the validation of the model, due to lack of measurements in 2004, the flows from the streams, Vive Møllebæk and Hodal Bæk, values from 2005 are used.

Another uncertainty regards the fact that, although the model describes the inner part of Mariager Fjord, a stream that has the discharge into the outer part has been included in the model. The release of nitrogen and phosphorus from the sediments in the outer part, which, due to the exchange, will migrate from the outer part to the inner part of the fjord, has not been included in the model, therefore it stands as uncertainty.

Other uncertainty is the constant values of salinity for Mariager Fjord and Kattegat. Since the salinity varies in place and time, there is still used a mean value of 16 PSU for Mariager Fjord and 26 PSU for Kattegat. However, this can be argued that the change of exchange flow, which depends on the salinity, is small and therefore the constant value can be accepted.

As well, another uncertainty of the model regards the fixation of atmospheric nitrogen, which diffuses across the water surface and into the water. Although there is about 78% nitrogen (N_2) in the atmosphere, the two atoms in the are firmly bound together, thus, a lot of energy is required by the phytoplankton to break them apart. Therefore, the phytoplankton will use the dissolved ions of nitrate, nitrite, ammonia and ammonium, which are more convenient to use, as they require less energy to be broken. [Tyrrell]

Finally, the measurements of the DIN and DIP concentration are taken from the first meter of the water column. Thereby it is uncertain whether the model is computing for the first meter or for the whole water column.

5.6 Implementation of the results

Now that the model has been validated for 2004, the calibrated model can be used to investigate the possible effects for the ecosystem, if or when the amount of nutrient input is reduced.

The reduction of nutrients is going to be approached through two perspectives. First the Laurentius relation presented in section 3.1 is going to be used to obtain the nitrogen load admitted by the system in order to fulfil the eelgrass depth from the WFD. Finally the nitrogen and phosphorous loads applied to the model are going to be reduced to the upper and lower recommended limits from Markager et al. [2008].

It is chosen to analyse the three state-variables, DIN, DIP and Phy because they are considered as being the most important state variables.

5.6.1 Increasing eelgrass depth colonization by reducing nitrogen

The total nitrogen from the model is obtained by the average DIN and Phy concentration between March and October. As described in section 3.1, the total nitrogen can be related to the depth colonization of eelgrass. The average summer concentration of total nitrogen in the system is $1.052\,\mathrm{g\,m^{-3}}$ or $1052\,\mathrm{\mu g\,L^{-1}}$. Using the type II relation, this gives an eelgrass colonization depth of 1.67 m, illustrated in figure 5.10 on the next page. It is suggested that the concentration of total nitrogen must be reduced to below $500\,\mathrm{\mu g\,L^{-1}}$ which represents a good quality as depicted in figure 3.4 on page 19. This requires a reduction of 46% of nitrogen input to the system. With this reduction, the amount of nitrogen in the system is now $499\,\mathrm{\mu g\,L^{-1}}$, which gives an eelgrass depth colonization of 3.57 m. This seems as a good estimate when comparing with figure 3.4 on page 19 where it lies between good and reference quality.

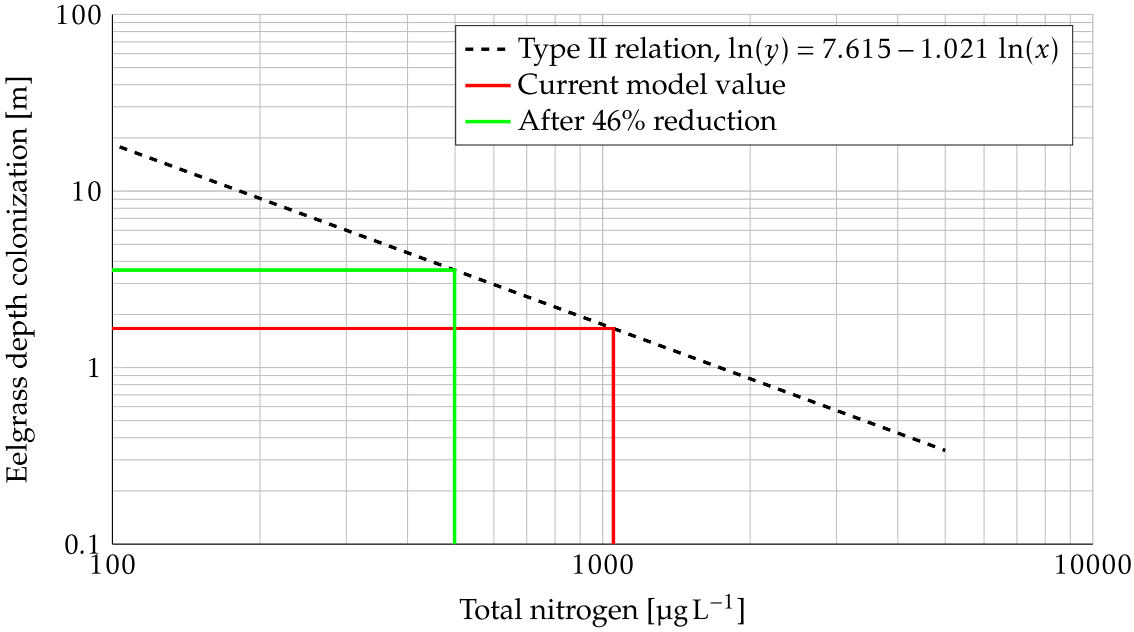


Figure 5.10: *The correlation between total nitrogen and eelgrass colonization depth in regards to the type II relation along with the current and reduced amount in the system.*

Although with this reduction is supposed that the water quality will be improved in Mariager fjord, with the results from the model only a clear reduction in the DIN concentration is observed, and not in the phytoplakton concentration neither in spring nor in summer.

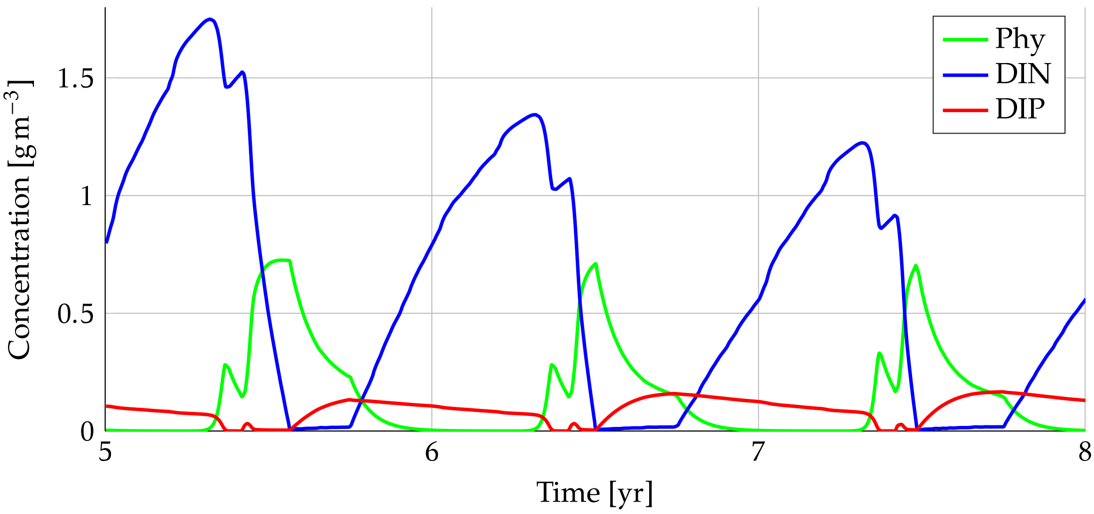


Figure 5.11: *The result of the Laurentius method, when reducing the nitrogen by 46%.*

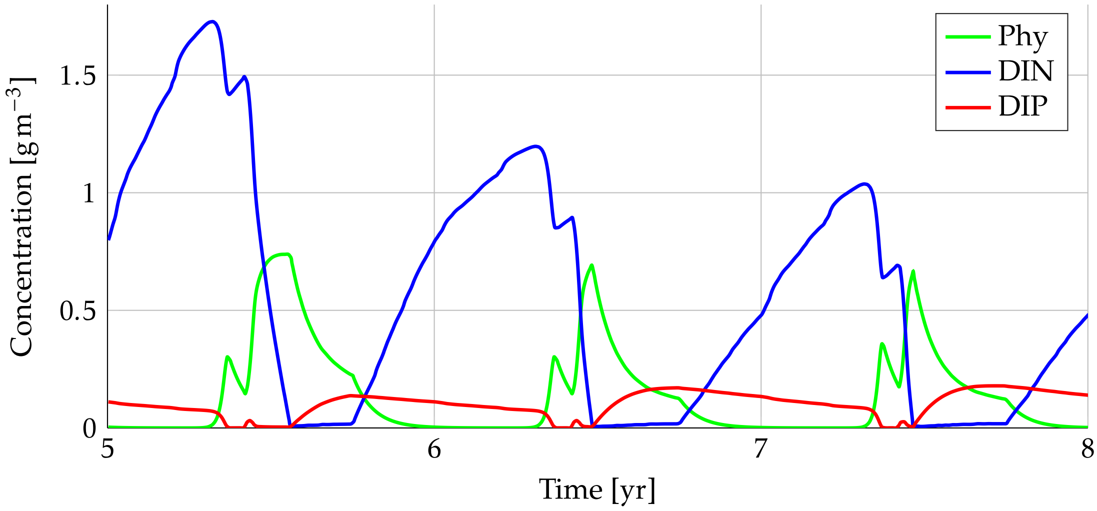
Due to the results obtained applying this approach, and the controversy of this relation, it was decided to assess also the effects of a reduction of nutrients with the recommendation from Markager et al. [2008].

5.6.2 Second approach

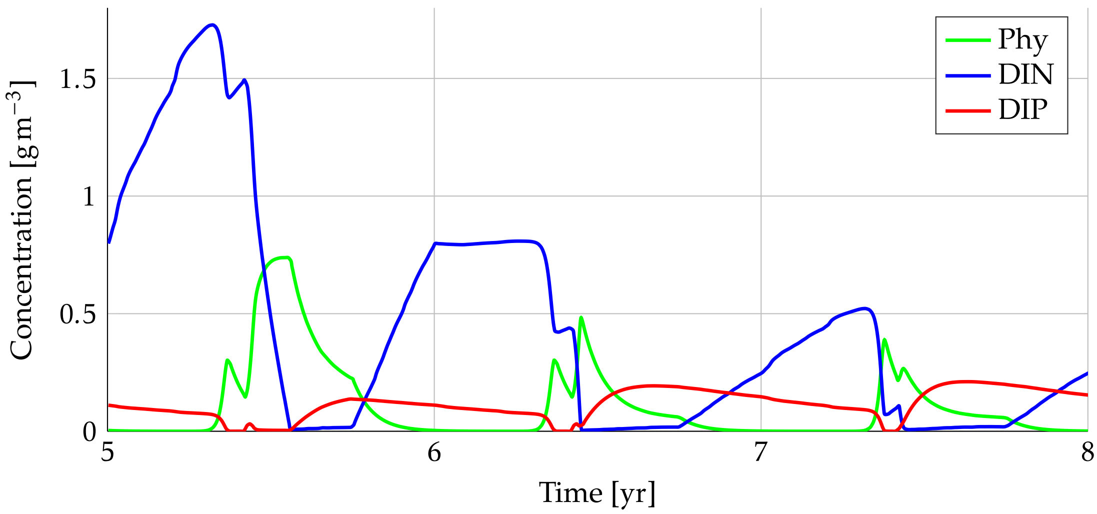
The input of nitrogen and phosphorus to the system is 694 ton yr^{-1} and 9.62 ton yr^{-1}, respectively. As mentioned in chapter 3, the recommended input is 200 ton N yr^{-1} to 400 ton N yr^{-1} and 6 ton P yr^{-1} to 8 ton P yr^{-1}, which means that the input must be reduced with around 40-70% and 15-35% for nitrogen and phosphorus, respectively.

Reducing nitrogen

The effect of reducing nitrogen is shown in figure 5.12. Since the state variables will stabilize within 2 years, it is chosen only to include 3 years.



(a) 40% reduced nitrogen.



(b) 70% reduced nitrogen.

Figure 5.12: *The effect of reducing the input of nitrogen to the ecosystem.*

From figure 5.12, it is shown how the peaks of the state variables are behaving. With a reduction of 40% in nitrogen input, the DIN concentration is reduced to a significantly lower peak concentration. However, as in the results from the previous subsection this reduction will not affect the peak of the phytoplankton significantly, but it has lowered the duration of the summer phytoplankton bloom that is controlled by nitrogen input.

When reducing the nitrogen by 70%, it has an effect on the spring and summer bloom of phytoplankton. The spring bloom is increasing, while the summer bloom is decreasing to more than half of the concentration. This increase in the spring peak can be explained by the higher DIP concentration due to the lower intake of phosphorus by phytoplankton in the previous summer when the nitrogen is the limiting factor.

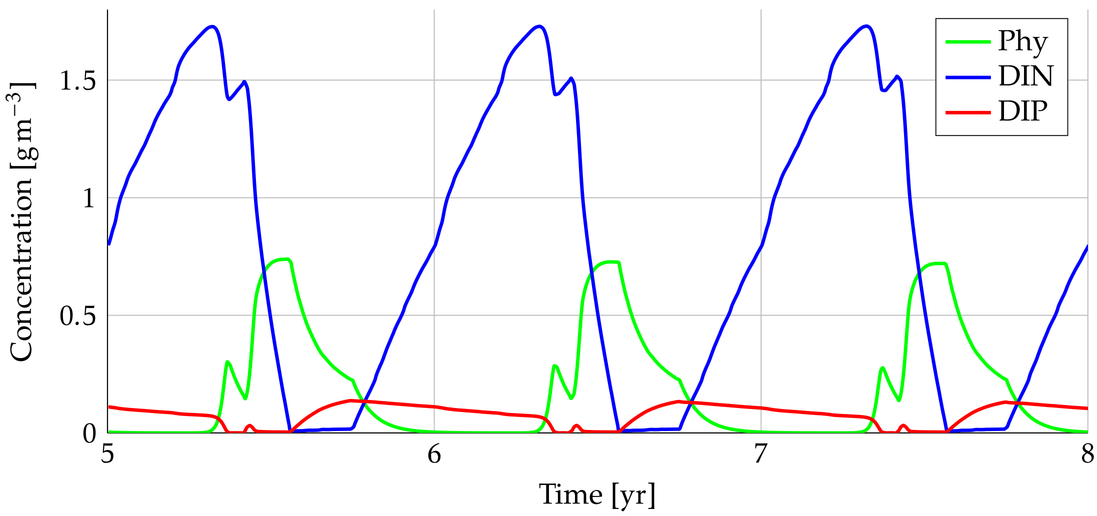
The peak concentration before and after nitrogen reduction, is summarized in table 5.3. In case of 70% nitrogen reduction, notice that the peak concentration for the phytoplankton is for the summer bloom and not the highest peak. The highest peak value for phytoplankton is $0.398\,\mathrm{g\,m^{-3}}$ and happens during spring.

