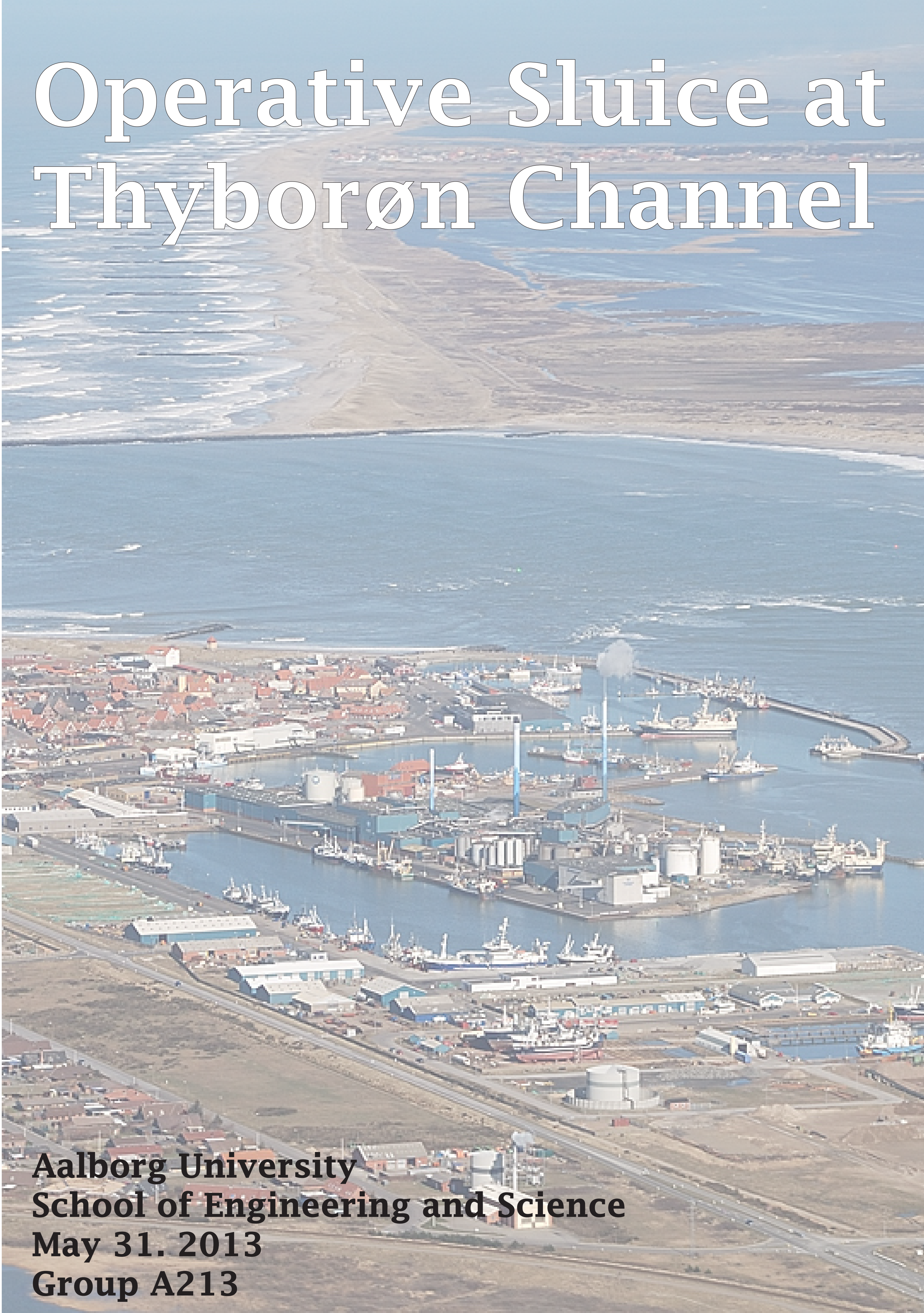
Operative Sluice at Thyborøn Channel



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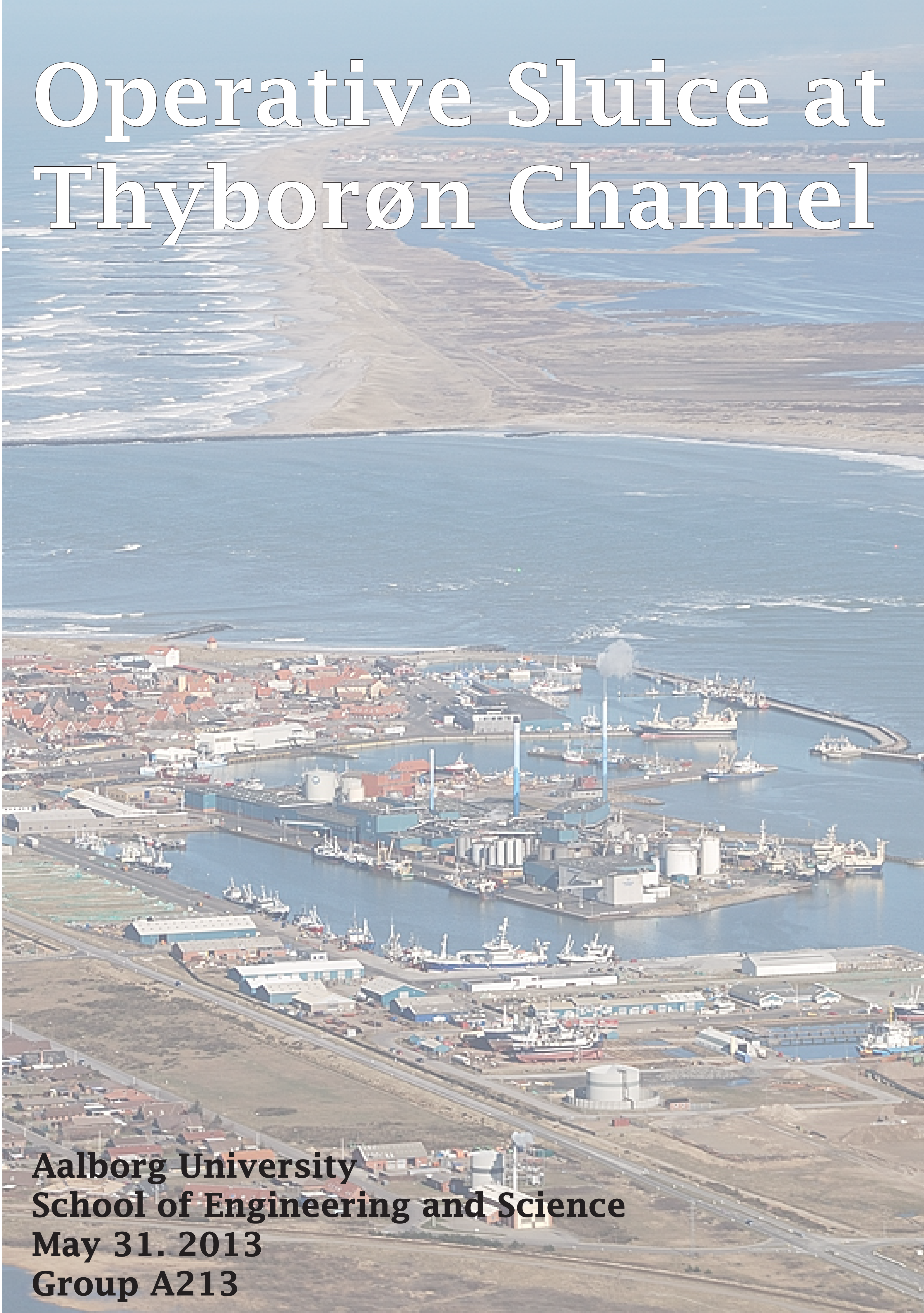

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Operative Sluice at Thyborøn Channel

Department of Civil Engineering
Sohngårdsholmsvej 57
9000 Aalborg
http://ses.aau.dk/

Titel: Operative Sluice at Thyborøn Channel

Theme: Pollution of Coastal Waters

Project period:
Spring semester 2013

Project group
A213

Participants:

Christoffer Kjær Bechgaard

Kristian Skov

Pernille Knudsen

Lasse Sørensen

María Bartolomé Criado

Rune Thomsen

Supervisors:
Torben Larsen
Niels Iversen

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Appendix numbers: 21

Project end at 31-05-2013

Synopsis:

The purpose of this report is to analyse the effect of constructing a sluice in Thyborøn Channel in respect to flooding. Furthermore the water quality of the Limfjord is analysed and how a sluice will affect the water quality.

To investigate the effect of a sluice in regard to flooding in the Limfjord, different scenarios are investigated, where both the location and the operation of the sluice are analysed. The result of the scenarios is that the sluice should be located on the West side of Thyborøn, if the sluice should be able to protect the city. The operation of the sluice should depend on weather forecasts, and closed 2-7 days before the storm.

The water quality analysis is conducted with two models; a simple box model and a comprehensive 3 dimensional model. In the box model the impact on the water quality as a consequence of the sluice is analysed. In the box model the sluice had a negative impact on the water quality. Therefore the 3 dimensional model is used to see if the box model is insufficient to analyse the consequence of a sluice. For the 3 dimensional model the effect of a sluice on the nitrogen concentration is also investigated. The result of the 3 dimensional model shows possible improvement of the water quality, if a sluice is built.

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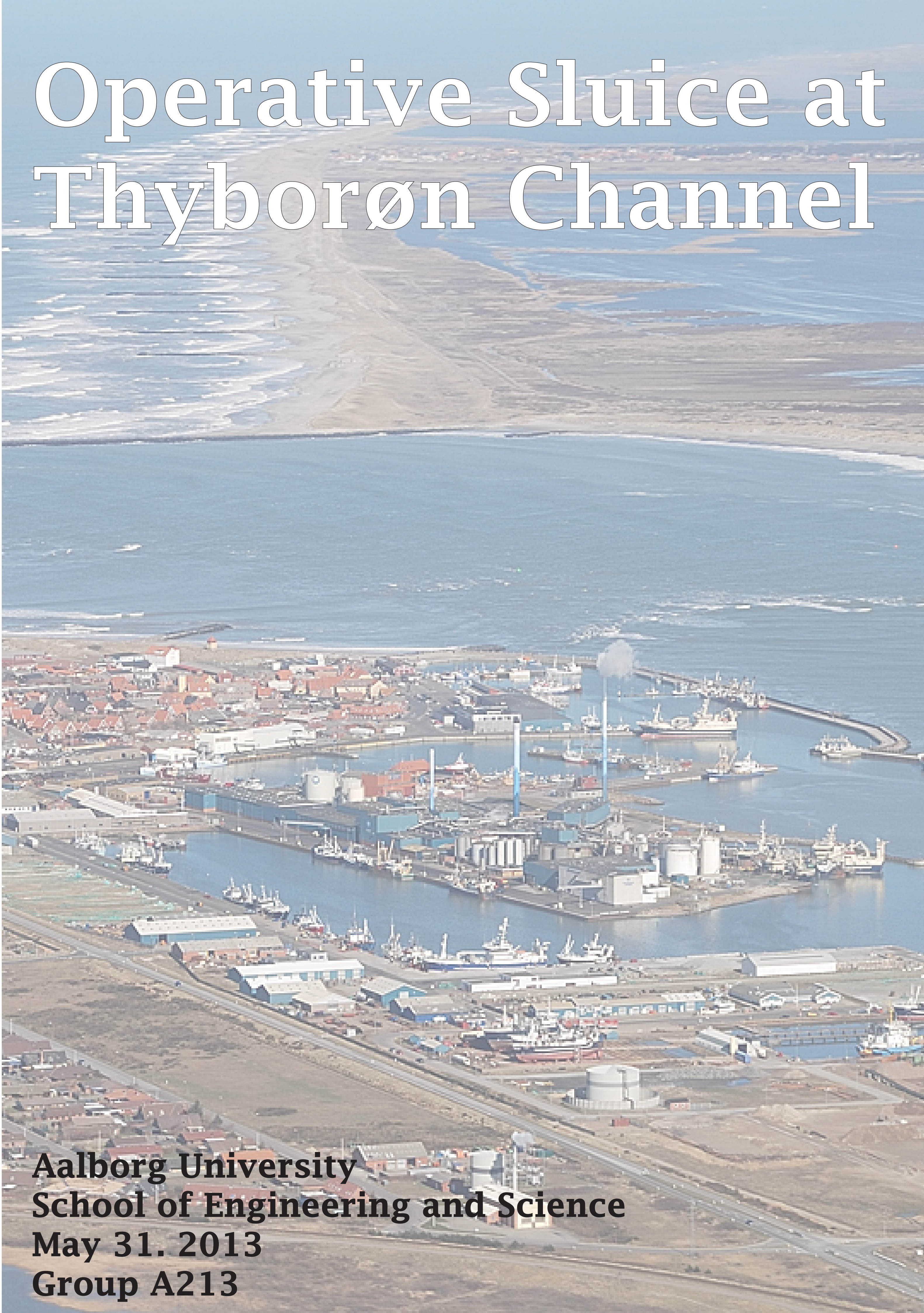

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Preface

This report is drafted by group A213 consisting of students of the 2st semester of the Master programmes ”Water and Environment”, ”Environmental Engineering” and ”Physical Geography”, School of Engineering and Science at Aalborg University, in the period from February 1th 2013 to May 31th 2013. The supervisors of the project are Torben Larsen, Professor, Department of Civil Engineering and Niels Iversen, Associate Professor, Department of Environmental Engineering. A Special thanks to Thomas Ruby Bentzen, Associate Professor, Department of Civil Engineering who has provided consultation in relation to Mike Zero.

The sources used in the report are noted in brackets with the last name of the author and the year of the publication, like [name, year]. The sources with several authors are listed [name et al., year]. All references are listed in the end of the report in the bibliography. The references to figures, tables and equations are numbered according to the chapters, for example figure 6.3 will be the third picture in chapter 6. If a source is mentioned in the caption for a figure, the picture is from this source. The Mike Zero models and the box model used for the project can be found in appendix F.

All elevations are in DVR90 and all figures are self-made unless something else is mentioned.

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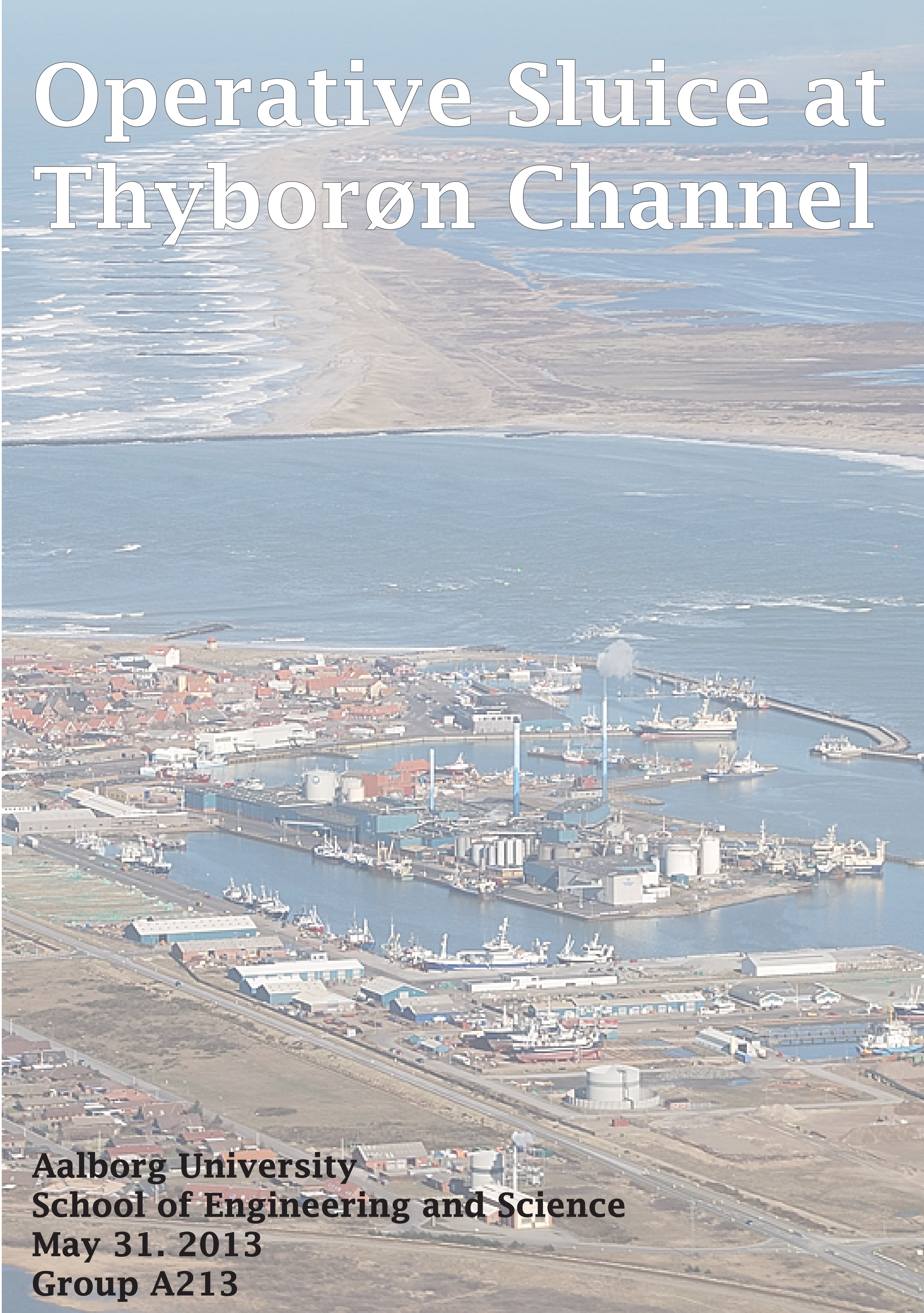

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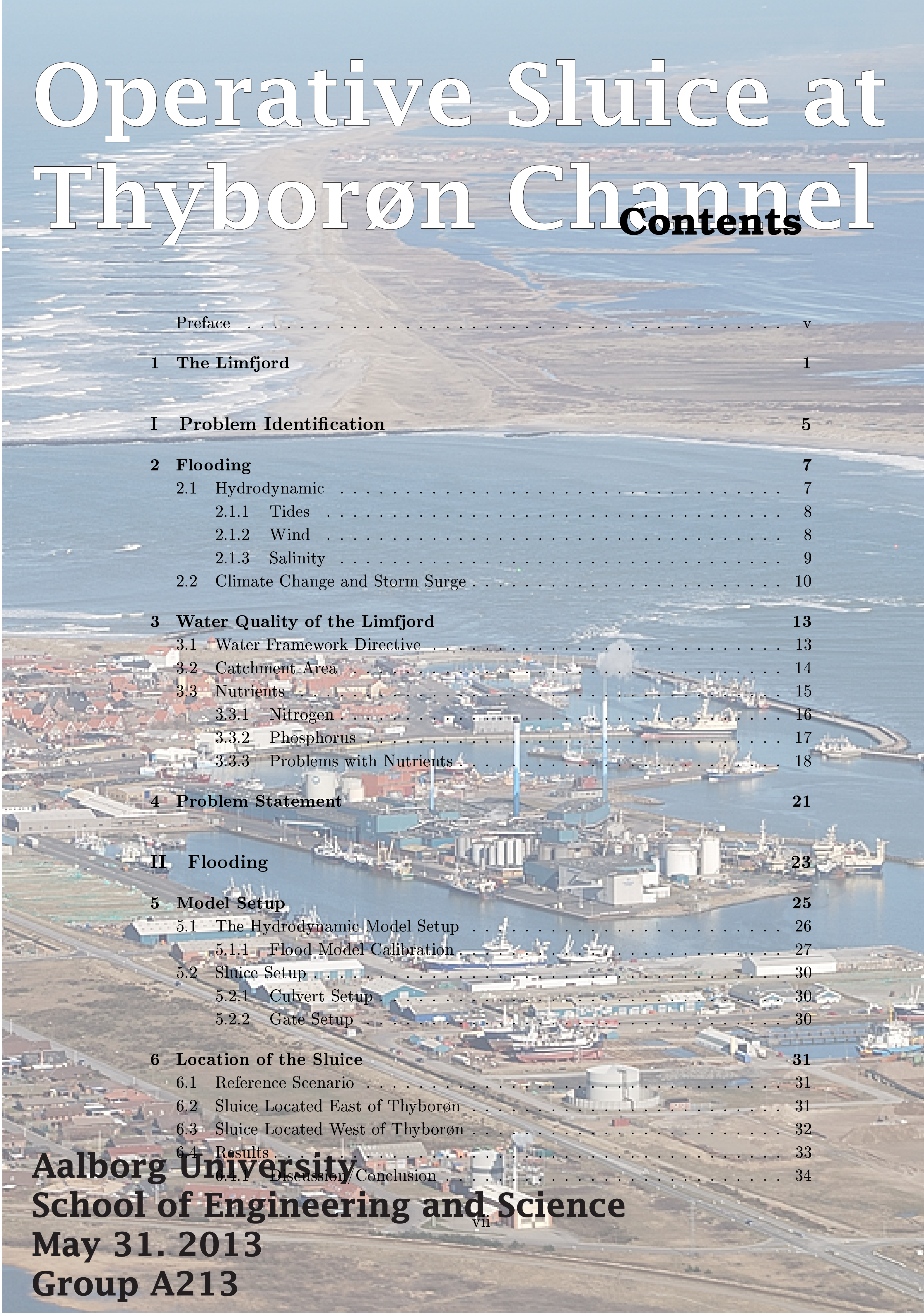

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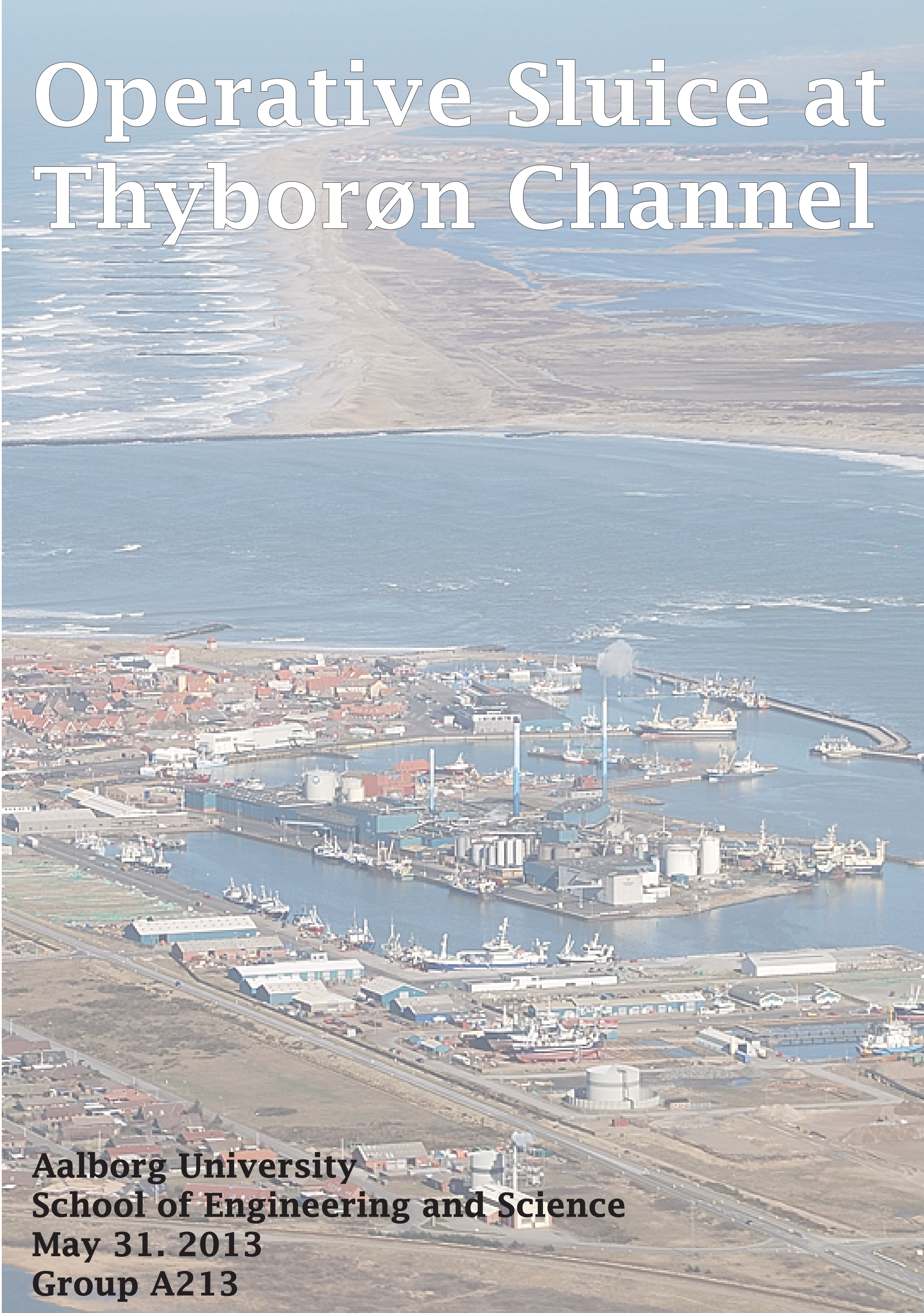

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1 The Limfjord

The Limfjord is the largest coastal water system in Denmark, which is located between the North Sea and Kattegat in the northern part of Jutland, and is illustrated in figure 1.1. The Limfjord extends an area of 1,500km^2 and covers approximately 1000km of coastline. It has an average depth of 4.9m and contains around 7.4km^3 water. Around 525,000 people live in the main catchment area of the fjord, which is approximately 1/6 of Denmark's area. [Miljøministeriet, By- og Landskabsstyrelsen, 2010]

The Limfjord and the North Sea have not always been connected. In 1825 there was a storm surge that invaded the land and created the Agger Channel. In 1862, a new storm surge occurred, and created the Thyborøn Channel. A few years later Agger Channel was closed due to sand transport with water, which left Thyborøn as the only connection between the Limfjord and the North Sea. The channel has been kept open and is now an excavated channel, known today as the Thyborøn Channel. Agger Channel was located a little north of Thyborøn Channel. [Miljøministeriet, By- og Landskabsstyrelsen, 2010]

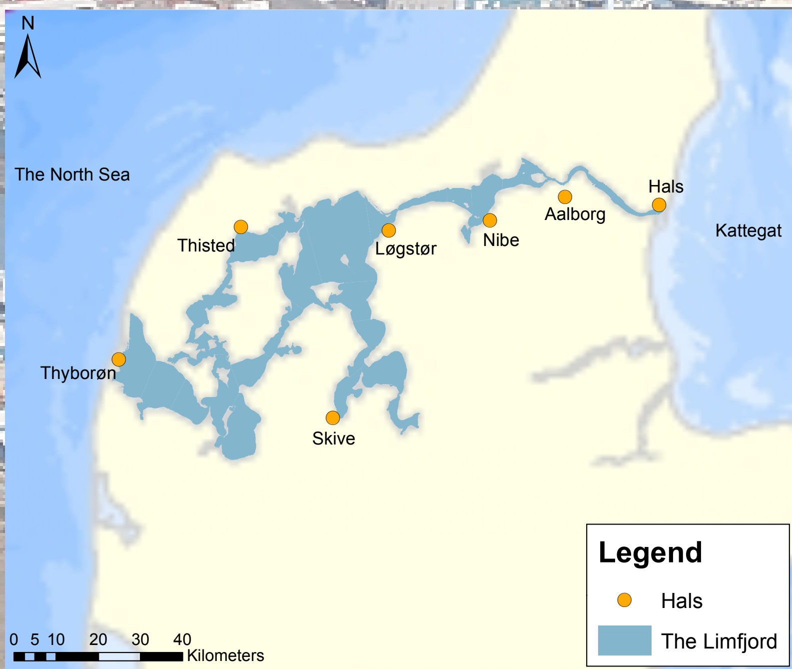

Figure 1.1: The northern part of Jutland and the Limfjord.

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Thyborøn Channel has allowed the water flow into the fjord from west due to tides and during stormy weather. The storms have led to flooding, and therefore it was discussed whether the channel should be closed again. In 1946 it was decided to do so. The project was started, but due to lack of money and academic controversy the project was shelved. Since then, the stormy weather which causes flooding happens more often due to climate changes, the discussion about precautionary measurements to prevent flooding has increased. [Nørgaard et al., 2013]

Thyborøn Channel is shown in figure 1.2. The channel allows water flow from the North Sea towards Kattegat. The higher salinity of the water from the North Sea has provoked an increase of the salinity in the fjord. The flow has also resulted in a flux of nutrients that moves the nutrients with the water flow towards Kattegat.

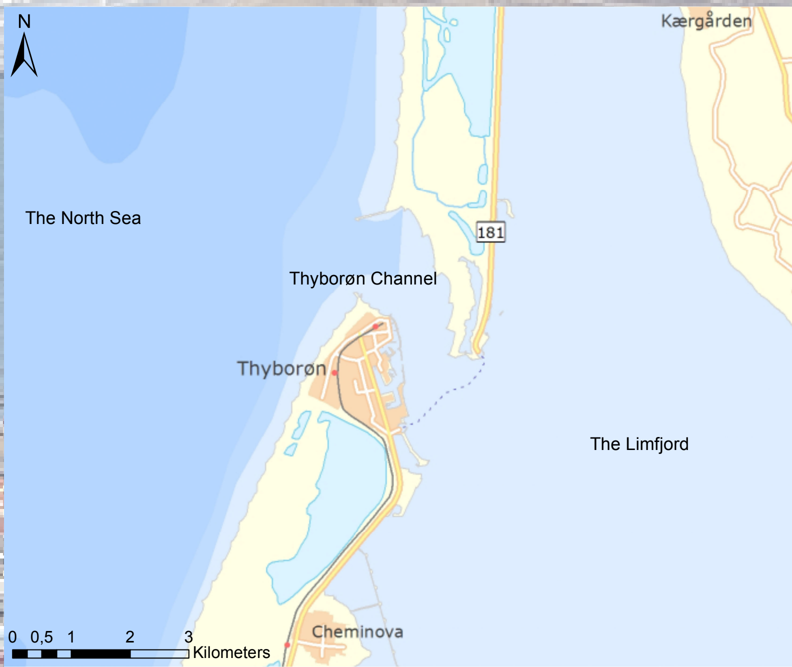

Figure 1.2: Thyborøn Channel, which is located in the western part of the Limfjord.

During the past century there has been an increased discharge of nitrogen and phosphorus from the catchment area. The increase of nutrients discharge to the Limfjord has resulted in several environmental problems regarding the ecosystem in the Limfjord.

One of the environmental problems is oxygen depletion, which has increased the last 30 years [Limfjordsamterne, 2006]. This has forced animals living in the area with oxygen depletion to flee if possible, or die from suffocation. After oxygen depletion has occurred, several years pass until the area is fully recovered [Powilleit and Kube, 1999]. Since the middle of the 1980's, the amount of nutrients led to the fjord has been reduced, but oxygen depletion still occurs every summer in some extend. The most exposed areas are Thisted Broad, Lovns Broad, Skive Fjord and Hjarbæk Fjord. In the last decades approximately 10-30% of the Limfjord has been affected by oxygen depletion. The affected areas of oxygen depletion the last 10 years are illustrated in figure 1.3 and compared with the affected areas in 1940. [Limfjordsamterne, 2006]

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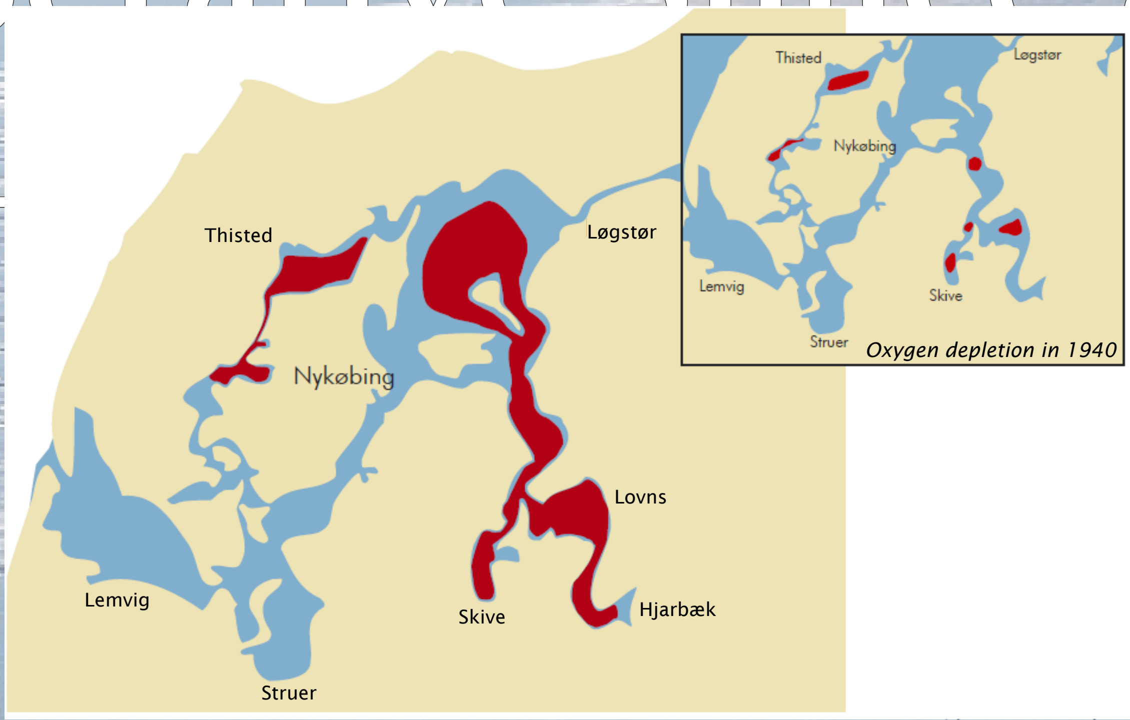

Figure 1.3: Areas affected by oxygen depletion in the Limfjord from 1996 to 2006, compared with 1940. [Limfjordsamterne, 2006]

The discharge of nutrients has also affected the eelgrass spread, which has disappeared from large areas of the fjord. In 1901 the eelgrass was observed at 5.5m below the water surface, and today the average depth for eelgrass is 2.2m. The reasons for the disappearance of the eelgrass are, among others, an increase of phytoplankton, bad oxygen conditions at the bottom and mussel scraping. Eelgrass has positive properties for both animals living in the fjord, but also on erosion and algae bloom. Since the spread of eelgrass has been measured since the beginning of the 20th century in Denmark, it has been used as an indicator of the water quality [Danmarks Naturfredningsforening, 2013]. [Limfjordsamterne, 2006]

The distribution of animals living on the bottom of the Limfjord has changed over the past 100 years. Now the bottom is dominated by common mussel and oyster's feeding by filtering the water. In the period between 1910 and 1952 the increased amount of nutrients discharged to the fjord resulted in a bigger productivity of, for example, benthic animals. The increasing discharges of nutrients have resulted in a decrease of the bottom animals since the 1960's. The conditions in the fjord from the 1960's until now have affected the amount of bottom fish living in the Limfjord. Figure 1.4 illustrates the amount of fish caught the same place with the same gear every year in the Limfjord from 1980 to 2005, indicating the biggest changes occurred in the beginning of the nineties. This has also meant that all commercial fishing in the fjord has stopped, except for mussel dredging. [Limfjordsamterne, 2006]

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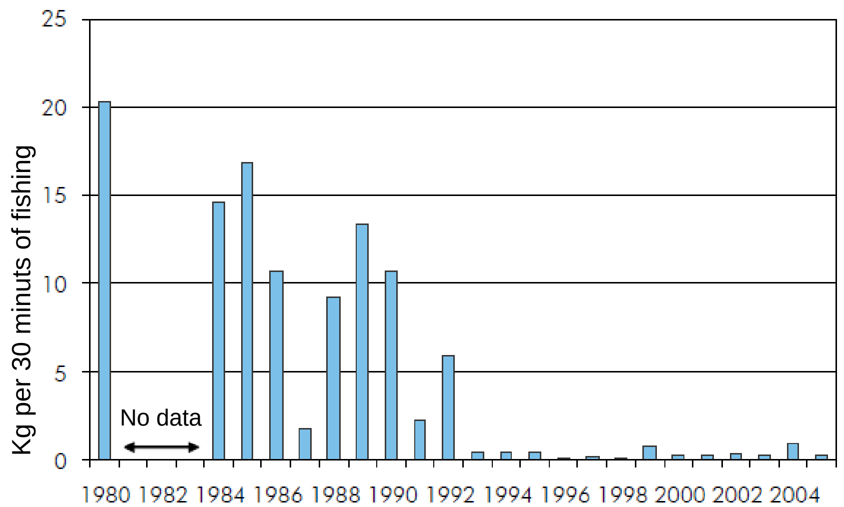

Figure 1.4: Illustration of the amount of fish caught the same place in the Limfjord with the same gear every year after 30 min of fishing. It should be noted that this figure does not include mussel dredging. [Limfjordsamterne, 2006]

During the last decades the status of the Limfjord has been declining due to increasing nutrient loadings, oxygen depletion and flooding. Furthermore the Limfjord will also be affected by the global warming and climate changes, which will further increase the problems in the Limfjord. In order to get better understandings of some of the problems concerning the Limfjord, it will be further investigated in the following chapter.