Table 5.3: *The peak concentrations of the state variables in the ecosystem when nitrogen input is reduced with lower and upper reduction level.*

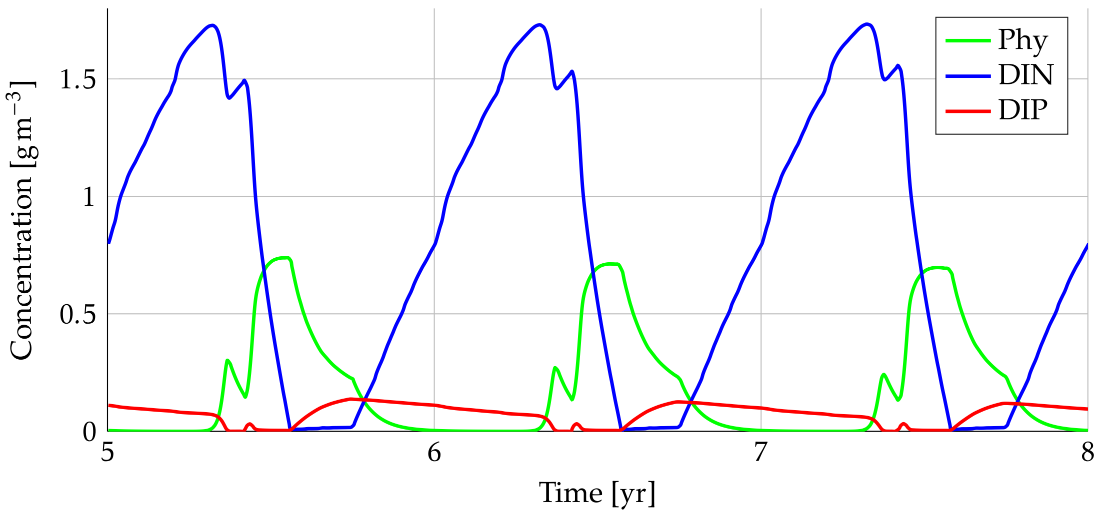
State variable	**Concentration [$\mathrm{g\,m^{-3}}$]**		
	Before reduction	*Reduction 40%*	*Reduction 70%*
DIN	1.728	1.037	0.522
DIP	0.138	0.179	0.211
Phy	0.739	0.666	0.389

Reducing phosphorus

Like the nitrogen, the effect of reducing the phosphorus input is shown in figure 5.13 on the following page.



(a) 15% reduced phosphorus.



(b) 35% reduced phosphorus.

Figure 5.13: *The effect of reducing the input of phosphorus to the ecosystem.*

As shown in the figure, reducing with 15 or 35% of phosphorus input does not show a large difference in the ecosystem. When it comes to the Phy concentration, it only has a slight reduction of the peak concentration, shown in table 5.4. The DIN and DIP also increase and decrease slightly and the reduction does not seem to have an influence.

Table 5.4: *The peak concentrations of the state variables in the ecosystem when phosphorus input is reduced with lower and upper reduction level.*

State variable	**Concentration [$g\,m^{-3}$]**		
	Before reduction	*Reduction 15%*	*Reduction 35%*
DIN	1.728	1.730	1.733
DIP	0.138	0.131	0.121
Phy	0.739	0.721	0.697

5.7 Key findings of the water quality model

The findings of this chapter are described as follows.

- It takes more than one year for the state variables to stabilize.
- The model can represent the real ecosystem of Mariager Fjord, despite of leaving some inputs out, like atmospheric nitrogen and additional but unavailable stream flow.
- The ecosystem of Mariager Fjord can be represented by a simple one-box model.
- Nutrient removal can be most effectively carried out by nitrogen reduction.

Even though this model can represent the ecosystem of Mariager Fjord to a somewhat acceptable degree, it is desired to take it a step forward by developing a more advanced model. This approach will take into account more aspects that are neglected in the previous model. Furthermore, the advanced model will represent the actual physical and geographical conditions in a broader area.

6 Hydrodynamic model

This numerical MIKE model was developed as an additional tool along with the ecological model in this project's two pronged approach of assessing the improving capacity of each solution.

In the first part of this section, an explanation of the area of study, which is considered in the hydrodynamic model is stated as well as the key parameters included in the model. Afterwards, the calibration and the uncertainties of the model are presented.

This model has not been fully developed due to time limitation. However, it is possible to make further enhancements. Thus, some suggestions that can be investigated in other projects as well as some solutions are presented, which can be resolved by the hydrodynamic model. All the time series, the flow model and the mesh files are included in the C.6.

6.1 Model delineation

The model area includes the whole Mariager Fjord and a small part of Kattegat and is delineated by two boundaries. Boundaries can be found at the edges of the model area and both of them have a specific characteristic, which is shown in figure 6.1. One of the boundaries is chosen to be a land boundary, which delineates Mariager Fjord from Kattegat to Hobro, whereas the other one includes a small part of the Kattegat sea. The surface elevation values have to be specified in the sea boundary, which will vary in time and is included in the time series of the water levels at Hals, presented in section B.2 and provided by [Bentzen, 2015]. Regarding the water level of the fjord, an initial value of 0 m is chosen. Thus, it will vary with the water level in the sea.

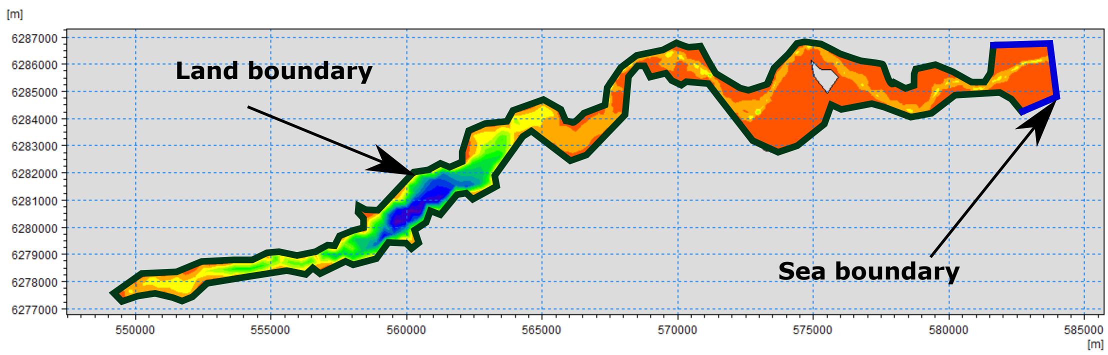


Figure 6.1: *Boundaries of the model. The black line indicates the land boundary, while the blue line indicates the sea boundary.*

It is essential to consider the bathymetry, which is shown in figure 2.7(a) on page 9, from which the mesh is going to be constructed. The mesh is an important part when establishing the hydrodynamic model and it has been constructed, as shown in figure 6.2.

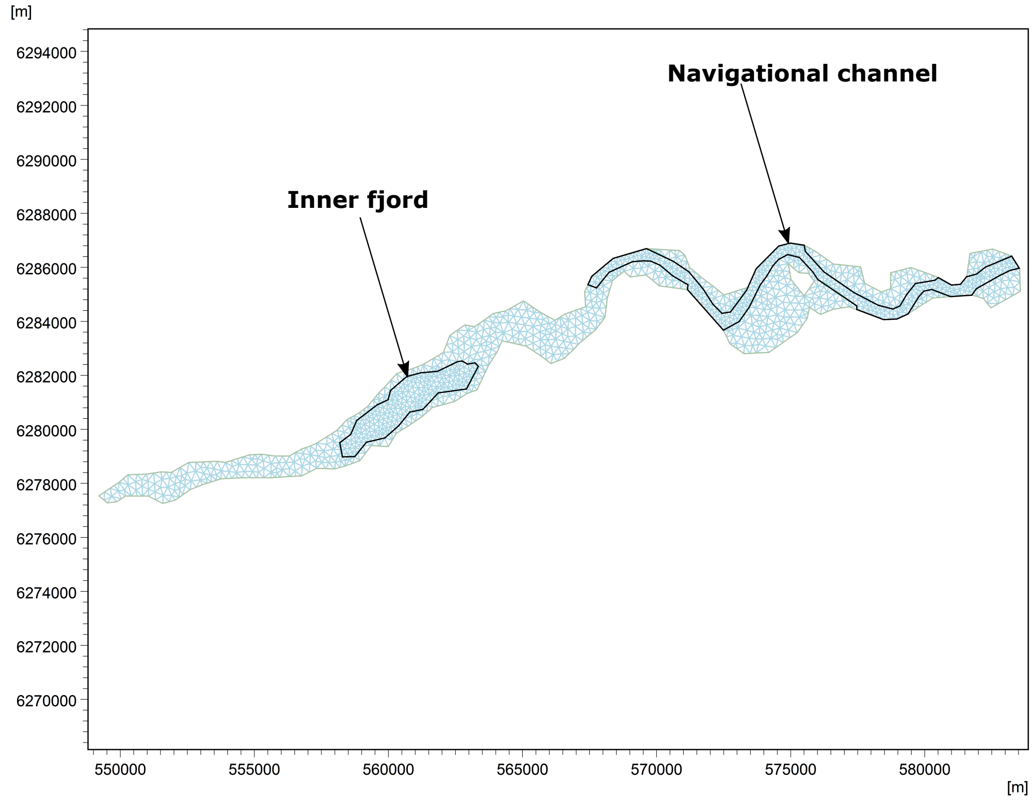


Figure 6.2: *The constructed mesh.*

The mesh has been created from scatter data, containing point to point information about the water depths. On the horizontal surface, the mesh is made out of irregular triangle cells, while the vertical grid is made out of six layers, from which each layer's fraction of the total depth is shown in table 6.1. Here, layer 6 is the top layer and layer 1 is the bottom layer.

Table 6.1: *Vertical layer distribution.*

Layer number	Fraction
6	0.4
5	0.05
4	0.05
3	0.05
2	0.05
1	0.4

In order to reduce the computational time, a large grid spacing is necessary. As it can be seen in figure 6.2 on the preceding page, a denser mesh was constructed for the navigational channel, because it was considered important in order to replicate the water exchange between the fjord and the sea. In addition, a denser mesh has been applied in the inner part of the fjord, because the focus will concentrated in this part.

As it is stated in section 5.1.1, some external influences are located in the model area that cause effects in the fjord. The main influence which is taken into account is the stream discharge whose data is important to include in the hydrodynamic model. The main six sources represent the rivers with the highest discharge. Figure 6.3 shows the location of the sources and in each one, the times series of 2005 provided by Danmarks Miljøportal [2015] are included.

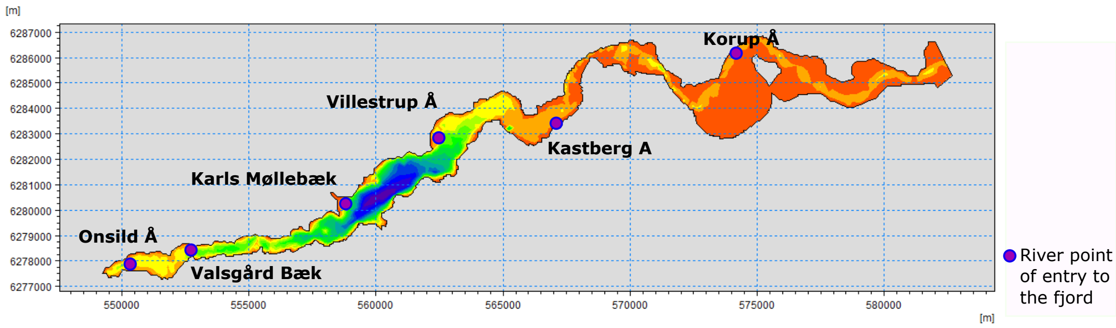


Figure 6.3: *The location of freshwater sources.*

The discharge data is shown in appendix B.1 and is varying in time. These values of the discharge data are added to the sixth layer, which represents the surface layer. Figure B.1 also shows that all the rivers have their peak in discharge from January to May and Villestrup Å is the one with the highest flow.

6.2 Key parameters

The parameters that are considered important in the hydrodynamic model are stated in this section. The values shown in appendix B.3 have been used as an initial estimation to build the model.

For the purpose of this model, a low order algorithm has been chosen due to its fast computational time, which has been considered to be suitable for the limited time of this project.

Because stratification occurs from high differences in densities, it is assumed that density is a key parameter in order to obtain correct results. In the east, Kattegat supplies the fjord with saltwater and in the inner part in the west, several rivers contribute with freshwater. This model has been chosen to be dependent on the salinity, so that the transport equation is calculated using salinity data. These data along with the reference temperature are presented in appendix B.3.

Table B.4 in appendix B.3 also presents the salinity values for the sources, initial conditions and the boundaries. In the sea boundary, the times series of salinity in Hals presented in section B.2 and provided by Bentzen [2015], are introduced.

The wind is one of the main hydrodynamic forces, which is influencing the flow by generating currents. The time series of the wind is corresponding with the time series from Hals, presented in section B.2 and provided by Bentzen [2015], where it ranges from $0\,\mathrm{m\,s^{-1}}$ to $19\,\mathrm{m\,s^{-1}}$.

6.3 Calibration

In order to perform the calibration, measurement data of the fjord is needed to be compared to the modelled values. The measurement data from DCE [2012] was collected from the station, shown in figure 2.7(a) on page 9. The available data is the salinity and water levels, that are measured for every meter in 2005. Thus, the measured salinity and the water levels are compared against the modelled salinity and water levels respectively.

The following parameters were changed, which are the eddy viscosity, bed resistance, initial salinity and dispersion. The calibration is done by changing a single parameter each time considering to be in the range. The ranges are obtained from DHI [2007].

The optimal time for calibration is considered to be three months, taking into account that it is enough time to evaluate the changes. Moreover, the computational time is suitable for the duration of this project.

Bathymetry

It has been noticed that among the bathymetry of the navigational channel in the outer part of the fjord, some gaps were present. Some changes were made in the bathymetry file in order to have a continuous channel, allowing the exchange with Kattegat.

Eddy viscosity

A lower mixing length means that the fluid is more viscous and it needs more energy to mix the water column. Thus, the horizontal eddy viscosity has been decided to be kept at 0.4, which is the standard value that represents a better stability of stratification. On the other hand, the vertical eddy viscosity is changing by varying the damping number.

Bed resistance

The bed resistance was changed according to the recommended values, so it has been attempted to simulate with a roughness of 0.01, but the changes are unnoticeable. So it is accepted to choose 0.05 as the roughness value.

Initial salinity

Since the inner fjord varies in depth from 0 to 30 m and stratification is observed, it is chosen to implement different salinities in the six layers of the model. The initial value for each layer is obtained from the measured salinity data of 2005 provided from DCE [2012]. However, it has been observed that the salinity in the fjord is lower than the measurement data. Thus, a value of 26 PSU has been chosen as the initial salinity, which lies in between the range of the highest values for the salinity in the boundary.

Dispersion

The horizontal dispersion value is set to 1, but the vertical dispersion is varied with different values: 1, 0.0001 and no dispersion in order to see the difference. With a value of 1 the water column is well-mixed as it was expected, whereas with a lower value the stratification is stabilized. No vertical dispersion is chosen in order to maintain the stratification.

Table 6.2 shows the parameters that have been chosen for the model. These are the most realistic values that have been found, which represent the stratification in Mariager Fjord. However, it has not been possible to fit the measured and the modelled values to all depths.

Table 6.2: *Values obtained from the calibration*

Rate constant	Units	Value
Horizontal Eddy Viscosity	–	0.4
Vertical Eddy Viscosity, maximum	$m^2\,s^{-1}$	0.4
Damping constant a	–	10
Damping constant b	–	0.5
Bed resistance	m	0.05
Initial salinity	PSU	26
Horizontal dispersion	–	1
Vertical dispersion	–	No dispersion

6.4 Results

First, a comparison between the measured water levels and the values taken from the hydrodynamic model for a period of two months have been performed, in order to observe how much the model differs from real conditions.