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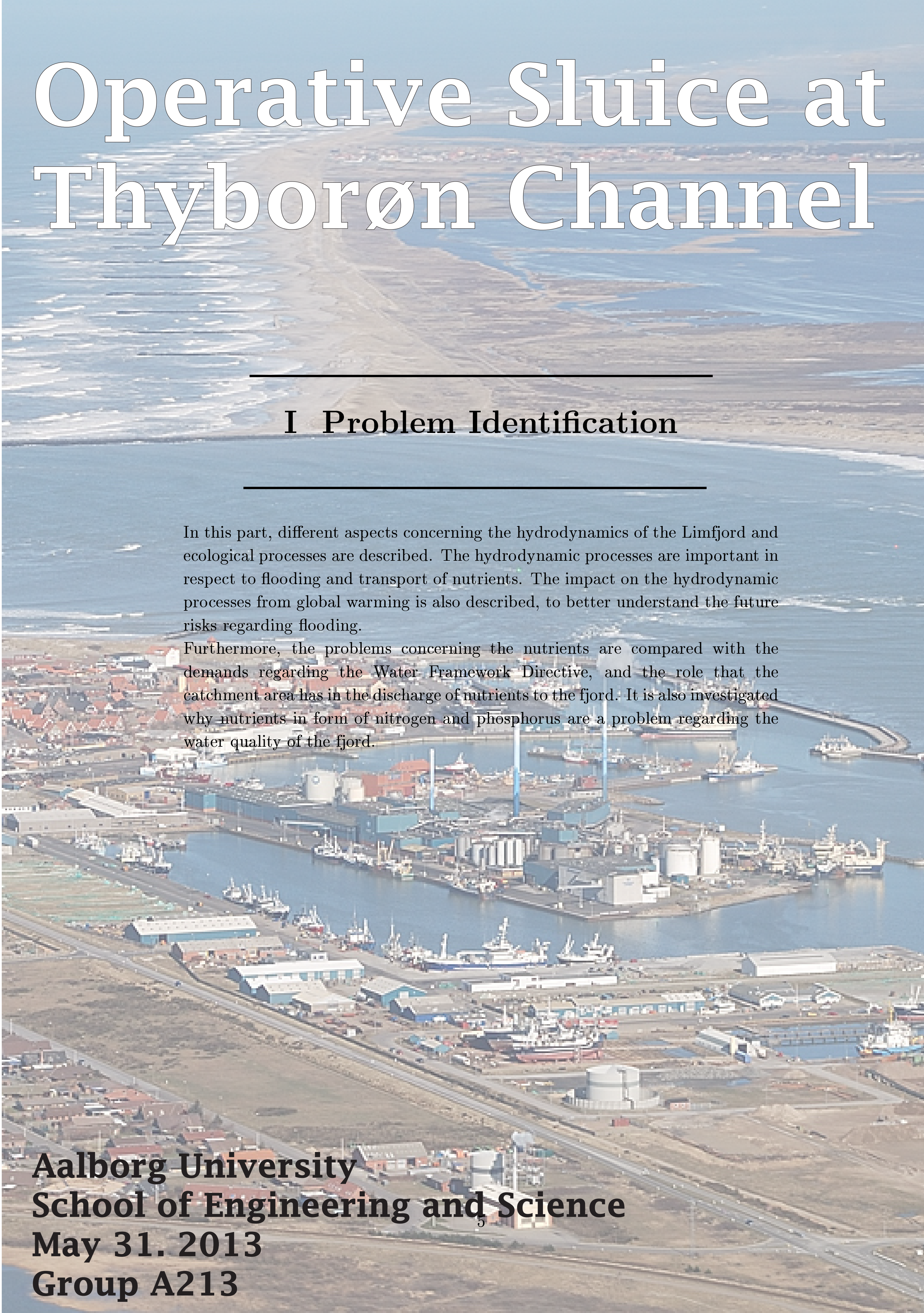

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I Problem Identification

In this part, different aspects concerning the hydrodynamics of the Limfjord and ecological processes are described. The hydrodynamic processes are important in respect to flooding and transport of nutrients. The impact on the hydrodynamic processes from global warming is also described, to better understand the future risks regarding flooding.

Furthermore, the problems concerning the nutrients are compared with the demands regarding the Water Framework Directive, and the role that the catchment area has in the discharge of nutrients to the fjord. It is also investigated why nutrients in form of nitrogen and phosphorus are a problem regarding the water quality of the fjord.

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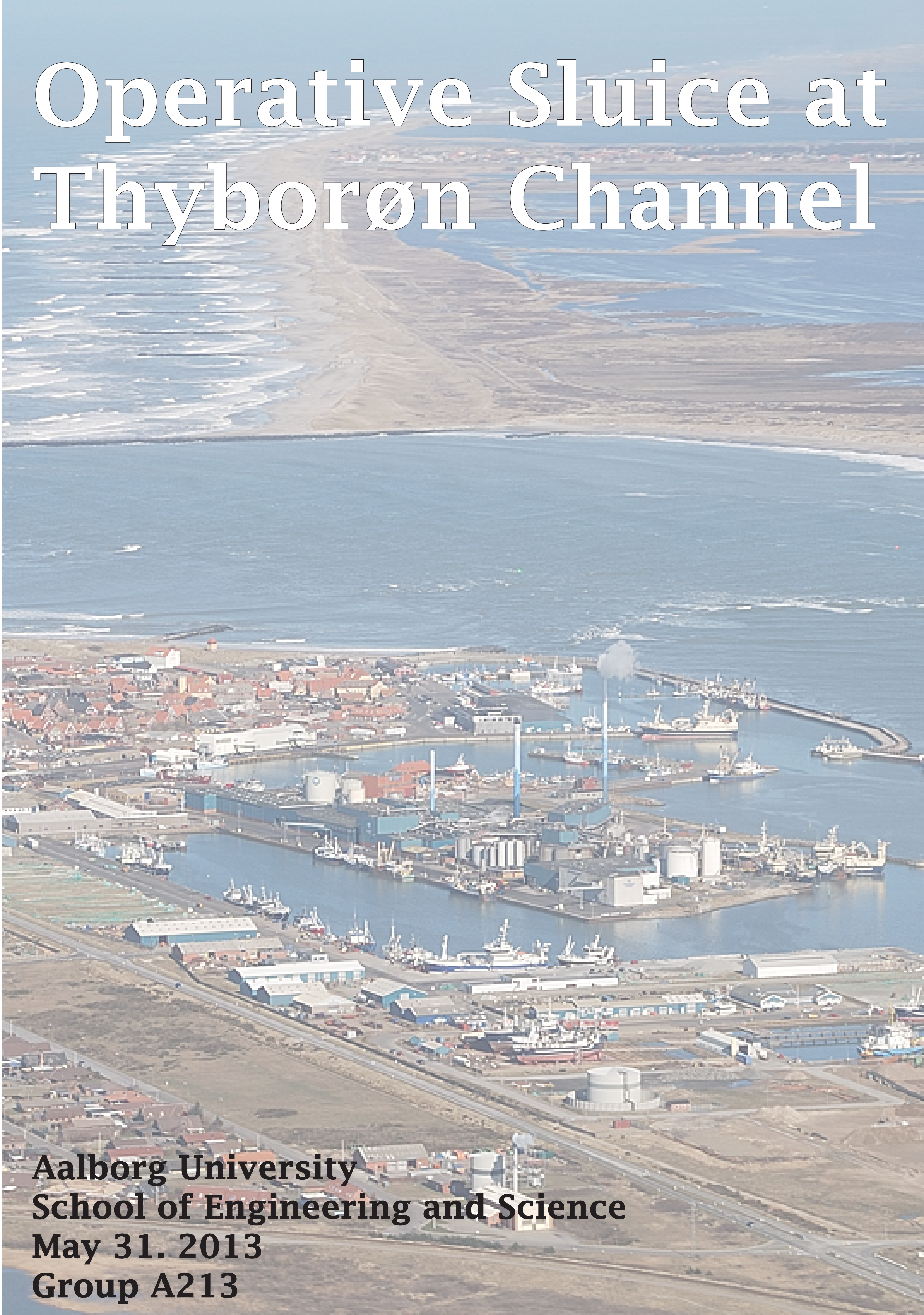

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2 Flooding

The hydrodynamics of the water in the Limfjord are important in order to study flooding and nutrient transport. Therefore, the tides, wind and salinity are described in this chapter.

Global warming will affect the water levels, precipitation rate, salinity and wind. Since the water level and wind speed will increase, the risk of storm surge and flooding will also increase, consequently having more flooding. [Larsen, 2007a]

2.1 Hydrodynamic

The hydrodynamics in the Limfjord are unique because the fjord in reality is a strait system connecting the North Sea with Kattegat. Because the Limfjord is connected with an ocean in both ends, the salinity through the fjord is higher than in the rest of the fjords in Denmark. In a simplified scenario, the Limfjord can be seen as a big basin between Thyborøn and Løgstør while from Løgstør to Hals it consists of a fairway which is illustrated in figure 2.1.

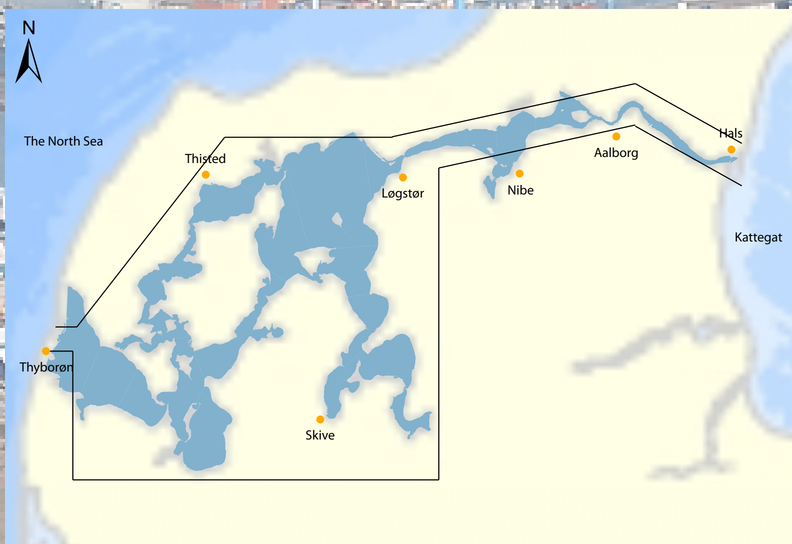

Figure 2.1: The Limfjord can in principle be divided into a big basin between Thyborøn and Løgstør, and a channel from Løgstør to Hals.

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The western part of the Limfjord consist mainly on straits and broads, where the straits are around $10-20m$ in depth and the broads are around 7 meters in depth. The eastern part of the fjord consists mainly of the fairway between Løgstør and Hals which is surrounded by broad shallow waters with a depth of around one meter. The highest hydraulic resistance of the fjord is in that part. [Larsen, 2005]

The movement of the water in the Limfjord is controlled by different flow parameters, which are described in the following sections.

2.1.1 Tides

The water level in the Limfjord is partly controlled by the tidal flows. The tide at the North Sea is the governing factor controlling the flow in and out of the Thyborøn Channel, and changes every 12.5 hours. Models have shown that if a drastic change of the water level in the North Sea occurs, e.g. a raise of one meter, it will take 24 hours before the water level in the inner part of the Limfjord reaches its maximum. So, tides have only a small influence on the water level variation in the fjord. At Thyborøn it is approximately $0.5m$, at Hals it is about $0.3m$, and at Skive it is around $0.1m$ 12.5 hours after the tidal wave affected Thyborøn. The delayed influence of the tidal waves is due to the friction through the fjord. The transport of pollutant out of the fjord is only partly affected by the tide because, as the simplified sketch of the fjord illustrates, the western part consists of a large basin and the water level only raises $0.1m$ at Skive. [Larsen, 2005]

2.1.2 Wind

In the Limfjord, one of the most important flow parameters is the wind, which due to the shear stress transferred to the water surface result in a flow. The surface stress caused by the wind can be expressed by the following equation.

$$\tau_w = \rho_a \cdot C_D \cdot W_{10}^2$$

τ_w	Shear stresses	$[Pa]$
ρ_a	Density	$[kg/m^3]$
C_D	Drag coefficient	[-]
W_{10}	Wind velocity at ten meters height	$[m/s]$

The wind stress makes the water move with the wind direction, which results in a wind-setup on the coasts with onshore wind. This will raise the water level and the change is inversely proportional to the depth, which can be seen in equation 2.1.

$$\Delta h = \frac{\tau_w}{\gamma \cdot h_0} \cdot \Delta x \qquad (2.1)$$

Δh	Change in water height	$[m]$
Δx	Affected distance	$[m]$
γ	Specific weight	$[N/m^3]$
h_0	Depth	$[m]$

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Because the fjord has an average depth of the $4.5m$, the wind can produce large wind set-up situations on the shallow broads, resulting in current through the straits. The average wind vector is towards the east during a year, which results in a net current of approximately $350m^3/s$ at Løgstør [Larsen, 2005].

2.1.3 Salinity

The salinity in the Limfjord is dependent on the salinity in the North Sea, which is controlled by addition of the Atlantic water and the English Channel. The North Sea salinity is 32-34PSU and Kattegat has a salinity of 19-25PSU. The low salinity in Kattegat is due to the water from the Baltic Sea, which has a very high input of fresh water. In the Limfjord, a large variation of salinity is observed, due to its dependency on the wind and freshwater addition [Larsen, 2005]. If the salinity in the North Sea changes, the full effect will first be reached one year later in the residual part of the Limfjord. This indicates that although the tide and wind move a lot of water around the fjord, it is the same water that is being moved around, and there is only a small exchange with water outside the fjord. [Larsen, 2005]

The discharge from the streams is about 20% of net flow in the fjord. The net flow and the dispersion through Thyborøn Channel has a large influence on the salinity in the western part of the Limfjord. The stratification of the fjord has been monitored over several decades. The measurements indicate the highest concentration at Thyborøn Channel, and a lower concentration towards Hals. Figure 2.2 shows a sketch of how the salinity is in the Limfjord from Thyborøn to Kattegat. The figure shows measured data from six stations in the Limfjord.

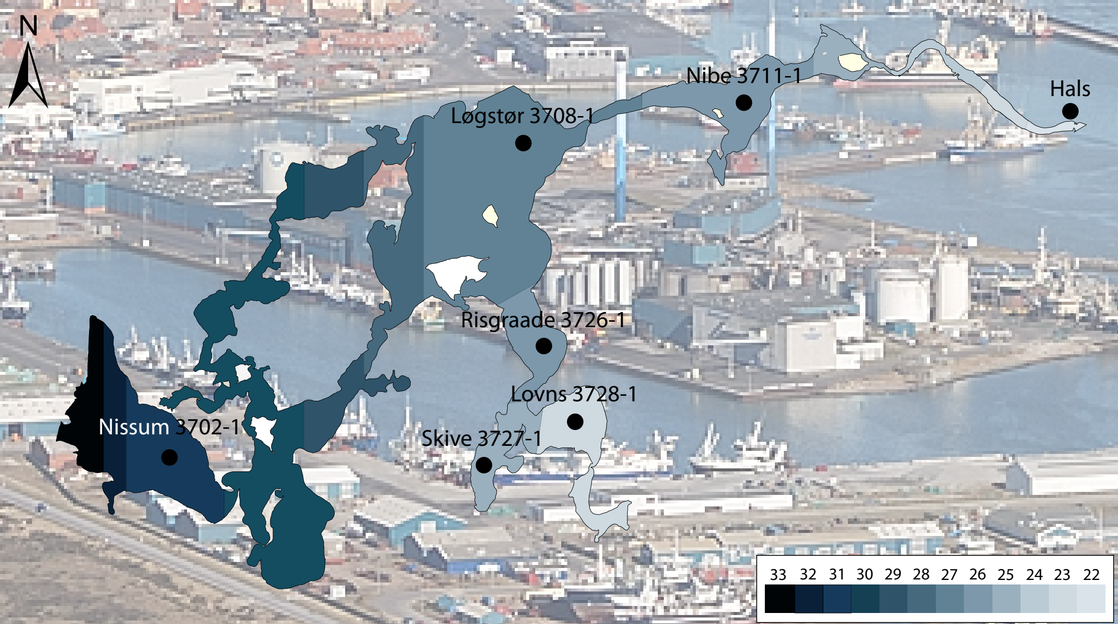

Figure 2.2: Sketch of the salinity through the Limfjord.

The used salinities are listed in 2.1, which is the mean of all depths and all measurements in 2005.

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Measurement station	Salinity [PSU]
Lovns Broad 3728-1	24
Løgstør Broad 3708-1	27
Nibe Broad 3711-1	26
Nissum Broad 3702-1	31
Risgaarde Broad 3726-1	27
Skive Fjord 3727-1	25

Table 2.1: Mean of salinities for the six measurement stations in 2005. [DMU, 2005]

2.2 Climate Change and Storm Surge

A consequence of the climate change is the increase of water levels and wind, which has a large influence on flooding. When the sea temperature rises, the water expands and the water level increases. Water is also added to the ocean from the melting ice from Greenland and Antarctica ice caps and glaciers. The water level is predicted to rise 0.7m if the ice caps melt completely.

During the next 50-100 years the water level is expected to rise with 0.19-0.58m. The large rise of the water level will have huge effects on coasts and flooding protection because at the same time global warming will also have an influence on the wind. The storm activity will be more frequent but also more powerful because the climate change will affect the average wind speed, and increase it with 5%. [Nørgaard et al., 2012]. This will result in more regular and stronger storm surges and waves. [Larsen, 2007a]

The storm surge frequency in Løgstør is 40 years, but in 2050 it will reduce its frequency to every 15 years, and every 1-2 years by 2100. [Region Nordjylland, 2011]

When a storm surge occurs, depends on the interaction with different parameters, such as wind velocity, tides and coastal development. The storm surges have become stronger in the period of 1931-2005, where only two of the twenty most powerful storm surges at Thyborøn Harbour occurred from 1931-1968. [Larsen, 2007b]

Climate change is pointed as the source of a larger number of storm surges and the greater frequency of the events between 1931-2005. The storm surge that hit the Limfjord in 2005 was a storm surge with a 1000 years frequency, and it is expected to occur more often in the future [Larsen, 2007b]. Figure 2.3 shows the coasts affected by the flood. It was the highest water level measured in the Limfjord. [Nielsen, 2005]

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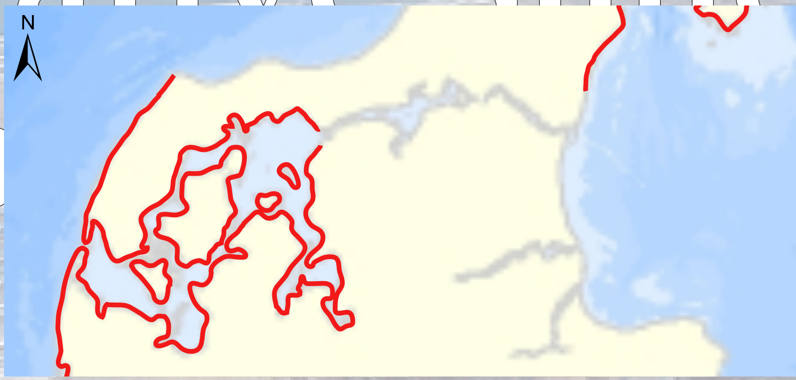

Figure 2.3: The coasts that were flooded during the storm the 8^{th} of January 2005, are marked with red. [Stormrådet, 2009]

On the 8^{th} of January 2005 a large part of the west coast of Jutland had wind from the west almost with a hurricane strength. The mean wind with Hanstholm reached up to $35 m/s$ and the rest of the country was the gust of wind on hurricane strength. During the period before the storm surge occurred, a long period with west wind had already increased the water level in the Limfjord. The storm surge resulted in strongly increased water levels in the Limfjord. At Thyborøn coast had the highest water level ever measured at $2.97 m$ [Nielsen, 2005]. After the storm surge, 424 damages were reported in Denmark, and 371 of the damages reviews came from areas near the Limfjord. The total compensation for the reported claims amounted to approximately 33 million DKK [Stormrådet, 2009]. After the flood, the discussion about the closure of Thyborøn Channel was resumed, this time based on the global warming and its effect on the water levels.

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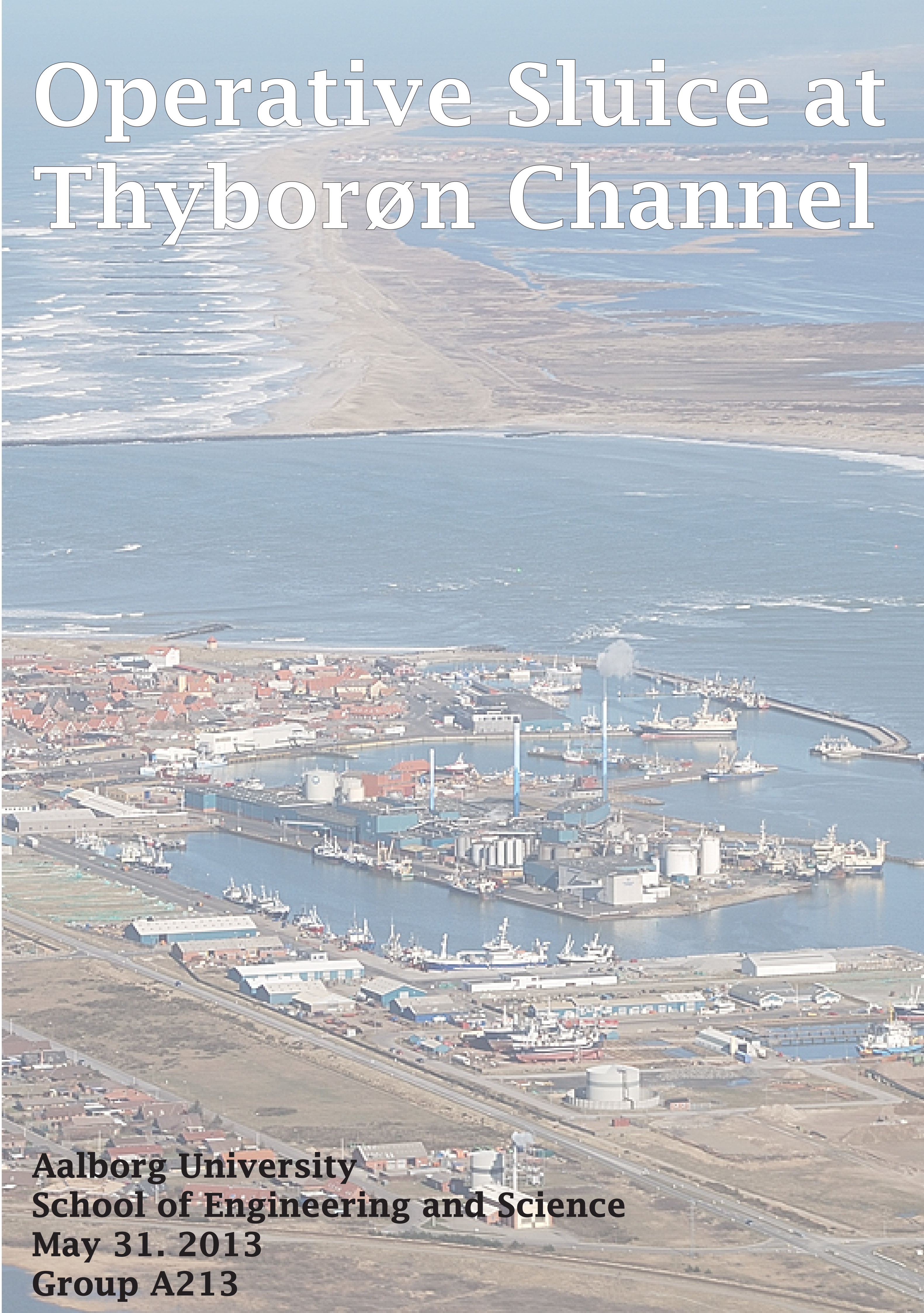

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3 Water Quality of the Limfjord

In this chapter, the water quality of the Limfjord is described. First the European Water Framework Directive is explained in regard to the water quality. Furthermore the different sources of nitrogen and phosphor are presented and why these nutrients are important for the ecological system of the Limfjord.

3.1 Water Framework Directive

As mentioned in the introduction, the Limfjord is affected by oxygen depletion which has influenced many of the species that live or lived in the fjord. This is not only a problem in the Limfjord but in most parts of Europe, which is why the EU has constructed the Water Framework Directive. Since Denmark is a part of the EU, they are also part of the EU Water Framework Directive. This was established in 2000 and each member of the EU was forced to comply with the directive by 2015 [Bidstrup et al., 2006].

EU's Water Framework Directive establishes a framework for the protection of rivers and lakes transitional waters (estuaries, lagoons, etc.), coastal waters and groundwater in all EU countries. As an instrument to reach these goals, Vandplanerne (Water Plans) are used. They describe how water areas should have a 'good status'. This has caused the Danish legislation in Miljømålsloven (Environmental Law). This provides a framework for the protection of the Danish waters [Miljøministeriet, 2009].

The aim of the directive is to reach a 'good status' for ground and surface waters, which includes the Limfjord. Good status includes both the chemical and ecological conditions, and is obtained if the status only deviates a little from the unaffected status. To figure out the status, a Basis Analysis is carried out, which for the Limfjord includes a characterisation of the water, description of man-made impacts on the Limfjord and an economic analysis of the use of the water. [Bidstrup et al., 2006]

As explained, eelgrass is used as indicator of the status of the fjord. The Water Plan for the Limfjord states that to reach a 'good status', the depth limit for distribution of eelgrass needs to be $4.1m$. To reach a 'good status' the depth for eelgrass should be 74% of the reference condition Miljøinisteriet Naturstyrelsen [2011]. To reach this objective in the fjord, a support parameter for the level of total nitrogen of $409 \mu gN/l$ is

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used [Miljøministeriet, By- og Landskabsstyrelsen, 2010]. However, this has been removed from the final Water Plan.

The Basis Analysis for the Limfjord was finished in 2006, and concluded that the aim for good status will not be achieved by 2015. The main reason for this is eutrophication, caused by large loads of nitrogen and phosphorus from the catchment area. The loads in 2005 from the agriculture were assumed to be 14,500 tonnes of nitrogen and 317 tonnes of phosphorus. To achieve a good status, the discharge should be reduced to 9,520 tonnes nitrogen and 364 tonnes of phosphorus per year. This result in a reduction of 4780 tonnes nitrogen and 47 tonnes of phosphorus compared to 2005. To get a better understanding of where the nutrients come from, the catchment area of the fjord is investigated. [Vandrammedirektivet, 2006]

3.2 Catchment Area

The catchment area of a fjord can have a huge influence on the recipient depending on what is imported to the recipient. The catchment area of the Limfjord covers $7608km^2$, which leads to an average discharge of water to the Limfjord of approximately $82m^3/s$ [Bidstrup et al., 2006]. Figure 3.1 shows the catchment area and all the streams discharged to the Limfjord. [Bidstrup et al., 2006]

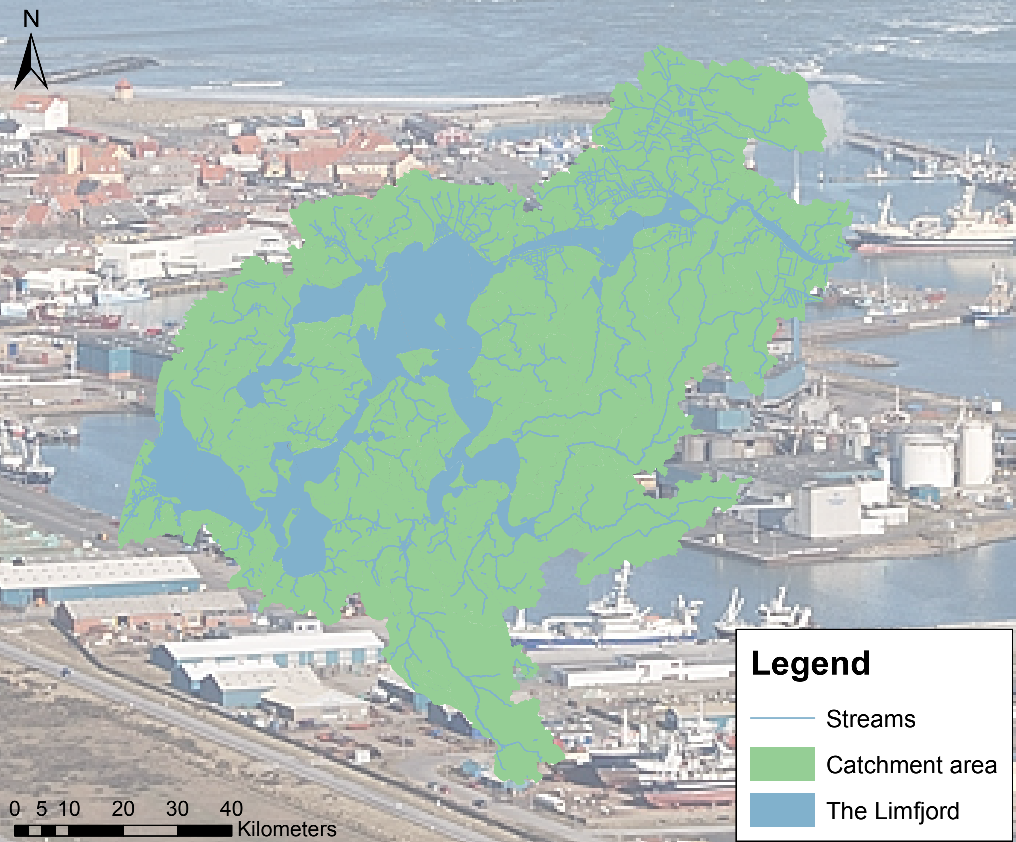

Figure 3.1: Catchment area of the Limfjord, and the streams dischared to the fjord.

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65-70% of the area is agriculture land and has a rather high density of livestock. This makes the catchment area a big source for loading of nutrients. Approximately 70% of the nitrogen and 30% of the phosphorus loading in the Limfjord from the catchment area comes from the agriculture [Limfjordsamterne, 2006]. Due to the high use for agriculture in the catchment area, there is accumulated a large amount of nutrients in the soil. The accumulated nutrients can, during flooding, be washed out to the Limfjord. [Department of Environment and Primary Industries, 2011]

Phosphorus and nitrogen to the Limfjord can be discharged from two types of sources, point sources and diffuse sources. Point sources can be, for example, waste water treatment plants and fish farms. Diffuse sources can be, for example, from the atmosphere or agriculture. The distribution of nitrogen and phosphorus added to the fjord from the catchment area can be seen in figure 3.2. [Limfjordsamterne, 2006]

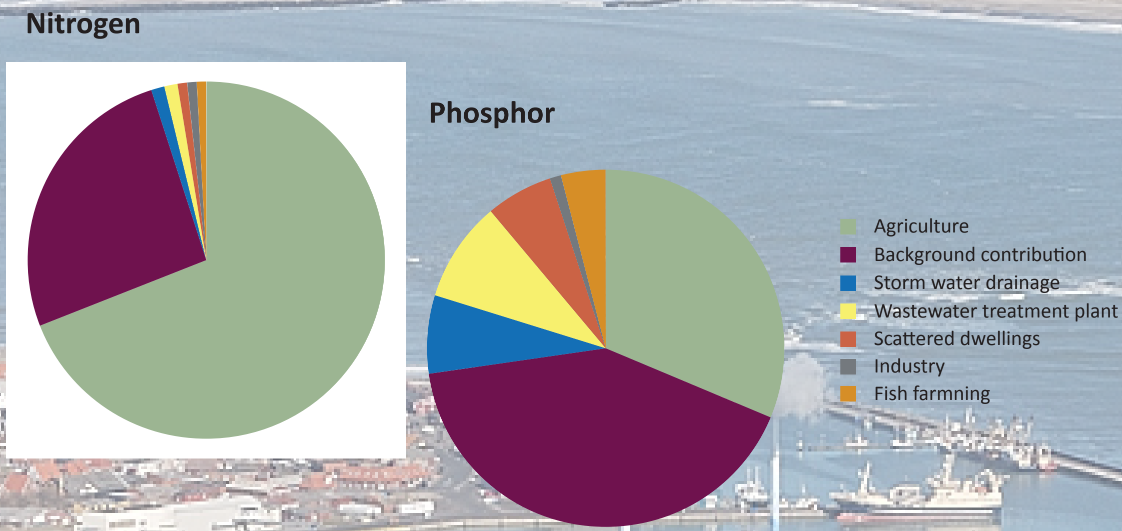

Figure 3.2: Distribution of nitrogen and phosphorus added to the Limfjord. [Limfjordsamterne, 2006]

Overall, a big effort in reducing nitrogen and phosphorus from the catchment area has been done. As result of this, the nitrogen discharge has been reduced by 20% and phosphorus by 70% since the 1980's. 3.1. [Limfjordsamterne, 2006]

The reason why nitrogen and phosphorus are important parameters is further explained in the next section.

3.3 Nutrients

Phosphorus and nitrogen overload in the last decades represent a big problem in the Limfjord. The use of fertilizers in agriculture has increased the nutrient load, in particular phosphorus and nitrogen, and it has conflicted with fisheries, NATURA 2000 areas, angling and bathing. [Bidstrup et al., 2006]

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Phosphorus and nitrogen limit the carbon uptake from the atmosphere, meaning that they regulate the photosynthesis rate. The Redfield ratio between nitrogen and phosphorus is 16:1. Due to the losses that take place in agriculture lands with erosion and crop production, and that as it is mentioned before it is limiting for primary production, phosphorus and nitrogen have been added in big amounts to the agriculture lands, representing a problem to the ecosystems. [Paytan and McLaughlin, 2007]

Nitrogen is considered the most important factor for the water quality in the fjord. Nitrogen is the limiting factor compared to phosphorus in the summer and late summer. More nitrogen to the fjord will therefore results in a bigger algae growth in this period when the fjord is vulnerable. [Larsen, 2013b]

3.3.1 Nitrogen

In the Limfjord, the main nitrogen load is from agriculture.

In the land, nitrogen is absorbed from the atmosphere as N_2, and fixed by photosynthetic organisms to NH_3, in a process called nitrogen fixation [Falkowski, 1997].

Since nitrogen limits the plant growth, there is large discharge of nitrogen as fertilizers to the arable lands. This way, nitrogen from arable land represents the largest load of nitrogen to the fjord.

Nitrate is the compound that is released from the water streams to the Limfjord, and is reduced by algae, bacteria and plants, to amine form, used for their metabolism. Ammonium is oxidized by nitrifying bacteria and converted into nitrite (NO_2^-). [Valiela, 1995] Denitrification is the process where NO_3^- is transformed into nitrogen N_2 or N_2O, which are gases, and can be released again to the atmosphere [Falkowski, 1997]. In the figure 3.3, the different processes of nitrogen can be seen.

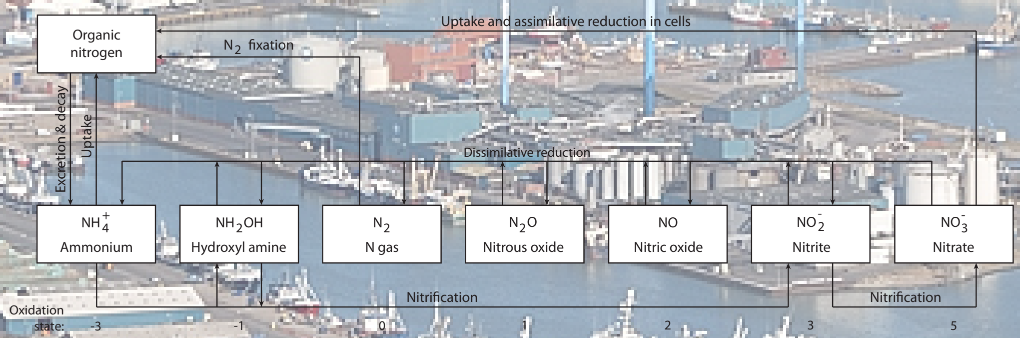

Figure 3.3: This picture shows the nitrogen chemical processes that take place in the nitrogen cycle. [Valiela, 1995]

Between 1990 and 2004, the Limfjord received annually 18,700 tons of nitrogen, where the catchment area contributed the biggest load. From 2005 the annually discharge is assumed to be 16,300 tonnes of nitrogen. The amount obtained from the atmosphere is 1,800 while the last 14,500 is from agriculture. [Limfjordsamterne, 2006]

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In figure 3.4, the main state variables of the nutrients and microfauna can be seen.

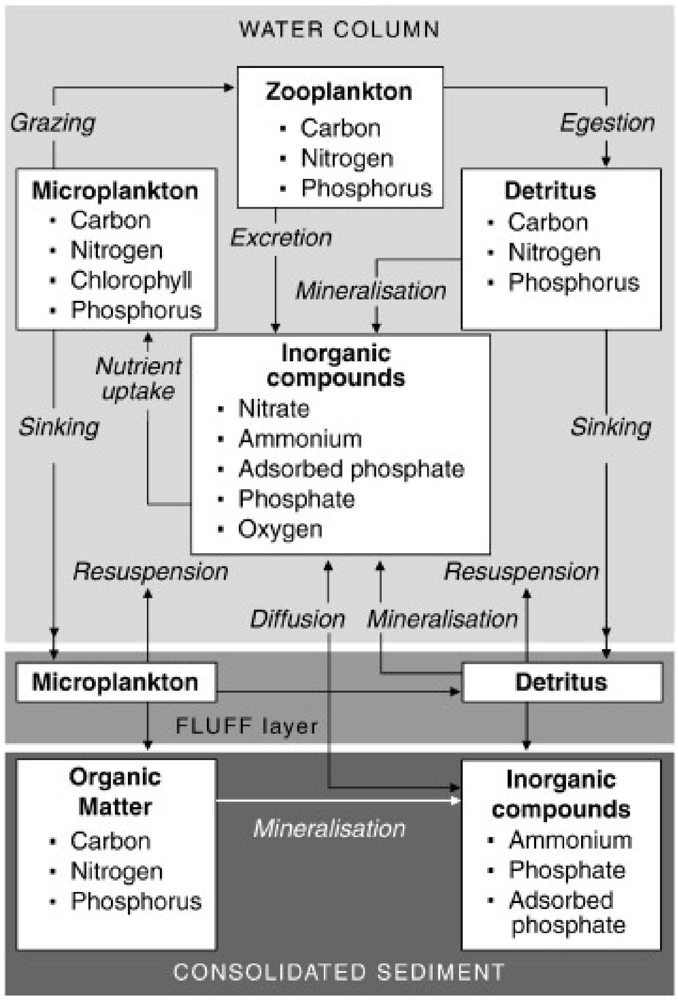

Figure 3.4: This picture shows the Limfjord water column and the main processes that take place through it, including the chemical compounds and the fauna and flora that process them [Maar et al., 2010]

3.3.2 Phosphorus

The anthropogenic sources of phosphorus in the Limfjord come from agriculture (fertilizers), Waste Water Treatment Plants, fish farming and industry. [Limfjordsamterne, 2006]

Phosphorus is loaded to the ocean as different chemical compounds: Particulate Inorganic Phosphorus (PIP), Particulate Organic Phosphorous (POP), and the second one is the most common. They take part of the components of dead organisms, precipitated phosphorus minerals (fluorapatite, phosphate minerals), or phosphorus adsorbed to particles. The other phosphorus compounds are dissolved in the water, either as organic form (DOP) or inorganic (DIP).

Processes concerning phosphorus that take place in sea water can be seen in figure 3.5

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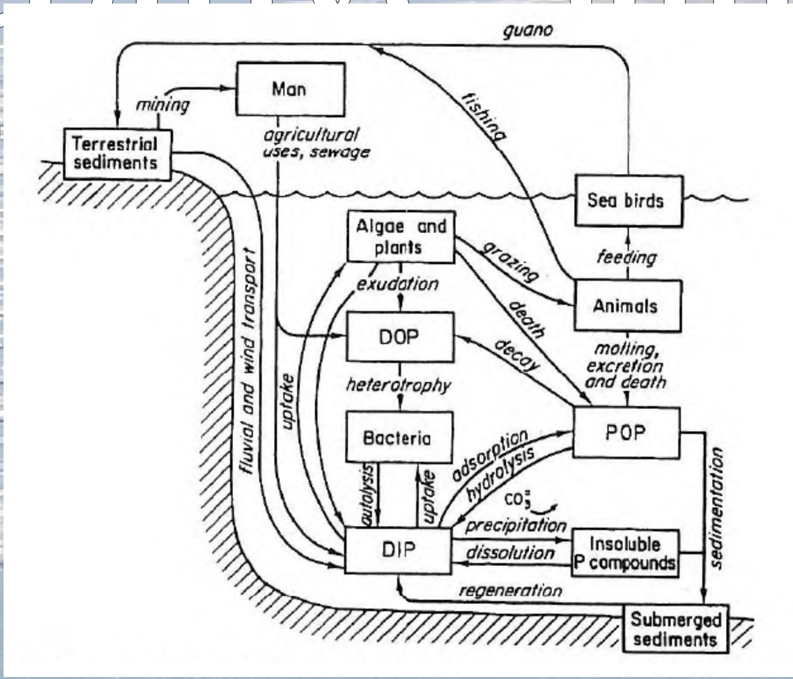

Figure 3.5: Phosphorus processes in the water column [Valiela, 1995]

The largest amount of phosphorus is buried in marine sediments. Particulate phosphorus can be regenerated to dissolved forms, or settle to the bottom. Dissolved phosphorus reacts with iron oxides and forms carbonate fluorapatite or is bounded to iron oxide particles. The deposition of phosphorus on the sediments is dependent of the redox conditions. Sediments with high content of ferric iron and manganese phase, in oxic conditions will enhance the uptake of phosphorus by adsorption and mineral formation, so the phosphorus will stay buried in the sediment because the retaining capacity is high. However, the retaining capacity in anoxic conditions is lower, and when iron is reduced, phosphorus bounded to it is released to the water column. Presence of oxygen in the bottom enhances the coupling between iron and phosphorus, while low oxygen bottom slows down organic matter oxidation and phosphate is released at a higher speed. [Paytan and McLaughlin, 2007]

3.3.3 Problems with Nutrients

The reason why eutrofication in the Limfjord represents a problem is because it leads to high productivity of algae. These algae have a short life cycle, so when they die, they sink and in the decomposition process oxygen is taken up, leaving hypoxia (low oxygen) or anoxia (no oxygen) conditions at the bottom of the water. This problem is specially relevant during the summer season, when the water temperature is high and the wind is low, so the water column is steady and the oxygen is not circulating up and down the water column [Larsen, 2007a]. Benthic fauna that have habitats there does not have enough oxygen and die, so especially the ecosystems in the bottom of the water are negatively affected. [Bidstrup et al., 2006]

A high production of algae will prevent the benthic vegetation from growing in deeper

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water. This happens because the algaes inhibit light penetration. Hereby areas with benthic algeas including eelgrass will disappear and thereby also the oxygen production on the bottom. Which accelerates the oxygen depletion. [Limfjordsamterne, 2006]

Climate Change

In the past 100 years the climate has changed and has affected water temperature and precipitation. Water temperature has increased 1.1°C, precipitation 15% and [Larsen, 2007a]. The average temperature in 2100 is expected to rise 2.2-3.5°C, and it will have a large influence especially at night.

Climate change will result in an increased annual precipitation of approximately 14%, even though there will be longer drought periods during the summer. The rain events occuring in summer will be more powerful.

The increase of precipitation will affect the nutrient runoff to the streams, since more water will run through the fields with the nutrients and be discharged both in streams and groundwater, and in the end to the Limfjord. If the precipitation rises with 10%, the input to the fjord rises with 10% [Limfjordsamterne, 2006].

The temperature rise will further increase the growth and decay of algae, which will result in more frequent oxygen depletion, and also be in a larger scale [Bendsøe et al., 2003]. Furthermore higher temperatures result in less oxygen can be dissolved in the water which also implies faster oxygen depletion [Limfjordsamterne, 2006].

A rise in precipitation and temperature will therefore have a bad effect on the fjord.

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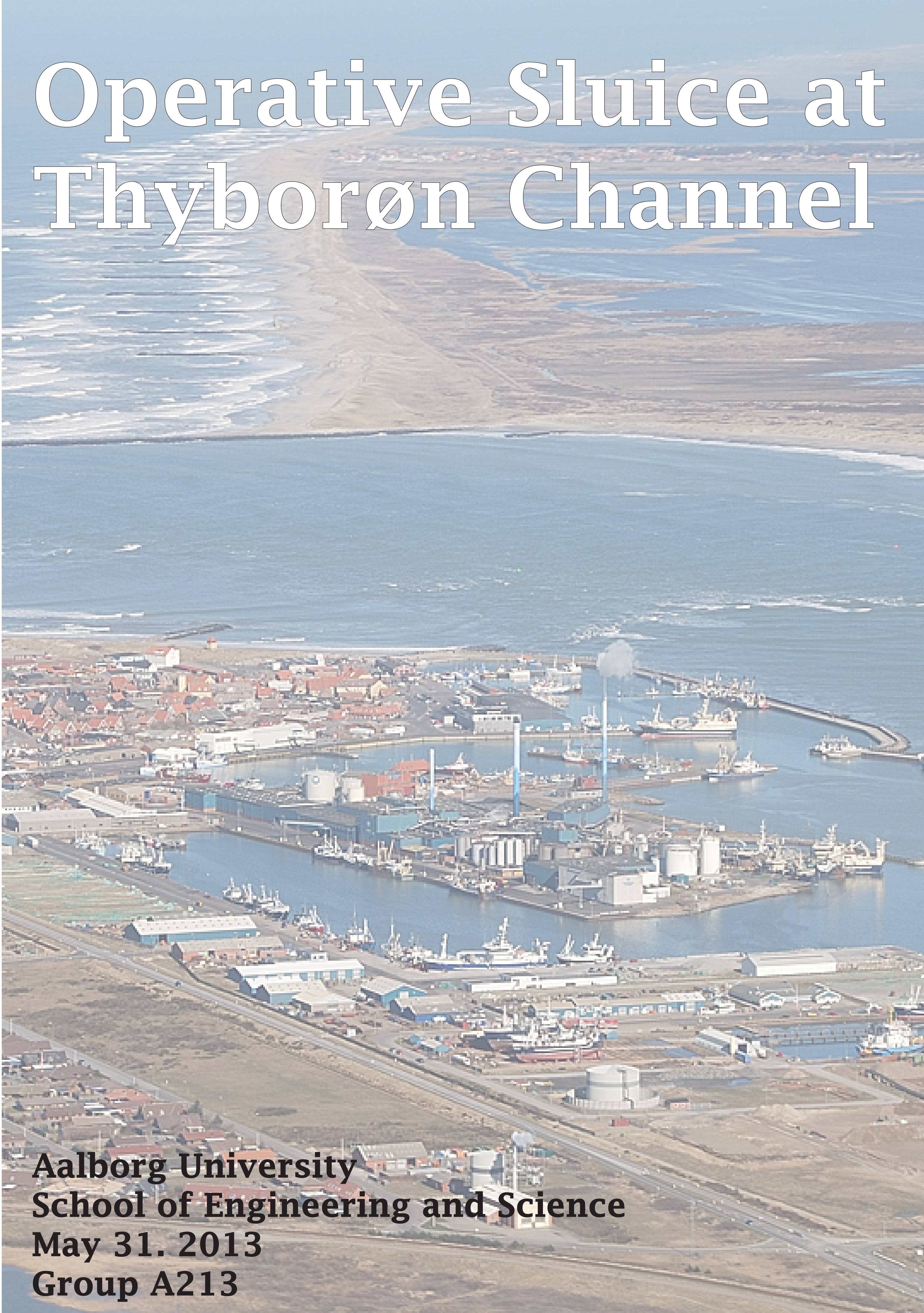

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4 Problem Statement

As mentioned before, the Limfjord has large problems with flooding and the water quality. The storm in 2005 resulted in severe flooding of the western part of the Limfjord. Different solutions to prevent flooding have been discussed. One of the possibilities is to construct a dam with a sluice at Thyborøn Channel, hereby making possible to regulate the water flow into the fjord and avoid the water build-up before the storm and during the storm. This should ensure a lower water level and minimise the effect of the storm, since less water would be moved around during the storm.

The construction of the sluice could also increase the flow in the Limfjord, which could enhance the wash out of nutrients, thereby improving the water quality.

Therefore, the construction of a sluice in Thyborøn Channel is investigated in this report in respect to both storm surge protection and water quality improvement, which results in the following problem formulation:

Is it possible to avoid flooding in the Limfjord today and in the future, by implementing and operate a sluice at Thyborøn, and would it hereby be possible to improve the water quality by reducing the nitrogen concentration in the Limfjord?

To investigate the problems, the report is divided into two parts. The first concerns the flooding on the Limfjord, and a model is made to analyse the problem and the effect of implementing a sluice. The second part concerns the biological and ecological status of the fjord. The present status will be analysed and how the status will be improved by implementing the sluice. To investigate this, two models will be made. One will consist on a simple box model and the second is an advanced model to better describe the processes and exchange of flow in the fjord.

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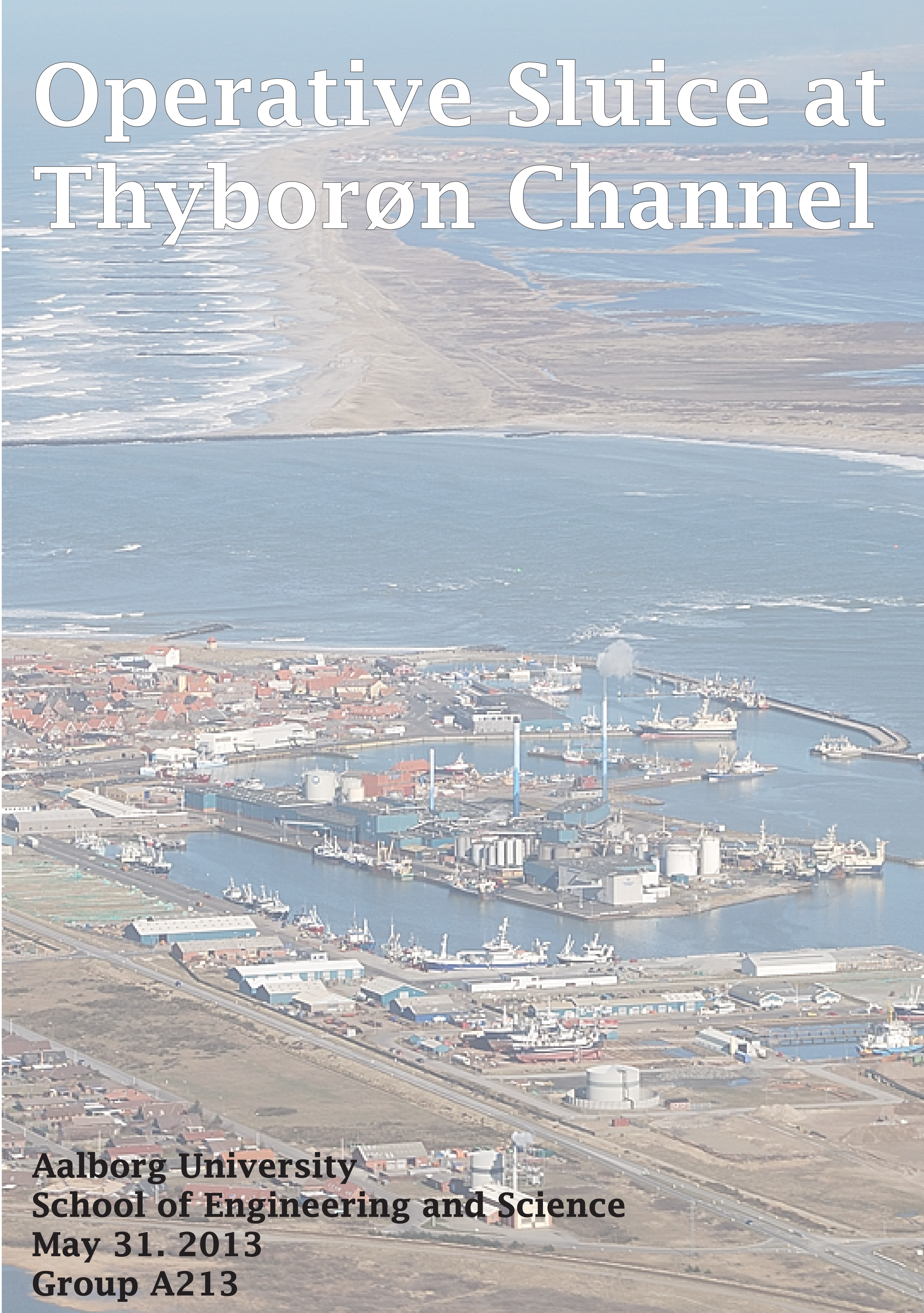

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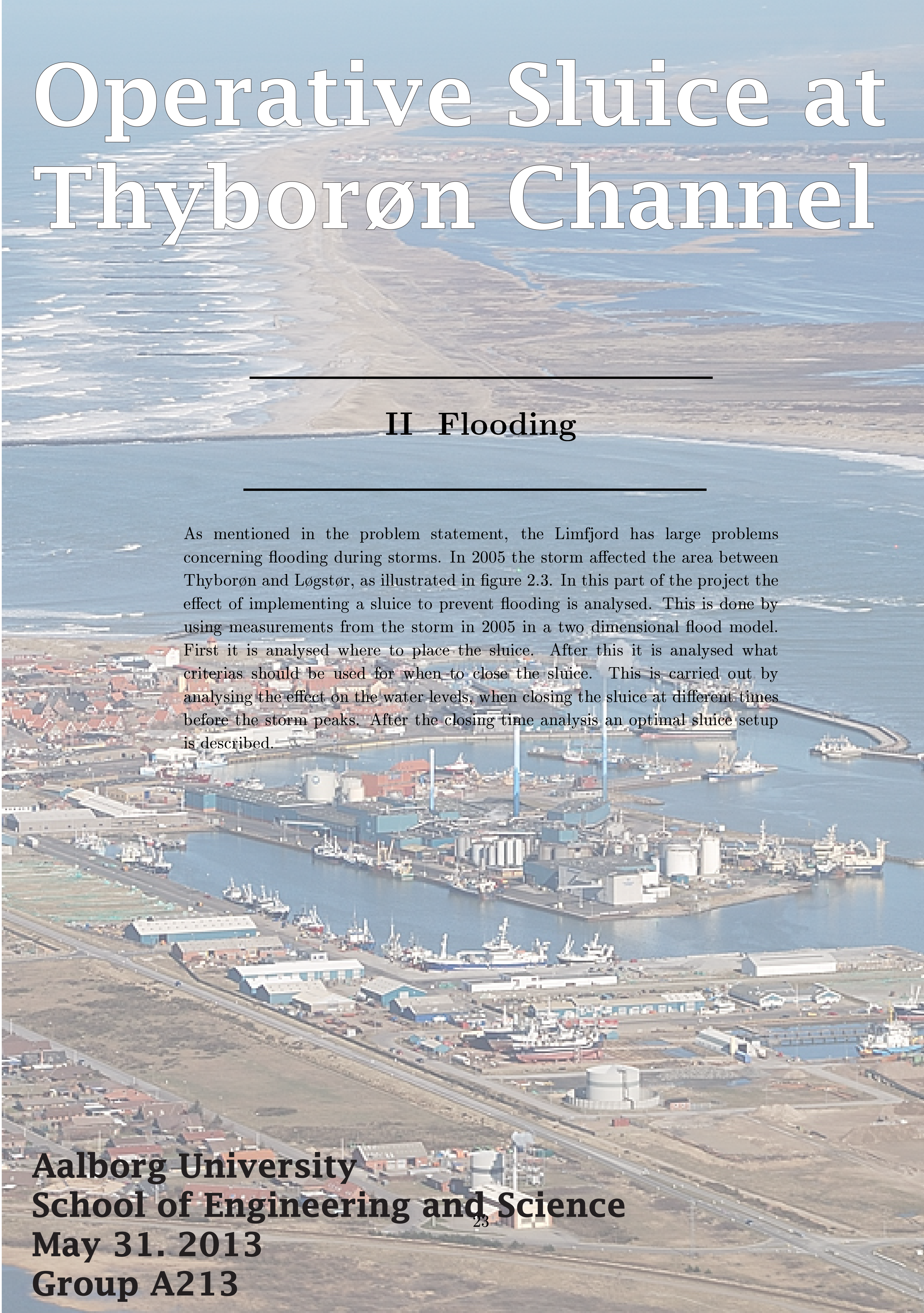

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II Flooding

As mentioned in the problem statement, the Limfjord has large problems concerning flooding during storms. In 2005 the storm affected the area between Thyborøn and Løgstør, as illustrated in figure 2.3. In this part of the project the effect of implementing a sluice to prevent flooding is analysed. This is done by using measurements from the storm in 2005 in a two dimensional flood model. First it is analysed where to place the sluice. After this it is analysed what criterias should be used for when to close the sluice. This is carried out by analysing the effect on the water levels, when closing the sluice at different times before the storm peaks. After the closing time analysis an optimal sluice setup is described.

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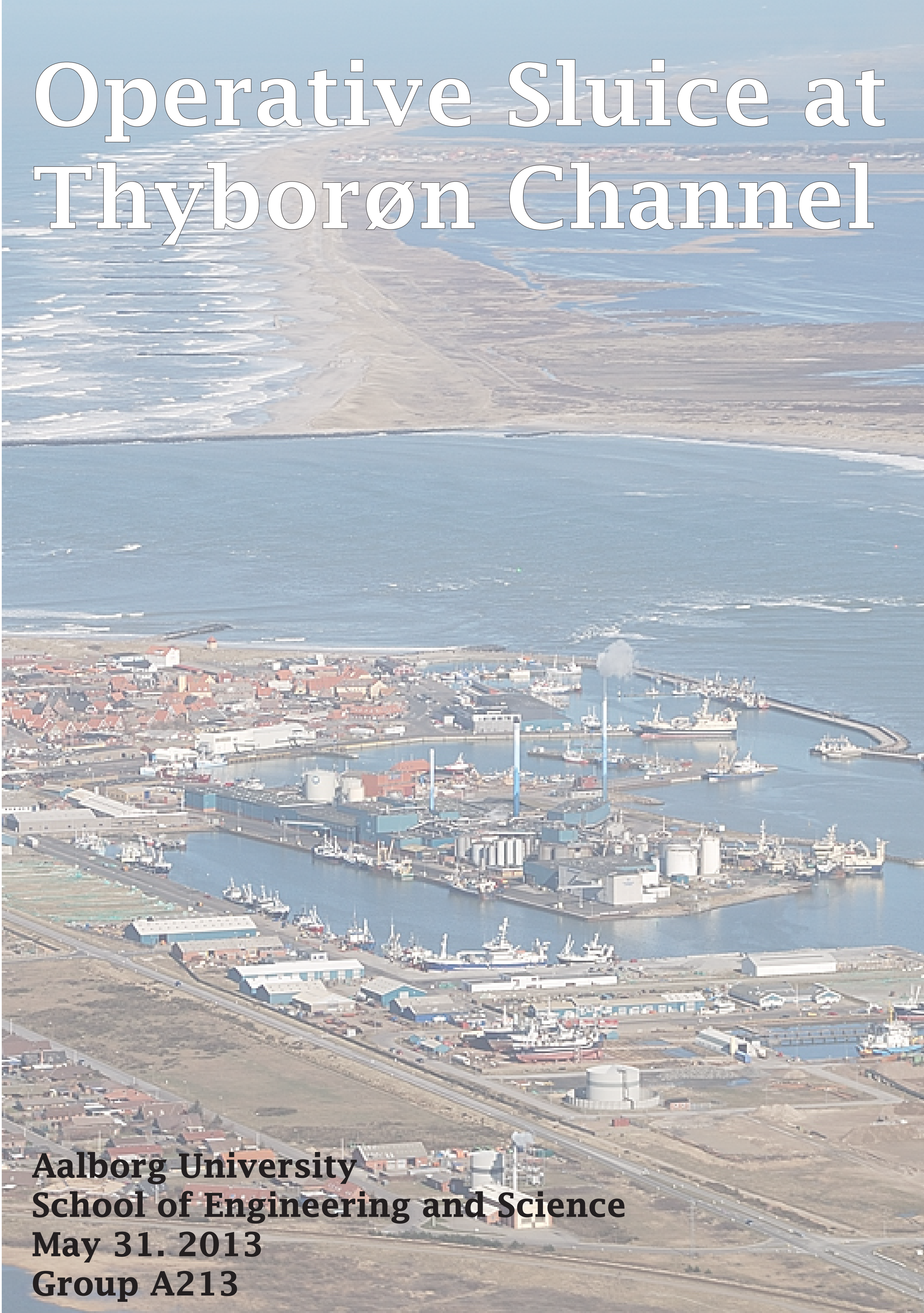

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5 Model Setup

To analyse different scenarios in respect to flooding, a Mike 21 model is created.

Mike 21 is a two dimensional model selection in the program called Mike Zero, which uses a numerical solution of the Reynolds Average Navier Stokes equation to calculate the flow parameters, further described in appendix D. Before any calculations can be done, a bathymetry of the Limfjord is made, describing the bathymetry of the Limfjord. This bathymetry consists of a triangular mesh where each note is assigned a depth corresponding to the scatter data. Hereafter the depths are interpolated between the notes. The grid size for the flood model is rough consisting of 2600 elements. This can be problematic if the grid cells are too large, and the triangles cover a total cross section of the fjord. This has in some areas resulted in very small depth as illustrated in figure 5.1. This can be solved by generating finer grid, but since this would increase the computational time, this is not desirable. Therefore the problem is solved by manually correcting the depths assigned to the problematic notes, this has been done several places in the fjord, and an example of a correcting is illustrated in figure 5.2

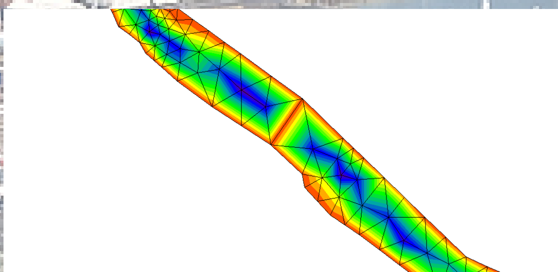

Figure 5.1: An area with small depths, the depth is increasing from red to blue.

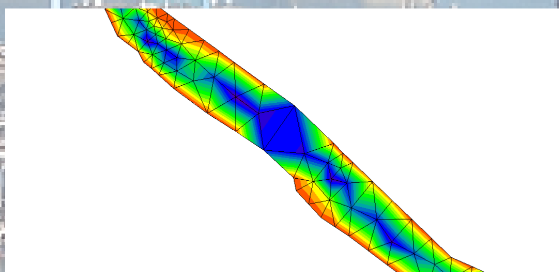

Figure 5.2: The same area where the depths have been corrected manually, the depth is increasing from red to blue.

On figure 5.2 it can be seen that the correction has resulted in too high depth. This is still a better solution than the low depth, which would have almost stopped the flow. To each side of the Limfjord there is assigned a boundary for the oceans. These boundaries are illustrated in figure 5.3.

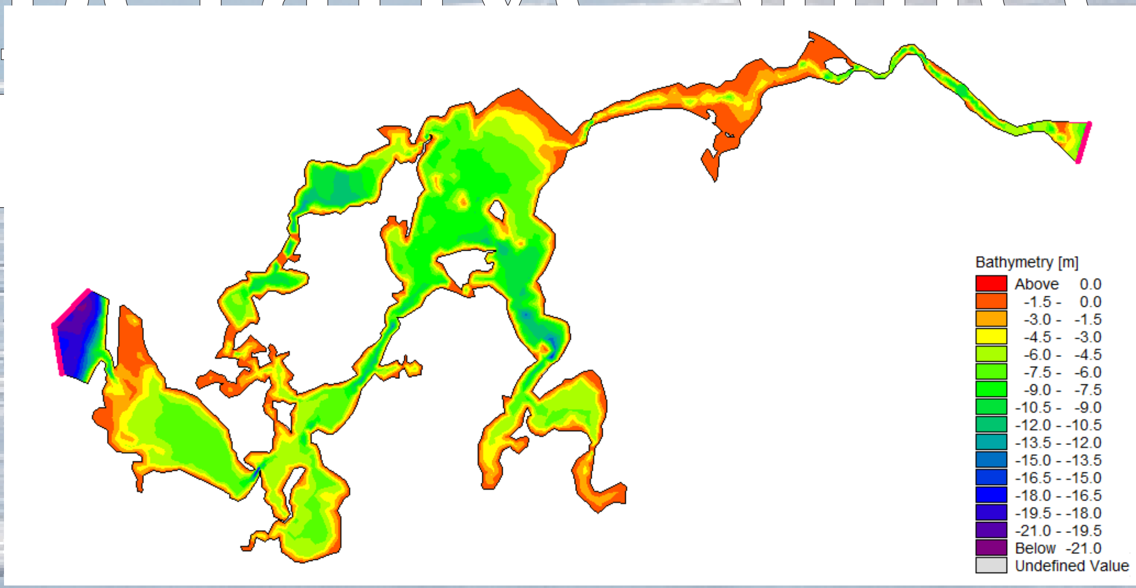

Figure 5.3: The bathymetry of the Limfjord used in the Mike 21 and the boundaries assign to each end.

The simulation period for the flood model is chosen to 14 days, from the 1^{st} to the 15^{th} of January, which corresponds to the period of the storm in 2005 including build up and the settling of the water after the storm. The time step is set to a maximum of 600 seconds for the model, which corresponds with most of the measured data.

5.1 The Hydrodynamic Model Setup

The hydrodynamic model includes of several elements, which have an influence on the flow. Two parameters with importance are the bed friction and the wind friction. The bed friction is described from the Manning number, where a number is assigned to each cell. These bed frictions are determined in section 5.1.1.

The wind forcing is constant in the domain but varying over time, the values are mean values of measurements of the wind speed from Hals and Thyborøn. The wind friction is the same for the entire grid, but is varying over time depended on the wind speed. The wind friction is increased by changing the drag coefficient (C_D) from the standard values of 0.0026 to 0.0045 for wind velocities above $25 m/s$, thereby better describing the effect of the maximum wind velocities. The value for the wind friction is from a case study, where the same data was used [Nørgaard et al., Not published].

The time dependent source input is, in the hydrodynamic model, the fresh water discharges from the streams connected to the Limfjord. The total amount of streams discharging to the Limfjord is combined in 31 sources. The sources location are illustrated in figure 5.4.

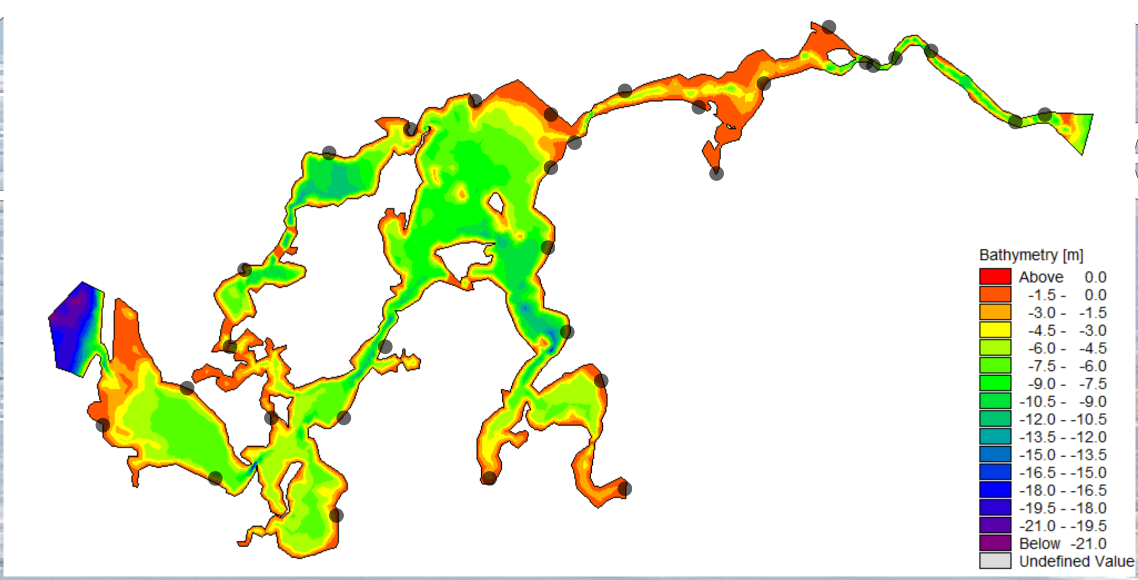

Figure 5.4: The streams location in the bathymetry to the Limfjord.

The two boundary conditions in each end of the fjord are assigned a water level, which varies in time. The two boundaries are measurements from Thyborøn and Hals. Apart from the two boundaries a land boundary surrounds the entire fjord. The land boundary works in principal as a vertical wall around the bathymetry, which means that the water level will stay in the Limfjord and not flood the surrounding areas.

5.1.1 Flood Model Calibration

The flood model is calibrated to make it capable to model the correct water level and flow. The data available for the calibration is the water level in Skive and Løgstør. There has not been used flow data for the fjord for calibrating the flows. But, since the water levels in the fjord are dependent of the flows, the flows are assumed correct if the water levels are correct. The calibration is then made by comparing the modelled with the water levels in the measurement stations in Løgstør and Skive.

For the first simulation, the model is run with a Manning number of $55 m^{1/3}/s$ for the entire grid, corresponding earthy channel. This resulted in too low modelled peaks, but peaking at the correct time compared with the measured water levels. Therefore the Manning number in the eastern part of the fjord was decreased to a value of $30 m^{1/3}/s$, which will increase the water level in the rest of the fjord. The chosen values for the bed friction are illustrated in figure 5.5.

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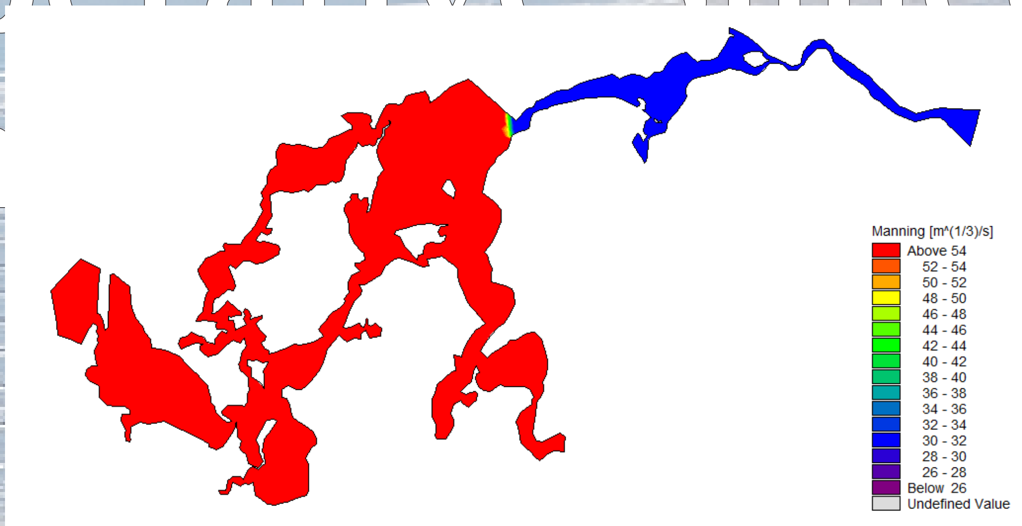

Figure 5.5: The bed friction in Manning numbers of the Limfjord.

The result from the new bed friction minimizes the errors between the measured and the modelled water levels. The measured and the calculated water levels for Løgstør are illustrated in figure 5.6.