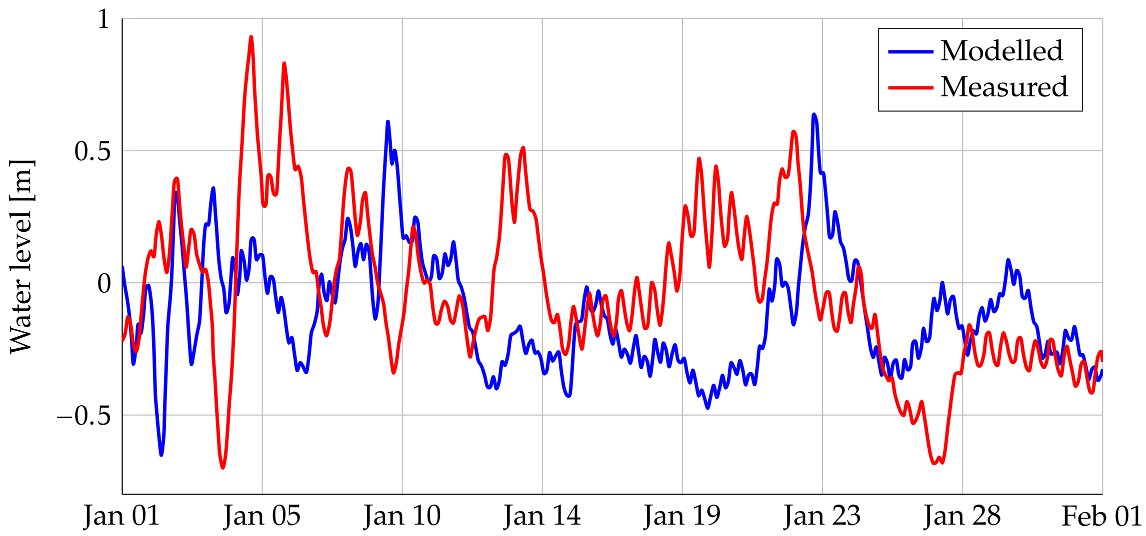
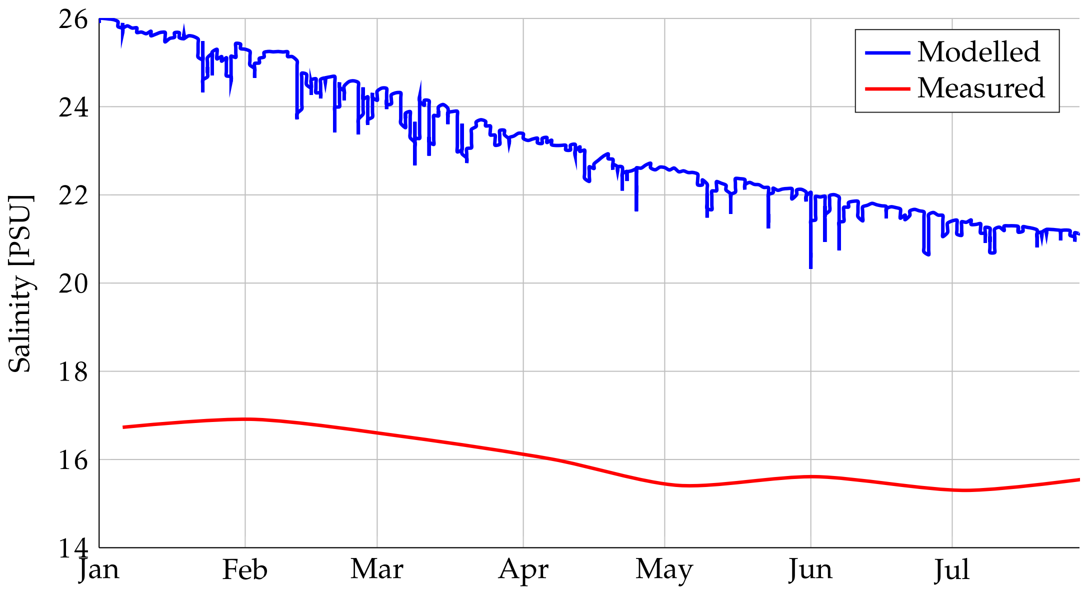
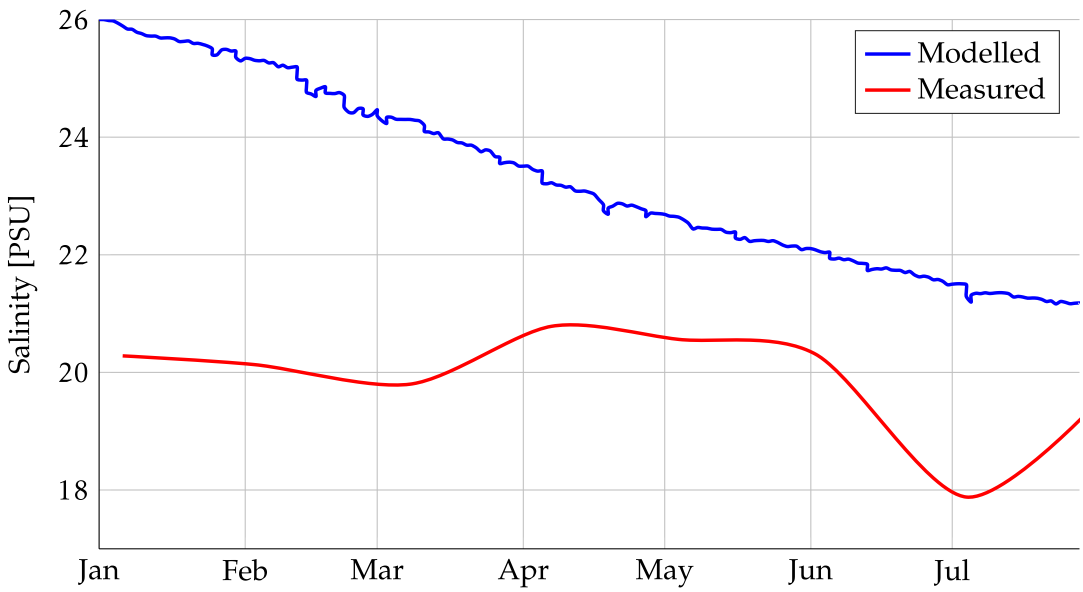


Figure 6.4: *Modelled against measured water levels.*

Although the modelled values have been obtained from 2005 and the measured values are from 2011, it is shown in figure 6.4 that the modelled values do not differ too much and even follow the same patterns occasionally over time. This is acceptable, because data from two different years has been used.



(a) Salinity at the top layer.



(b) Salinity at the bottom layer.

Figure 6.5: *Salinity at the top surface and bottom layer, which decreases over time.*

As seen in figure 6.5(a) the modelled salinity in the top layer do not compare well with the measured data but it may be possible to achieve the desired values with a more longer simulation. As for the bottom layer salinity (figure 6.5(b)), at the ending of the simulation, the trends are progressing closer to each other. This concludes that a desired salinity in the bottom part can be achieved within the next months.

Furthermore, it can be seen that in figure 6.5 the modelled salinity trends observed in the surface and the top are similar to each other so it can be concluded that stable stratification was not achieved.

The probable reason behind not being able to fully develop the hydrodynamic model is the water exchange with Kattegat, as can be seen in figure 6.5 on the preceding page the salinity in the inner part of the fjord is continually decreasing. This is because the fjord gets its saltwater exchange every two or three years [Fallesen et al., 2000]. This concludes that a stable model could only be achieved in potentially two to three years.

6.5 Uncertainties

A model simulating real conditions in a perfect manner is almost impossible to achieve, because there are some processes that the modelling software cannot reproduce perfectly. This implies that the user must make a certain number of assumptions, which will rise a relative number of uncertainties.

6.5.1 Grid uncertainties

The first factor that will give a high number of uncertainties is the grid covering the modelled area. The constructed mesh is of crucial importance, due to the fact that a finer mesh will lower the uncertainty opposite to creating a larger mesh which result an increase in the uncertainty.This is why the finer mesh was only constructed in the inner deep part of the fjord and in the navigational channel, which were considered as points of interest.

Another uncertain element is the distribution of the vertical layers. Because the fjord is shallow in the outer part and deeper in the inner part, the vertical layers were manually adjusted to replicate the stratification phenomenon. Furthermore the bathymetry file proved to be quite inaccurate so a few manual adjustments were made.

6.5.2 Input uncertainties

Wind

One of the inputs that has probably the highest influence in the model is the wind forcing. Unfortunately, wind data for Mariager Fjord has not been available, so a different time series has been used. This time series of the wind forcing were located approximately 50 kilometres north of Mariager Fjord, which is presented in section B.2 and was provided by Bentzen [2015]. It is supposed that there is no significant differences between the winds, but it is classified as an uncertainty.

Boundary conditions

For the boundary conditions in Kattegat, two different time series have been used, both of them having the same uncertainty probability, due to the fact that both of the data correspond to Hals. The first time series contained water levels for Kattegat, which corresponded with the tidal oscillations. The second time series contained the salinity concentration is varying between 18 and 29 and is presented in section B.2.

7 Solution suggestion

The main goal is to save the inner fjord from eutrophication. Nitrogen is considered to be the most affecting nutrient. Meanwhile, the deep part in the fjord is considered to be anoxic by nature. The idea is to force the stream water directly to the bottom of the deep basin located in the inner part, through a pipeline by gravity. By doing this, the nitrogen load will end in the anoxic part, which may act as a natural reactor for denitrification. Hence, the upper part is spared from eutrophication along with an increased biodiversity. This pipeline idea is to be investigated through this section.

Some considerations are taking into account as the oxygen dilution in the anoxic part as well as the effect of dilution by designing a diffusor in the depth water which it is explain in appendix B.1. Figure 7.1 shows the conceptual model that is going to be discussed in this section.

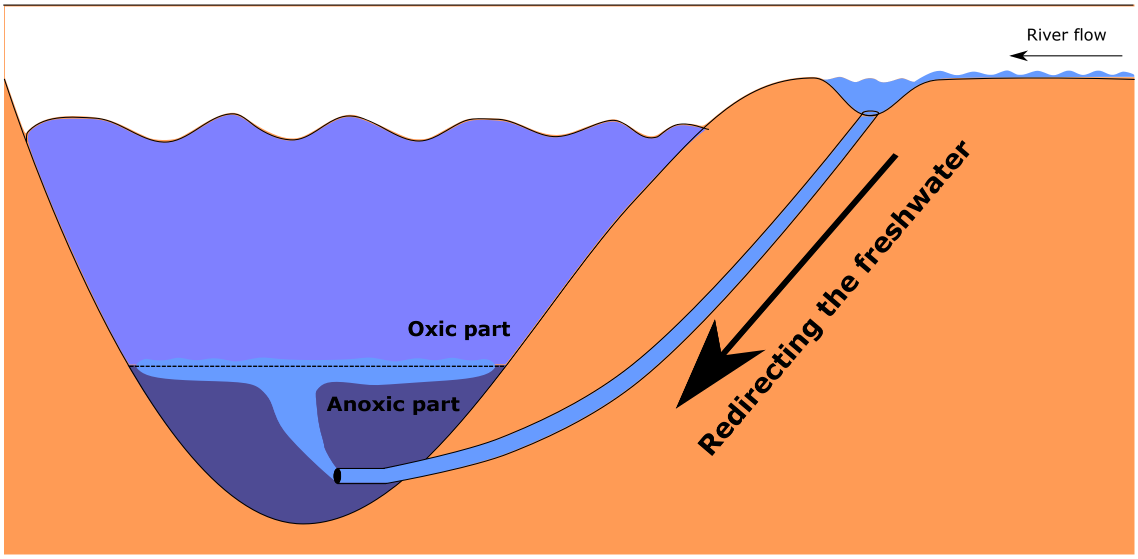


Figure 7.1: *Conceptual model of river re-direction.*

7.1 Method

To support the idea of forcing the stream water directly down to the bottom of the anoxic part, it has to be ensured that no significant changes are done to the anoxic part. First of all, the anoxic part must stay anoxic in order to maintain the denitrification. Furthermore, the biodiversity, which is adapted to the anoxic part must not be affected by oxygen supply. It is therefore needed to check whether the oxygen gets diluted enough after entering the anoxic part.

In order to study this solution, one of the adjacent streams, Karls Møllebæk, is chosen. This stream has an average yearly concentration of $17.38\,\mathrm{g\,m^{-3}}$ with a stable mean flow throughout the year of around $0.06\,\mathrm{m^3\,s^{-1}}$, which is shown in figure B.1 on page 89. It is the nearest stream to the deepest part of the fjord, which is shown in figure 6.3.

In order to create a static pressure difference, it is necessary to establish a lake in the stream from where the pipeline would go to the anoxic part. Due to the pressure difference between the lake and the fjord, with a higher pressure head in the lake, the water will flow by force of gravity. A high slope of the terrain around the fjord as mentioned in section 2.3, this solution is considered to be of ease, since the lake can be established relatively close to the fjord. Thereby, a relatively short pipeline is needed to connect the lake with the anoxic bottom of the fjord.

As it is stated above, the denitrification process must be taken into account. In order to maintain the denitrification, the concentration of oxygen that is introduced must be below 15 µmol, which is around $0.5\,\mathrm{mg\,O_2\,L^{-1}}$ [Jensen et al., 2009]. Hence, the flow is calculated to be maximum $0.3\,\mathrm{m^3\,s^{-1}}$, which results in an oxygen concentration below $0.5\,\mathrm{mg\,O_2\,L^{-1}}$. The performed calculations are presented in appendix B.1.

7.2 Discussion

When freshwater is introduced to the anoxic part, some physical and biological changes in the system will take place. First thing that has to be taken into account is that freshwater contains nutrients and oxygen that will affect the biochemical system in the anoxic part of the fjord.

Among other nutrients, nitrate and nitrite will also get into the deep water. Then, the denitrification will increase and release atmospheric nitrogen. The ongoing increase of oxygen concentration during input is considered to be of less significance, since it is not expected to exceed the hypoxic condition required for denitrification. Moreover, the bottom part of the water column has been anoxic for too long time to experience any significant changes through this oxygen input.

Another consideration has to be made, since the density of the anoxic layer will decrease gradually as the stream water is added. This yields to a gradually lowered density difference between the anoxic part and the input water, which affects the values in the investigation of the effect of dilution. However, the decrease in density in the anoxic part after two months of constant freshwater input is found to be uncritical (from $1014\,\mathrm{kg\,m^{-3}}$ to $1012\,\mathrm{kg\,m^{-3}}$), since there was no significant changes in the further calculated values.

Since the establishment of a gravity pipeline will not have any operational cost, it could be the first intention to use it throughout the whole year. This will, however, not be profitable, because there is a need for a stable stratified system to prevent the anoxic part intruding the oxic part and threatening the fauna. Such a stable system can be found in the warmest months with the least wind. It is considered that it will be most effective to open the pipeline during July and August and have it closed the rest of the year. While the pipeline is closed, the water should be able to overflow the established lake and follow its natural pathway down to the fjord.

There will be changes in the DIN concentration of the ecological system of Mariager Fjord due to the nutrient input from this stream, which will not reach the upper part of the fjord. According to this solution, the nutrients will be directly led to the anoxic part and the nutrients in the upper fjord will decrease. However, it has been calculated that just around 5% of the total nitrogen input to the fjord may be removed and no significant changes will happen in the DIN concentration.

Implementing this solution is not enough to reduce the nutrients in Mariager Fjord in order to meet the criteria. Thus, it is necessary to study other solutions, which can remove a higher percentage of nutrients, keeping the pipeline solution as a complementary solution. In the following section, it is explained how this complementary solution can be included in the ecological and hydrodynamic model. Moreover, the possibilities for wetlands, as an alternative solution, to remove a higher amount of nutrients is considered.

8 Perspectives

In this section, the possible further analysis to develop tools to help to improve the water quality model are going to be discussed.

8.1 Improvement of the water exchange calculations

In order to improve the results from this project in the future and to assess the proposed solution given in chapter 7, it is considered important to improve the water exchange calculations with a more complex model. To do so, two possible approaches are considered.

- Develop a three-box model dividing the fjord in oxic and anoxic parts and the outer fjord.
- Obtain the water exchange from the hydrodynamic model

8.1.1 Explanation of the three box model

Due to the special characteristics of Mariager Fjord, it is considered to develop a three-box model, dividing the inner fjord in an oxic upper box and an anoxic bottom box, and considering the outer fjord as a third box, which could be an improvement in different ways. With this approach, a more accurate calculation of the water exchange could be done, with the more dense water from the outer fjord entering the system directly to the bottom, and an outer flow from the upper part. Salinity as in section 5.1.1 is going to be used as a tracer to find the water exchange flow between the boxes, making the assumption of steady state. Figure 8.1 on the following page illustrates the conceptual model.

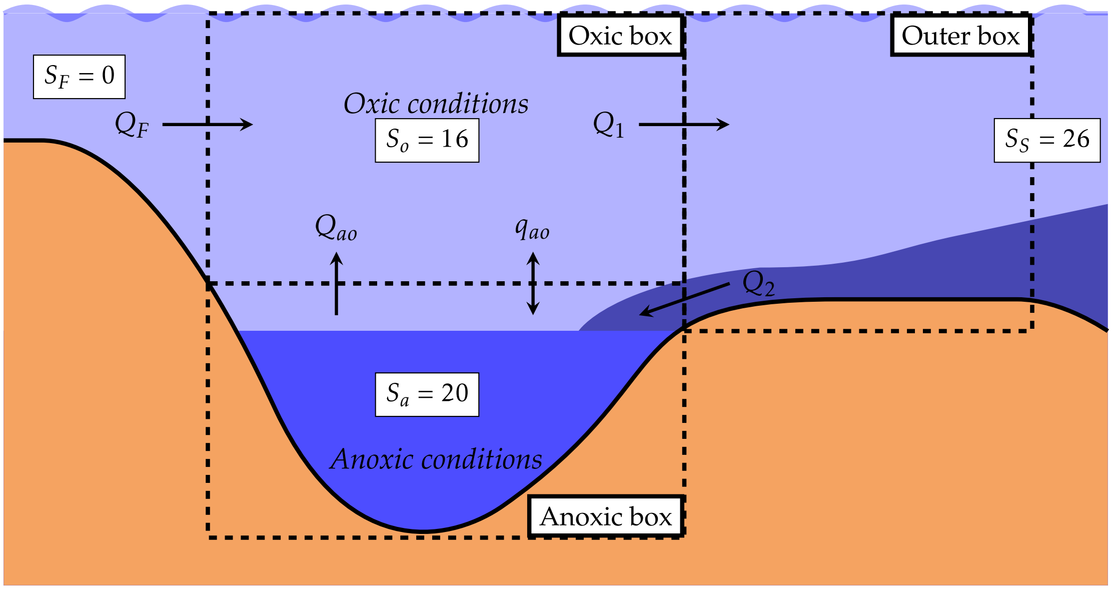


Figure 8.1: *The conceptual model of the three-box model.*

Figure 8.1 presents the conceptual model to obtain the water exchange. The oxic box has an input of freshwater from the terrestrial system in the form of streams. Furthermore, due to higher salinity in the bottom, water enters from the anoxic box into the oxic box (Q_{ao}) and an exchange rate also appears (q_{ao}). The water from the oxic box is leaving into the outer part and further on to Kattegat (Q_1).

For the anoxic box, water is coming in from the outer part in the form of saline water (Q_2) that is heavier than freshwater and will be "stored" at the bottom. The outer box will react as a simple mass balance system. The dense saline water comes in from the bottom, while the lighter fresh water leaves at the top in the stratified water.

This three-box water exchange model was developed, giving much higher exchange rates between the anoxic part and the outer part of the fjord. However, later on it can be calibrated with the residence times from the upper and lower layers in order to be used in further investigations.

Three-box water quality model

A more accurate representation of Mariager Fjord can be achieved using the previous three box water exchange model to describe the biochemical system. The same state variables and processes as in the previous model, described in section 5.1, can be included in the oxic box, while in the lower anoxic box the only state variable recommended to be taken into account is the DIN concentration, illustrated in figure 8.2 on the facing page. Then a new process taking into account the higher denitrification rates in the anoxic water can be included.

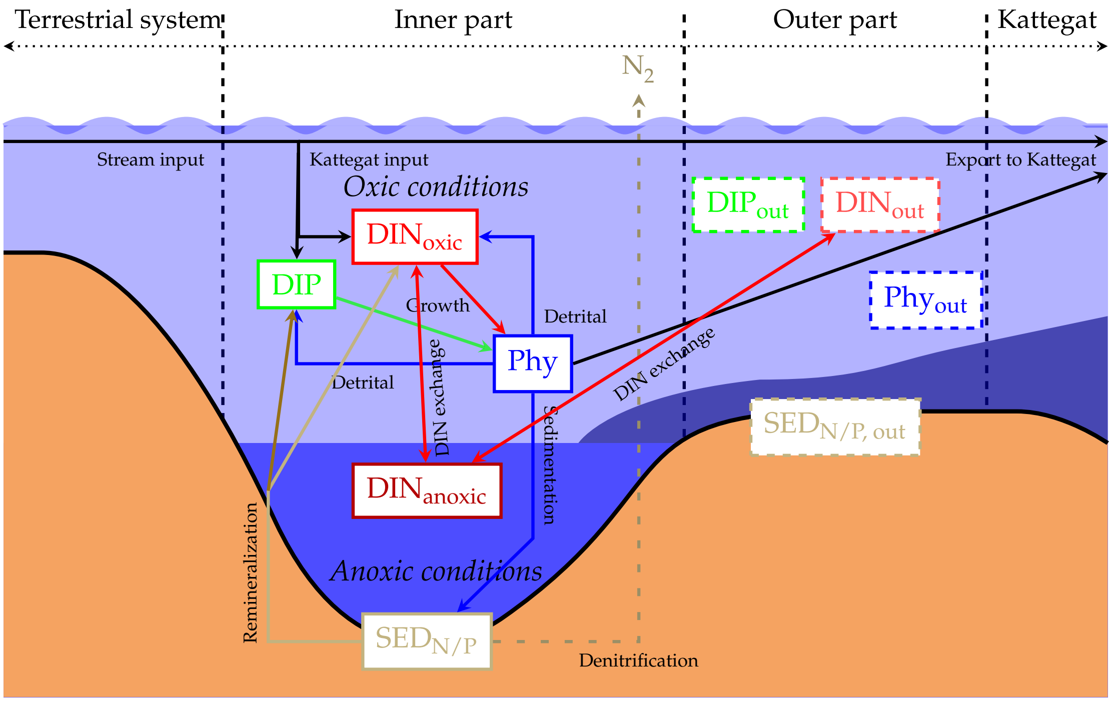


Figure 8.2: *The state variables and processes of the water quality model for the three-box model.*

For the box of the outer part, marked by the dashed state variables, this part is similar to the previous one-box model. Here, the state variables are the mean phytoplankton, DIN and DIP. In addition, for further investigations, some of the processes applied before, such as the denitrification in the sediments, can be applied in this outer part by including new equations.

The inputs of DIN for the anoxic box will be the exchange with both the oxic part and the outer fjord box as well as a part of the sedimentation process corresponding to the surface of the chemocline.

The three box water quality model should be calibrated for the same state variables in the upper box as in the previous model. Furthermore, the measurements for the anoxic bottom of DIN concentration can be compared with the concentration in the lower box and used in the calibration.

In addition, by developing this three-box model, a direct assessment of the solution presented in chapter 7 can be done. The flow from the chosen stream, Karls Møllebæk, can be directed to the anoxic bottom in order to assess the changes in the system. As nutrients are included in the lower anoxic box, the DIN concentration will increase as well as the denitrification rate so more nitrogen will be removed. Then, the DIN concentration in the outer fjord will decrease, but not significantly. As stated in the solution, the system is not going to change significantly.

8.1.2 Hydrodynamic model

It may be possible to achieve a 'symbiotic' relation between the two models. For instance, obtaining the water exchange from the hydrodynamic model and applying it to the three-box model. Furthermore, the models can be calibrated against each other with regards to some of the states variables presented in figure 8.2.

Ecolab module can be used to model oxygen depletion in the anoxic part alongside with the high primary production of algae in certain periods of the year. This module can simulate the biological and chemical process for the above mentioned processes. After this module is implemented, it would be possible to model different possible scenarios and observe the model behavior. By applying a nitrogen reduction in the rivers which transports the nutrients into the fjord, it can be observed how primary production is affected.

Once the hydrodynamic model is built, the pipeline solution, presented in section 7, can be implemented by including an additional input of freshwater on the bottom layer in the warmer months. To make it more detailed this solution can also be apply with Ecolab module and see the changes of nutrients over the year. It can be applied to the reduction of maximum of 5% of nutrients in the stream Karls Møllebæk and adding it to the bottom layer.

8.2 Alternative solutions

In this section it will be investigated whether establishment of wetlands along the streams considered in the project may represent a feasible solution for the reduction of nutrient loads.

Natural processes have always cleaned water as it flowed through streams, rivers, lakes and wetlands.

A wetland is an area that is saturated with water, permanently or seasonally, that presents characteristic vegetation of aquatic plants.

Constructed wetlands are simple and low cost engineered water treatment systems that are designed and constructed to utilize in a more controlled manner, the natural processes involving wetland vegetation, soils and their associated microbial assemblages to assist in treating water. Wetlands reduce nutrients by encouraging sedimentation, sorbing nutrients to sediments, taking up nutrients in plant biomass and enhancing denitrification. [Hammer and Bastian, 1989]

As stated in Hammer and Bastian [1989], the hydrology in wetlands is generally characterized by either shallow waters or saturated substrates and it slows down the flows, as the vascular plants in the wetland will limit channelized flow and slowing water velocities, therefore having high retention time of the water in the system and enhancing sedimentation.

8.2.1 Method

As it has been presented in this project, most of the nutrients input into Mariager Fjord origin from agricultural activities, that come along with the streams flow into the fjord.

An attempt has been made in order to investigate the feasibility of establishing wetlands to reduce the nutrient loads to Mariager Fjord. It is desired to reach the average of the range of the criteria stated in section 5.6.2. Thus, the reduction must be 55 % and 25 % for nitrogen and phosphorus respectively.

In order to investigate a potential solution throughout the establishment of wetlands, it is crucial to know the loading rate of nutrients in each stream. These rates are found by multiplying the yearly flow with the yearly average concentration of nutrients for each of the streams. Once the rates have been found, they are compared to the nutrient removal efficiency (RE) relation found by [Richardson and Nichols, 1985], where it is studied, that RE is usually high at low nutrient loading rates. In figure B.5 in appendix B.4, the relation between RE and the loading rates, developed by [Richardson and Nichols, 1985] is presented for nitrogen and phosphorus, respectively.

By implementing the reduction criteria in the relation presented in figure B.5, it is found that the loading rate must be $38\,g\,m^{-2}\,yr^{-1}$ and $56\,g\,m^{-2}\,yr^{-1}$ for nitrogen and phosphorus respectively.

The required area for wetland establishment is found by dividing the total year load from each stream with the loading rate found through the relation of RE and loading rate. In table B.5 in appendix B.4, the year load of nitrogen and the required wetland area are presented for all the streams. As well, the same information for phosphorus is presented in table B.6 in appendix B.4.

8.2.2 Discussion

It is found that, in order to meet the reduction criteria, only by implementing wetlands, requires a total area of around $0.172\,km^2$ for phosphorus, and much more area is required for nitrogen removal, around $20\,km^2$.

The magnitude of the required area is considered to be impractical as it is too broad. Furthermore, the investigation of the land use in the catchment area showed that most of the land along the streams are occupied for agricultural purposes. Thus, in order to implement such a broad area of wetlands, the only possibility is that the government expropriates parts of the agricultural fields in this purpose. Although the construction of wetlands is considered to be a cost-efficient solution, it would not be the fact in this case.

Removal of phosphorus on the other hand requires an area which is practical to find along the streams. Hence, wetlands as a solution for phosphorus removal in this area is considered to be practical.

Projection of wetlands requires more measurements and advance studies regarding the topography, geology and hydrology of the catchment area. Moreover, in accordance to these studies, the suitable types of wetlands must be chosen. Hence, this section can stand as a platform for more complex investigations in the future.

9 Conclusion

According to the Water Framework Directive [2000], all water bodies of the European Union must reach a good ecological status at the end of 2015. From Markager et al. [2008], it has been stated that a reduction to $200\,\text{ton}\,\text{N}\,\text{yr}^{-1}$ to $400\,\text{ton}\,\text{N}\,\text{yr}^{-1}$ and $6\,\text{ton}\,\text{P}\,\text{yr}^{-1}$ to $8\,\text{ton}\,\text{P}\,\text{yr}^{-1}$ is required to accede the goals given by the Water Framework Directive [2000]. In this report, models have been applied, which can replicate the system in Mariager Fjord. With these models, nutrient reduction can be assessed.

A simplified ecological model has been applied for the inner part of Mariager Fjord, which can represent the ecosystem. It was found from the calibrated model that the yearly load of nitrogen and phosphorus into the system is $694\,\text{ton}\,\text{N}\,\text{yr}^{-1}$ and $9.62\,\text{ton}\,\text{P}\,\text{yr}^{-1}$, respectively. Thus, the model can be used to predict the possible improvement of the system when reducing the input of nitrogen and phosphorus by 40-70% and 15-35%, respectively. There were no significant changes in the system when phosphorus was reduced with 15 and 35%. With nitrogen reduction, radical changes were observed. With a reduction of 40% in nitrogen, the algae bloom keeps decreasing during the summer period, while 70% in nitrogen reduction had a great impact on the algae bloom in spring that tended to increase in contrast to the summer bloom.

In order to get a more accurate understanding of the hydrodynamics of the Mariager Fjord, a numerical tool was setup in MIKE 3 FM. Even though the model was behaving properly in simulating the flows, exchange rates and surface elevation, the model still had troubles in simulating the salinity. Thus, the model was not able to replicate a stable stratification with a 1-year simulation period. The reason why the simulation period was no longer than one year was the lack of measurement data and the long computational time. Due to this issue, the Ecolab module has not been applied to the hydrodynamic model. Hence, the desired goal of comparing the two models was not achieved. It is believed that with a longer simulation period and more computational power, the model can be improved.

For the purpose of reducing the nitrogen load, the pipeline solution concept was proved to be effective by achieving this reduction through denitrification that takes place in the anoxic deep part of the fjord. Unfortunately the nitrogen reduction is not sufficient to comply the goals set by the Water Framework Directive [2000]. Furthermore, this solution can to some degree change the natural characteristics of the fjord. However, this approach was carried out to maintain the stability of the stratification. Thus, this solution can be a supplementary choice for achieving the goal.