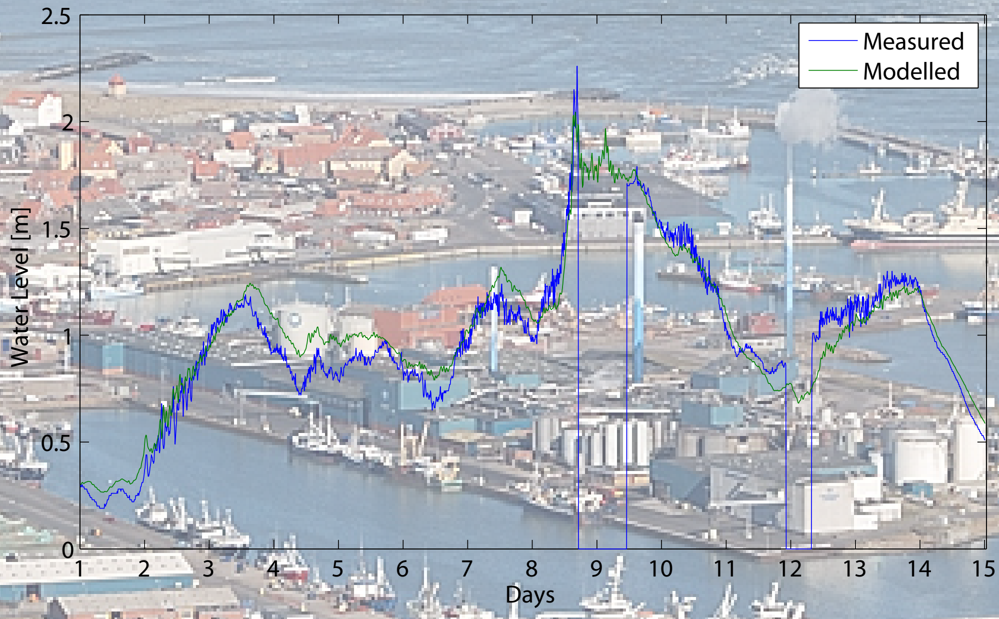

Figure 5.6: Modelled and measured water levels for Løgstør from the 1^{st} to the 15^{th} January.

From the figure it can be seen that the model is close to the maximum measured water level. The difference from the modelled and measured maximum peak is approximately $0.2m$. This should be taken into account when analysing the results in the different scenarios.

The modelled water levels for Skive after the calibration are illustrated in figure 5.7.

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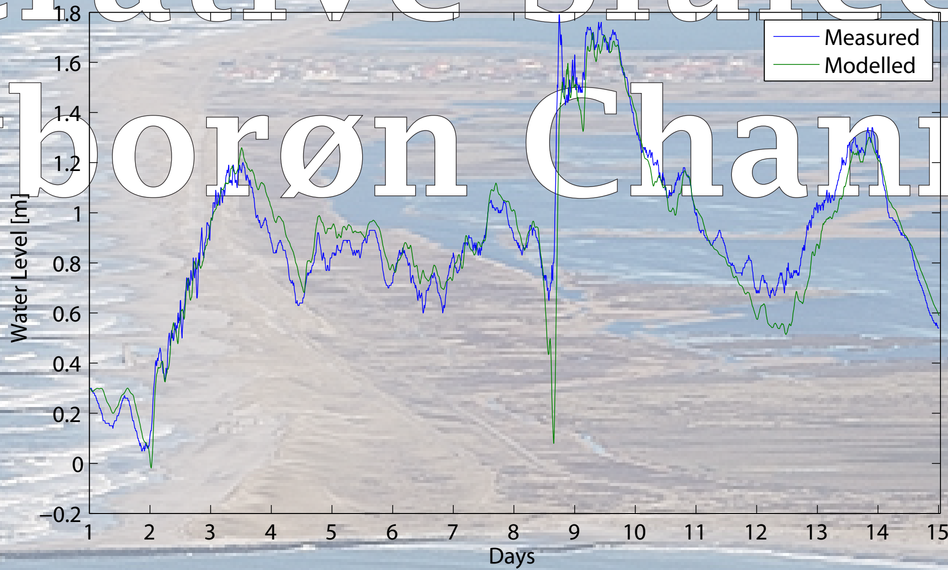

Figure 5.7: Modelled and measured water levels for Skive.

In figure 5.7 it can be seen that the water level during the peak of the storm has not been possible to model. The reason for this might be that the wind friction is set very high in order to get a sufficient flow through the fjord. But this also result in a very big build up in this area, removing the water from the measurement station illustrated in figure 5.8 and thereby making the modelled water levels too low.

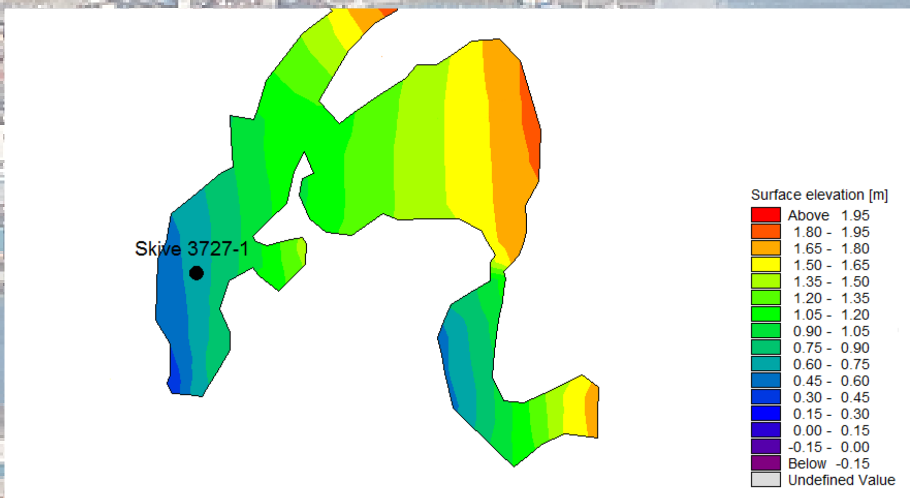

Figure 5.8: Modelled water levels in the area of Skive during the strongest wind speeds ($31 m/s$).

Although there are problems with calculating the highest peak, the maximum value is not that wrong, since the water is "released" when the wind speeds decreases.

This should be taken into consideration when investigating the scenarios. The accuracy of the model is assumed high enough, to investigate scenarios in respect to storm surge protection.

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5.2 Sluice Setup

The sluice has two functions. The first one of the sluice is the ability to close completely before and during a storm. The second function is to ensure one direction flow, so the flow is only from the North Sea into the Limfjord. To do this, the sluice setup is using two structures in the model. The first structure is a culvert, which defines a hollow cross section, where the water flow direction can be assigned. The rest of the cross section is solid and not allowing water to flow. The second structure is a gate, which makes it possible to close the sluice for a period. The implementations of the two structures are not changing the bathymetry, but assigned as a parameter for the cells in the cross section.

5.2.1 Culvert Setup

The sluice has a width of $15m$ and the culverts have a cross section area of $36m^2$. The position of the bottom of the culvert is set $6m$ below zero. The Manning Number describing the roughness through the culvert is set to $77m^{1/3}/s$ and the head loss factor for each culvert is set to 0.3 at the inlet and 0.8 at the outlet. The culvert setup is ensuring a one direction flow, so the water is only flowing into the Limfjord.

5.2.2 Gate Setup

The gate is implemented, since the culvert is unable to have both one direction flow and no flow. The gate setup is carried out by first determining the position of the gate and then creating a time series, which regulates when the gate is opened and closed.

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6 Location of the Sluice

In this chapter it is be investigated whether the sluice should be located west or east of Thyborøn. In order to determine where the sluice should be located, the two locations are analysed regarding flooding at Thyborøn. The two locations are compared with a reference scenario, where the current conditions are used.

The input data for the flood model is water levels and wind speed from the storm the 8^{th} of January 2005, where extreme water levels were measured at Thyborøn Harbour and the rest of the Limfjord. Furthermore, the scenarios are analysed in respect to a future scenario with extrapolated data for wind speed and water levels in 2100.

On basis of the Danish Coastal Authority it is assumed that serious flooding will occur in Thyborøn at water levels of $2.05m$ [Kystdirektoratet, 2010]. If the modelled water does not exceed the flooding criteria, flooding could still occur in some extent.

6.1 Reference Scenario

The reference scenario is modelled with the conditions as they were in 2005. Furthermore, the reference scenario describes the conditions in 2100 due to global warming. To simulate this, the water level and wind speed has been increased. The water level at the boundary conditions is increased with $0.4m$ and the wind speed is increased with 5% [Nørgaard et al., 2012]. The results from this scenario will then be compared with the two different locations, and thereby illustrating the effects of the sluice locations.

6.2 Sluice Located East of Thyborøn

The reason for locating the sluice east of Thyborøn is that it would still be possible to use Thyborøn Harbour as an emergency harbour. Hereby ships can seek shelter during storms. The location of the sluice is illustrated in figure 6.1.

With the sluice implemented, the cross section area where the water can flow will be smaller, than the original cross section of the channel. The cross section of the sluice, where water can move, is determined by the number of culverts placed in the sluice. The total amount of culverts used in these scenarios is 168, which corresponds to an effective cross section area of $6{,}048m^3$, which is approximately 80% of the smallest cross section of the channel. The reason for using this effective cross section is that the sluice itself will

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not limit the inflow to the fjord a lot. Hereby the water level is almost only affected by closing the sluice.

The storm peaked with the highest mean wind speeds in 10 minutes of $31m/s$, the 8^{th} of January at 16:30. In this scenario, the sluice is closed the first time the mean wind in 10 minutes is above $20m/s$, which was 3 hours and 50 minutes before the storm peaked.

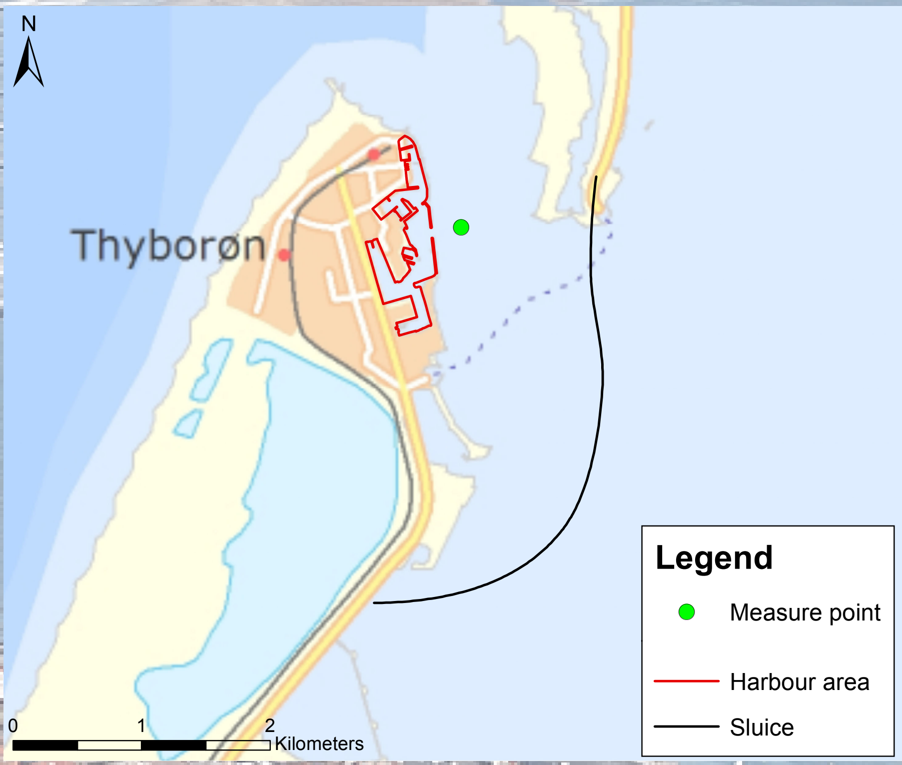

Figure 6.1: The location of the sluice east of Thyborøn and the measure point for water levels.

A downside by implementing the sluice east of Thyborøn is that the city is not protected against flooding. Therefore it is investigated whether the water level will exceed the critical water level at Thyborøn both for 2005 and the future scenario.

6.3 Sluice Located West of Thyborøn

It is investigated if Thyborøn can be protected against flooding if the sluice is located west of Thyborøn. In figure 6.2 the location of the sluice west of Thyborøn is illustrated. By placing the sluice west of Thyborøn, the harbour can no longer function as an emergency harbour during storms. The sluice has the same effective cross section and closing time as explained in section 6.2, and is also investigated with data from both 2005 and the extrapolated storm for 2100.

Due to the increased wind friction explained in section 5, the used flood model is very wind dependent illustrated in figure 5.8 on page 29. This result in a high gradient on the water surface, therefore the modelled water levels in the harbour are too low.

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In order to get around this problem, the sluice and the water level measurement point had to be adjusted. This was done by moving the sluice and the measurement point for the water level at Thyborøn further out of the channel. In figure 6.2 a sketch is illustrating the model location and intended location.

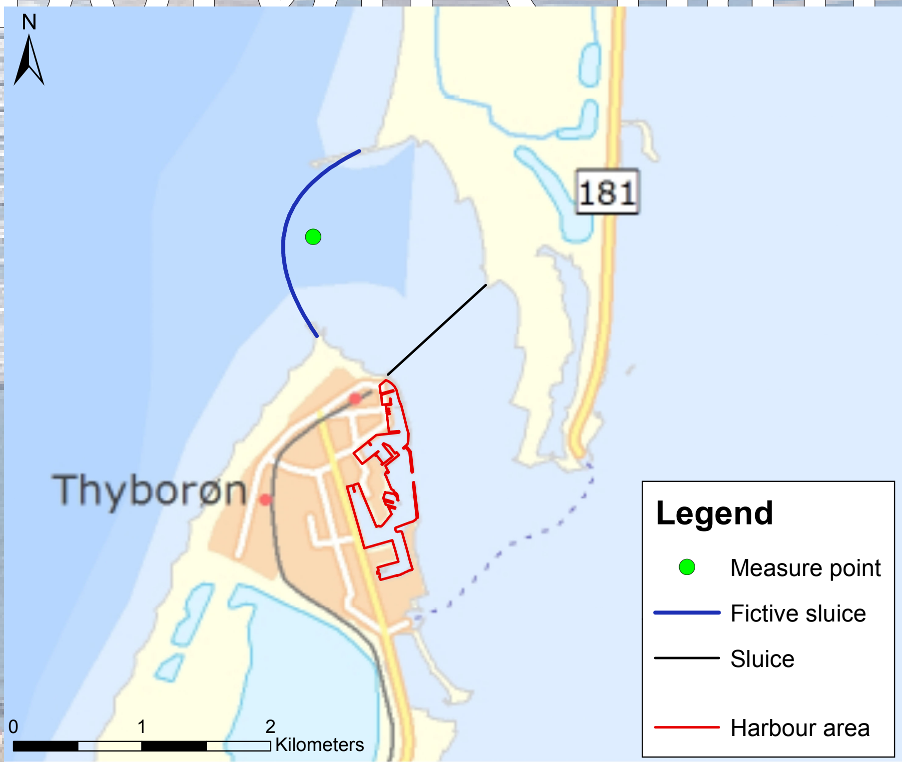

Figure 6.2: Sketch of the intended and model location for the sluice and the measuring point.

6.4 Results

The highest water levels modelled in the reference scenario in 2005 and the extrapolated data are presented in table 6.1.

Thyborøn	$[m]$
Water level, 2005	2.02
Water level, 2100	2.34
Flooding criteria	2.05

Table 6.1: Water levels at Thyborøn with the current conditions in 2005 and in 2100 with climate changes along with flooding criteria.

The reference scenario shows that with the current conditions flooding will not occur at Thyborøn since the highest modelled water level at Thyborøn is below the flooding criteria. This corresponds well with actual measured water level at Thyborøn during the storm which was $1.97m$. Though the modelled water level from 2005 ($2.02m$) are close to the flooding criteria ($2.05m$).

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In 2100 the modelled water level ($2.34m$) shows that flooding will occur at Thyborøn, if nothing is changed from the way it is today since it exceeds the flooding criteria.

For both sluice locations the highest modelled water levels in Thyborøn along with the flooding criteria is presented in table 6.2.

Sluice location	**Thyborøn**
Water level, 2005	
- East	2.96 [m]
- West	-0.88 [m]
Water level, 2100	
- East	3.35 [m]
- West	-0.37 [m]
Flooding	2.05 [m]

Table 6.2: Water level at Thyborøn with the sluice located east and west of Thyborøn, both for the current conditions in 2005 and in 2100 with climate changes.

If the sluice is located east of Thyborøn, the water level at Thyborøn will exceed the flooding criteria. This is the case both with the current conditions and in 2100. In 2005 the modelled water level is $0.91m$ above the criteria. If the sluice is located west of Thyborøn, the city is protected against flooding for both the storm in 2005 and with the extrapolated data for 2100.

6.4.1 Discussion/Conclusion

If Thyborøn should be protected by the sluice, the location needs to be west of Thyborøn. If the sluice is located east of Thyborøn additional storm surge protection should be constructed, but this would ensure Thyborøns function as an emergency harbour. Whether the value of maintaining the emergency harbour is worth the additional cost of storm surge protection is unknown. The primary aim of the sluice is to protect against flooding, and therefore the western location is chosen.

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7 Operation of the Sluice

In this chapter it is analysed how the sluice should be operated to avoid flooding. In Chapter 6 the best location for the sluice was determined to be West of Thyborøn, and therefore this location is used in this analysis. The exact location of the sluice has a very small influence on the water levels in the fjord, and therefore this investigation will also be valid if it should be chosen to locate the sluice East of Thyborøn.

It is analysed how the closing of the sluice will affect the water levels in the fjord. By closing the sluice before the storm strikes, the thought is that a build-up of water can be avoided, resulting in lower water levels during the storm. To figure out when to close the sluice different scenarios are made with different closing periods of the sluice. The previously described reference scenario is used to compare with the results with the storm in 2005 and the extrapolated scenario for 2100 for the entire fjord.

To analyse the consequences regarding closing time of the sluice, the highest modelled water level is presented for (Løgstør, Skive and Nissum) during the storm the 8^{th} of January. The location of the three different measurements points are presented in figure 7.1.

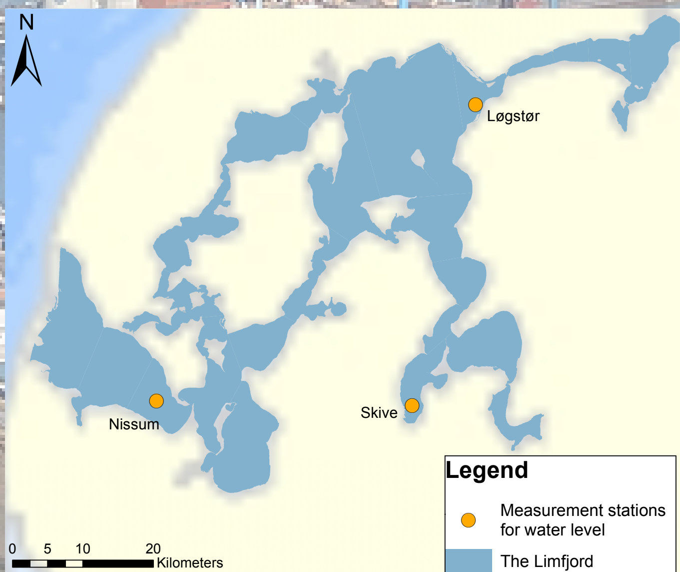

Figure 7.1: Location of the measurement stations for which the water levels are compared.

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In order to investigate if the sluice prevents serious flooding in the Limfjord, water levels where flooding occur for the different areas are determined. These levels are determined from the Danish Coastal Authority who has made, a flooding criteria for areas around the fjord. These water levels are used as criteria for when flooding will occur and are listed in table 7.1.

Places	Water level
Løgstør	1.90 m
Skive	1.90 m
Nissum	1.90 m

Table 7.1: Water levels where flooding will occur at the different measurement stations. [Kystdirektoratet, 2010]

The locations investigated are the ones listed in the table. The choice of these locations are chosen because the model is calibrated for Løgstør and Skive, and because it is desired to describe the flooding in the western part of the fjord, since the eastern part was not affected during the storm, illustrated in figure 2.3 on page 11.

7.1 Operation Analysis

In this section, it is analysed how the water levels are related to when the sluice is closed before the storm peaks. The first investigated scenario is with the sluice opened during the storm, and thereby only limiting the flow into the fjord because of the smaller effective cross section. In the rest of the scenarios the sluice is closed from 1 and up to 7 days before the storm peaks, and kept closed until one day after the storm has peaked. This interval is chosen, because the data used is from the 1^{st} of January and the storm is the 8^{th}.

7.2 Results

In this section the results for the scenarios are presented.

The water levels modelled in the reference scenario are listed in table 7.2.

Measurement station	Water level, 2005 [m]	Water level, 2100 [m]	Flooding criteria [m]
Løgstør	2.04	2.50	1.90
Skive	1.72	2.17	1.90
Nissum	1.86	2.31	1.90

Table 7.2: Water level at the measurement stations with the current conditions in 2005 and the extrapolated data for 2100 with climate changes along with flooding criteria.

The modelled water level in Løgstør for the reference scenario shows that serious flooding occurred during the storm in 2005 where the modelled water level (2.05m) is above the flooding criteria of 1.90m. This was also the case during the storm in 2005, where the

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measured water level was 2.26m but as explained in section 5.1.1 the model have some difficulties modelling the peaks.

The modelled water level at Nissum is close to the flooding criteria. Therefore flooding could potentially occur in Nissum as well.

With the extrapolated data for 2100, flooding will occur in all the measurement stations. The modelled water levels are 0.27-0.60m above the flooding criteria, which implies serious flooding.

In figure 7.2, 7.3 and 7.4 the modelled water levels for the measurement stations with different closing days of the sluice in 2005 and extrapolated data for 2100 are compared with the flooding criteria.

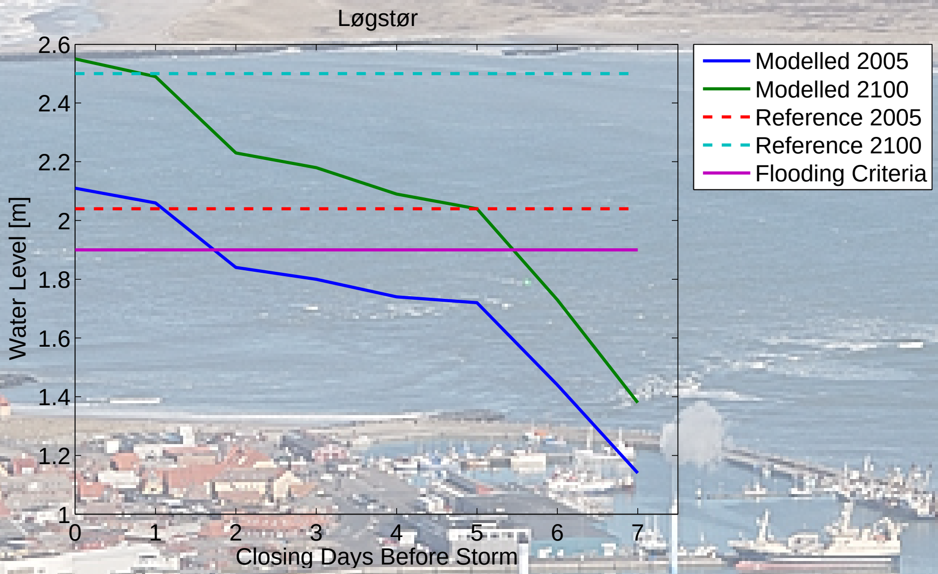

Figure 7.2: Modelled water levels at Løgstør in 2005 and 2100 data for different closing days, and the flooding criteria.

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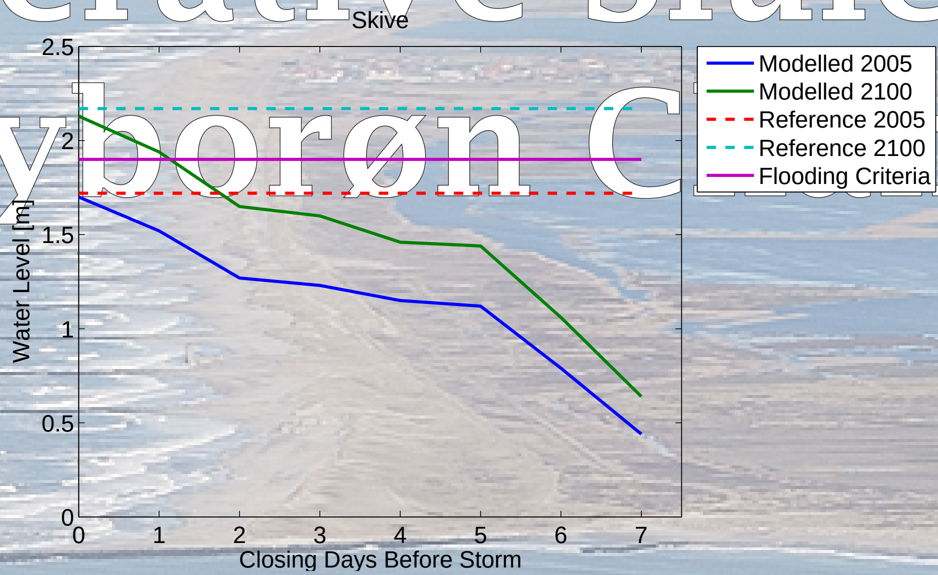

Figure 7.3: Modelled water levels at Skive in 2005 and 2100 data for different closing days, and the flooding criteria.

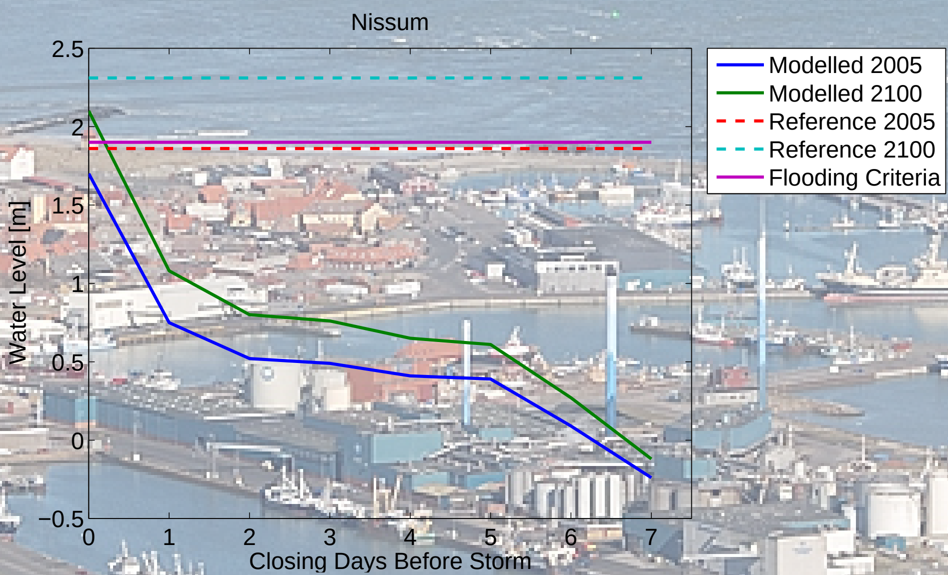

Figure 7.4: Modelled water levels at Nissum in 2005 and 2100 data for different closing days, and the flooding criteria.

The results shows, that by implementing a sluice at Thyborøn, the water level could be lowered. Since the sluice has a smaller cross section area than the channel, the amount of water flowing into the fjord is decreased. Figure 7.3 and 7.4 illustrates that only by implementing the sluice and not close it, the flooding might be prevented in Skive and Nissum for the conditions in in 2005.

In figure 7.2 it can be seen that the sluice has to be closed two days before the storm, to prevent flooding in Logstør with the conditions in 2005. With extrapolated data for 2100

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the sluice should be closed six days before to prevent serious flooding.

Figure 7.4 shows that to prevent flooding in Nissum with the 2100 data the sluice should be closed one day before the storm peaks.

These assumptions are made without taking the uncertainties of the model into account.

7.2.1 Discussion/Conclusion

The extent of flooding is very dependent on the build-up in the fjord before the storm. The storm in 2005 had a long period with wind from the west, which resulted in high water levels in the fjord. With this westerly wind, the sluice's potential for preventing flooding is good, since it can limit or prevent the water build-up in the fjord before the storm. If the wind direction before the storm was from the east, the effect of closing the sluice before the storm might increase the potential of flooding. The wind direction before a storm should therefore be taken into account before closing the sluice.

The results from the different closing periods showed significant effect on the water levels in the fjord. These results are without taking the missing water level heights from the calibration into account. Furthermore, the extent of flooding is also unknown for the rest of the Limfjord, but since the calibration is only based on Skive and Løgstør, the precision of the model in the rest of the fjord is unknown. A validation of the model is needed to make a full investigation of flooding in the Limfjord and the effect of implementing a sluice. Furthermore, the effect of waves is not included, which would result in wash up and potential lead to flooding in some areas. The results used from the model are still considered valid for investigating the effect of the sluice.

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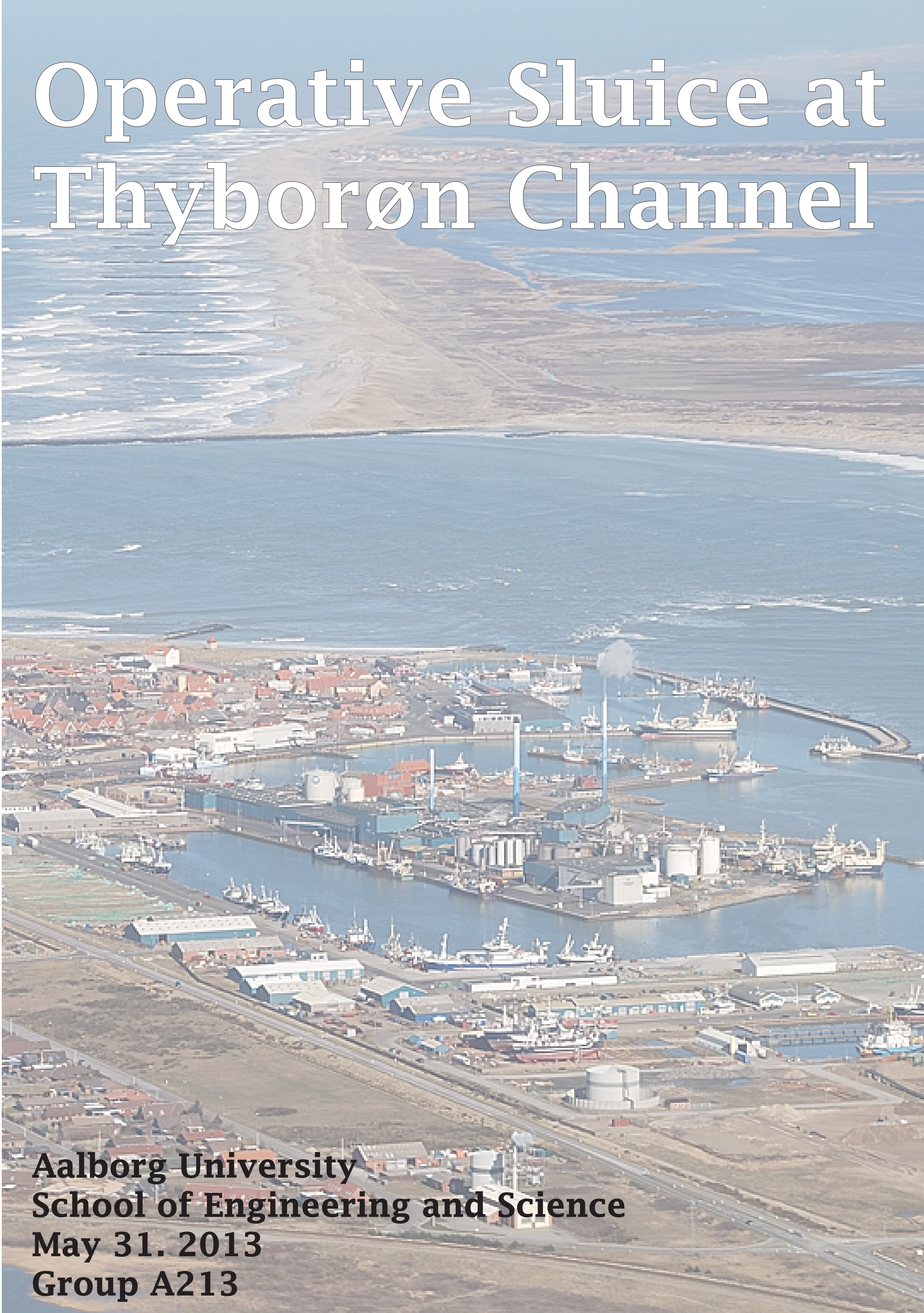

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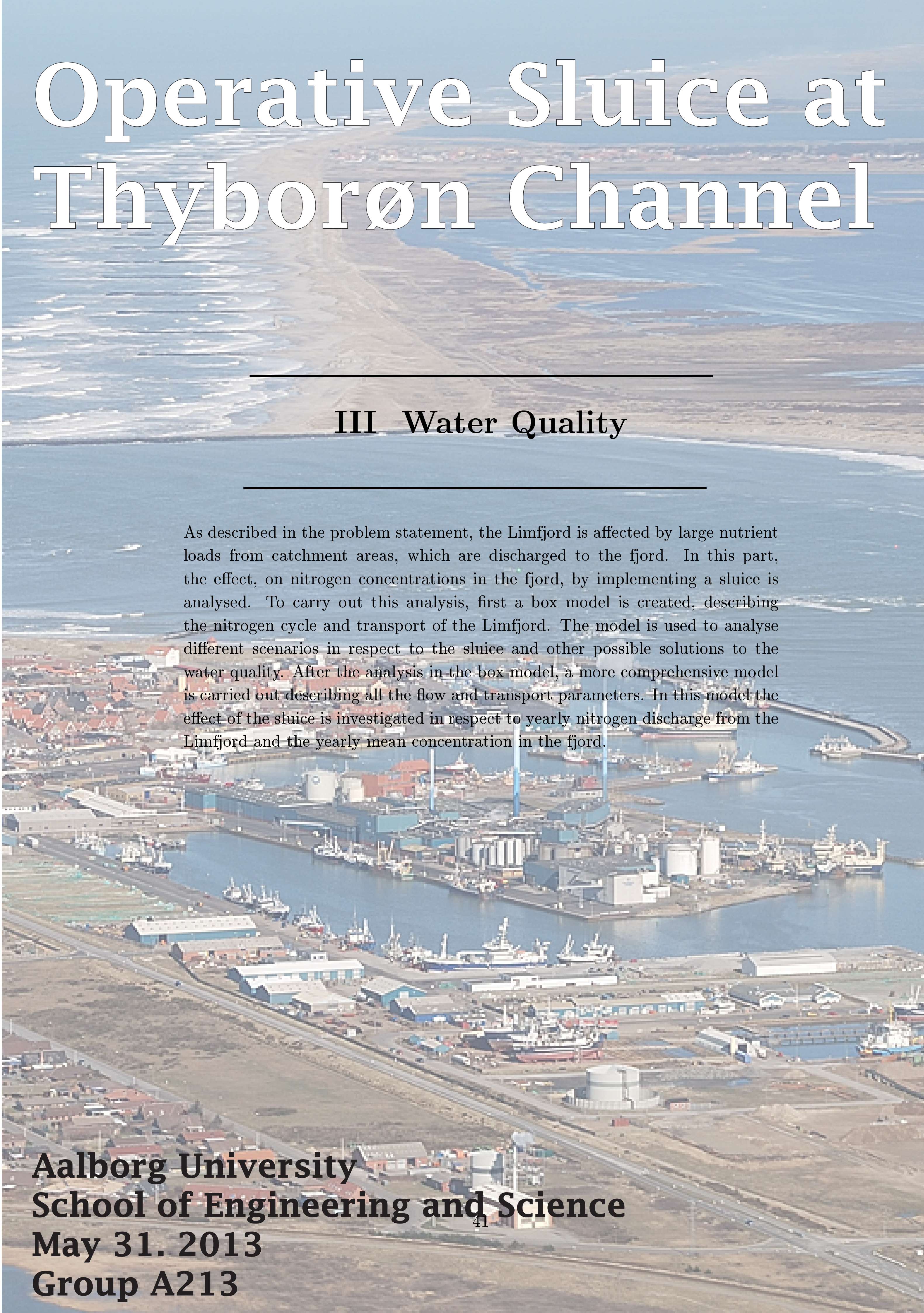

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III Water Quality

As described in the problem statement, the Limfjord is affected by large nutrient loads from catchment areas, which are discharged to the fjord. In this part, the effect, on nitrogen concentrations in the fjord, by implementing a sluice is analysed. To carry out this analysis, first a box model is created, describing the nitrogen cycle and transport of the Limfjord. The model is used to analyse different scenarios in respect to the sluice and other possible solutions to the water quality. After the analysis in the box model, a more comprehensive model is carried out describing all the flow and transport parameters. In this model the effect of the sluice is investigated in respect to yearly nitrogen discharge from the Limfjord and the yearly mean concentration in the fjord.