An alternative solution through constructed wetlands was analysed for the same objective as the previous method. It is found that wetlands as a single solution for reduction of nutrients is impractical due to the heavy nitrogen load, which requires a broad area for establishing wetlands. However it may be considered to use the wetland solution partly by using the lands that are available in the catchment area. A part of the nitrogen load can be reduced through this solution. Thus, there is a need for investigating alternative solutions for further reduction of nitrogen load and thereby meet the criteria for a good ecological status in the fjord.

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A Water quality model

This appendix contains additional information regarding chapter 5 that deals with the water quality of Mariager Fjord.

A.1 Stream stations

The stream flow and concentration are gathered from the measurement stations, presented in figure A.1. Table A.1 contains additional information about the stations.

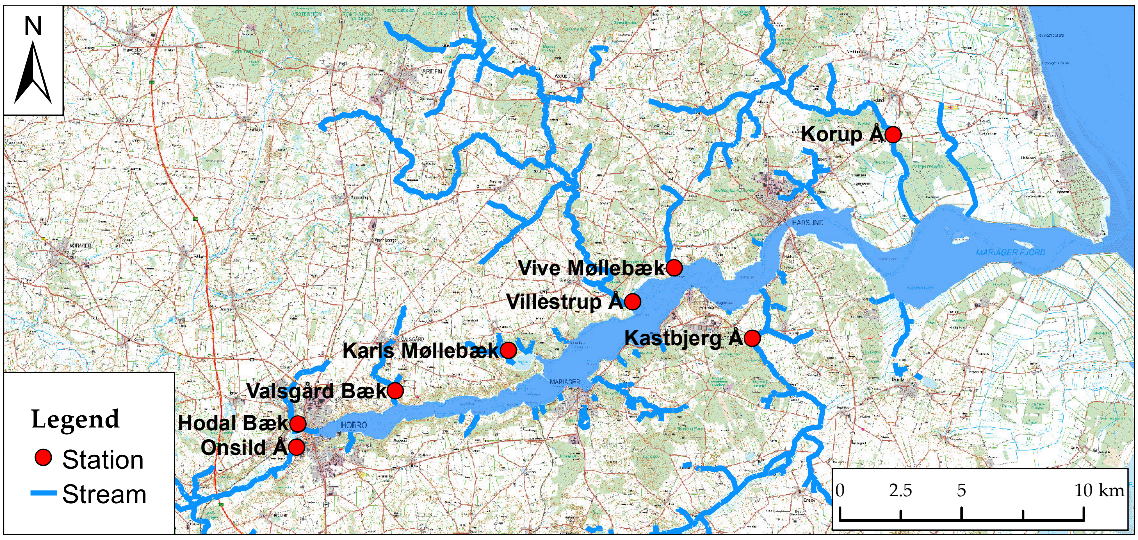


Figure A.1: *The measurement stations of the 8 streams that are taken into account in the model [Schmidt et al., 2005; Danmarks Miljøportal, 2015].*

Table A.1: *Additional information about the stations for the 8 streams included [Schmidt et al., 2005; Danmarks Miljøportal, 2015].*

Stream name	DMU no.	DDH no.	NST no.	Coordinates (UTM) X	Coordinates (UTM) Y
Kastbjerg Å	150043	15.14		567 010	6 281 442
Karls Møllebæk	150045		150098	557 023	6 280 927
Korup Å	150046	15.17	150069	572 804	6 289 787
Onsild Å	150042	15.12	150052	548 343	6 276 970
Hodal Bæk	150044		150053	548 377	6 277 917
Valsgård Bæk	150034	15.11	150005	552 383	6 279 271
Villestrup Å	150035	15.08	150011	562 110	6 282 935
Vive Møllebæk			150097	563 823	6 284 308

A.2 Flow in 2004 and 2005

Figure A.2 shows the yearly cycle of the flow for 2004 and 2005.

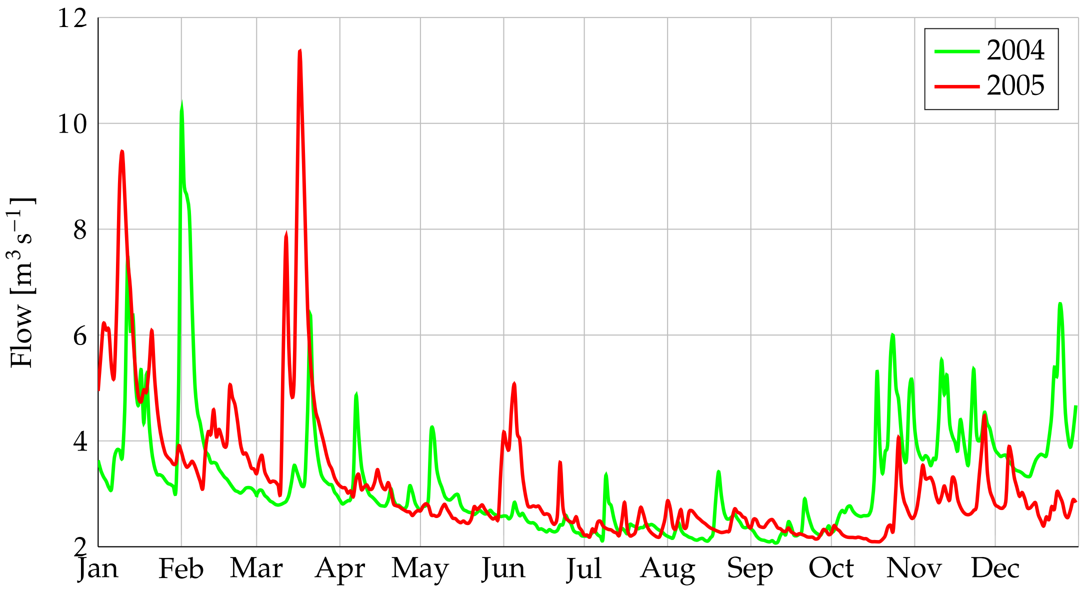


Figure A.2: *The yearly cycle of the flow for 2004 and 2005 [Danmarks Miljøportal, 2015].*

A.3 Nitrogen model

A first attempt to model the water quality in Mariager fjord was to use only the biological processes associated with nitrogen. The state variables used in this model were DIN, Phy and SED_N. The governing equations are the same presented in section 5.1 without the two equations that correspond to phosphorous processes. The model was calibrated against the measured concentrations, resulting in the rate constants, shown in table A.2.

Table A.2: *Calibrated rate constants of the nitrogen model.*

Rate constant	Symbol	Value [day^{-1}]
Maximum growth rate	μ_{max}	0.3
Remineralization rate in the water phase	k_1	0.008
Sedimentation rate	k_2	0.03
Remineralization rate of nitrogen in the sediments	k_3	0.01
Denitrification rate	k_4	0.05

In figure A.3 it can be seen how the modelled peak of chlorophyll is more than double than the measured concentration. The modelled algae bloom shows also an early response in late May decreasing rapidly after reaching the maximum. This response of the phytoplankton growth does not correspond with the observed algae blooms in Mariager fjord.

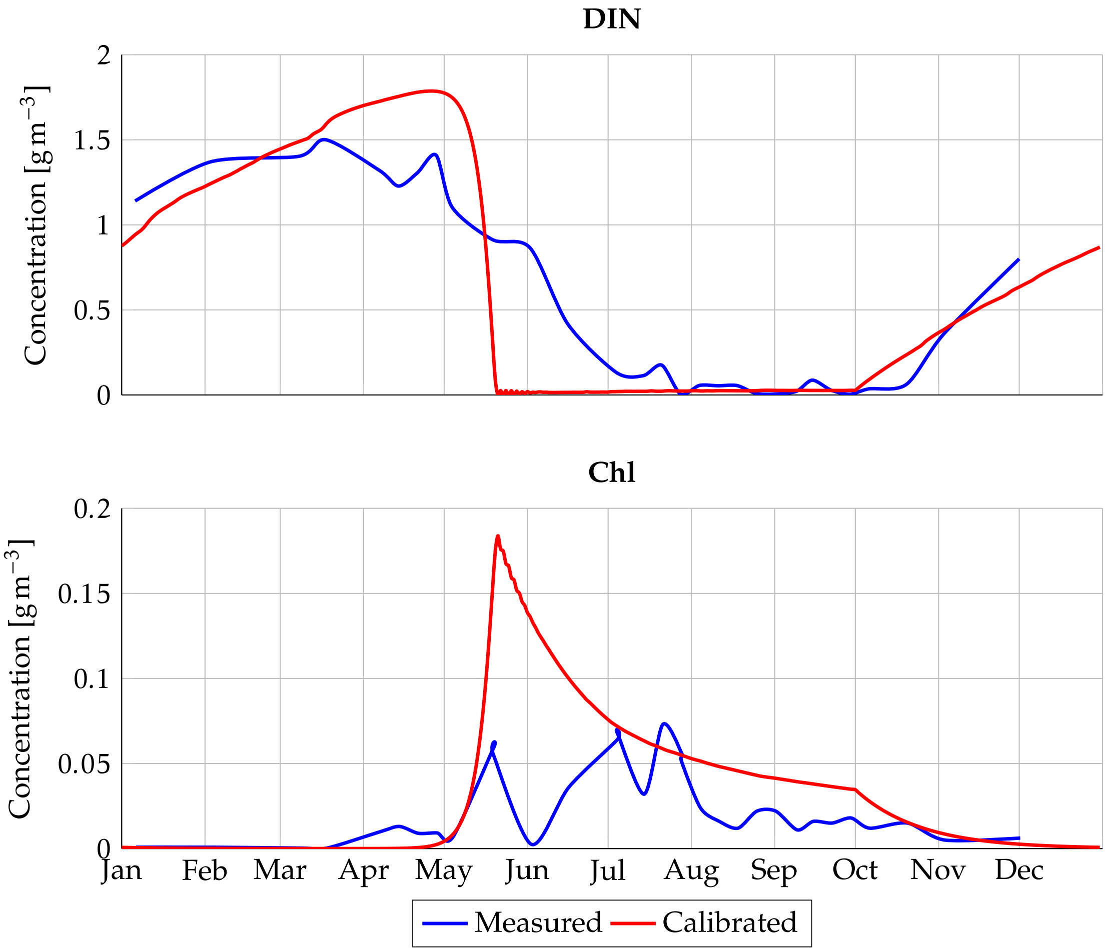


Figure A.3: *The calibrated nitrogen model in contrast to the measured values in 2005.*

After obtaining these results, it was considered that this model was not able to replicate the real behaviour of the system, and it was concluded that phosphorous should be included although in other models of water quality in the baltic sea such as Fennel [1995] is not being taken into account. In the specific case of Mariager phosphorous is an important factor that controls early algae blooms.

A.4 Photosynthetically available radiation (PAR)

The sine function, presented in equation (5.21) on page 31 is plotted in figure A.4.

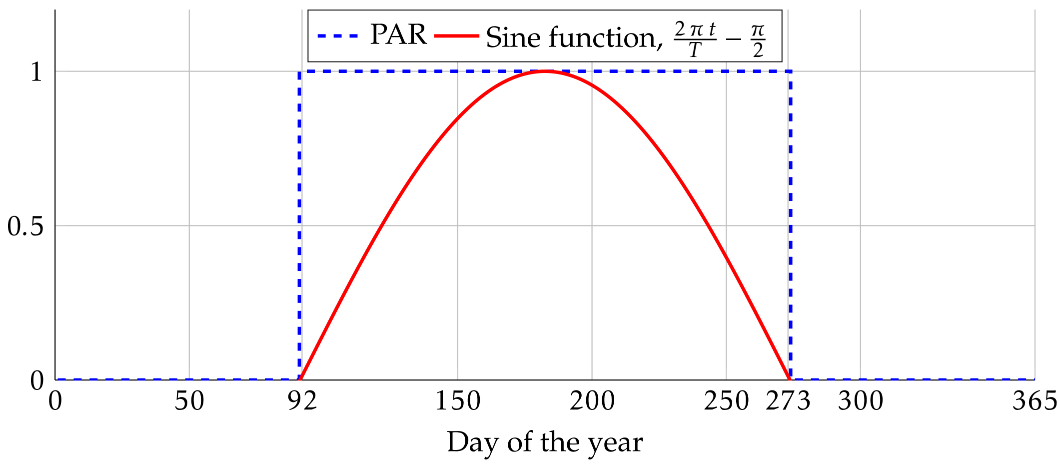


Figure A.4: *The function that is used to describe the PAR-value that is either 0 or 1 [Fennel, 1995].*

A.5 Release of phosphorous in the sediments

In order to obtain an approximate value for the release of phosphorous in the summer months from the sediments to the water phase, the following approach was used:

References values were taken from Viktorsson et al. [2013] in where ranges between ($-0.003\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1} \pm 0.04\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1}$) for sediments in oxic condition to ($0.376\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1} \pm 0.214\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1}$) for anoxic bottoms where found.

With this reference values a total concentration for the sediments pool of phosphorous can be obtained. This total concentration is obtained using the molar weight of phosphorous and with the surface area for the inner fjord as a rough approximation for the sediments surface.

It was chosen to use a value of $0.25\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1}$ as an average value for the model before calibration, justified by the fact that a part of the sediments are in permanent anoxic and hypoxic conditions. In the calibration this value was changed to the higher value of $0.5\,\text{mmol}\,\text{m}^{-2}\,\text{day}^{-1}$.

A.6 Analysis of the limiting function

The concentration of DIN and DIP is controlling the growth of the model by the two limiting functions, presented in section 5.1. The growth process is multiplied with the minimum of both functions. In figure A.5, the variations over the year of the limiting functions after the calibration of the model can be observed.

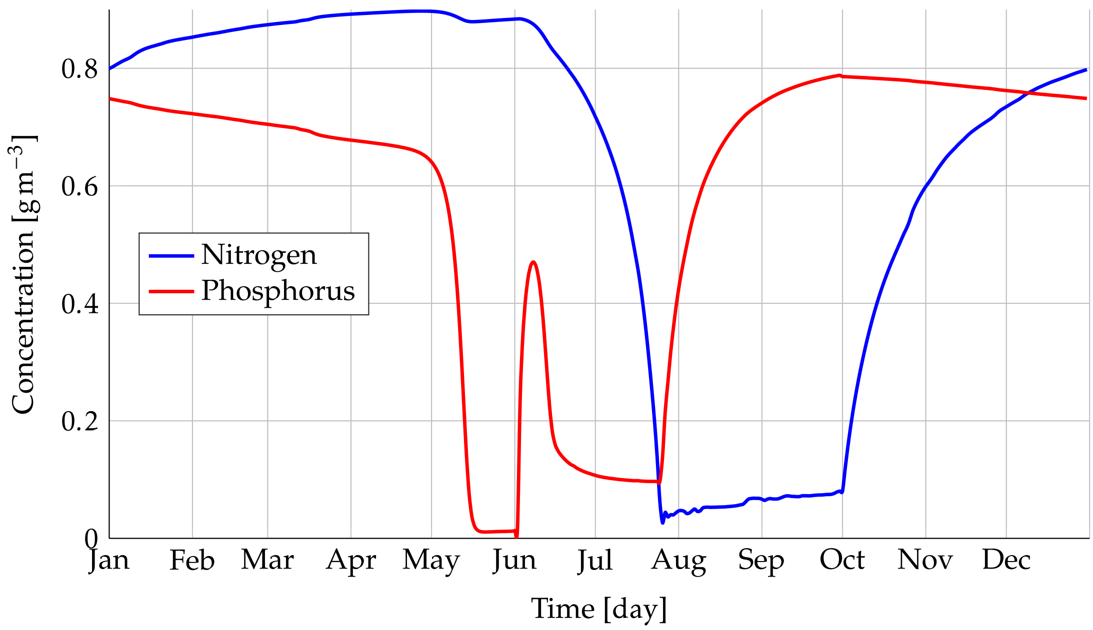


Figure A.5: *The limitations of nitrogen and phosphorus, which is seasonal dependent.*

The limiting factor from the beginning of the growth season controlled by the PAR switch in early April is the DIP concentration. The growth season starts in early April controlled by the PAR switch, so this limitation is effective from this moment until early august when due to the uptake of nitrogen by the phytoplankton nitrogen is not completely replaced by the inputs of freshwater and the DIN starts to be the restriction factor in the growth process equation until the end of the growth season. The peak observed in June for the DIP limiting function correspond with the switch on of the release of phosphorous from the sediments.