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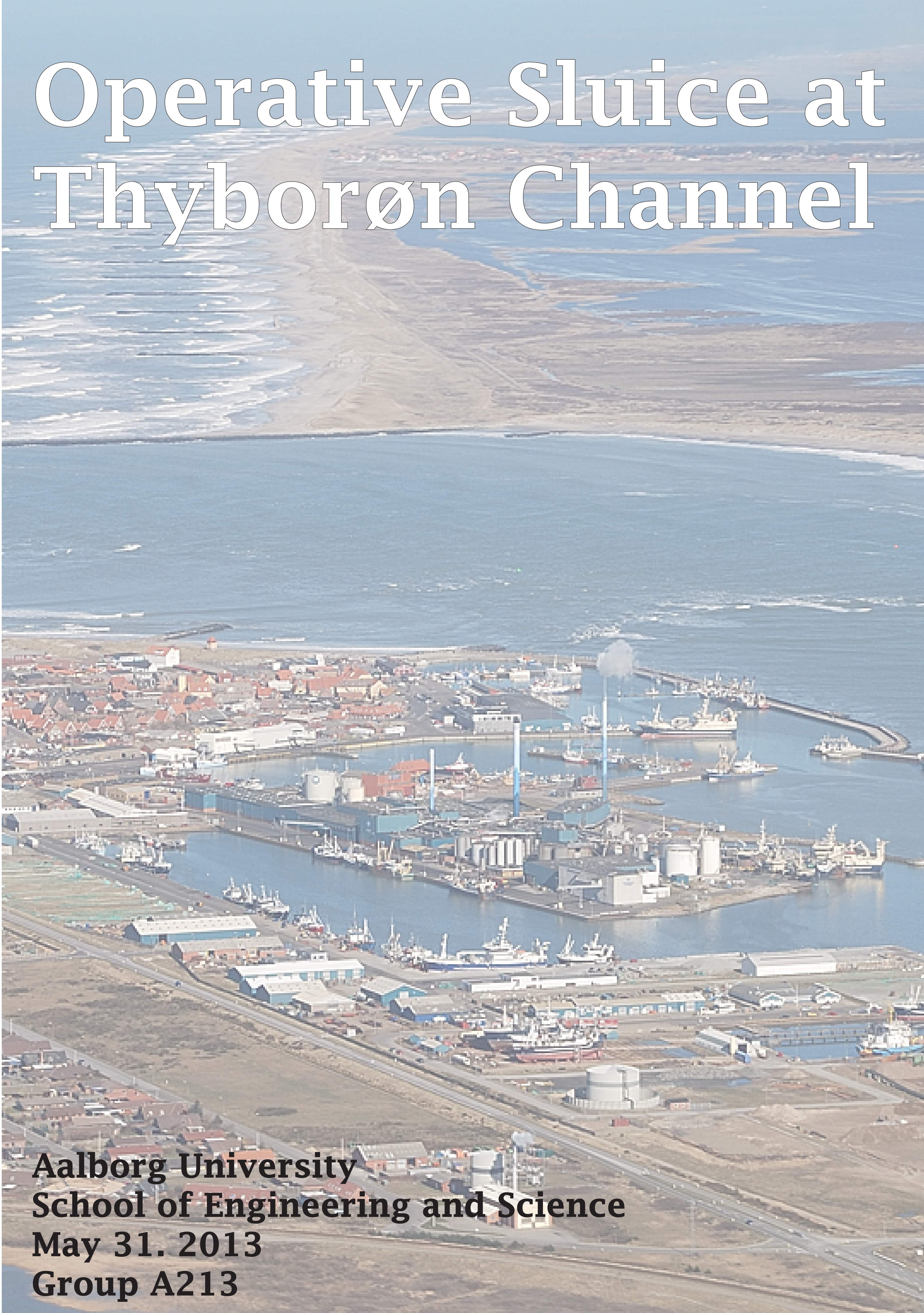

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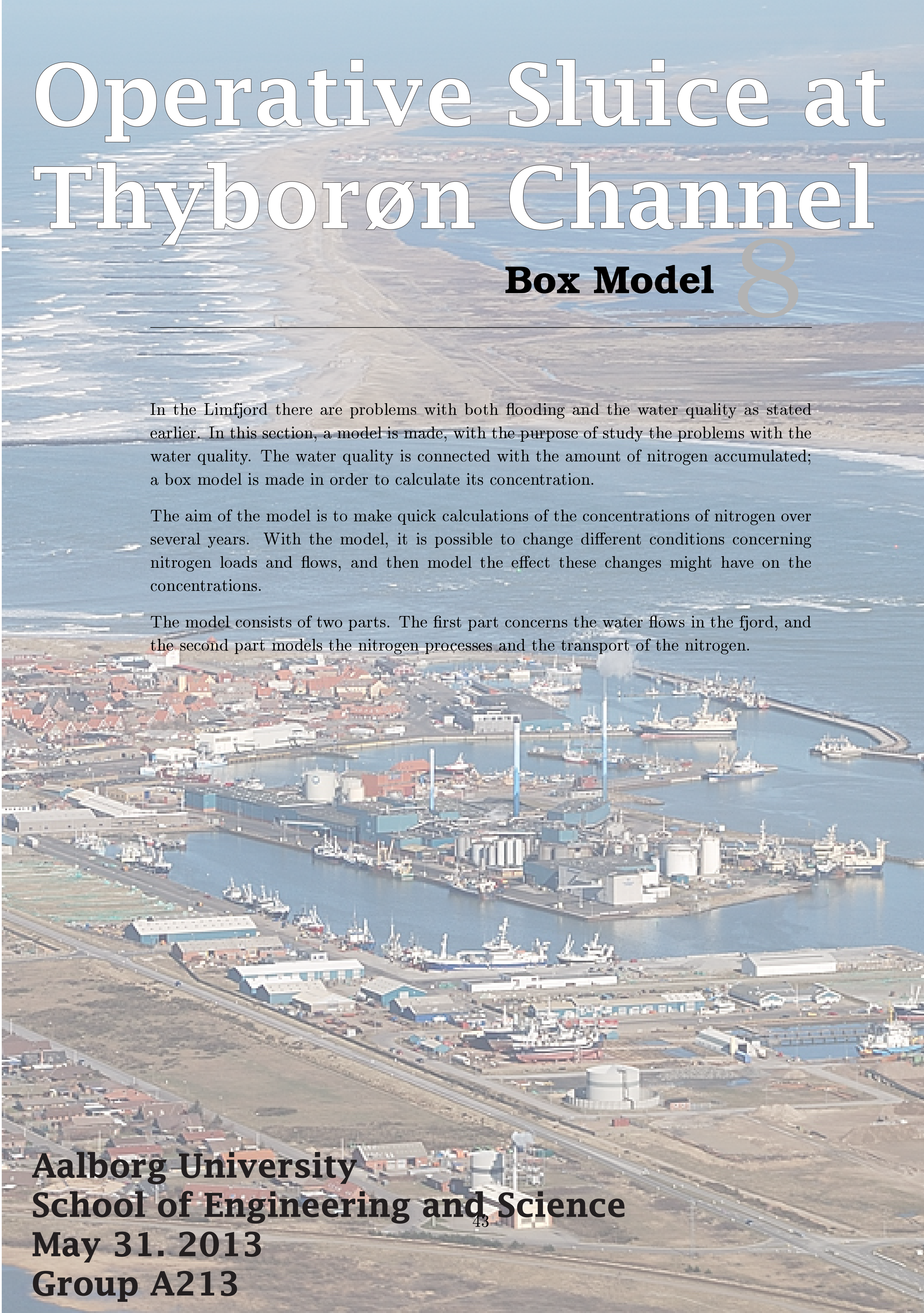

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8 Box Model

In the Limfjord there are problems with both flooding and the water quality as stated earlier. In this section, a model is made, with the purpose of study the problems with the water quality. The water quality is connected with the amount of nitrogen accumulated; a box model is made in order to calculate its concentration.

The aim of the model is to make quick calculations of the concentrations of nitrogen over several years. With the model, it is possible to change different conditions concerning nitrogen loads and flows, and then model the effect these changes might have on the concentrations.

The model consists of two parts. The first part concerns the water flows in the fjord, and the second part models the nitrogen processes and the transport of the nitrogen.

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8.1 Box Setup

The model is set up as a box model based on conservation of volume and soluble matters. The Limfjord is divided into six boxes, each of them describing different areas of the fjord. The areas used for the model are illustrated in figure 8.1.

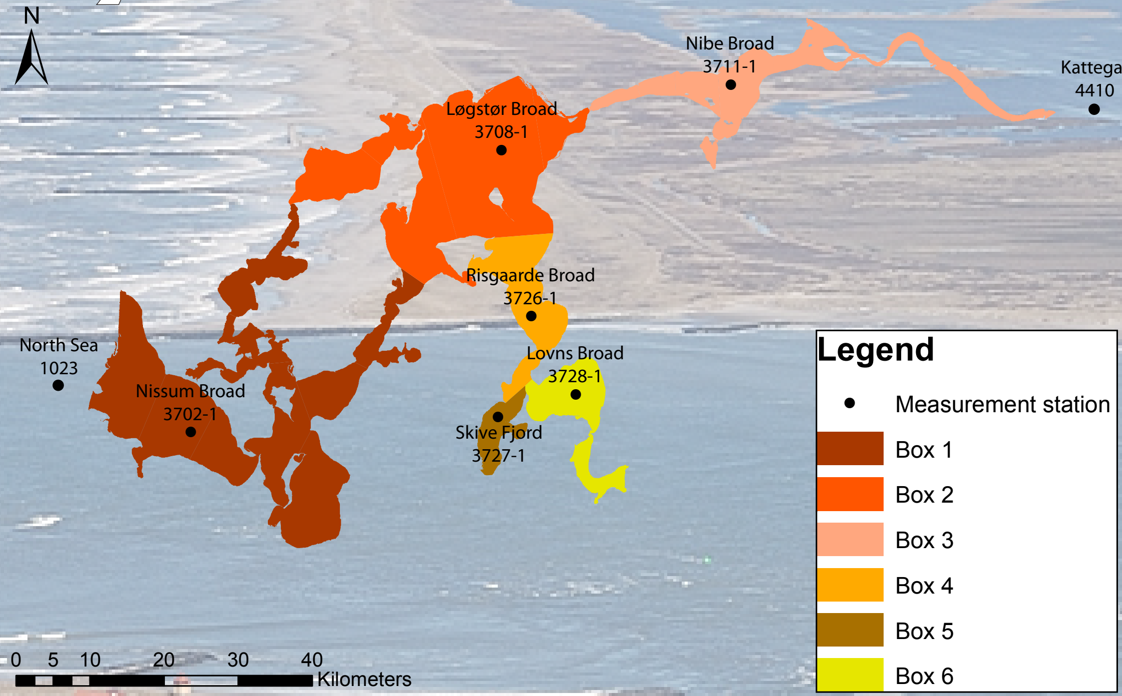

Figure 8.1: Areas of the boxes used in the box model and the measurement stations from which data is used.

The boxes have been divided according to the geography. Boxes 1 and 2 are broad areas, while Box 3 is a narrow channel. Boxes 4, 5 and 6 are smaller and represent the inner part of the fjord. A reason for using this division is that there are only six stations with measurements of the salinity, which are used for calibration, situated in the different boxes, illustrated in figure 8.1.

The volume of the different boxes is determined as the mean depth times the surface area. The surface areas are determined in ArcMap from polygons and the mean depths from scatter points in Mike Zero [Bentzen, 2013]. The mean depth, surface area and volume of each box are listed in table 8.1.

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Box	Mean depth $[m]$	Surface area $[km^2]$	Volume $[m^3]$
1	4.73	594	$2.81 \cdot 10^9$
2	6.01	504	$3.03 \cdot 10^9$
3	2.19	180	$3.94 \cdot 10^8$
4	7.91	116	$9.15 \cdot 10^8$
5	3.24	38	$1.24 \cdot 10^8$
6	3.80	94	$3.56 \cdot 10^8$

Table 8.1: The mean depth, surface area and volume of the boxes used in the box model.

The determined total surface area is 1,526 km^2 and the total volume is $7.63 \cdot 10^9$ m^3.

The model is made with time steps of one hour. This means that all processes and flows are calculated as a mean over one hour. This can be done since the aim of the model is to model the changes over long time periods.

8.2 Flow Model

The first part of the model is the flow model. The flow in the Limfjord is controlled by several elements, where the ones of biggest importance is the wind, tide and the discharges from rivers. The principle of the box model regarding the flows is illustrated in figure 8.2.

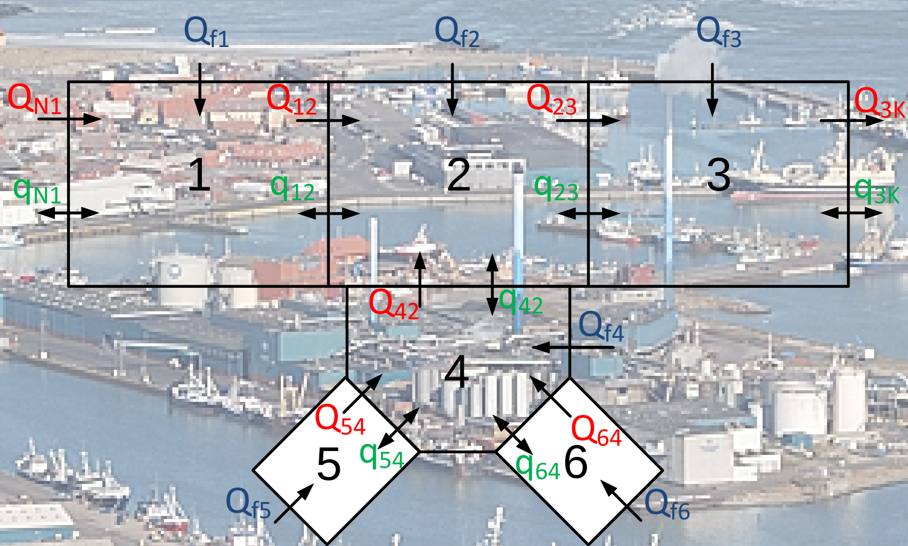

Figure 8.2: Principle of the box model regarding the flows. The 'q's' (green) are exchange flows, Q_f (blue) are fresh water flows into the system, and the flows Q (red) are determined flows as a result of wind and fresh water discharge.

Figure 8.2 illustrates all the fresh water flows into the model, the net flows controlled by the wind and the exchange flows, mainly controlled by the tide.

The flow from the tides is assumed to be a flow of the same size in both directions between two adjacent boxes, depending if the tide is high or low. The effect of the exchange flows is described later on.

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The inflows from the streams to the fjord are determined in 31 catchment areas, where time series are available for the entire year of 2005 [Bentzen, 2013]. The discharge from the streams is added to their respective box for each time step.

The flow due to the wind is determined in the cross section between Box 2 and 3 at Aggersund the location is illustrated in figure 8.3). The flow is determined by the following equation.

$$Q_{23} = W \cdot C_{wind} \cdot A$$

Q_{23}	Water flow at Aggersund	$[m^3]$
W	Projected wind speed	$[m/s]$
C_{wind}	Wind factor	$[-]$
A	Area of cross section between Box 2 and 3	$[m^2]$

The reason why this equation can be used is because the wind factor is a constant, as well as the cross section area is assumed to be constant. Therefore the flow is only linearly depending on the wind. This is further described in Appendix A.1.

The cross section area at Aggersund between Box 2 and 3 is the smallest in the model. Since this is the smallest cross section in the fjord, it limits how much water that can pass through the fjord. The small area at Aggersund is illustrated in figure 8.3. The projected wind speed is the measured wind speed projected to an angle of 65°, illustrated on figure 8.3.

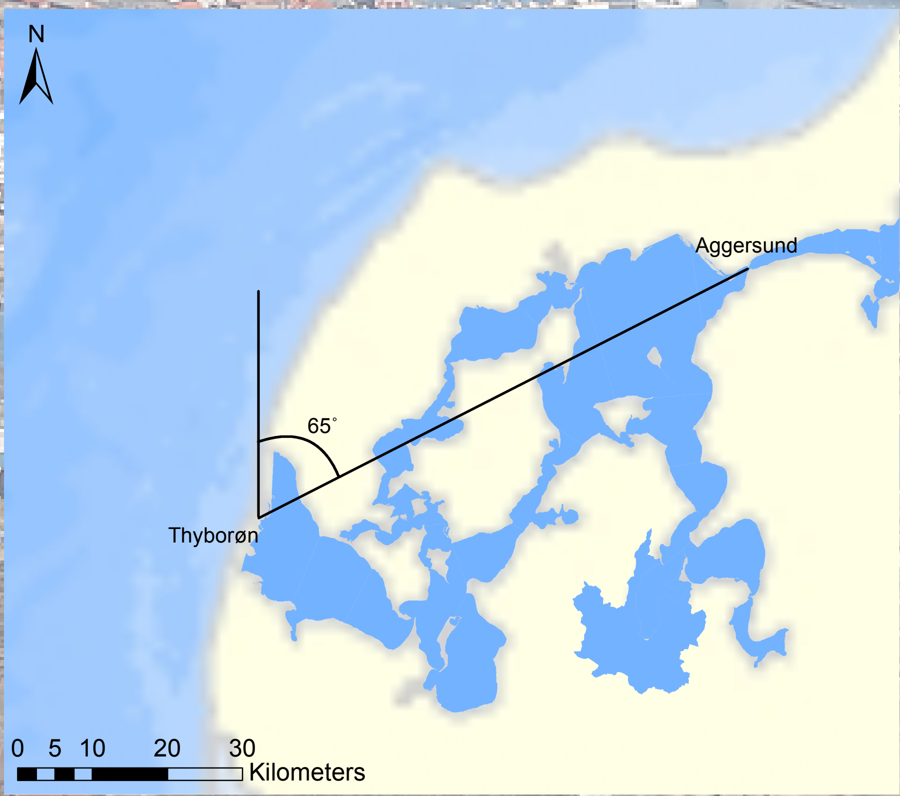

Figure 8.3: Angle to which the measured wind data is projected.

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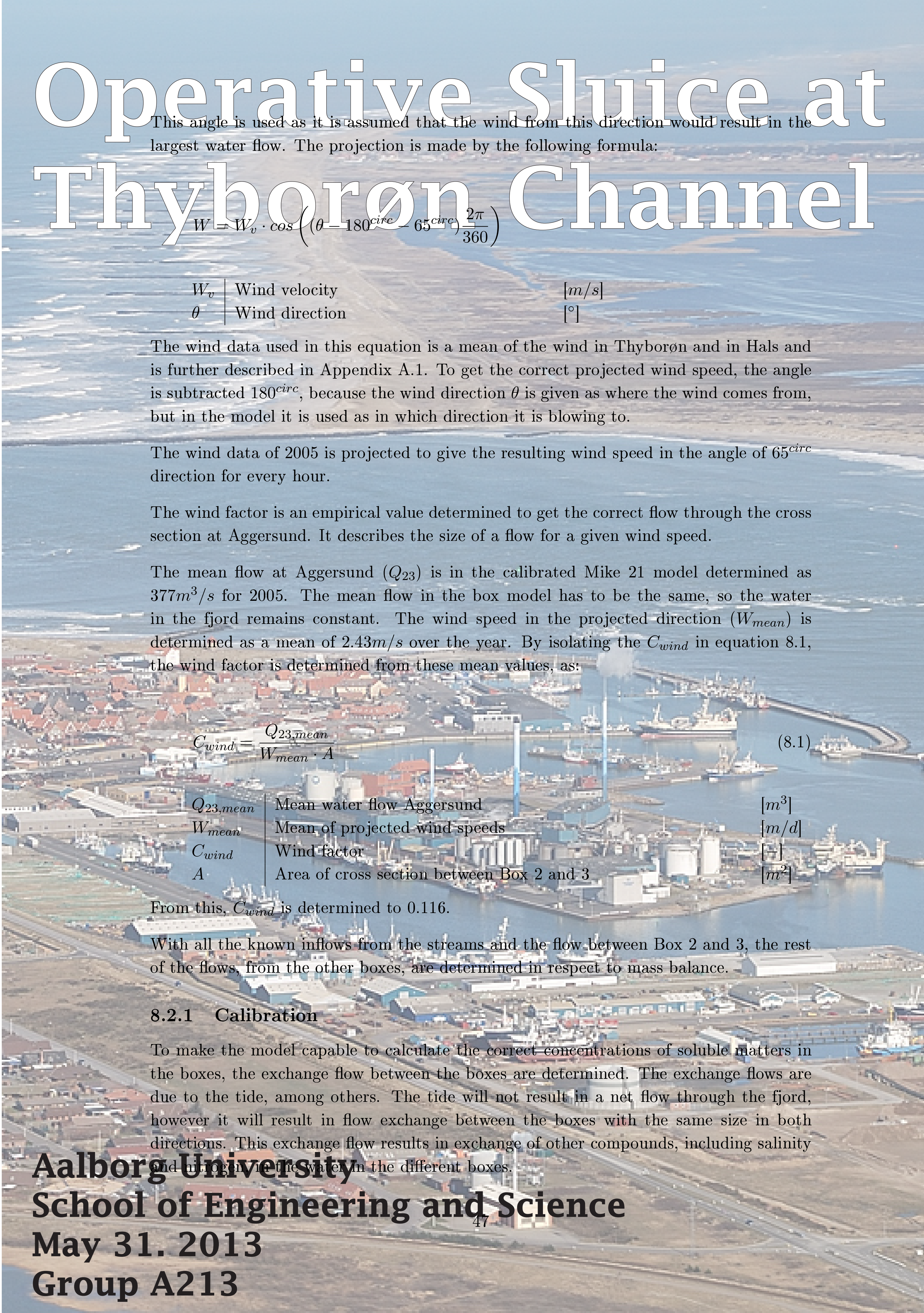

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This angle is used as it is assumed that the wind from this direction would result in the largest water flow. The projection is made by the following formula:

$$W = W_v \cdot cos\left((\theta - 180^{circ} - 65^{circ})\frac{2\pi}{360}\right)$$

W_v	Wind velocity	$[m/s]$
θ	Wind direction	$[°]$

The wind data used in this equation is a mean of the wind in Thyborøn and in Hals and is further described in Appendix A.1. To get the correct projected wind speed, the angle is subtracted 180^{circ}, because the wind direction θ is given as where the wind comes from, but in the model it is used as in which direction it is blowing to.

The wind data of 2005 is projected to give the resulting wind speed in the angle of 65^{circ} direction for every hour.

The wind factor is an empirical value determined to get the correct flow through the cross section at Aggersund. It describes the size of a flow for a given wind speed.

The mean flow at Aggersund (Q_{23}) is in the calibrated Mike 21 model determined as $377m^3/s$ for 2005. The mean flow in the box model has to be the same, so the water in the fjord remains constant. The wind speed in the projected direction (W_{mean}) is determined as a mean of $2.43m/s$ over the year. By isolating the C_{wind} in equation 8.1, the wind factor is determined from these mean values, as:

$$C_{wind} = \frac{Q_{23,mean}}{W_{mean} \cdot A} \tag{8.1}$$

$Q_{23,mean}$	Mean water flow Aggersund	$[m^3]$
W_{mean}	Mean of projected wind speeds	$[m/d]$
C_{wind}	Wind factor	$[-]$
A	Area of cross section between Box 2 and 3	$[m^2]$

From this, C_{wind} is determined to 0.116.

With all the known inflows from the streams and the flow between Box 2 and 3, the rest of the flows, from the other boxes, are determined in respect to mass balance.

8.2.1 Calibration

To make the model capable to calculate the correct concentrations of soluble matters in the boxes, the exchange flow between the boxes are determined. The exchange flows are due to the tide, among others. The tide will not result in a net flow through the fjord, however it will result in flow exchange between the boxes with the same size in both directions. This exchange flow results in exchange of other compounds, including salinity and nitrogen in the water in the different boxes.

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Since measurements, of the salinity from the measurement stations, illustrated in figure 8.1 through the year of 2005 in all of the boxes are available, they are used to calibrate the exchange flows. The salinities are available for every half meter down through the water column, but since the box model only has one layer, the mean of all the depths are used.

The model is calibrated with the assumption that the salinity in Kattegat has a constant value of $22PSU$, while the salinity in the North Sea (S_N) varies between 32 and $34PSU$ described by the following function:

$$S_N(t) = 33 + \sin\left(\frac{2\cdot\pi}{365}(t-131)\right) \tag{8.2}$$

t	Day of the year	[–]

The function is based on salinity measurements in the North Sea at measurement stations, 50-100km south of Thyborøn from the years of 1987-1991 [Ringkjøbing Amtskommune, 1992, page 11]. From these measurements the salinity is assumed lowest in the spring and highest in the late summer. This also fits with the salinity measurements in Box 1, see figure 8.4, which are mainly influenced by the salinity in the North Sea.

The exchange flows between the boxes are calibrated until the model calculates the measured salinities with sufficient accuracy in all the boxes over the year. The result of the calibration can be seen in figure 8.4.

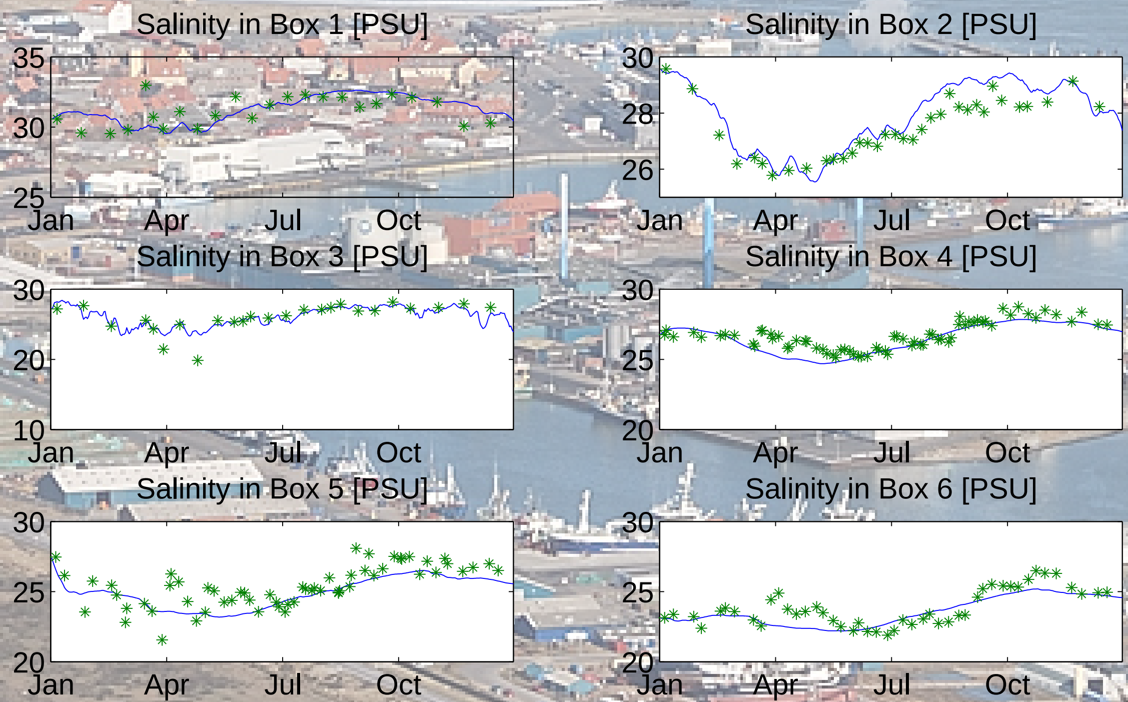

Figure 8.4: Result of calibration for the six boxes, where the green dots represent measured salinities, and the blue lines are the modelled salinities.

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The result of the calibration shows that the mean salinity in the boxes is close to the measured, although there might be some problems calculating the correct salinity variations over the year for some of the boxes.

The exchange flows between the boxes determined by the calibration of the model are listed in table 8.2.

	Exchange flows $[m^3/s]$
q_{N1}	700
q_{12}	300
q_{23}	700
q_{3K}	250
q_{42}	500
q_{54}	150
q_{64}	130

Table 8.2: The calibrated exchange flows between the boxes.

The variation between the exchange flows listed in table 8.2 are large. The largest exchange flows occur at the main fjord, Box 1-3, where the tide influence is highest. The smallest exchange flows are q_{54} and q_{64}, where the water level is less affected by the tide.

The exchange flows influence the flux of compounds, and therefore it is important that it is able to calculate the correct salinity values, so it can be used to calculate the correct exchange of other compounds.

In general the model is assumed to calculate the salinities with sufficient accuracy, and thereby it can be used to calculate exchange of other compounds as well.

8.3 Nitrogen Model

The nitrogen model is made to calculate different aspects of the nitrogen cycle and combine this model with the flow model to get the exchange of nitrogen between the boxes. By calculating the concentration of nitrogen in the different parts of the fjord, it is possible to get an idea of the water quality and whether different scenarios might have an effect on the water quality.

The nitrogen load to the Limfjord, is in the model assumed only to originate from three different sources, the atmosphere, the streams and the two oceans. The uptake from the atmosphere is 1,800 tonnes per year and the annual discharge from streams was approximately 14,500 tonnes in 2005 [Limfjordsamterne, 2006]. The load from the two oceans depends on the flows from the oceans to the Limfjord.

In the box model the nitrogen cycle is described, by calculating the nitrogen in three different stages, listed:

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C_{ON}	Concentration of organic nitrogen in water phase	$[mg/l]$
C_{IN}	Concentration of inorganic nitrogen in water phase	$[mg/l]$
M_B	Accumulated nitrogen at the bottom	$[mg/l]$

The three stages are in this model dependent on the processes illustrated in figure 8.5

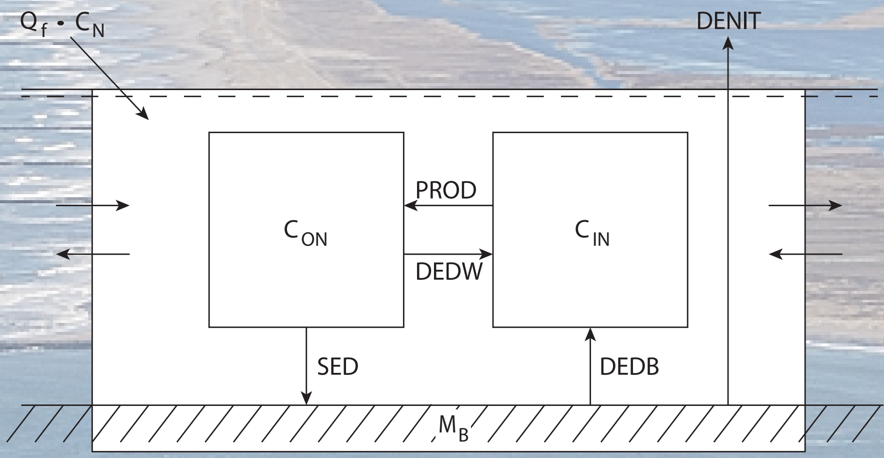

Figure 8.5: Principle of the nutrient model, where $DEDW$ is the degradation of dead algae in water phase; $DEDB$ is the degradation of dead organic matter in bottom sediment; $DENIT$ is the denitrification in bottom sediment; SED is the sedimentation, and $PROD$ is the production of algae. The arrows illustrate the result of the processes.

The processes of the nitrogen cycle depend on several factors. In this model they are described by a temperature dependent first order rate. Furthermore, the primary production is described as a Monod equation limited by the concentration of inorganic nitrogen. The used equations for the different processes are listed below.

$$SED = C_A \cdot K_{SED} \cdot \Theta_{SED}^{(T-20)}$$
$$DEDB = M_B \cdot K_{DEDB} \cdot \Theta_{DEDB}^{(T-20)}$$
$$DEDW = C_A \cdot K_{DEDW} \cdot \Theta_{DEDW}^{(T-20)}$$
$$DENIT = M_B \cdot K_{DENIT} \cdot \Theta_{DENIT}^{(T-20)}$$
$$PROD = C_A \cdot K_{PROD} \cdot \Theta_{PROD}^{(T-20)} \cdot \frac{C_N}{C_N + K_N}$$

K	1^{st} order rate for process at $20°C$	$[h^{-1}]$
Θ	Temperature constant for process	$[-]$
K_N	Half saturation constant of nitrogen growth	$[g/m^3]$
T	Temperature	$[°C]$

The temperature is described by a sinus curve, with a mean of $9°C$, which varies between $1°C$ and $17°C$. It is made by fitting it to measured data from measurement station Løgstør Broad, see figure 8.1. Both the measured data and the curve can be found in appendix A.6. The rest of the parameters are calibration parameters.

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The processes are calculated for each box, and thereafter the transport of the organic and inorganic nitrogen in the water phase between the different boxes is calculated. The transport of nitrogen is modelled by the flows determined in section 8.2.1. The flows are multiplied with the concentrations in the boxes to get the fluxes in and out of each box at each time step.

The sources of nitrogen to the Limfjord are in this model described by a discharge from streams, uptake from the atmosphere and contribution from the oceans. The atmospheric contribution of nitrogen is distributed according to the surface area of each box. As described the annual addition of nitrogen to the fjord from the streams is approximately 14,500 tonnes[Limfjordsamterne, 2006]. This is distributed equally over all the discharge of water to the fjord, which results in a concentration of $5.62 mg/l$.

Since the purpose of the model is to investigate whether different scenarios with the sluice will have a positive or negative effect on the nitrogen level over several years, the yearly variation of concentrations is neglected.

The inflow from the North Sea and Kattegat results in a flux of nitrogen into the fjord. The total concentration of nitrogen in the North Sea is determined from measurement station North Sea 1023. In this station there has been made measurements in six different depths, 25 times in the period between 1998 and 2006. The measurements comes in the unit $\mu mol/l$, but since the model calculates in mg/l the concentrations are recalculated to this unit, by multiplying with the molecular weight of nitrogen. From all the measured data the mean of total nitrogen is determined to $0.27 mg/l$. For the Kattegat boundary, measurement station Kattegat 4410 is used. In this station measurement has been made in two depths, 178 times in the period of 1999 to 2006. From these measurements the mean concentration of nitrogen is determined to $0.24 mg/l$. This results in an addition of nitrogen to the Limfjord depending on the flows in and out of the fjord.

This is implemented in the model by providing the inflows from the North Sea with constant concentrations of inorganic nitrogen at $C_{IN} = 0.22 mg/l$ and a concentration of organic nitrogen at $C_{ON} = 0.05 mg/l$. In Kattegat the applied concentrations are $C_{IN} = 0.19 mg/l$ and $C_{ON} = 0.05 mg/l$. These ratios are by far most inorganic nitrogen, and will especially in the summer not be correct. Since the processes in the summer are fast, the nitrogen will quickly be used by the algae and become organic in the model. The same assumption is made for the streams, were all the nitrogen is assumed inorganic. Therefore this error is assumed to be small.

All the input parameters used in the nutrient model are listed in table 8.3.

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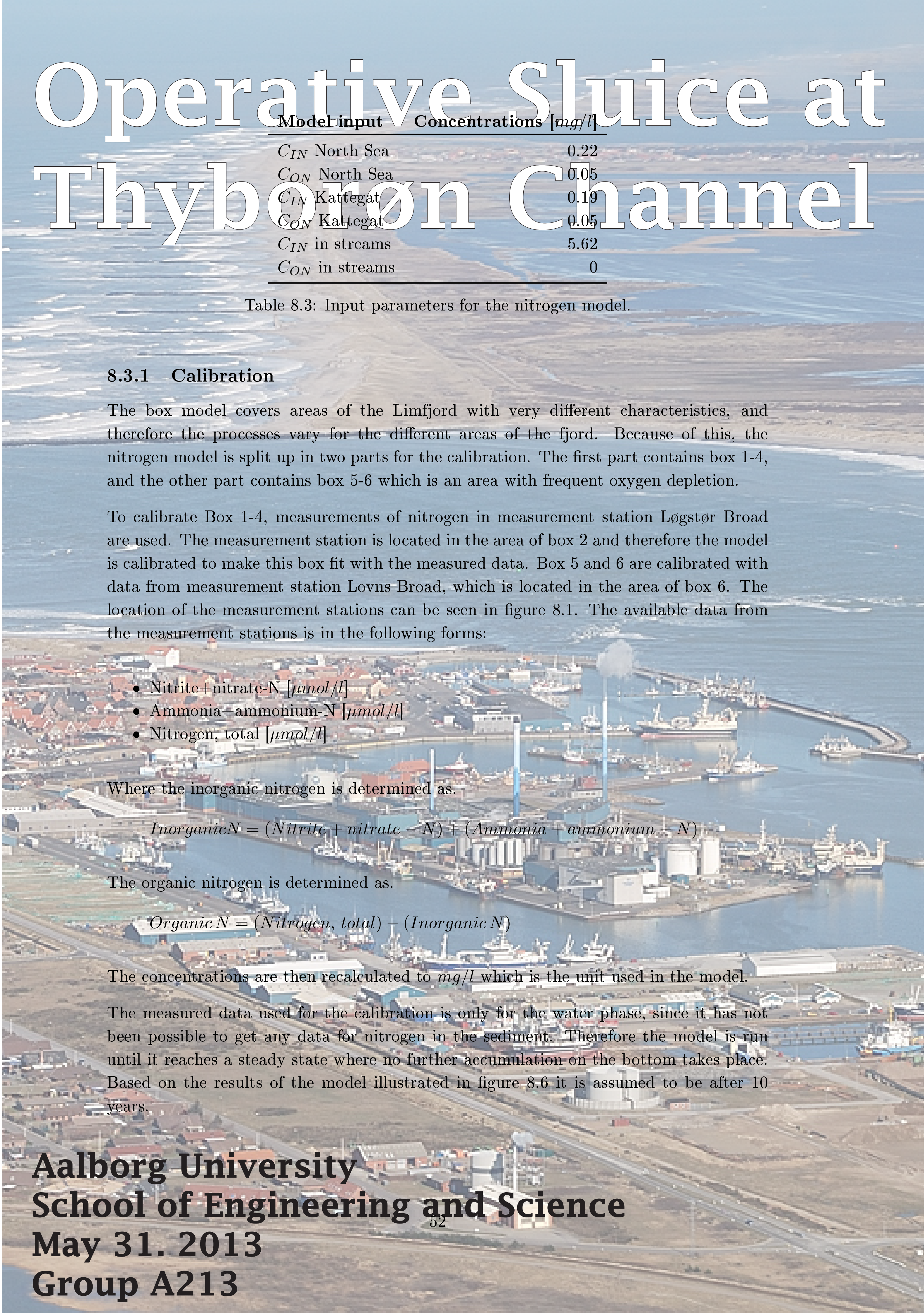

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Model input	Concentrations [mg/l]
C_{IN} North Sea	0.22
C_{ON} North Sea	0.05
C_{IN} Kattegat	0.19
C_{ON} Kattegat	0.05
C_{IN} in streams	5.62
C_{ON} in streams	0

Table 8.3: Input parameters for the nitrogen model.

8.3.1 Calibration

The box model covers areas of the Limfjord with very different characteristics, and therefore the processes vary for the different areas of the fjord. Because of this, the nitrogen model is split up in two parts for the calibration. The first part contains box 1-4, and the other part contains box 5-6 which is an area with frequent oxygen depletion.

To calibrate Box 1-4, measurements of nitrogen in measurement station Løgstør Broad are used. The measurement station is located in the area of box 2 and therefore the model is calibrated to make this box fit with the measured data. Box 5 and 6 are calibrated with data from measurement station Lovns Broad, which is located in the area of box 6. The location of the measurement stations can be seen in figure 8.1. The available data from the measurement stations is in the following forms:

- Nitrite+nitrate-N [$\mu mol/l$]
- Ammonia+ammonium-N [$\mu mol/l$]
- Nitrogen, total [$\mu mol/l$]

Where the inorganic nitrogen is determined as.

$$Inorganic N = (Nitrite + nitrate - N) + (Ammonia + ammonium - N)$$

The organic nitrogen is determined as.

$$Organic\,N = (Nitrogen,\ total) - (Inorganic\,N)$$

The concentrations are then recalculated to mg/l which is the unit used in the model.

The measured data used for the calibration is only for the water phase, since it has not been possible to get any data for nitrogen in the sediment. Therefore the model is run until it reaches a steady state where no further accumulation on the bottom takes place. Based on the results of the model illustrated in figure 8.6 it is assumed to be after 10 years.

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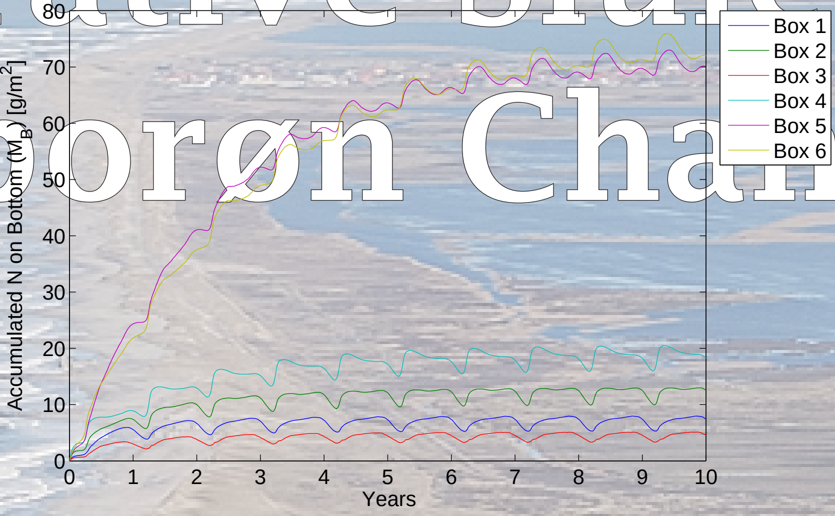

Figure 8.6: Accumulation of nitrogen in the bottom sediment over a period of 10 years.

Figure 8.6 shows that the accumulation decreases with time and is close to steady state after 10 years. Therefore the model is run for 10 years every time something is changed in the model.

The result of the calibration regarding organic and inorganic nitrogen in box 2 and 6 can be seen in figure 8.7 and 8.8.

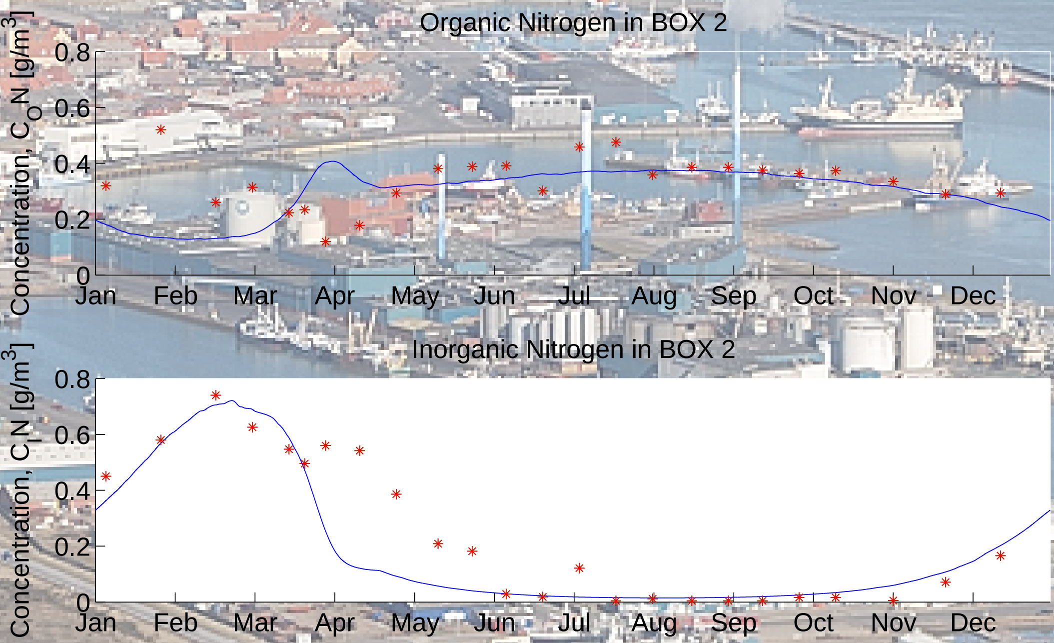

Figure 8.7: Result of calibration, where the blue line is the calculated data when model has reached equilibrium for Box 2, the dots are the measured data in station Løgstør Broad.

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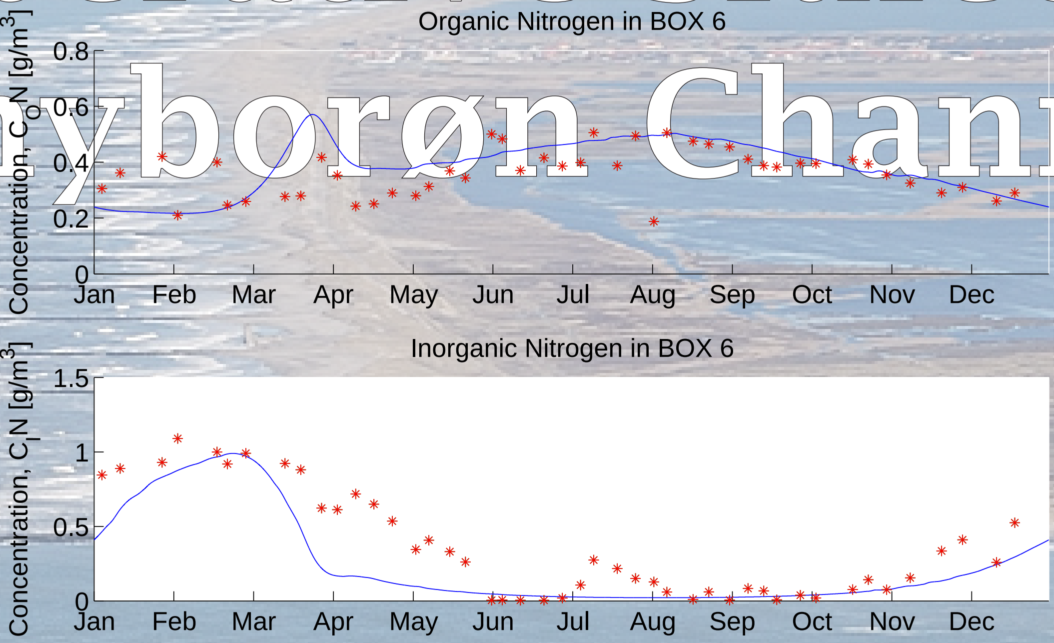

Figure 8.8: Result of calibration, where the blue line is the calculated data when model has reached equilibrium for Box 6, the dots are the measured data in station Lovns Broad.

The calibration for both box 2 and 6 shows a good coherency between the calculated data and the measured data. The concentrations of both the organic and inorganic nitrogen have the correct magnitude. Although the yearly variation does not fit that accurately with the measured data, where the model calculate a large algae bloom in the spring. This can be because the growth in the spring in practice is limited by low concentrations of phosphorus, which are not included in the model. But since it is the wash-out effect of nitrogen over longer periods the errors over the year are without importance.

The calibrated parameters for the different processes in the model are listed in table 8.4.

Parameter		**Box 1-4**	**Box 5-6**
K_{SED}	$[h^{-1}]$	$10 \cdot 10^{-3}$	$18 \cdot 10^{-3}$
Θ_{SED}	[-]	1.05	1.07
K_{DEDW}	$[h^{-1}]$	$7.0 \cdot 10^{-3}$	$7.0 \cdot 10^{-3}$
Θ_{DEDW}	[-]	1.11	1.11
K_{DEDB}	$[h^{-1}]$	$0.45 \cdot 10^{-3}$	$0.45 \cdot 10^{-3}$
Θ_{DEDB}	[-]	1.13	1.15
K_{DENIT}	$[h^{-1}]$	$0.08 \cdot 10^{-3}$	$0.15 \cdot 10^{-3}$
Θ_{DENIT}	[-]	1.07	1.07
K_{PROD}	$[h^{-1}]$	0.7	0.8
Θ_{PROD}	[-]	1.27	1.27
K_N	$[mg/l]$	0.4	0.4

Table 8.4: Values for calibrated parameters for the different boxes.

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The size of the values are a difficult to compare with reality, since they are all depending on each other, and if one is to small another one might be too big, but still resulting in a correct result.

The removal of organic material in the water phase depends on two processes; the sedimentation and the degradation in the water phase. The sum of these processes describe the life time of the algae.

The sedimentation parameters (K_{SED} and T_{SED}) for box 1-4 result in a rate of $0.17d^{-1}$ in summer ($17°C$) and $0.09d^{-1}$ in winter ($1°C$). The degradation parameters in the water phase (K_{DEDW} and T_{DEDW}) result in a degradation rate in the water phase of 0.12 in summer and 0.02 in winter. The sum of these results in a mean time for the nitrogen of 3.4 days as organic in the water phase for box 1 to 4. In winter the period for nitrogen as organic in water phase is 8.8 days. This longer time is due to the slower rate for all processes at lower temperatures.

For box 5 and 6 the period for nitrogen as organic in water phase is 2.1 days during summer.

The degradation parameters (K_{DEDB} and T_{DEDB}) on the bottom describe the biodegradation, mineralisation, and release of inorganic nitrogen to the water phase from the bottom. For Box 1-4 the parameters result in a release of inorganic nitrogen of 7 times the entire accumulated amount on the bottom every year. This is possible since the nitrogen only is in the water phase a few days during summer, after then it sediments down to the bottom again. From the bottom it can be released again, and used several times a year.

For Box 5 and 6 the nitrogen is used around 3 times a year. This does not mean that there is less nitrogen released from the bottom, just a lower rate of the accumulated nitrogen.

The denitrification (K_{DENIT} and T_{DENIT}) taking place on the bottom is much like the degradation that releases nitrogen to the water phase. But instead of release to the water phase, some of the mineralised nitrogen in the sediment is denitrified under anaerobic conditions and released to the air. For Box 1 to 4 approximately 25% of the accumulated nitrogen is denitrified every year. For Box 5 and 6 the parameters result in a denitrification of around 33% of the accumulated nitrogen in the sediment.

The last process used in the model is the primary production described by K_{PROD}, T_{PROD} and the half saturation constant K_N. As all the other processes this is described with a 1^{st} order rate and a temperature constant. But the primary production is also very depending on the light, since it needs this to make photosynthesis. There are no parameters describing exactly this in the model. This does not mean that the light is not taken into account. The light is almost following the temperature it is just offset a little and peaking earlier in the year. So by making the primary production more temperature dependent the light is taken into account. This results in a temperature constant of 1.27 for both Box 1-4 and Box 5-6. Meaning that the primary production is 48 times faster with an increase of $16°C$ which is the amplitude of the temperature in the model. The primary production rate in the summer, only taking the temperature into account, is $8d^{-1}$ for Box 1-4 and $9d^{-1}$ for Box 5 and 6. But since they are also very limited by nutrients the actual maximum growth

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rate in the model is between 0.2 and $0.3 d^{-1}$ for the different boxes.

8.3.2 Validation

To validate the model it is run and compared with nitrogen measurements from other measurement stations which are located in different boxes, but for measured data from the same year (2005). Box 1-4 are validated from measurement station Risgaarde Broad, which are situated in Box 4, while Box 5-6 are validated from measurement station Skive Fjord located in Box 5. The result of the validation can be seen in figure 8.9 for Box 1-4 and in figure 8.10 for Box 5-6.

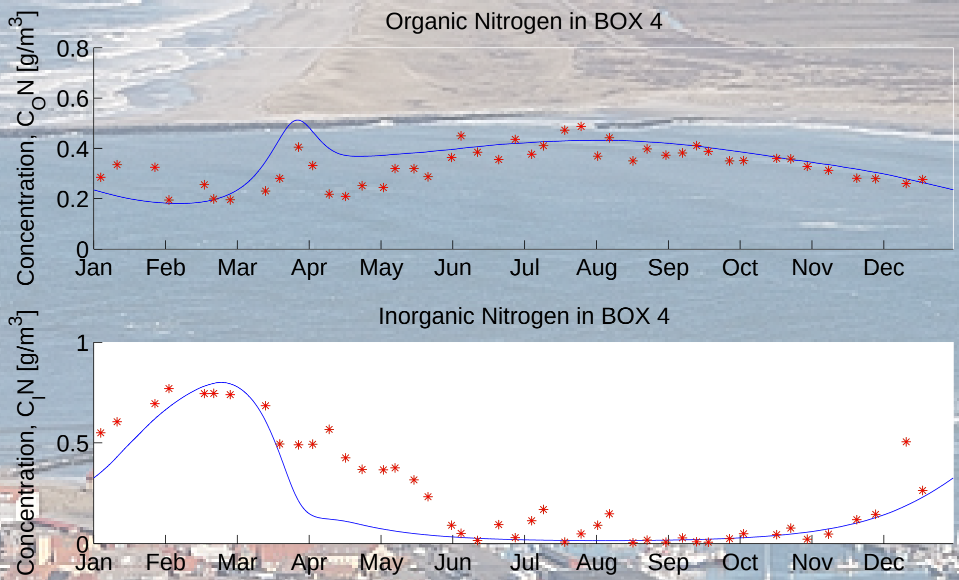

Figure 8.9: Result of validation, where the blue line is the calculated data when model has reached equilibrium for Box 4, and the dots are the measured data in station Risgaarde Broad.

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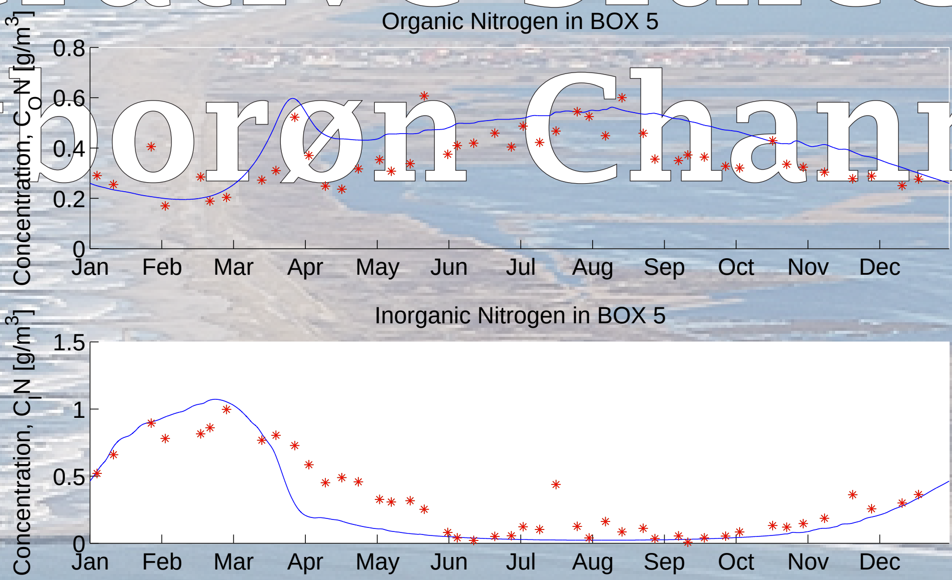

Figure 8.10: Result of validation, where the blue line is the calculated data when model has reached equilibrium for Box 5, and the dots are the measured data in station Skive Fjord.

The results illustrated in figure 8.9 and 8.10 show some coherency between the modelled and measured concentrations for other boxes. The modelled concentration in Box 5 is higher than the measured, but the errors are in a size where the model is assumed capable of calculating for the other boxes as well. To make a certain validation another year should be used. Since a total data set has not been available for another year, this has not been possible to do.

8.4 Scenarios

In this section different scenarios are presented and analysed, in respect to nitrogen concentrations in the fjord. Beside from the establishment of the sluice, two scenarios are investigated, Scenario 2 and Scenario 3. Scenario 2 concerns a reduction of the discharge concentration from the streams. Scenario 3 analyses the effects of closing the channel permanently.

To do this first a reference scenario with the current conditions is analysed. After this, the different scenarios are analysed and compared with the reference scenario. The scenarios are set up with the same conditions as described in section 8.3, unless else mentioned in the scenario description.

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To analyse the result of the different scenarios the net discharge of nitrogen from the fjord to the seas is determined. This discharge is determined as the output to the seas minus the input from them. The larger this net output is, the bigger an amount of nitrogen is washed out from the fjord every year. Furthermore the summer mean concentrations (March to October) of total nitrogen in the water phase are compared for each box with the support parameter of $409\mu g/l$ for eelgrass growth described in Section 3.1.

8.4.1 Scenario 0

Scenario 0 is made with the current conditions in the Limfjord. This scenario is used as a reference scenario, to compare the effect of the other scenarios.

The flows used in this model are the ones described in chapter 8, which gives mean net flow of $377m^3/s$ over the year. In this scenario the net wash out to the seas is modelled to approximately 10,000 tonnes of nitrogen per year. This then is the amount of nitrogen removed from the fjord by flows. Since the addition from the atmosphere and discharge is 16,300 tonnes a year, there also has to be removed this amount because the model is in steady state and no further accumulation takes place. This means that the last 6,300 tonnes is removed by denitrification.

	Box 1	**Box 2**	**Box 3**	**Box 4**	**Box 5**	**Box 6**
Scenario 0 [$\mu g/l$]	345	432	457	490	613	548

Table 8.5: Summer mean concentration of total nitrogen in the different boxes for Scenario 0.

From the results listed in table 8.5 it can be seen, that Box 1 is the only one, which full fills the demand at $409\mu g/l$, while the rest of the summer mean concentrations are too high.

8.4.2 Scenario 1

Scenario 1 implies the construction of a sluice in Thyborøn Channel. The sluice is implemented so water can only pass through it and into the fjord. From the flow analysis in Appendix B it is chosen to make a sluice with an effective cross section area 25% of the original cross section area. From the flow model it is determined that it is possible to increase the net flow in the cross section at Aggersund from $377m^3/s$ to $613m^3/s$ with this sluice. This is implemented in the model by adding the extra flow which is $236m^3/s$ to all the net flows Q_{N1}, Q_{12}, Q_{23} and Q_{3K}. By implementing this sluice the water is not able to run out of the fjord at Thyborøn, and therefore the exchange flow (q_{N1}) is set to $0m^3/s$. A result of the sluice is that the difference in water level from tide in the fjord will be smaller, which also results in smaller exchange flows in the rest of the model. Since the size of the exchange flows are unknown, the values determined in 8.2.1 are still used.

With these input parameters, the discharge of nitrogen to Kattegat is modelled to 9,700 tonnes per year. This is slightly less than without the sluice, which means that less nitrogen is washed out from the fjord to the oceans and so an accumulation will occur in the fjord.

	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Scenario 0 [$\mu g/l$]	345	432	457	490	613	548
Scenario 1 [$\mu g/l$]	395	476	527	522	635	563

Table 8.6: Summer mean concentration of total nitrogen in the different boxes for Scenario 1.

From the summer mean concentrations listed in table 8.6 it can be seen that concentrations in all the boxes are higher than for Scenario 0 listed in table 8.5. This is due to the smaller discharge of nitrogen to the seas.

8.4.3 Scenario 2

According to the basis analysis described in section 3.1, the annual discharge of nitrogen should be 9,520 tonnes to achieve 'good status'. The effect of this reduction is analysed, by decreasing the concentration used in the reference scenario. To get this amount discharged the concentration from the streams is changed to $3.69mg/l$ instead of the $5.62mg/l$ used in the reference scenario. The results of the decreased discharge are listed in table 8.7.

	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Scenario 0 [$\mu g/l$]	345	432	457	490	613	548
Scenario 2 [$\mu g/l$]	299	338	357	370	451	416
Scenario 2 with sluice [$\mu g/l$]	330	355	373	382	457	420

Table 8.7: Summer mean concentration of total nitrogen in the different boxes for Scenario 2.

The summer mean concentrations are the result after 10 years of simulation, thereby ensuring that no further accumulation on the bottom will take place in the model. With the reduction in the streams, the support parameter ($409\mu g/l$) for eelgrass is reached for Box 1-4, both with and without the sluice implemented. The two last boxes do not achieve the support parameter, and additional measures should be conducted if a 'good status' should be reached in these areas.

8.4.4 Scenario 3

As previously described, the possibility of totally closing the channel has been debated, in order to avoid flooding. In scenario 3, the consequence of this is investigated. To do this, the flow and exchange flow from the North Sea to Box 1 are removed, thereby making the Limfjord an estuary. The exchange flows for the rest of the fjord are preserved, since exchange between the boxes will still occur, due to the tide in Kattegat and the wind. The flow is only controlled by the discharges from the streams, which result in a flow towards Kattegat.

The discharge from the Limfjord will be insignificant, since most of the flow is removed. Therefore the summer mean concentration is determined. The summer mean concentrations, listed in table 8.8, shows, that the support parameter for eelgrass is exceeded in every box.

	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Scenario 0 [$\mu g/l$]	349	440	465	497	620	555
Scenario 3 [$\mu g/l$]	578	570	599	570	660	571

Table 8.8: Summer mean concentration of total nitrogen in the different boxes for Scenario 3.

The summer mean concentrations obtained by closing the channel will increase the problems in the Limfjord and the growth potential for eelgrass would decrease.

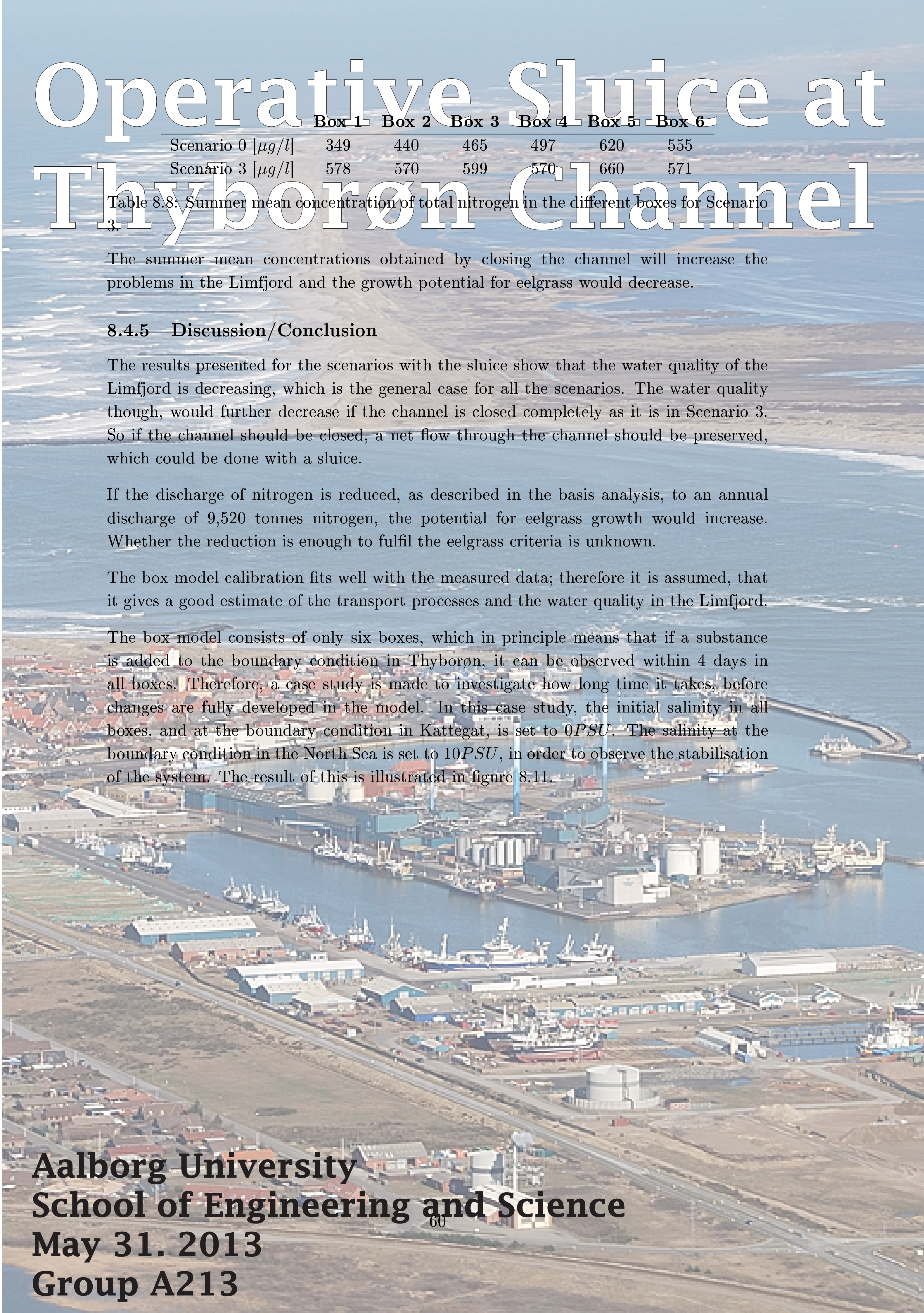
8.4.5 Discussion/Conclusion

The results presented for the scenarios with the sluice show that the water quality of the Limfjord is decreasing, which is the general case for all the scenarios. The water quality though, would further decrease if the channel is closed completely as it is in Scenario 3. So if the channel should be closed, a net flow through the channel should be preserved, which could be done with a sluice.

If the discharge of nitrogen is reduced, as described in the basis analysis, to an annual discharge of 9,520 tonnes nitrogen, the potential for eelgrass growth would increase. Whether the reduction is enough to fulfil the eelgrass criteria is unknown.

The box model calibration fits well with the measured data; therefore it is assumed, that it gives a good estimate of the transport processes and the water quality in the Limfjord.

The box model consists of only six boxes, which in principle means that if a substance is added to the boundary condition in Thyborøn, it can be observed within 4 days in all boxes. Therefore, a case study is made to investigate how long time it takes, before changes are fully developed in the model. In this case study, the initial salinity in all boxes, and at the boundary condition in Kattegat, is set to $0PSU$. The salinity at the boundary condition in the North Sea is set to $10PSU$, in order to observe the stabilisation of the system. The result of this is illustrated in figure 8.11.



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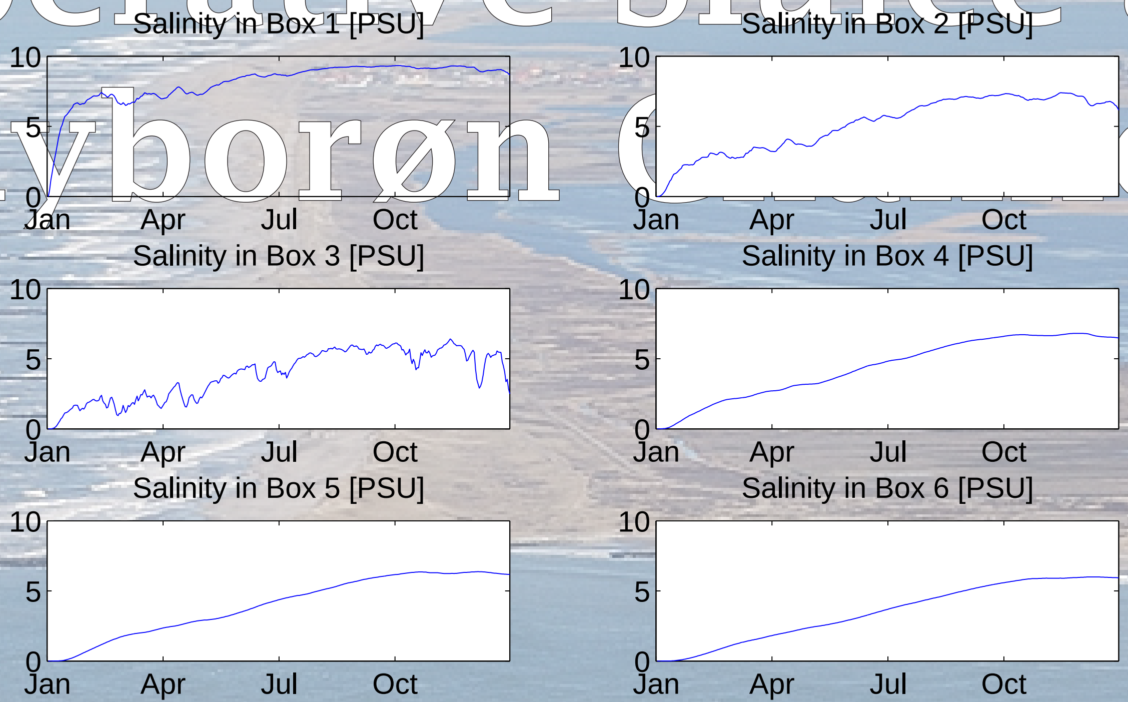

Figure 8.11: Modelled salinities in the box model, with a boundary condition of $10PSU$ in the North Sea and $0PSU$ in Kattegat and an initial salinity of $0PSU$ in the entire model.

As illustrated in figure 8.11, it takes approximately one year for the model to stabilise. This corresponds well with information obtained from [Larsen, 2013a]. This indicates that all though the substances can be tracked in all boxes after four time steps, the overall transport is slower.

The box model consists only of six boxes to describe the entire Limfjord, as previously described, which will lead to errors. Furthermore, the flow direction governed by the wind is either from east to west or in opposite direction, which means that water flow due to wind from the south or north is not included. Thereby, flows into the fjords in Box 4 to 6 are only described as a mean exchange, and not due the wind direction. The consequences of these simplifications are further analysed in the following chapter, where a three dimensional model with a finer grid is made in Mike3 FM, including more flow and flux parameters.

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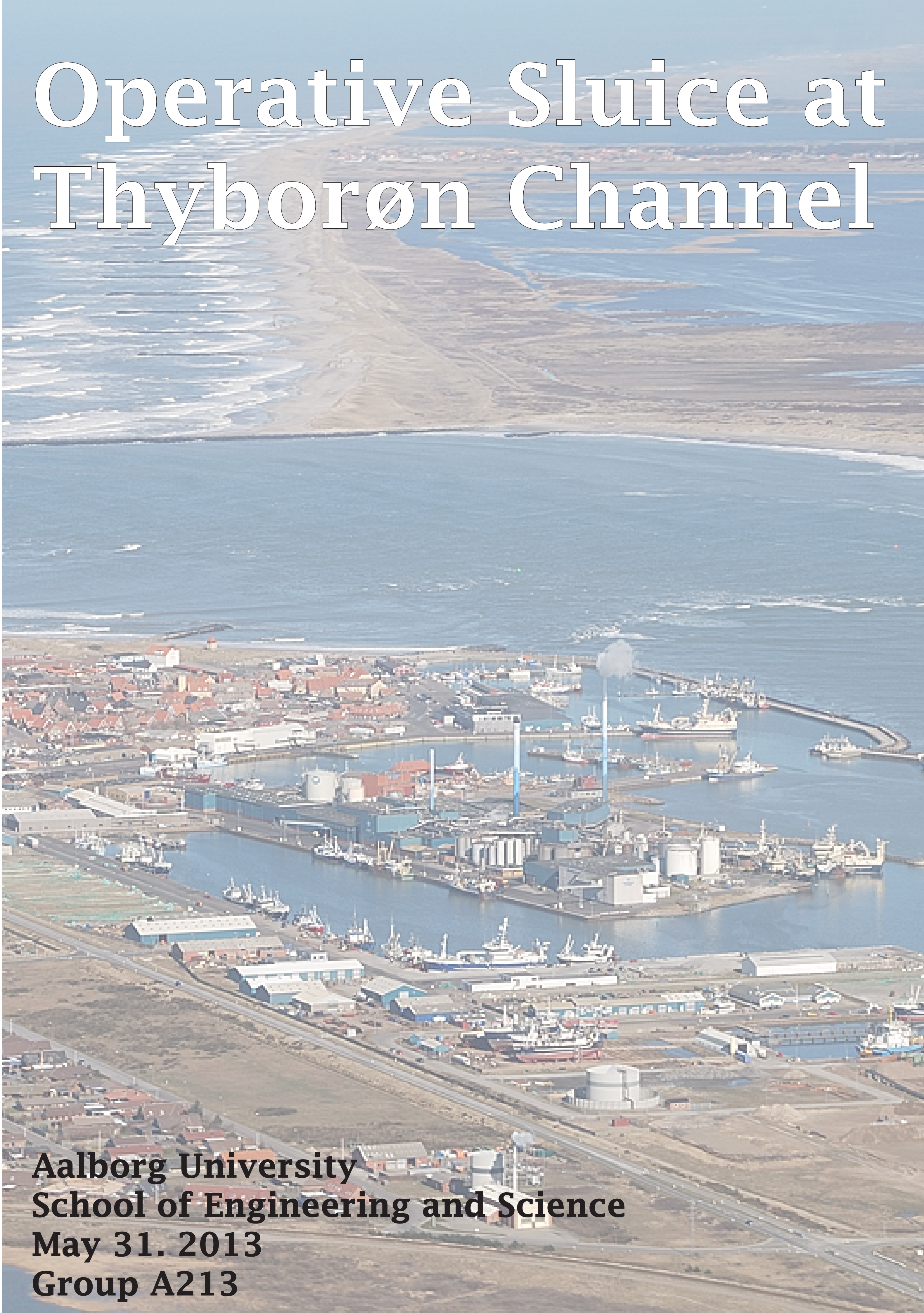

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9 Mike 3 FM

In this chapter the nitrogen concentration in the Limfjord is analysed. This is done with a three dimensional model setup in Mike 3 FM. The model is used to investigate the effect of the sluice on the wash out of nitrogen, by controlling the water flow and ensuring a one direction flow. In this model it is possible to add an ecological module (ECO Lab) which includes the interaction between nitrogen and phosphorus, and the dissolved oxygen. In this model, as well as in the box model, the nitrogen level will be investigated. The reason to analyse the nitrogen in this model is to see how the implementation of the sluice affects its concentration, when the net flow is increased. Different scenarios are investigated in respect to the wash out effect.