A.7 Model input parameters of the water quality model

Table A.3: *The input parameters for the biological model.*

Description	Value	Unit	Citation / Reference
	Constants		
Volume of the fjord, V	$1.72 \cdot 10^8$	m^3	GIS-analysis
Salinity in Mariager Fjord, S_E	16	PSU	Assumed
Salinity in Kattegat, S_S	26	PSU	Assumed
Time-step, Δt	1	day	Assumed
Redfield ratio between nitrogen and phosphorus, $r_{N:P}$	5.59	$g\,N\,g\,P^{-1}$	Assumed from figure 2.11
Half-saturation coefficient for nitrogen, k_n	0.2	$g\,m^{-3}$	Larsen [2015]
Half-saturation coefficient for phosphorus, k_p	0.03	$g\,m^{-3}$	$\frac{k_n}{r_{N:P}}$
	Rate constants		
Maximum growth rate, μ_{max}	0.3	day^{-1}	Humborg et al. [2000]
Remineralization rate in the water phase, k_1	0.05	day^{-1}	Humborg et al. [2000]
Sedimentation rate, k_2	0.02	day^{-1}	Humborg et al. [2000]
Remineralization rate of nitrogen in the sediments, k_3	0.02	day^{-1}	Humborg et al. [2000]
Denitrification rate, k_4	0.1	day^{-1}	Humborg et al. [2000]
Remineralization rate of phosphorus in the sediments, k_5	0.04	day^{-1}	Humborg et al. [2000]
	Concentrations		
Background concentration of DIN in Kattegat	0.12	$g\,m^{-3}$	Assumed from figure 5.5(a)
Background concentration of DIP in Kattegat	0.02	$g\,m^{-3}$	Assumed from figure 5.5(b)
Initial concentration for DIN	1	$g\,m^{-3}$	Starting value at the station
Initial concentration for DIP	0.1	$g\,m^{-3}$	Starting value at the station
Initial concentration for Phy	0.001	$g\,m^{-3}$	Starting value at the station
Initial concentration for SED_N	0	$g\,m^{-3}$	Starting value at the station
Initial concentration for SED_P	0.194	$g\,m^{-3}$	Analysis in appendix A.5

A.8 Additional inflow from the streams in 2004

Due to the fact that more runoff appears on a monthly basis from the streams in 2004 compared to 2005, it is chosen to add some extra flow in order to obtain a more representable model. The extra flow will be added to the two streams, Hodal Bæk and Vive Møllebæk, since no measurements are available in 2004.

For 2004 and 2005, there is calculated a monthly average. Then, a percentage deviation is calculated between the flow in 2005, Q_{2005}, in contrast to the flow in 2004, Q_{2004}, given by the following equation. Hence, the result is shown in figure A.6.

$$1 - \frac{Q_{2005}}{Q_{2004}} \tag{A.1}$$

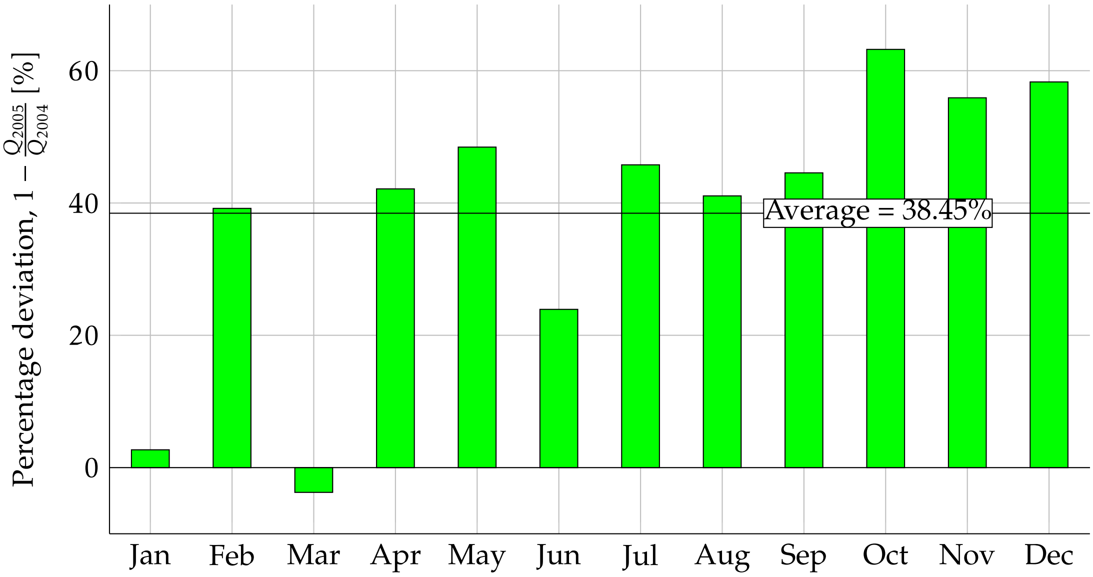


Figure A.6: *The deviation of the monthly average flow in 2005 compared to 2004. The overall average is* 38.45 %.

As shown in figure A.6, it is estimated that an average of 38 % more flow appears in 2004 compared to the 2005. This flow is added to the two streams, Hodal Bæk and Vive Møllebæk, in order compensate for the missing measurements.

A.9 MATLAB code for the water quality model

In this section, the MATLAB document that forms the basis of the water quality model will be described chronologically in further details. There will not be explained on how to plot the output of the model, since these results are shown in the main report. Furthermore, there will not be explained small details that is irrelevant for the model results. If smaller details are desired, it is possible to run the full document in the electronic appendix C.5.

The explanation includes the code in small paragraphs, where the content of each paragraph will be described as good as possible. Furthermore will there be referred to line numbers, which should improve the understanding.

First, some initial constants that really does not a longer explanation. Most of these constants can be found in table A.3 on the facing page.

```
1 dt = 1;                % Time step [d]
2 A = 1.759e+7;           % Surface area of the inner fjord
3 V = 171581722.5;        % Volume of Mariager Inner fjord [m^3]
4
5 SE = 16;                % Salinity in estuary (Mariager Fjord)
6 SS = 26;                % Salinity in sea (Kattegat)
7 SR = mean([SE SS]);     % Salinity at the boundary
```

Next is to define the yearly cycle of the model. This is done by the vector `days` that can be described as the number of days in the year. It goes from 1 day to 365 days with a timestep `dt` of 1 day. The maximum number of days in the year, `T`, is the end value of that vector.

Furthermore, the maximum number of years, which the model is running for is also defined by the constant `year_max`. This becomes useful in the definition of `dayyear`. Here the command `repmat` is a synonym for *repeat matrix* by m rows and n columns. In this particular case, the vector `days` is repeated by `year_max` times, which is 10, in the rows and 1 time in the column. Hence, a time vector, repeating 365 days for 10 years, is made and contains `Tmax` numbers.

```
days = 1:dt:365;     % Days in the year [d]
T = days(end);  % Maximum days of the year
year_max = 10;   % Maximum years [yr]

dayyear = repmat(days',year_max,1);      % Repeating vector (year_max * days)
Tmax = length(dayyear);                          % Maximum timestep
```

Now the flow and stream concentrations are loaded into the document. These values are stored in what could be called a matrix database. The daily flow for 2005 is then again repeated for `year_max` times, since there is value for each day of the year. The flow is also converted to the correct units, which is $\mathrm{m^3\,day^{-1}}$.

Finally, when the flow and salinities are known, the exchange flow can be calculated, using equation (5.2), where `Q` is the residual flow, Q_R.

```
load('input.mat')    % Loading in concentrations from streams
load('Q2005.mat')    % Loading in flows from streams
Q = repmat(Qin,year_max,1).*3600*24;
q = SE*Q./(SS-SE);           % Water exchange
```

The file `'input.mat'` contains the flow and concentrations as a monthly average for each stream. That is matrices of 8×12 values each, which can be translated as 8 streams over 12 months each. Recall from section 5.1.1 that the concentration for DIN and DIP is based on a weighted average for each month. It is chosen to perform an easy loop operation that calculates the weighted average for DIN and DIP, one month at a time. This loop operation can be related to equation (5.3) and (5.4) on page 26.

The output of this loop is vectors for the DIN and DIP concentration that contains 12 numbers, where each number represents the monthly average of the streams.

```
for i = 1:length(Qstream(1,:))
    DINstream(i) = sum(Qstream(:,i).*DINinput(:,i)/1000)/sum(Qstream(:,i));
    DIPstream(i) = sum(Qstream(:,i).*DIPinput(:,i)/1000)/sum(Qstream(:,i));
end
```

The output of the previous loop operation is used to set a daily concentration over the year, based on the monthly average. For instance, each day in January will have the value corresponding to the monthly average. This is done by a self-made function `monthdep` that basically takes 12 numbers (1 value for each) and the current day of the year as an input in order to define an input concentration over the year. The self-made function will not be evaluated any further.

The other self-made function `timemonth` defines the date with the current day of the year and the year itself as an input. This is simply done in order to compare with measured values that is based on date and not on days in the year.

```
for i = 1:Tmax
    DINin(i) = monthdep(DINstream,dayyear(i));
    DIPin(i) = monthdep(DIPstream,dayyear(i));

    % Setting the time
    dateval(i) = timemonth(dayyear(i),2005);
end
```

The next thing is to define the state variables and the initial concentration for these state variables. The state variables are vectors that holds a value for each day, which the model runs for. Therefore, these vectors are filled with zeros of the maximum days, which is simply done in order to save computation time.

The first value each state variable is the initial concentration, which is indicated by `(1)`. The initial concentration of the sediment pool that contains phosphorus, `SED_P` can be related to appendix A.5.

```
% Defining state variables
Phy = zeros(Tmax+1,1);                 % Phytoplankton
DIN = zeros(Tmax+1,1);                 % Dissolved inorganic nitrogen in the water column
DIP = zeros(Tmax+1,1);                 % Dissolved inorganic phosphorus in the water column
SED_N = zeros(Tmax+1,1);             % Sediment DIN
SED_P = zeros(Tmax+1,1);             % Sediment DIP

% Initial concentration of state variables
DIN(1) = 1;
DIP(1) = 0.1;
Phy(1) = 0.001;
SED_N(1) = 0;
SED_P(1) = 0.5*A*summer_days*31/(V*1000);
```

More constants are defined, shown below. The first constants are the relevant ratios, described in section 2.6. The 8 other constants are the rate constants along with the half-saturation constant for nitrogen and phosphorus, which are shown in table A.3 on page 78. Lastly, the DIN and DIP concentration in Kattegat are defined, which is a constant value.

```
42 % Constants
43 r = 0.129383205408346*SE + 3.523048394229751;     % Redfield ratio between nitrogen and phosphorus [g N/g P]
44 r_CN = 5.6;                     % Redfield ratio between carbon and nitrogen
45 r_ChlC = 50;                    % Redfield ratio between chlorophyll and carbon
46
47 mu_max = 0.45;               %     Maximum Growth rate
48 kn = 0.2;                   %     Half-saturation coefficient for nitrogen
49 kp = kn/r;                 %     Half-saturation coefficient for phosphorus
50 K1 = 0.003;                  %     Remineralization from water rate
51 K2 = 0.038;                 %     Sedimentation rate
52 K3 = 0.01;                 %     Remineralization rate from sediment - nitrogen
53 K4 = 0.15;                 %     Denitrification rate for nitrogen
54 K5 = 0.045;                 %     Remineralization rate from sediment - phosphorus
55
56 DINkat = 0.001453870856156*SS + 0.080331947413609;              % DIN concentration in Kattegat
57 DIPkat = 0.000157147516363*SS + 0.015529864105101;           % DIP concentration in Kattegat
```

Now the model is ready to be initiated. The model is initiated with a time-dependent loop operation, starting from day 1 to the maximum number of days, `Tmax`.

First, in line 59 to 64, the PAR value is defined with the sinus step function, presented in section 5.1.3. The `if`-operator controls the value y and sets the value of PAR to either 0 or 1, if y becomes below or above 0, respectively.

Next, in line 66 and 67, the limiting function of nitrogen and phosphorus is calculated as a function of time. The reason why it is time-dependent is because it is easier to plot, since the values are stored in a vector. And the resulting graph can be seen in figure A.5. Hence, the growth rate is calculated in line 68.

The processes that is calculated from line 71 to 86 can be related to table 5.1 on page 30. It is pretty much the same that is going on. The processes are using the initial values of the state variables when these are calculated. This is indicated by the parentheses `(t)`. Most of the processes are not time dependent, since it is quite irrelevant to store the values that is calculated for each day.

Another thing worth mentioning is the switch of the sediment pool of phosphorus. In this model, it is assumed that there is no remineralization rate of phosphorus from the sediments into the water column, indicated in line 75. However, when the day of the year reaches the range of 152 day to 273 day (summer time) in line 76, the remineralization of phosphorus is turned on (line 77). In addition, the initial concentration of the state variable SED_P is reset to the initial value in line 41, every first day of each year. This is further explained in section 5.1.3.

The processes that takes the input of DIN and DIP into account (line 85 and 86) is also made time dependent. This is done in order to summarize the input concentration of nitrogen and phosphorus in units of ton yr^{-1} every year.

Finally in this loop operation comes the state variables, which is the desired output of the model. Here, from line 89 to 93, the differential equations of the state variables, presented in equation (5.5)- (5.9) on page 28, are resolved. This means that the state variables are using the processes to calculate the next time-step of the variables, indicated by `(t+1)`. Furthermore, there cannot be a negative amount for the state variables, which is why they either are positive or equal to 0, given by the `if`-operator.

```
58 for t = 1:Tmax
59     theta = 2*pi*dayyear(t)/T - pi/2;
60     y = sin(theta);
61     PAR = 0;
62     if y > 0
63         PAR = 1;
64     end
65 
66     N_lim(t) = DIN(t)/(DIN(t)+kn);
67     P_lim(t) = DIP(t)/(DIP(t)+kp);
68     mu = mu_max*PAR*min([N_lim(t) P_lim(t)]);       % Growth rate;
69 
70     % Processes
71     Growth = mu*Phy(t);                                % Growth
72     RW = K1*Phy(t);                                 % Remineralization
       in water phase
73     Sedimentation = K2*Phy(t);                      % Sedimentation from
       Phytoplankton
74     RS_N = K3*SED_N(t);                        % Remineralization in
       sediment phase from nitrogen
75     RS_P = 0;
76     if dayyear(t) > 152 && dayyear(t) < 273
77         RS_P = K5*SED_P(t);          % Remineralization in sediment
           phase from phosphorus
78     elseif dayyear(t) == 1
79         SED_P(t) = SED_P(1);
80     end
81     Denitrification = K4*SED_N(t);        % Denitrification to N2
82     DIN_export = (Q(t) + q(t))*DIN(t);
83     DIP_export = (Q(t) + q(t))*DIP(t);
84     Phy_export = (Q(t) + q(t))*Phy(t);
85     DIN_input(t) = Q(t)*DINin(t) + q(t)*DINkat;
86     DIP_input(t) = Q(t)*DIPin(t) + q(t)*DIPkat;
87 
88     % State variables
89     Phy(t+1) = Phy(t) + Growth - Sedimentation - RW -(Phy_export*dt)/V
       ;
90     DIN(t+1) = DIN(t) - Growth + RW + RS_N +(dt/V*(DIN_input(t)-
       DIN_export));
91     DIP(t+1) = DIP(t) - Growth/r +RW/r + RS_P + (dt/V*(DIP_input(t)-
       DIP_export));
```

```
92      SED_N(t+1) = SED_N(t) + Sedimentation - RS_N - Denitrification;
93      SED_P(t+1) = SED_P(t) + Sedimentation/r - RS_P; %Denitrification_P
           ;
94      if DIN(t+1) < 0
95          DIN(t+1) = 0;
96      elseif DIP(t+1) < 0
97          DIP(t+1) = 0;
98      elseif Phy(t+1) < 0
99          Phy(t+1) = 0;
100     elseif SED_N(t+1) < 0
101         SED_N(t+1) = 0;
102     elseif SED_P(t+1) < 0
103         SED_P(t+1) = 0;
104     end
105 end
```

In order to convert the phytoplankton state variable into chlorophyll, the state variable must be converted to carbon and further onto chlorophyll by use of the ratios, presented in section 2.6.

```
106 C = Phy.*r_CN;
107 Chl = C./r_ChlC;
```

In the calibration phase, the modelled results are compared with the measured values. Thus, the measured values that represents the measured state variables, is loaded in from `'meas_data.mat'`.

Since there are measurements from almost all depths, it is decided from section 5.2 that the modelled results will be compared with the measured values in 1 m depth. Hence, all measured values from the depth of 1 m must be found. This is done by the syntax `find`, which basically finds the indices of all values that have a depth of 1 m. The indices means that it finds the row number and does *not* return the values itself. For instance, if the 4th value have a depth of 1 m, the returned value will be 4 and not 1 m. Even though that sounds unusable, it is the exact opposite. Because what would the returned result of 1 m be used for? This is just an entry point in order to locate the concentrations that is in the depth of 1 m. Because now the concentrations can be returned when putting the `depth_index` in parentheses, as seen in line 112, 114 and 116-118.

Since the concentrations are loaded in units of $\mu g\,L^{-1}$, these are divided by 1000 to obtain the correct units.

```
load('meas_data.mat')
d = 1;
depth_index = find(meas_depth == d);
depth_index_Chl = find(meas_depth_Chl == d);
meas_depth = meas_depth(depth_index);
meas_depth_Chl = meas_depth_Chl(depth_index_Chl);
meas_date = meas_date(depth_index);
meas_date_Chl = meas_date_Chl(depth_index_Chl);
meas_DIN = meas_DIN(depth_index)./1000;
meas_DIP = meas_DIP(depth_index)./1000;
meas_Phy = meas_Phy(depth_index)./1000;
meas_Chl = meas_Chl(depth_index_Chl)./1000;
```

B Other appendices

This appendix includes additional material that is described through the report.

B.1 Pipeline solution

In the following section the calculations behind this methods are going to be presented which are also included by an excel file in the electronic appendix C.7 on page 98.

B.1.1 Oxygen dilution

It is assumed that the stream water is saturated with oxygen and has a temperature of 15°C during the summer, therefore has a concentration of $10\,\mathrm{mg\,O_2\,L^{-1}}$. The total volume of the input water in the corresponding period can be calculated by the average flow. The anoxic part is assumed to constitute one fifth of the total volume of the inner fjord and considered to have zero oxygen. The diluted concentration is then found by taking the fraction of the input volume in the anoxic volume and multiplying with the saturated oxygen concentration. In table B.1, the important values used for calculating the diluted oxygen concentration in the anoxic part, are presented.

Table B.1: *Parameters and total oxygen concentration entering in the anoxic part of the fjord*

Description	Symbol	Value	Units
Volume anoxic part	V_a	$3.44 \cdot 10^7$	$\mathrm{m^3}$
Design flow	Q_d	0.3	$\mathrm{m^3\,s^{-1}}$
Volume entering	V_e	$1.56 \cdot 10^6$	$\mathrm{m^3}$
Concentration oxygen anoxic part	C_a	0	$\mathrm{mg\,O_2\,L^{-1}}$
Concentration oxygen entering	C_e	10	$\mathrm{mg\,O_2\,L^{-1}}$
Total concentration oxygen	C_{tot}	0.45	$\mathrm{mg\,O_2\,L^{-1}}$

When water has the oxygen concentration value below 15 µmol, so around $0.5\,\mathrm{mg\,O_2\,L^{-1}}$ is considered that inhibits the denitrification process [Jensen et al., 2009]. Then it is possible to reach a pipe flow of $0.3\,\mathrm{m^3\,s^{-1}}$ which is having a oxygen concentration value of $0.45\,\mathrm{mg\,O_2\,L^{-1}}$ as shown in table B.1.

B.1.2 Design of diffusors

To calculate the effect of dilution the initial discharge velocity from the diffusor must be known. By knowing the pipe flow which might be entering in the system and stated above, a diameter should be chosen in order to get the outlet velocity. Some considerations must be taken into account while a diameter is select. First of all, the Froude number is calculate by applying equation (B.1), and might be considered a value higher than 1 to avoid intrusion of water but not so high due to a higher energy will be high mixing. The parameters are seen in the table B.2 and the results in the table B.3.

Table B.2: *Parameters for the design of the diffusor*

Description	Symbol	Value	Units
Fresh water density	ρ_f	1000	$kg\,m^{-3}$
Anoxic part density	ρ_a	1014	$kg\,m^{-3}$
Diameter	D	1.3	m
Area	A	1.33	m^2
Water depth	y	10	m

$$F_d = \frac{U_0}{\sqrt{\frac{\Delta\rho}{\rho} g\, D}} \tag{B.1}$$

Where:

F_d	Densimetric Froude number	[−]
U_0	Outlet velocity	$[m\,s^{-1}]$
$\Delta\rho$	Difference in densities between ambient water and receiving water	$[kg\,m^{-3}]$
ρ	Ambient water density	$[kg\,m^{-3}]$
g	Gravity	$[m\,s^{-2}]$
D	Diameter	[m]

On the other hand [Cederwall, 1968], the equations (B.2) and (B.3) are used to calculate the diffusion in the jet. These equations are applied for a horizontal discharge in a homogeneous and stagnant recipient.

It is considered that y is the water depth from the outlet until the surface plume. In that case is 10 m; the depth of the anoxic part. Once one of the two equation is used the centerline dilution Sm is calculated and the results can be seen in the table B.3.

$$S_m = 0.54\,F_d \left[\frac{y}{F_d\,D}\right]^{\frac{7}{16}} \qquad \text{for} \quad \frac{y}{D} < 0.5\,F_d \tag{B.2}$$

$$S_m = 0.54\,F_d \left[0.38\,\frac{y}{F_d\,D} + 0.66\right]^{\frac{5}{3}} \qquad \text{for} \quad \frac{y}{D} > 0.5\,F_d \tag{B.3}$$

Where:

S_m	Centerline dilution	[times]
y	water depth	[m]

Table B.3: *Results for the design of diffusor*

Description	Symbol	Value	Units
Densimetric Froude number	F_d	1.29	–
Outlet velocity	U_0	0.23	$\mathrm{m\,s^{-1}}$
Dilution	S_m	4.17	times

In order to came with that idea the discharge can be divided in small outlets which if it wants to get a diameter around 0.3 m each a total of 20 diffusors might be designed.

B.2 Time series used in the hydrodynamic model

In the following section the data for the time series implemented in the hydrodynamic model are going to be presented.