This program is similar to Mike 21 except that it is three dimensional. Therefore, most of the setup is the same as in the flood model, described in chapter 5. However, due to the computational time of the flood model, a simpler bathymetry is created, illustrated in figure 9.1, in order to reduce the modelling time, since in principle the model was run for twenty years. Furthermore, the water column is divided into two layers with the purpose of describing the stratification in the Limfjord. The upper layer is thinner, representing 30% of the water. The second layer, the one in the bottom, contains 70% of the water. Thereby reducing the mixing, due to wind between the two layers, so the bottom layer had bigger salinity.

The fresh water discharges from the rivers are attached to the upper layer. The layers are flexible, so they are able to adjust to the variation of depths of the bottom.

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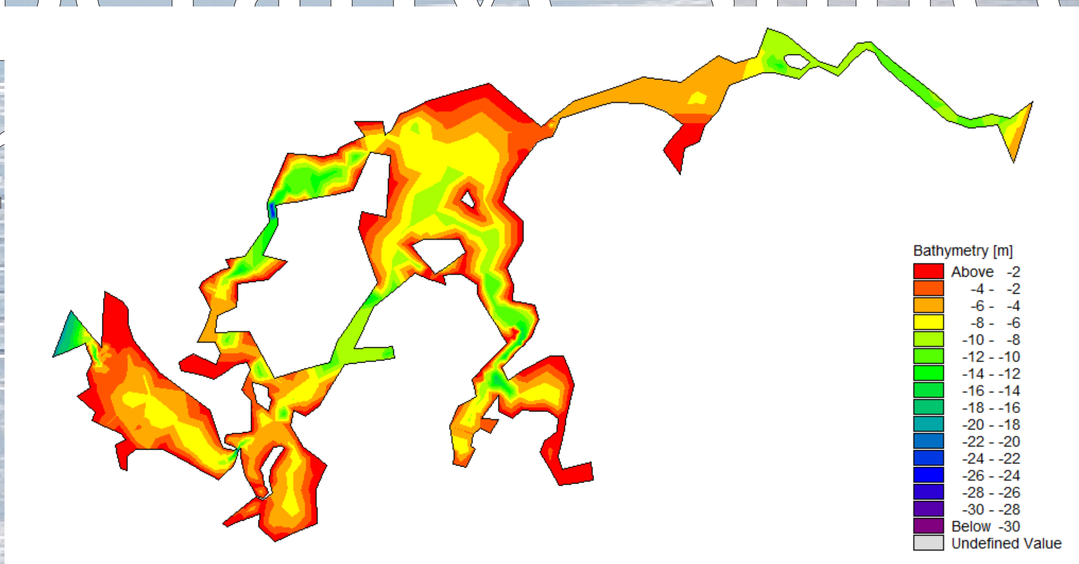

Figure 9.1: Bathymetry of the Limfjord.

When making the bathymetry with this rough grid, there were some issues with interpolating the correct depths. This has resulted in areas of the model with very shallow water. Therefore, the depth has been changed manually in some part of the fjord to get a more correct cross section of the fjord. The corrections are shown in figure 9.2.

Figure 9.2: Green areas show the places where the depth is changed to calibrate the model.

The changed bathymetry has resulted in a too large net flow of approximately $930 m^3/s$ through the fjord compared to the net flow in Mike 21, where it is $377 m^3/s$. This large flow is not correct and will result in a bigger nutrient reduction. Although it cannot be said that the nutrient concentration is correct, the effect of the sluice on the nitrogen before and after the implementation can be studied.

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The model is run with time steps of maximum 600 seconds, the same as in the flood model. In this hydrodynamic model, the water levels and salinities are calibrated. The salinity is an important parameter, since the dispersion of nutrients is similar to the salinity dispersion. Hereafter the ECO Lab module is setup and calibrated in respect to the measured nitrogen in the Limfjord, to get the correct amount of nutrients and sedimentation in the fjord.

9.1 Hydrodynamic Model Setup

In this model, the same wind setup, fresh water discharges and time step interval as the Mike 21 model explained in chapter 5 is used. In the model, the density is set only as a function of salinity, although in reality water density depends on temperature and salinity. Eddy viscosity describes the turbulence in a flow. It is added in the model, both in horizontal and vertical directions. The horizontal eddy viscosity follows a Smagorinsky formulation type, with a constant value of 0.4. The vertical one includes a log law formulation and furthermore, damping is included, in order to lower the mixing of the two layers and get stratification in the water.

Regarding salinity, the initial condition is set to $29PSU$ in the fjord, and at Thyborøn and Hals to respectively $33PSU$ and $20PSU$. The fresh water sources is set to $0PSU$.

9.1.1 Water Level Calibration

The water level calibration in this model is done the same way as in section 3.1. The results of the water level are calibrated with the water level measurements in Skive and Løgstør. Since the roughness is the input to the program, it is calculated from the Manning number obtained from Mike 21 (see equation 9.1), and added to Mike 3. To make the water level fit with the measurements, the Limfjord is divided in two parts, each of them with a different roughness, which can be seen in figure 9.3.

$$M = \frac{25.4}{k^{\frac{1}{6}}} \tag{9.1}$$

M	Manning number	$[m^{1/3}/s]$
k	Roughness	$[m]$

The roughness used in the model can be seen in the following figure.

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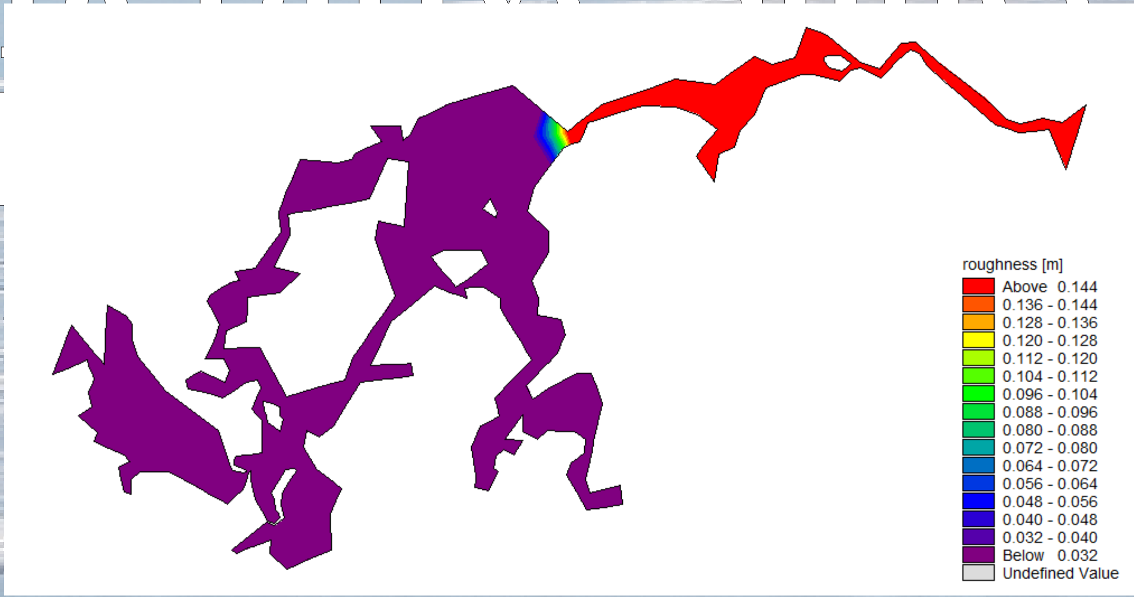

Figure 9.3: Roughness in the Limfjord used for the water level calibration

The result from the water level calibration can be seen in the histogram in figure 9.4, which illustrates how often the modelled values are either below or above the measured values from Skive.

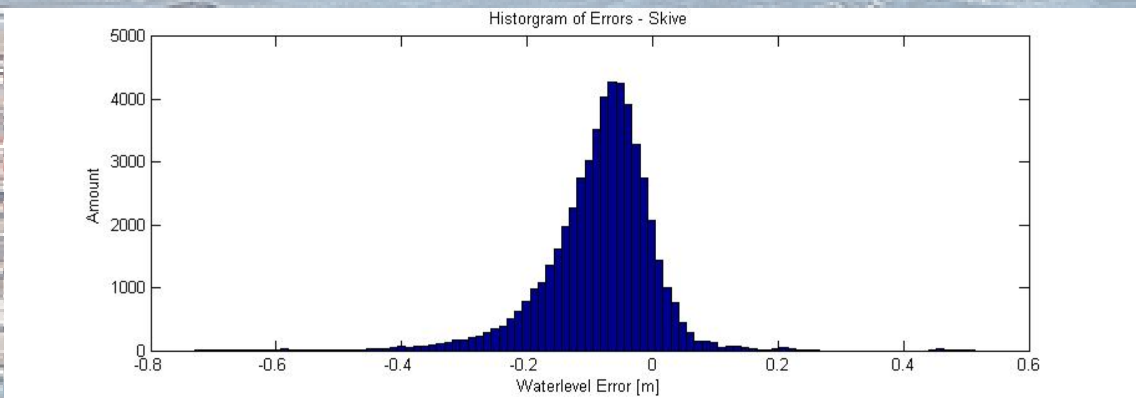

Figure 9.4: Histogram of the error of the difference between modelled and measured water level in Skive.

In figure 9.4, it can be seen that the modelled water level is slightly lower than the measured water level. One reason that the model is unable to reach the same water level, may be the modified bathymetry. However, this should not have a large effect on the exchange of nutrients, as long as the salinity calibration fits.

9.1.2 Salinity Calibration

Salinity is calibrated with the data of six measurement stations shown in figure 9.5. The salinity is measured in different depths in the measurement stations, where they are measured every $0.5m$ throughout the water column.

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Figure 9.5: Measurement stations used to calibrate the salinity.

Calibration is done through dispersion. The dispersive transport is modelled in a horizontal and vertical dispersion. The horizontal dispersion is chosen as a scaled eddy viscosity formulation, and a variation in domain format. This is chosen because the salinity was not moving into Risgaarde, Skive and Lovns, since the main water flow in the Limfjord is going from west to east. The water flow into Risgaarde, Lovns and Skive is very low, meaning that the modelled salinity in that part of the fjord is too low compared to the measured values. Therefore, a constant horizontal value of 15 is included in this part of the fjord in order to get higher salinity values (see figure 9.6). In the rest of the Limfjord, the constant is set to 1. Vertical dispersion is not included in the model, because the numerical dispersion in the model assumed to be correct enough according to the salinity calibration, so it is no necessary to include more.

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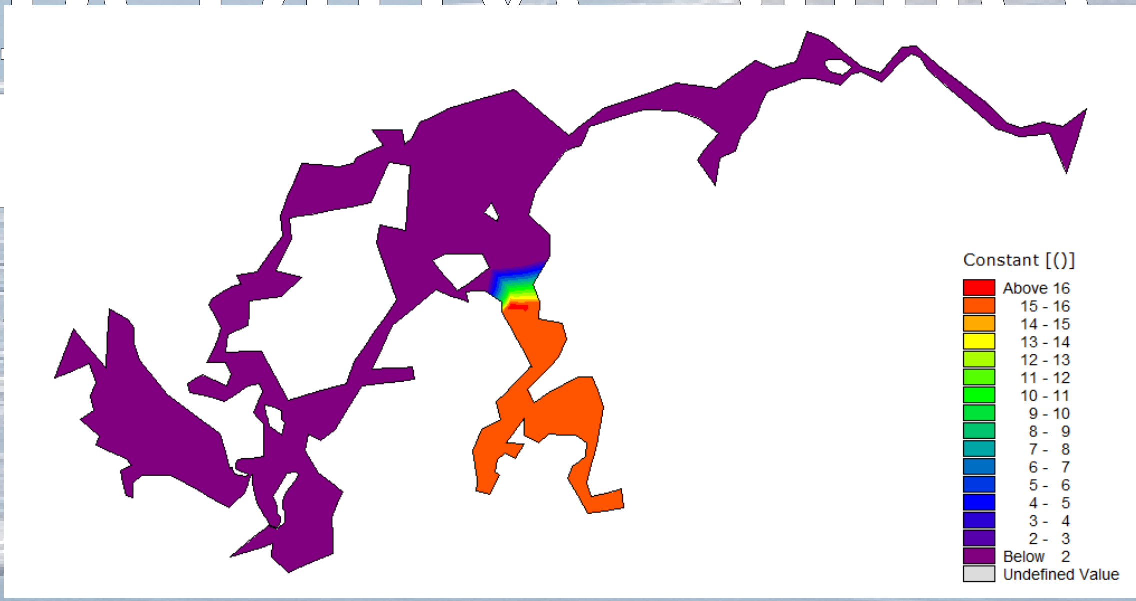

Figure 9.6: Horizontal dispersion in the Limfjord

In figure 9.7, the difference between the measured and modelled salinities for the calibrated model is illustrated.

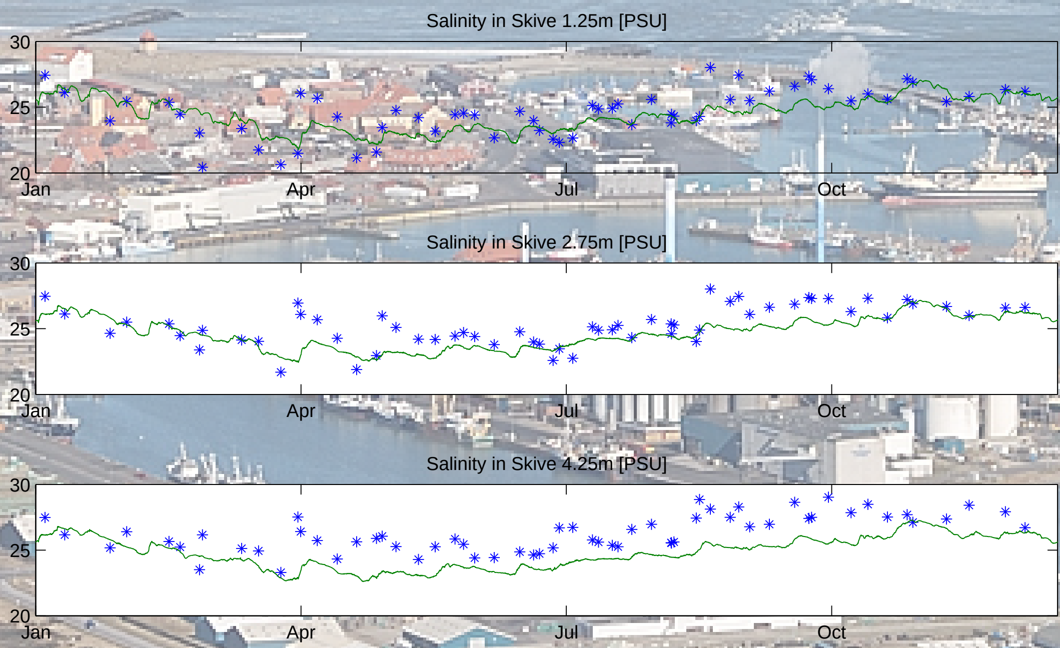

Figure 9.7: Modelled and measured salinity values for Skive Fjord in different depths.

Calibration gives a good approximation to the measured values at Skive Fjord. In figure 9.7, it can be seen that the salinity fits better in 1.25m and 2.75m depth, and it is too low in 4.25m depth. This might be because the dispersion in the lower part of the fjord is too low, and less salt can get there.

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The result for the calibration for all the measurement stations is shown in appendix E. The result is acceptable for Risgaarde Broad and Nibe Broad because the difference between the modelled and measured values is considered to be small. However, the salinity does not fit in Løgstør and Nissum Broad. In general, the modelled salinity value is too high. The reason of these high salinity values might be because there is a too high flow from the North Sea in the model so, in the measurement station located in the main flow (from Thyborøn to Hals), there is a big amount of salt coming through. This is related to the larger mesh, which gives a large flow. Furthermore, since the depth is changed in the fjord, the depth in Thyborøn Channel is bigger, which allows more water to come in.

9.2 ECO Lab

ECO Lab is a module in Mike Zero used to study the water quality. The ECO Lab model chosen for this report is the *Water Quality Simple with nutrients*. This model includes nitrogen and phosphorus, biological oxygen demand (BOD), and dissolved oxygen (DO) as variables. This model is chosen because the purpose of the report is to analyse whether implementing and operating a sluice at Thyborøn can reduce the concentration of nutrients.

The nutrient input data for the model is obtained from the total discharge to the Limfjord according to [Limfjordsamterne, 2006] in 2005. Nitrogen input is set as 16,300 tonnes per year, 14,500 tonnes corresponding to the land discharge, and 1,800 tonnes from the atmosphere. In the model, the atmosphere data is added to the Limfjord via the fresh water discharge. The total input of phosphorus is set as 375 tonnes, which is also added to the fresh water discharge. The nutrients are added by the assumption that all the fresh water sources have the same concentration.

The model requires differing between nitrate and ammonium, as well as phosphate. From the measurements obtained from [Bentzen et al., 2002], the ratios of the different compounds are calculated. The total nitrogen contains 89.4% of nitrate and nitrite, 3.5% of ammonium and ammonia and 7.1% is organic. The same procedure is done with the phosphorus, assuming that 43.7% of the total phosphorus corresponds to phosphate. This phosphate is the ratio of the total phosphorus in water which is available to react. Nutrient data used for the ECO Lab is shown in table 9.1.

Nutrient	Concentration [mg/l]	Ratio [%]
Nitrate and nitrite	5.648	89.4
Ammonium and ammonia	0.221	3.5
Phosphate	0.145	43.7

Table 9.1: Nutrient data used for all the fresh water sources in ECO Lab

The model requires BOD sediment as an input. But this data was not available. Therefore, the initial idea was to run the model for twenty years in order to get the sedimentation and accumulation of BOD with time and have a BOD sediment value close to the real value in the fjord.

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Then, the model was run for a two year period, and the output result was included as input value for the next two years. This was done several times until reaching twenty years. The reason of running it for a two year period is to decrease the computational time. This way, the model could use the output flow after two years for the next period.

However, the program did not allow to get the BOD sediment as an output, so it was not possible to include the BOD sediment obtained after two years as an input for the next period. Therefore, the accumulation after twenty years was the same as after two years, and consequently the model was run only for two years.

In order to solve this problem, an initial concentration of $5.5 g/m^2$ of BOD sediment is assumed, and is added to all the fresh water sources. The influence of this value on the nitrate was very small compared to the results without any initial BOD in the sediments, and therefore this value was not further investigated.

The data of the DO input is obtained for the different fresh water sources from the database of *DMU - Danmarks Miljøundersøgelser*. Total BOD for the fresh water sources is obtained from the same database as the DO, and it is considered that 70% of it is suspended, and 30% is dissolved. [DMU, 2012] This ratio is chosen because the model requires both BOD suspended and dissolved as an input. However, this ratio is unimportant because the oxygen will be used very quickly after being discharged to the fjord.

Since data is available only for six streams, they are geographically associated, and the data is set as the same for all the rivers in the same area. The dissolved BOD, BOD suspended and DO input concentration can be seen in appendix E.

The boundaries are located in the west of Thyborøn and in Kattegat. Data is determined from the database from *DMU - Danmarks Miljøundersøgelser* and is listed in table 9.2 [DMU, 2012]. Since both the dissolved and suspended BOD for the boundaries has not been available, values from the stream Hesteskoen were used. The values can be seen in appendix E.

Model inputs	**West of Thyborøn** $[mg/l]$	**Kattegat** $[mg/l]$
BOD dissolved	0.446	0.446
BOD suspended	1.041	1.041
Dissolved oxygen	9.553	12.998
Ammonia	0.003*	0.052*
Nitrate	0.002*	0.233*
Phosphate	0.00015*	0.00043*

Table 9.2: Input parameters for the ECO Lab module at the boundaries. *These values are too low. The real values in the west of Thyborøn are $0.051 mg/l$ for ammonia, $0.119 mg/l$ for nitrate, and $0.0146 mg/l$ for phosphate. In Kattegat, the real values are $0.052 mg/l$ for ammonia; $0.233 mg/l$ for nitrate, and $0.0418 mg/l$ for phosphate.

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Phosphorus is only added from the fresh water sources, while nitrogen is included both from fresh water sources and atmosphere. However, point sources in the Limfjord, such as waste water treatment plants (WWTP) are not considered in this model. The reason why it is done this way is to simplify the model. In addition, they are not very significant to the nitrogen cycle in the Limfjord.

9.2.1 ECO Lab Calibration

The ECO Lab is calibrated in order to determine the nitrate concentration in the fjord. The reason why nitrogen, in the form of nitrate, is chosen as the calibration parameter in ECO Lab is because, as mentioned in chapter 3.3, it represents the main problem in the Limfjord.

Calibration of ECO Lab is done through dispersion and the constants that take part on all the processes regarding the nutrient cycle. Dispersion is set up as 6 times the eddy viscosity for all the parameters (Nitrate, ammonia, phosphate, DO and BOD), both on the vertical and the horizontal direction.

There are 38 constants to calibrate the model that describe the processes related to nutrients, oxygen and sediments. The calibration constants are listed in table E.2 in appendix E. The big amount of parameters used to calibrate the model makes it difficult to get an accurate approximation between the modelled and the measured values. Furthermore, the processes are related to each other, but since there was no accessible literature to know the ratios defining their relation, some of the numbers are chosen aleatory. The model was first run with the standard values in the ECO Lab module. This resulted in too low concentrations of nitrate compared to the measurements, and too high concentration for ammonia. Although ammonia is not calibrated, it is considered important that its concentration is realistic. Therefore, the constants for the processes that affects its concentration are modified. The standard values are split into different processes consisting of the following:

- BOD processes
- Resuspension processes
- Sedimentation processes
- Nitrification processes
- Oxygen processes
- Ammonia processes
- Nitrate processes
- Phosphorous processes

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The modified constants, included in the different processes, are explained below. There are no changes for BOD processes and phosphorus processes.

Resuspension Processes

In order to get more resuspension, the critical flow velocity is lowered to $0.1m/s$, and the resuspension rate of BOD is increased to $0.5d^{-1}$. The reason for this is that, if the actual flow velocity is higher than critical flow velocity, resuspension takes place. This is desired because before the calibration, the nitrate was too low, so if more BOD is suspended, there is more nitrogen available to be transformed into nitrate and fit the measurements.

Sedimentation Processes

Sedimentation rate for BOD is increased to $2d^{-1}$ because the modelled nitrate values are too high compared to the measured ones.

Nitrification Processes

Nitrification first order decay at $20°C$ is set as $3d^{-1}$, to get more nitrate and reduce the ammonia concentration. Temperature dependence is modified in order to get more differences between the rates in summer and winter. The equation describing the temperature dependence is equation 9.2, where Φ is the temperature coefficient that is changed to calibrate, and T is the temperature. For the nitrification processes, the temperature coefficient is increased to 1.2.

$$f(T) = \Phi^{(T-20)} \tag{9.2}$$

Oxygen demand by nitrification is lowered to $4g\,O_2/g\,NH_4-N$ to make it easier to nitrify and get a higher value of nitrate.

Nitrification half saturation constant is defined as the oxygen concentration needed to reach half of its maximum value. By lowering it, more nitrification and therefore, nitrate, is obtained. Therefore, it is set as $0.5mg/l$.

Oxygen Processes

In order to get the light deeper in the water column, Secchi depth is established as an average of $4m$, a value obtained by the literature [DMU, 2008].

Respiration of plants is set as $4d^{-1}$. The half saturation concentration for oxygen is set as 0.5.

Ammonia Processes Since in principle ammonia is too high, the ratio of ammonium released by BOD decay is reduced to $0.01g\,NH_4-N/g\,BOD$. Later on, the concentration of nitrate was too high, so the amount of ammonia taken up by bacteria and plants is lowered to $0.02g\,N/g\,DO$ and $0.03g\,N/g\,DO$, respectively. The half saturation concentration for N uptake determines the nitrogen concentration where the ammonium is half of its maximum value. It is set as $0.3mg/l$.

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Nitrate Processes To make the denitrification rate variable with the temperature, the temperature coefficient for denitrification rate is increased to 1.3.

Measured values in $4.5m$ from Nissum Broad, Nibe Broad, Løvns Broad, Risgaarde Broad, Skive Fjord and Løgstør Broad are compared with the modelled values in the same depth. The result of the calibration in Risgaarde is shown in figure 9.8.

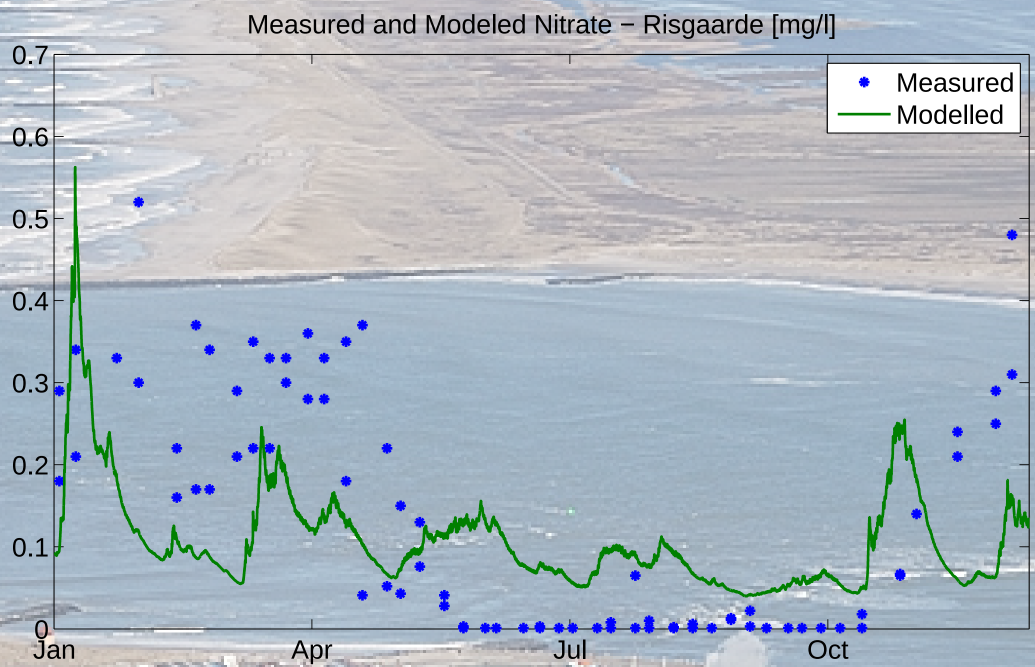

Figure 9.8: Modelled and measured nitrate data in Risgaarde in $4.5m$.

In figure 9.8, it can be seen that the nitrate concentration is higher than the measured values in summer and lower than the measured values in winter. The calibration results for the other measurement stations are shown in appendix E. In general, the modelled values do not fit with the measurements.

As stated before, calibrating the ECO Lab is a complex task due to the big amount of parameters to calibrate. The lack of data and the unawareness of all the interactions between the processes when calibrating, as well as the standard values for the processes in for an estuary, have been a big barrier for the calibration.

Having a rough mesh has shortened the computational time for calibrating, but it has resulted in a very big flow in the Limfjord, which does not correspond to the real one. This might have influenced the nutrient movement and concentration, especially in Løvns and Risgaarde.

Despite all of uncertainties, since the purpose of the ECO Lab is to analyse the effect that a bigger flow has after implementing a sluice in the Limfjord, the model is used to study how the nitrate values vary over time.

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9.3 Scenarios

As earlier stated, the main objective is to analyse how the implementation of a sluice will affect the concentration of nitrogen and thereby improve the water quality. The analysed parameters are yearly mean concentration of total nitrogen and the difference of net discharge of total nitrogen with and without the sluice.

First, a reference scenario is made with the current conditions in order to investigate the effects of implementing a sluice. The sluice is located at west of Thyborøn, with the setup decribed in chapter 6 where the water only flows from west to east.

The different scenarios investigated are listed in table 9.3.

Scenario	**Cross section** $[m^2]$
Reference	-
A	6000

Table 9.3: The different scenarios in the analysis of the influence of the sluice on nitrogen content in the fjord.

9.4 Results

The yearly average of the total inorganic nitrogen discharge is calculated and compared in ThyborÃ¸n and Kattegat before and after implementing a sluice with a cross section area of $6000m^2$. The result is shown in table 9.4.

Inorganic N discharge to Kattegat	$[tonnes/year]$
No sluice	2,485
With Sluice	3,674

Table 9.4: Variation of the inorganic nitrogen discharge from the Limfjord with the implementation of the sluice.

In table 9.4, it can be seen that the yearly discharge of nitrogen is increased with a sluice. The increase in discharge is 1,190 tonnes, which corresponds to 47.9% more discharged inorganic nitrogen from the Limfjord. This means that there is more inorganic nitrogen moved from the Limfjord to Kattegat, so the inorganic nitrogen content in the Limfjord will be smaller, and the water quality might improve.

For a further analysis, the annual mean concentration of inorganic nitrogen is calculated. This is done in the three measurement stations, where the concentrations in the model is closest to measured concentrations. The total inorganic nitrogen is obtained by taking the sum of the mean yearly concentration of NH_4 and NO_3 at $1.5m$ and $4.5m$ depth. The mean concentration from the two depths is listed in table 9.5.

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	Inorganic nitrogen concentration [mg/l]		
Location	No sluice	Sluice	Difference
Løgstør Broad	0.024	0.022	-0.0024
Risgaarde Broad	0.023	0.021	-0.0014
Nibe Broad	0.055	0.040	-0.0143

Table 9.5: The table shows the variation of the total inorganic nitrogen concentration before and after implementing the sluice.

In table 9.5, it is seen that the implementation of the sluice reduces the inorganic nitrogen concentration in the three locations.

9.4.1 Discussion/Conclusion

The results show that the increased flow caused by the implementation of the sluice has increased the removal of inorganic nitrogen in the Limfjord. After two years modelling with the sluice, the accumulated inorganic nitrogen discharge from the Limfjord is increased by 1,190 tonnes in the last year. The concentration analysis also reflects a reduction of inorganic nitrogen in the fjord.

As it is mentioned before in the subsection 9.2.1, the model setup, with a rough mesh has caused some problems and the model is not realistic. The changed bathymetry has influenced the flow, which results to be $930m^3/s$, although in reality is $377m^3/s$, according to the flood model. This made the further calibrations used for the nutrients not so precise. Furthermore, the lack of input data and the unavailability of the ratios between the processes concerning the ECO Lab made it difficult to create a very realistic model.

Besides, the real nutrient added as an input to the boundaries is too low compared to the real values, as it is shown in table 9.2. Consequently, the results obtained with the model do not correspond to the real nitrate concentrations, and the model cannot be used to simulate a possible real improvement of water quality in the Limfjord.

However, it would be necessary to run a model with the correct values for ammonia, nitrate and phosphate, and get a more accurate calibration, in order to confirm that the sluice has a positive effect on the water quality on the Limfjord.

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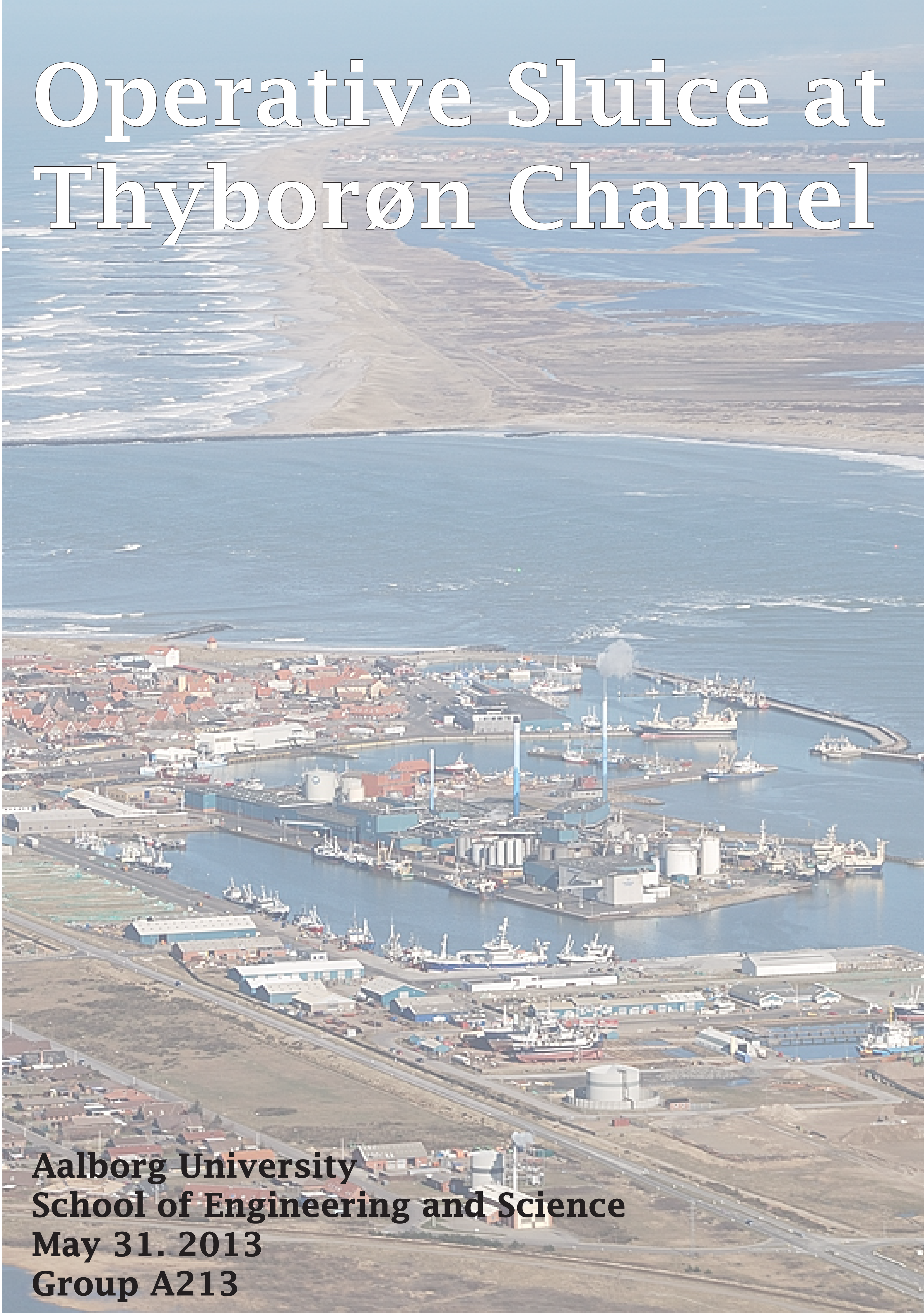

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10 Discussion

In this report it is studied if it is possible to avoid flooding by implementing a sluice in Thyborøn, and how this would affect the concentration on nitrogen in the fjord. The models in the report are based on data from the storm that occured the 8^{th} of January of 2005.