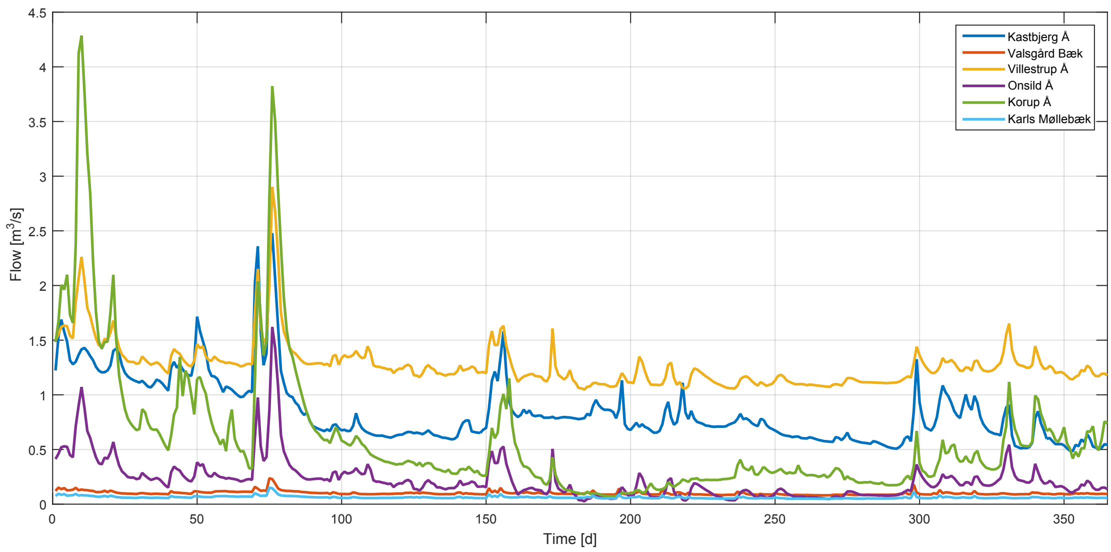


Figure B.1: *The discharges of each stream in 2005*

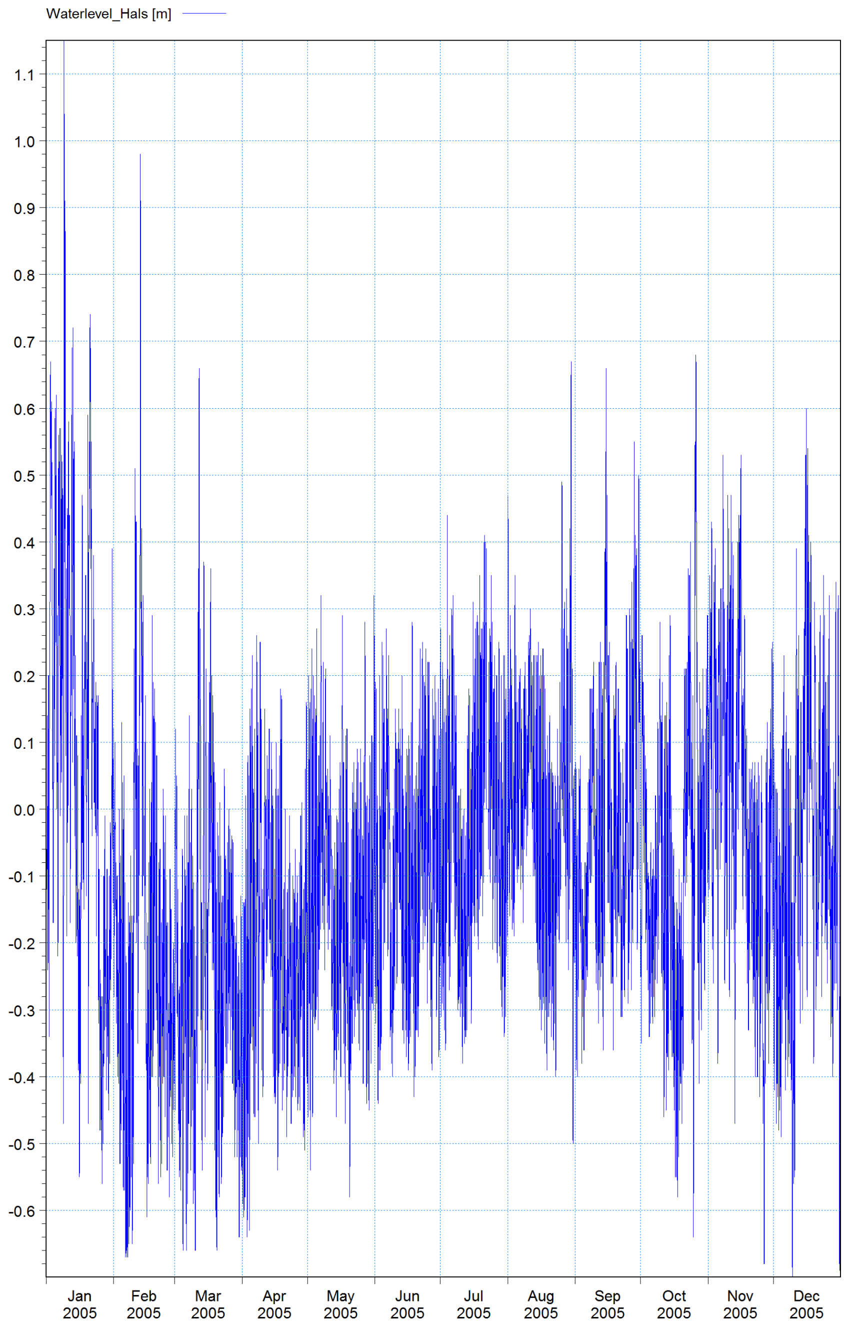


Figure B.2: *Water elevation in Hals*

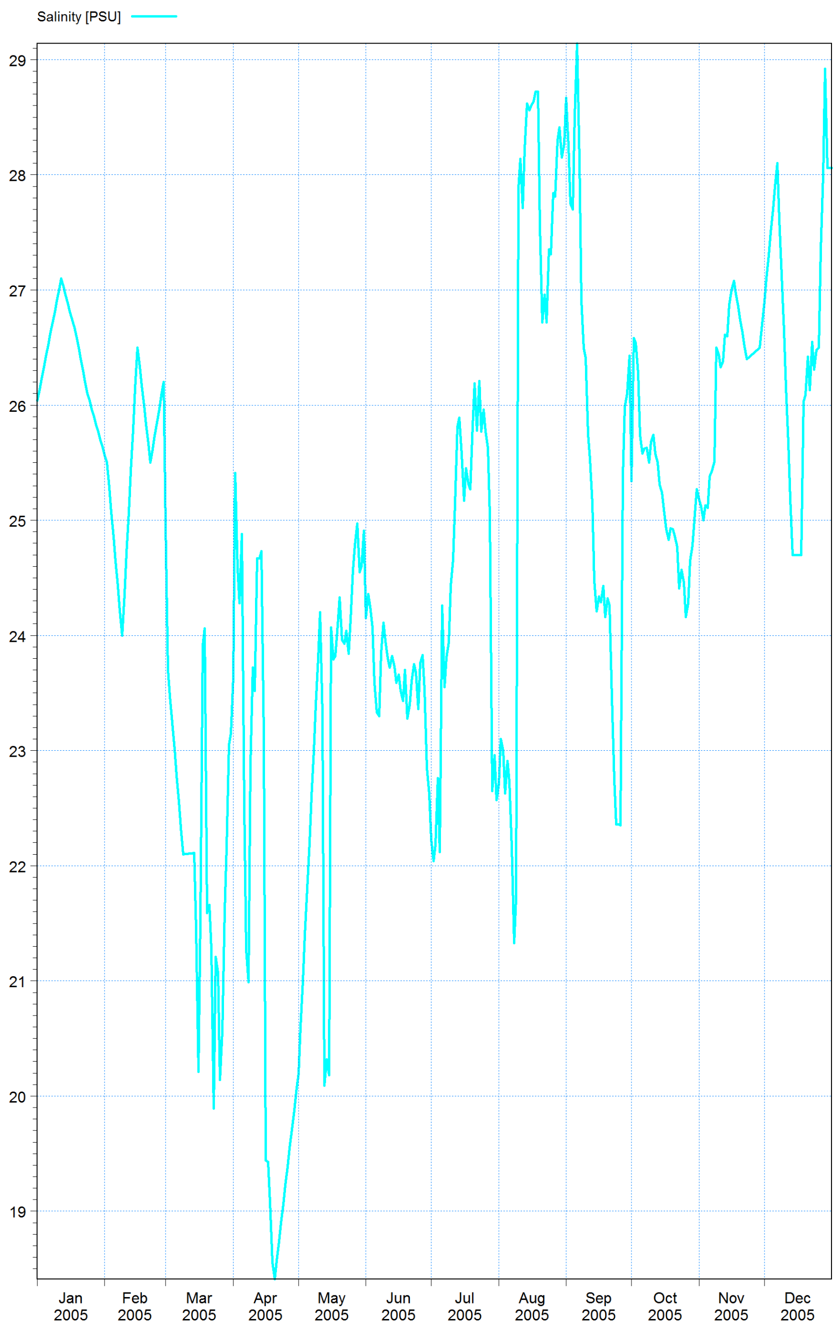


Figure B.3: *Salinity variation Hals*

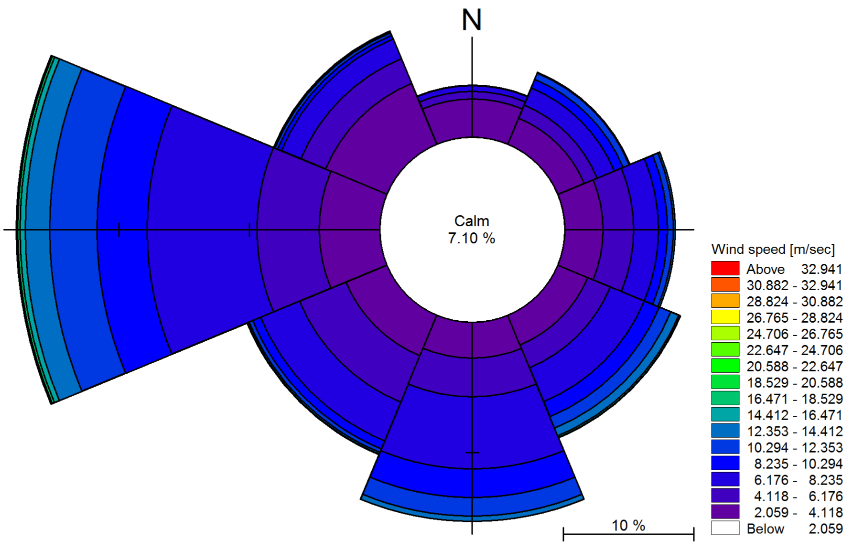


Figure B.4: *Wind rose displaying speed and direction*

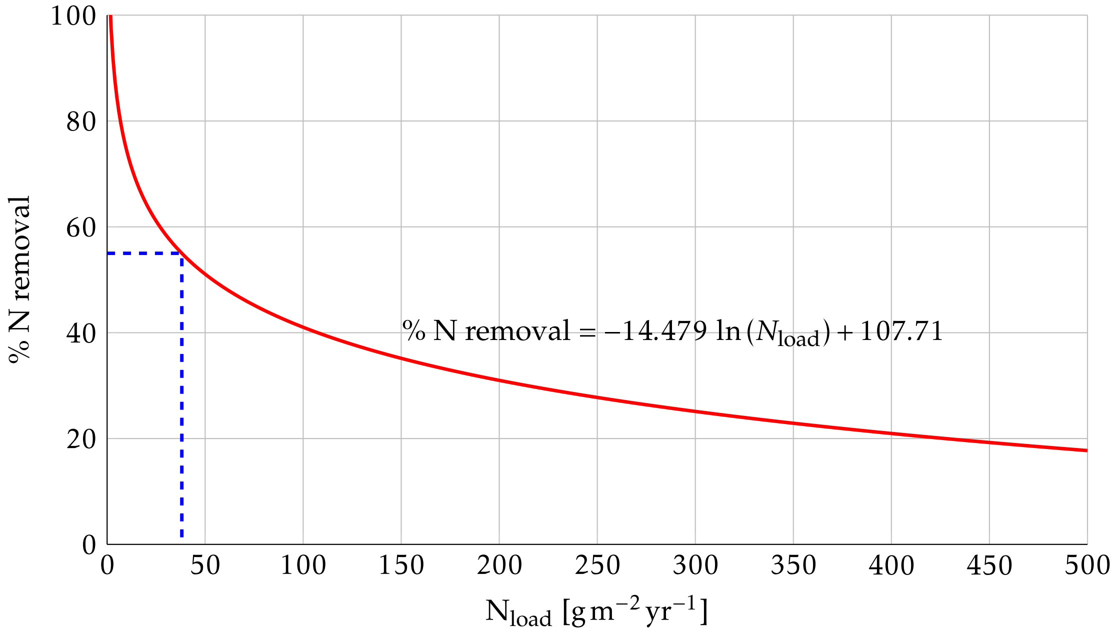
B.3 Model input parameters of the hydrodynamic model

Table B.4 shows the used input parameters used in the hydrodynamic model.

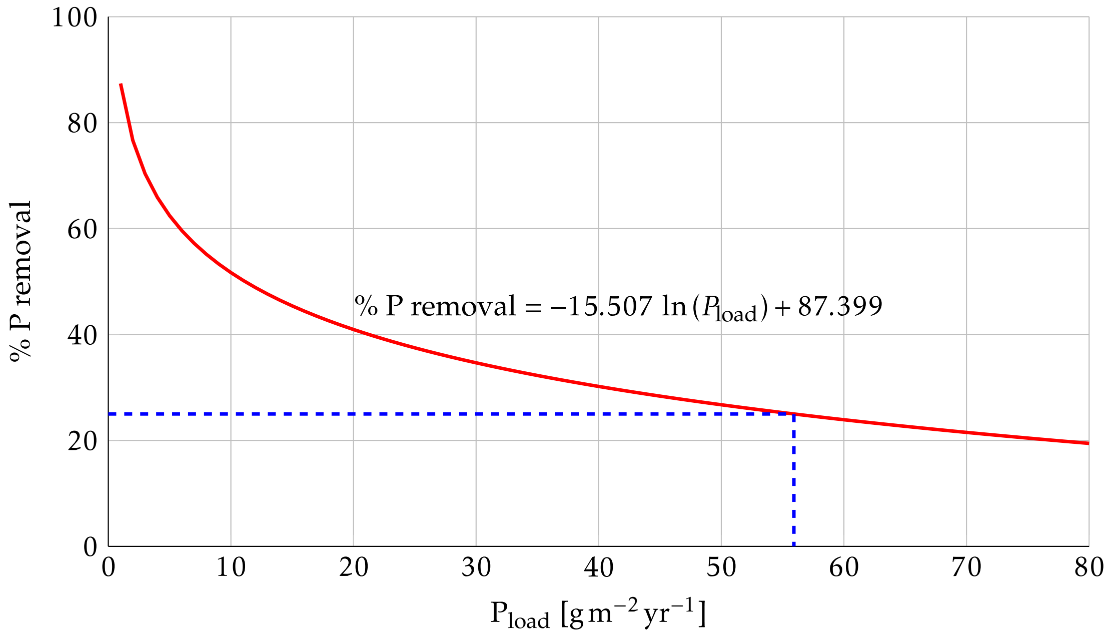
Table B.4: *The input parameters for the hydrodynamic model.*

Description	Type	Value	Unit
	Flow model		
Domain	Vertical mesh	6 layers	–
Simulation period	-	1	yr
Time step interval	-	600	s
	Hydrodynamic module		
Solution technique	Log order fast algorithm	-	–
Density	Function of salinity	-	–
Reference temperature	-	10	°C
Reference salinity	-	16	PSU
Horizontal Eddy viscosity	Smagorinsky formulation	0.4	–
Vertical Eddy viscosity	Log law formulation	0.4 max	$m^2 s^{-1}$
Bed resistance	-	0.05	m
Wind	-	Varying in time	$m s^{-1}$
Sources	Discharges	Varying in time	$m^3 s^{-1}$
Initial conditions	Surface elevation	0	m
Boundary conditions	Surface elevation	Varying in time	m
	Temperature and salinity module		
Sources	Salinity	0	PSU
Initial conditions	Salinity	26	PSU
Boundary conditions	Salinity	Varying in time	PSU
Horizontal dispersion	-	1	–
Vertical dispersion	-	0	–

B.4 Alternative solution



(a) Nitrogen reduction.



(b) Phosphorus reduction.

Figure B.5: *The percentage removal of nitrogen and phosphorus when placing wetlands near the streams, redrawn after [Richardson and Nichols, 1985].*

Table B.5: *Nitrogen load and required area for establishment of wetland for nitrogen removal*

Stream name	**Nitrogen load** [ton yr^{-1}]	**Area required** [km^2]
Kastbjerg Å	200	5.26
Karls Møllebæk	34.8	0.91
Korup Å a	112.2	2.95
Onsild Å b	52.23	1.37
Hodal-Baek	12.53	0.33
Valsgård Bæk	20.22	0.53
Villestrup Å	318.5	8.38
Vive Mølebaek	7.75	0.2
Total required area	–	19.955

Table B.6: *Phosphorus load and required area for establishment of wetland for phosphorus removal*

Stream name	**Phosphorus load** [ton yr^{-1}]	**Area required** [km^2]
Kastbjerg Å	2.448	0.0437
Karls Møllebæk	0.091	0.0016
Korup Å a	1.857	0.0332
Onsild Å b	0.948	0.0169
Hodal-Baek	0.114	0.002
Valsgård Bæk	0.331	0.0059
Villestrup Å	3.737	0.0667
Vive Mølebaek	0.117	0.0021
Total required area	–	0.1723

All the performed calculations regarding this approach can be found in electronic appendix C.7 in the file `wetlands calculation`.

C Electronic appendices

In this appendix, there is an overview of the electronic material used in the project, which is included on the CD.

C.1 Background concentration and Redfield ratio related to salinity

This appendix contains the salinity data and background concentration for Kattegat. The data is used to define a constant Redfield ratio and background concentration in Kattegat, related to the salinity.

The concentrations are converted from the unit mol into g by use of the molar weight for nitrogen and phosphorus.

The files are:

1. `background_rf.m` – MATLAB code that calculates the Redfield ratio and defines a background concentration in Kattegat for DIN and DIP.
2. `data.xlsx` – Data from DEPA and NERI [2002].
3. `data.mat` – Data from the Excel spreadsheet converted from the unit mol into g by use of the molar weight for nitrogen and phosphorus.

C.2 Stream flow measurements 2004 and 2005

In the same stations as where chemistry data was obtained from the eight streams, there is also stream flow available in the unit of $m^3\,s^{-1}$.

The measured flow data from the streams are stored in two Excel spreadsheets, each one representing the year of 2004 and 2005, respectively. The file names are:

1. `Stream flow measurements - 2004.xlsx` – contains data for 2004
2. `Stream flow measurements - 2005.xlsx` – contains data for 2005

C.3 Chemistry data from streams 2004 and 2005

Chemistry data for the streams can be found in this appendix. It keeps concentration data for the eight streams that is measured at the stations, presented in appendix A.1. The concentrations are the following dissolved compounds:

- Ammoniac + ammonium-N
- Nitrate + Nitrite-N
- Orthophosphate-P
- Total nitrogen (TN)
- Total phosphorus (TP)

The concentration data, which is data from 2004 and 2005, is two Excel spreadsheets with the following file names:

1. `Chemistry data from streams - 2004.xlsx` – contains data for 2004
2. `Chemistry data from streams - 2005.xlsx` – contains data for 2005

C.4 Chemistry data 2004 and 2005 in Mariager Fjord

This appendix presents three Excel spreadsheets that contains chemistry data for the year of 2004 and 2005, applicable for the location, shown in figure 2.7(a) on page 9. Two of the spreadsheets, keeps concentration data in the unit $\mu g\,L^{-1}$ for the following dissolved compounds in different depts of the water column over various dates:

- Ammoniac + ammonium-N
- Nitrate + Nitrite-N
- Orthophosphate-P
- Total nitrogen (TN)
- Total phosphorus (TP)
- Chlorophyll

The third Excel spreadsheet contains information about the temperature, salinity and oxygen content over various years.

The two Excel spreadsheets have the following filenames:

1. `Chemistry data - 2004.xlsx` – contains data that is described in the above list for 2004
2. `Chemistry data - 2004.xlsx` – contains data that is described in the above list for 2005
3. `CTD data.xlsx` – the third Excel spreadsheet that contains data for several years.

C.5 Water quality model

The water quality is devoped in MATLAB. Thus, this appendix contains several MATLAB files that is used to develop and describe the model. A more detailed description of what is going in the MATLAB program, is further explained in appendix A.9.

The water quality model consist of the following files:

`boxmodel_input_np.m`	This file is the water quality model with input of nitrogen and phophorus. This is the uncalibrated model of the system.
`boxmodel_input_np_calibration.m`	This is the model when the rate constants is calibrated, shown in table 5.2 on page 37. The modelled state-variables are compared with the measured values from 2005.
`boxmodel_input_np_validation.m`	The validated water quality model, using input for 2004 and comparing with values for 2004.
`boxmodel_results.m`	The water quality model that is used for assessing the nutrient reduction, presented in section 5.6. This takes basis in the calibrated model.
`boxmodel_input_calibration.m`	This is the water quality model that only included nitrogen as the limiting factor, presented in appendix A.3. It is chosen to only include the model with the calibrated rate constants in table A.2.
`monthdep.m`	This MATLAB file is a function, which returns a month dependent value.
`timemonth.m`	A function, which returns a date of the year, corresponding to the actual day of year in the range of 1 to 365 days.
`input.mat`	This file stores the input concentration of DIN and DIP along with the flow from the stream on a monthly basis for 2005.
`input_valid.mat`	The same as above, just for 2004.
`meas_data.mat`	This file stores the measured DIN, DIP and Chl concentrations that is used for comparison with the model. The data is for 2005.
`meas_data_valid.mat`	The same as above, just for 2004.
`Q2004.mat`	Daily flow data for 2004.
`Q2005.mat`	Daily flow data for 2005.

C.6 MIKE model

The folder contains the following files that were used to setup the mike model:

1. `Mariager model.m3fm` – the flow model
2. `Mariager mesh.mesh` – the mesh containing the bathymetry
3. `Hals time series` – time series about the wind,salinity and water elevation.
4. `Time series river sources` – time series about the river flows

C.7 Solution suggestion

This folder contains the calculations in Excel that have been used to develop the pipeline solution suggestion and wetlands as a solution for nutrient removal:

1. `Solution suggestion.xlsx` – contains calculations regarding pipeline solution.
2. `Wetlands calculation.xlsx` – contains calculations regarding wetland solution.