Flooding

In Part II of the report it is investigated whether it is possible to prevent flooding in the inner part of the Limfjord by placing a sluice, capable of closing totally, in Thyborøn Channel. The purpose of the sluice is to prevent the build-up of water in the Limfjord before a storm, so the water build-up is decreased.

In the article "Storm Surge Protection can Improve Water Quality in the Limfjord", similar investigations were made. In the article, among others, the water level was investigated when the sluice was closed the 2^{nd} of January, which almost correspond with the closing period of six days in this report. In the article it was possible to reduce the water level with 48.1 % and 55 % at Løgstør and Skive respectively. As a comparison, the results obtained in this report, showed a water level lowered with 31.7 % and 53.5 % at Løgstør and Skive respectively. [Nørgaard et al., Not published]

The less reduction in water levels may be due to modified tides in the article. The maximum daily tide coincides with the maximum storm surge peak. This results in higher water level and thereby a greater reduction is possible. The different water level reduction might also be due to the bathymetry used in the flood model. In this report the bathymetry only consists of 2,600 elements and one layer, compared to 6,000 elements and three layers for the one used in the other report. [Nørgaard et al., Not published]

The results from 2005 showed that by closing the sluice 2 days before the storm flooding is prevented. While other storm events will have different build-up periods, it is not given that flooding is prevented by closing the sluice 2 days before the peak of the storm. A possible solution to this could be to combine a weather forecast with a flood model to assess possible risks of flooding. A principle of this is illustrated in figure 10.1

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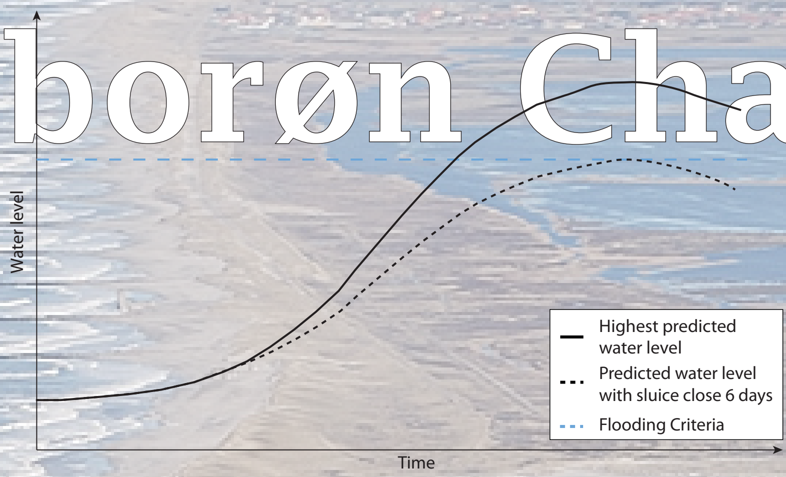

Figure 10.1: Illustration of risk assessing water level forecast based on weather forecasts.

The risk assessment model in regard to flooding could then model the effect of closing the sluice and at what time it should be done in a worst case scenario. With this, the sluice and this risk assessment setup future storm surges could be prevented.

If the weather forecast later shows that the storm will not be a reality, the sluice could be opened again.

Water Quality

In the water quality analysis two models are created to investigate the effect that a sluice would have on the water quality. The two models are calibrated for salinity in the fjord, before calibrating the nitrogen concentrations.

The box model showed that by implementing a sluice there was not an improvement of the water quality.

The calibration of the model showed a high coherency with the measured data, which indicates that the model should be reliable. At the same time, it is a simple model where several parameters and processes regarding both flow and nitrogen have been simplified. The model has also not been validated, which means that it cannot be stated that the model calculating correctly. The validation could have been done if data from another year was available.

Other ways of operating the sluice could also be investigated. For instance, if a long term weather forecast predicts net wind from east, then the sluice should allow a west going flow. This might increase the discharge from the Limfjord in some periods during the year.

The Mike 3 FM model showed that the discharge of nutrient was increased by implementing the sluice. The calibration of the model showed a poor coherency with the measured data, which indicates that the model is not reliable. At the same time, the results correlate in some extent with the results obtained from the article ”Storm Surge Protection can Improve Water Quality in the Limfjord”, where there was an increase of salt discharge from the Limfjord by implementing a sluice. [Nørgaard et al., Not published]

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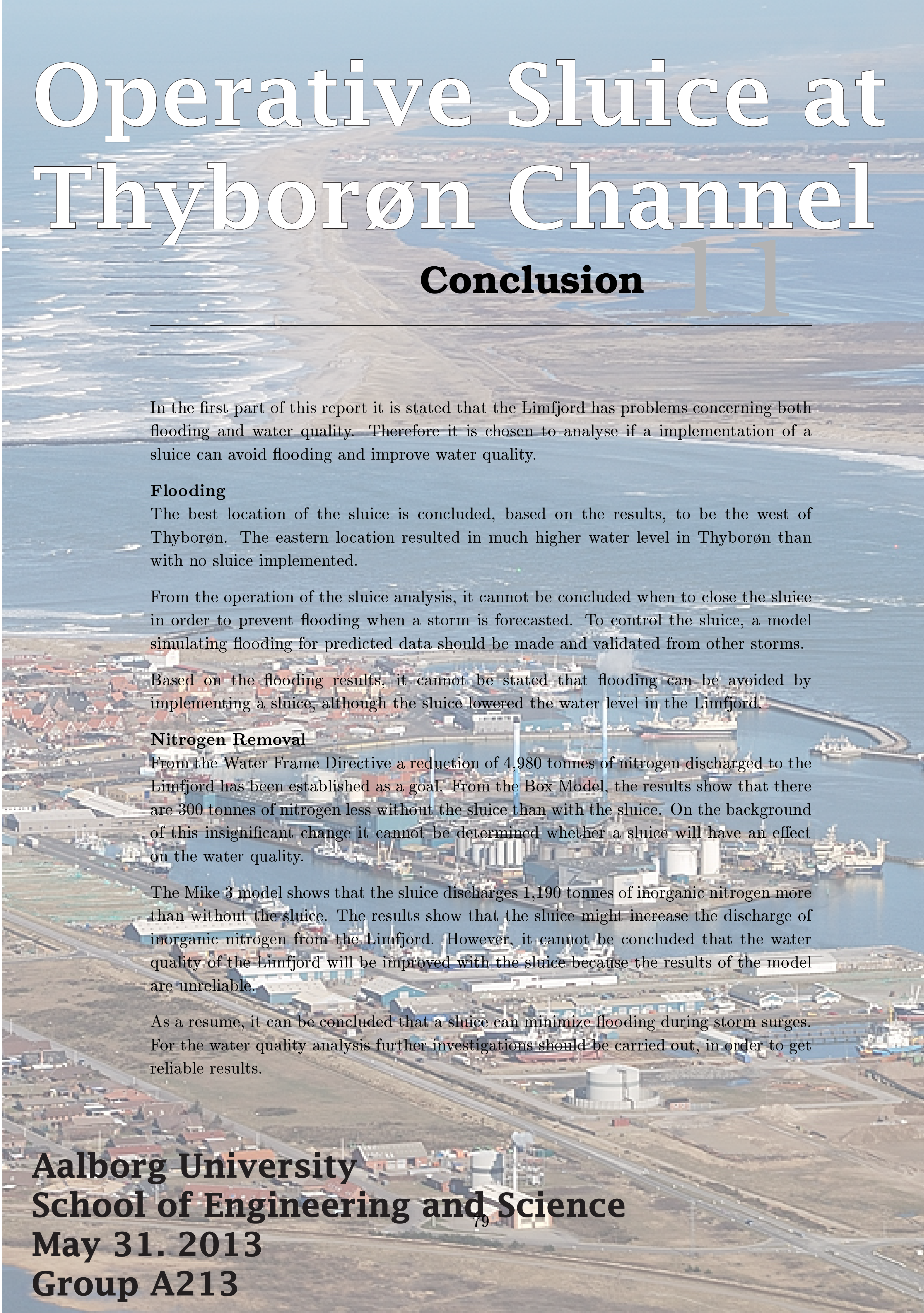

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11 Conclusion

In the first part of this report it is stated that the Limfjord has problems concerning both flooding and water quality. Therefore it is chosen to analyse if a implementation of a sluice can avoid flooding and improve water quality.

Flooding

The best location of the sluice is concluded, based on the results, to be the west of Thyborøn. The eastern location resulted in much higher water level in Thyborøn than with no sluice implemented.

From the operation of the sluice analysis, it cannot be concluded when to close the sluice in order to prevent flooding when a storm is forecasted. To control the sluice, a model simulating flooding for predicted data should be made and validated from other storms.

Based on the flooding results, it cannot be stated that flooding can be avoided by implementing a sluice, although the sluice lowered the water level in the Limfjord.

Nitrogen Removal

From the Water Frame Directive a reduction of 4,980 tonnes of nitrogen discharged to the Limfjord has been established as a goal. From the Box Model, the results show that there are 300 tonnes of nitrogen less without the sluice than with the sluice. On the background of this insignificant change it cannot be determined whether a sluice will have an effect on the water quality.

The Mike 3 model shows that the sluice discharges 1,190 tonnes of inorganic nitrogen more than without the sluice. The results show that the sluice might increase the discharge of inorganic nitrogen from the Limfjord. However, it cannot be concluded that the water quality of the Limfjord will be improved with the sluice because the results of the model are unreliable.

As a resume, it can be concluded that a sluice can minimize flooding during storm surges. For the water quality analysis further investigations should be carried out, in order to get reliable results.

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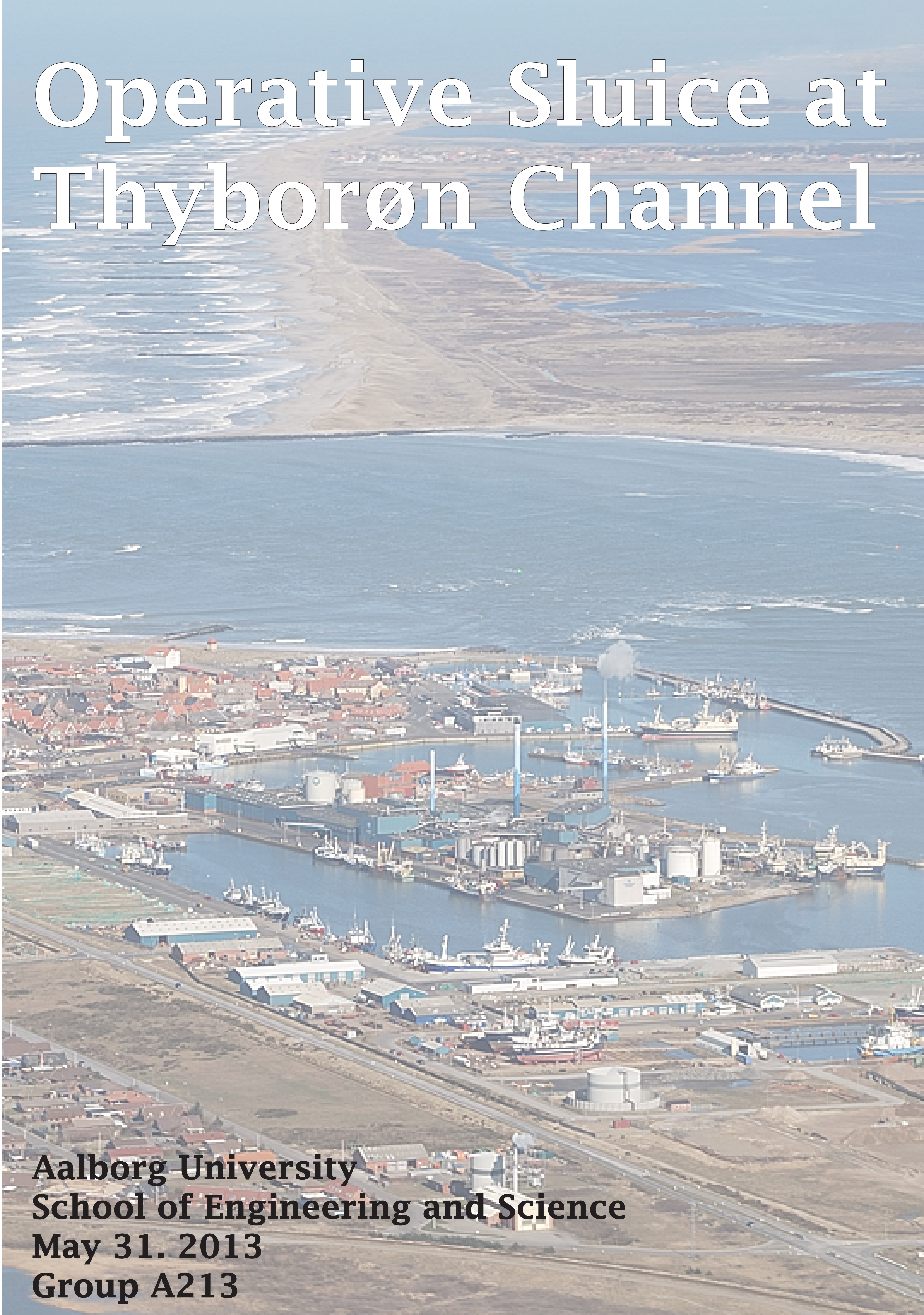

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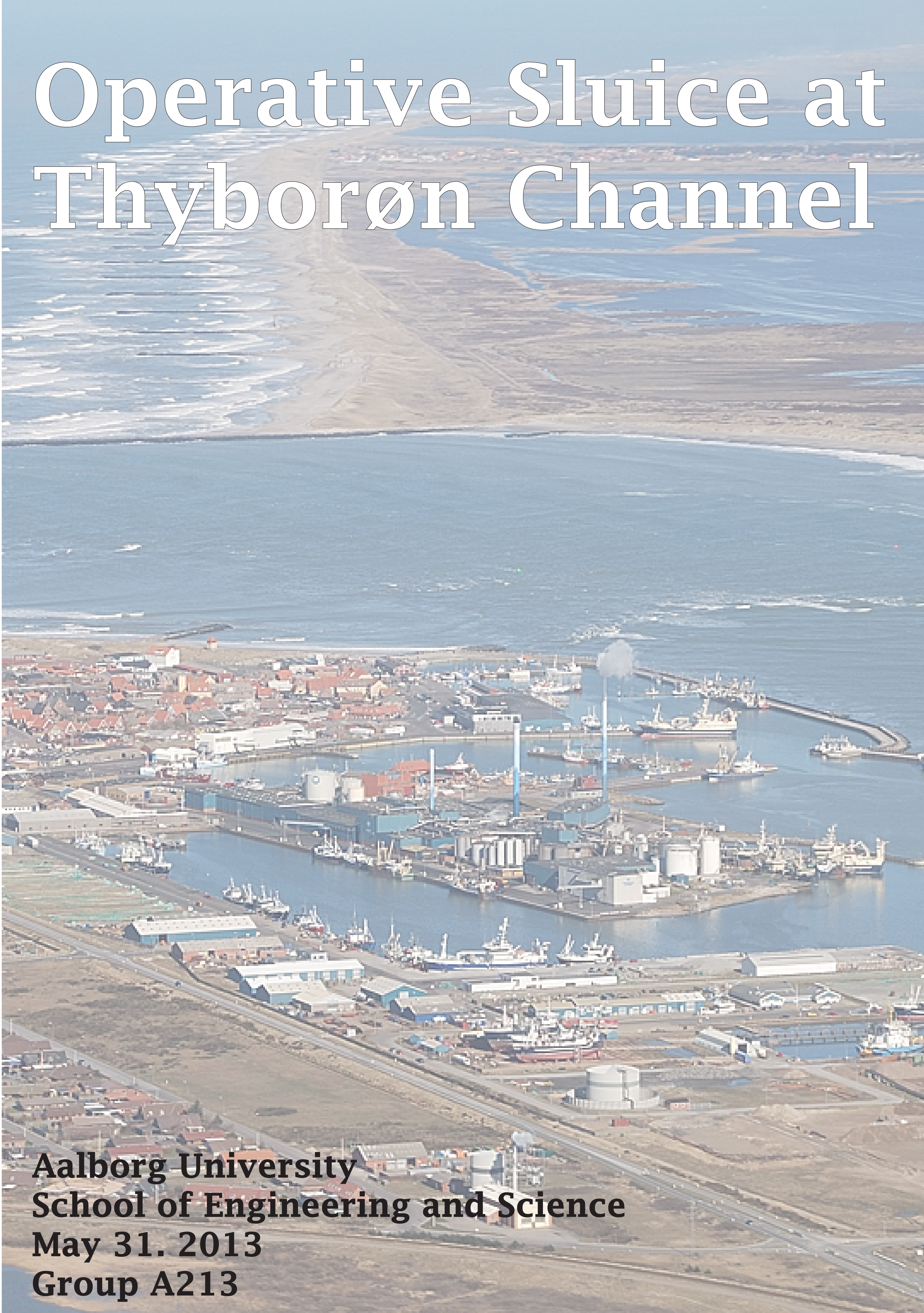

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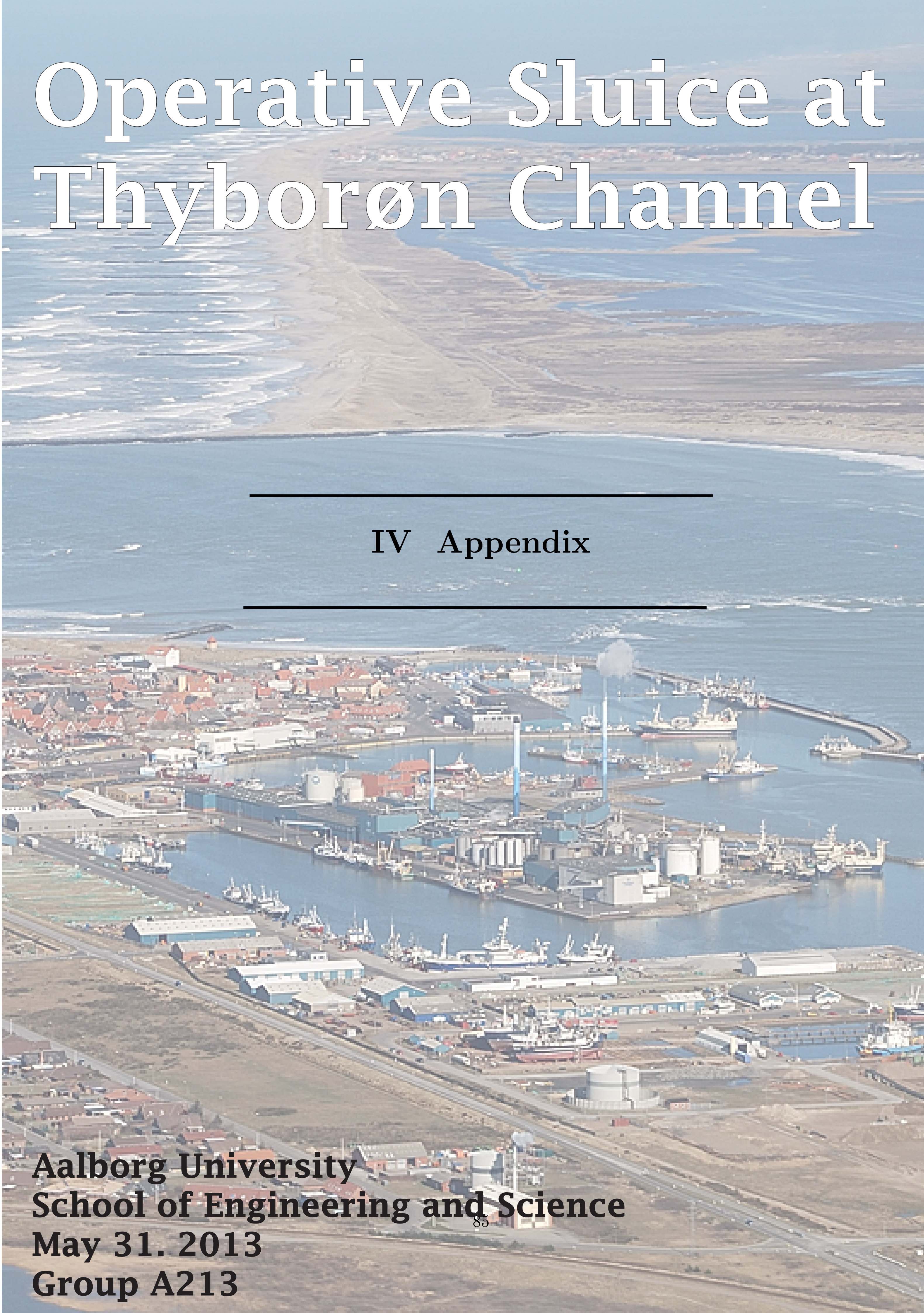

Operative Sluice at Thyborøn Channel

IV Appendix

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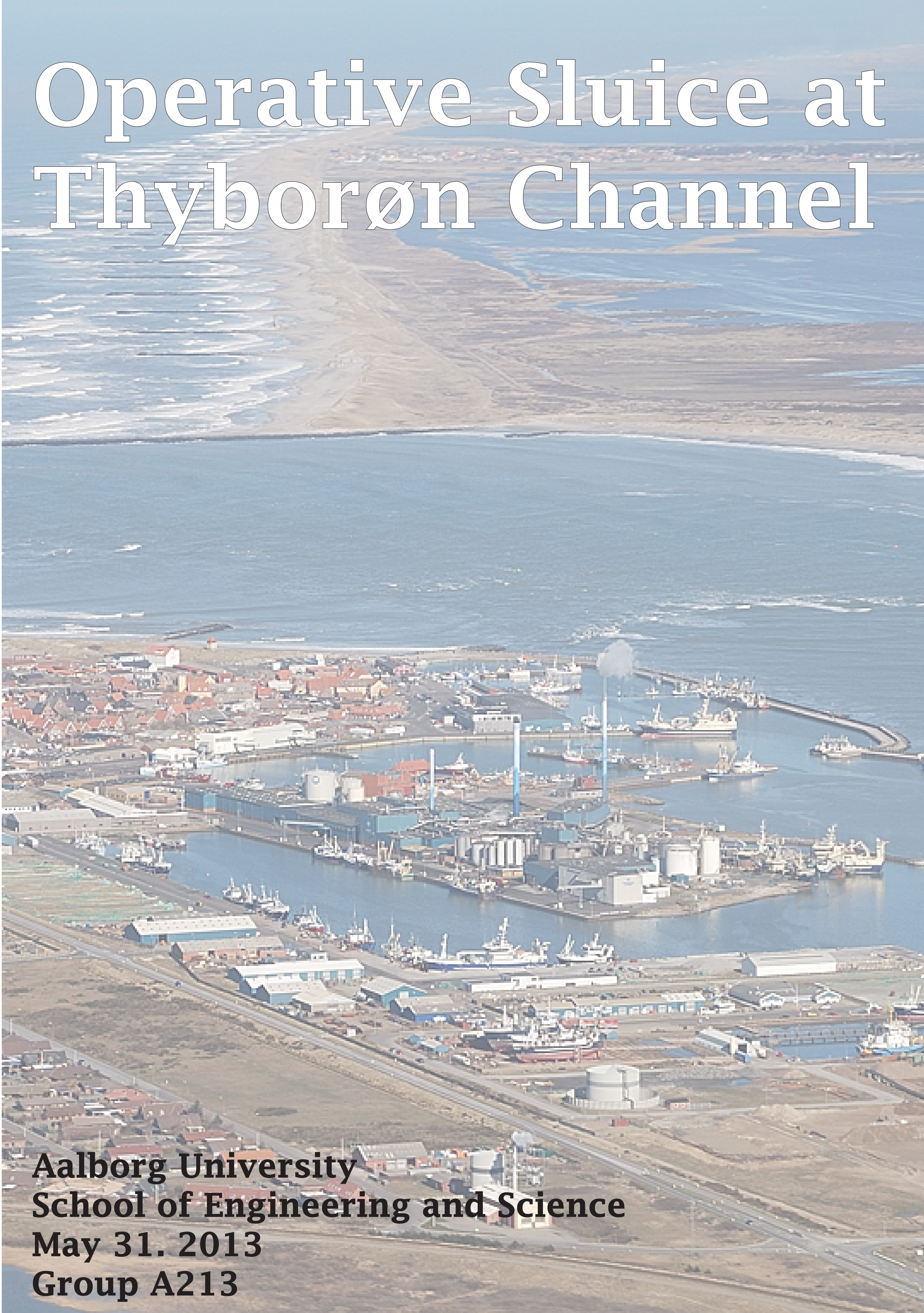

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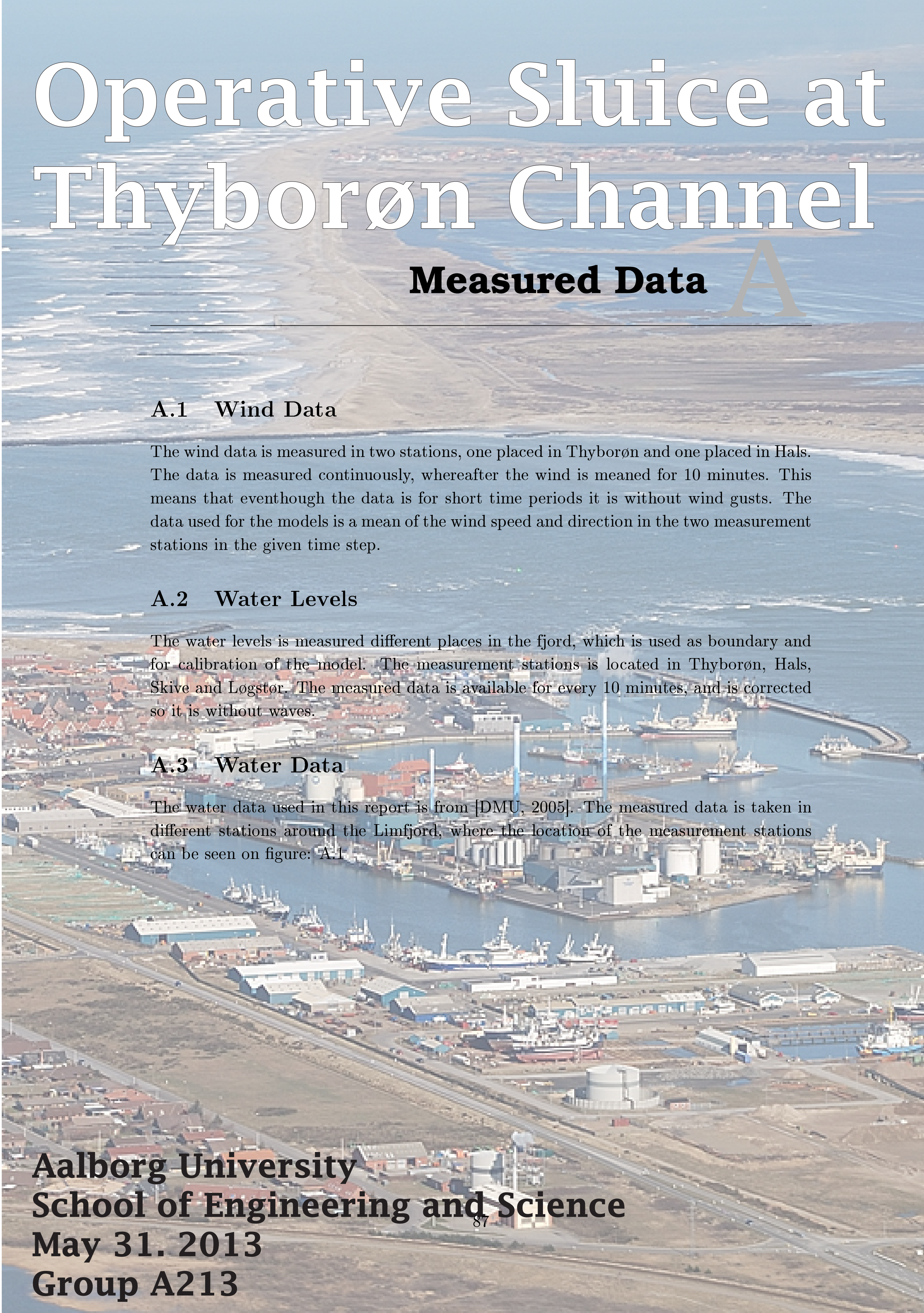

Operative Sluice at Thyborøn Channel

A Measured Data

A.1 Wind Data

The wind data is measured in two stations, one placed in Thyborøn and one placed in Hals. The data is measured continuously, whereafter the wind is meaned for 10 minutes. This means that eventhough the data is for short time periods it is without wind gusts. The data used for the models is a mean of the wind speed and direction in the two measurement stations in the given time step.

A.2 Water Levels

The water levels is measured different places in the fjord, which is used as boundary and for calibration of the model. The measurement stations is located in Thyborøn, Hals, Skive and Løgstør. The measured data is available for every 10 minutes, and is corrected so it is without waves.

A.3 Water Data

The water data used in this report is from [DMU, 2005]. The measured data is taken in different stations around the Limfjord, where the location of the measurement stations can be seen on figure: A.1

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Figure A.1: Location of measurement stations i the Limfjorden.

A.4 Salinty

The salinity used in the project is from the measurement stations located in the fjord.

A.5 Temperature

The water temperature used in the box model is from measurement station 3708-1, see figure A.2. At this station the temperature is measured in 14 depths at 35 different days covering the hole year of 2005. In this project there is taken a mean of these 14 values. Because the temperature is only measured 35 times a year there is fitted a sinus curve to the temperature used for describing the rest of the days. The measured data is shown in figure A.2 together with the fitted temperature curve.

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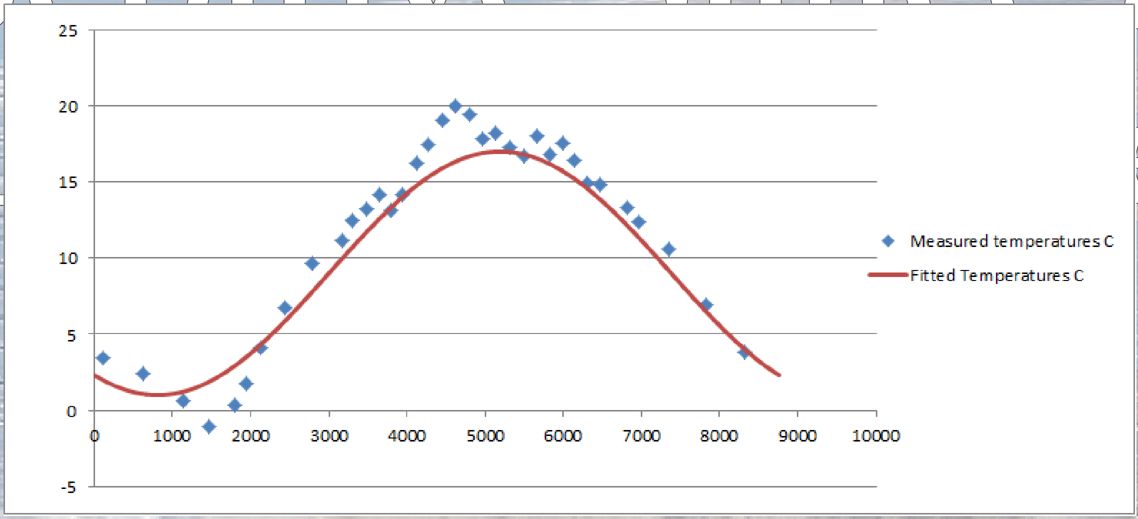

Figure A.2: Measured salinities from measurement station Løgstør Broad [DMU, 2005].

The fitted temperature curve is made with a mean og $9°C$ varying between 1 and 17 $°C$ is described from the following equation.

$$Temp(t) = 9°C + 8°C \cdot \left(\sin \left(\frac{2\pi}{8760} \cdot t - 5760 \right) \right) \quad \text{(A.1)}$$

Where t is hour of the year.

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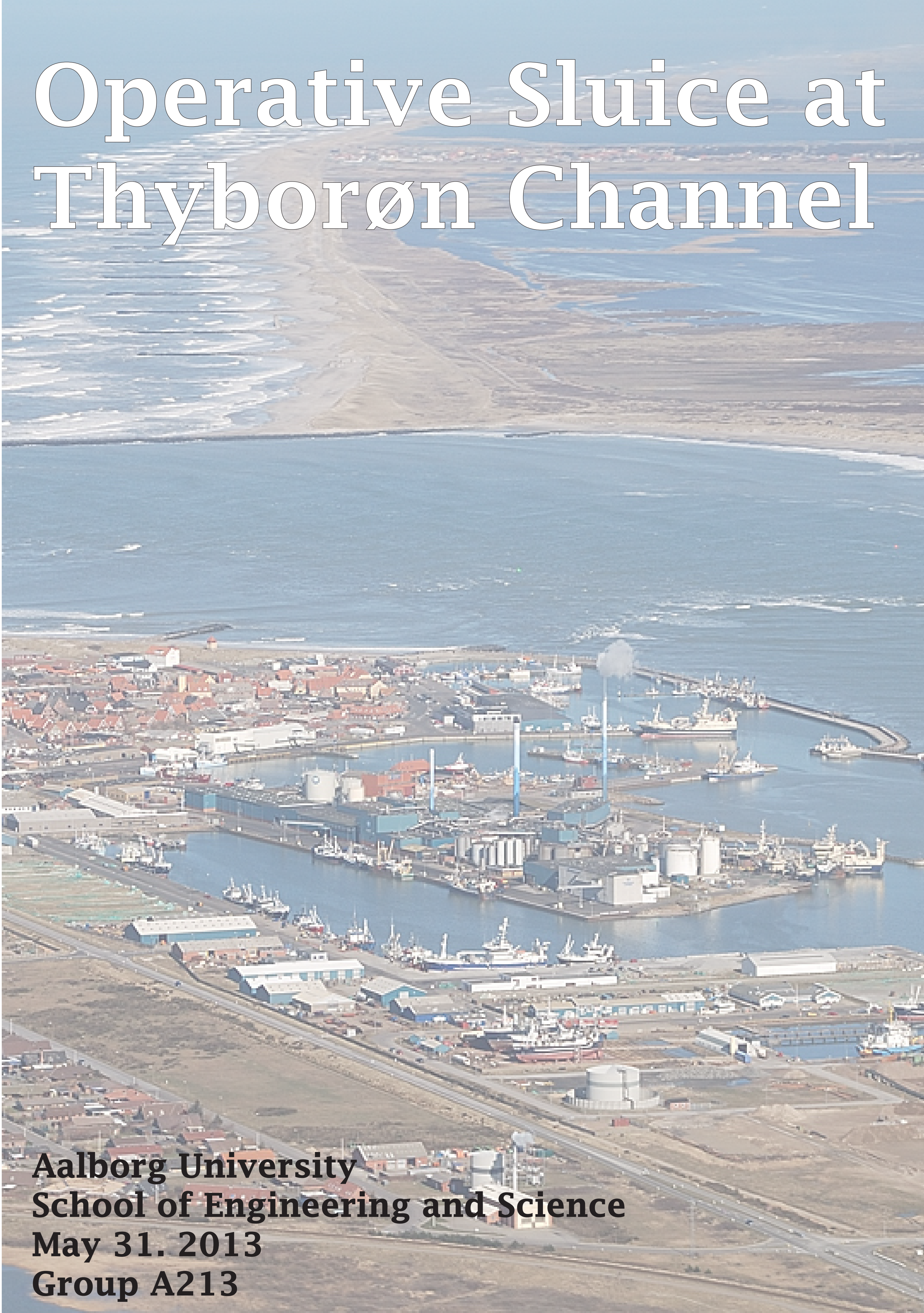

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B Cross Section Analysis

There are two reasons for analysing the relation between the cross section in the sluice and the net flow over a year. The first reason is that the wash out effect of nutrients is depending on the net flow, because a higher net flow can wash out more nutrients. The other reason for investigating it, is because the bigger a sluice, the more expensive it is. Therefore it is desirable to have almost the maximum net flow, but avoid making a bigger sluice, if it does not increase the flow. The smallest cross section of Thyborøn Channel is around $7600m^2$ [Kystdirektoratet, 2009]. The weather data used is from 2005, which includes the storm in January, but to make this more like an average year, the sluice is closed six days before the storm and one day afterwords.

The net flow is investigated without a sluice and then with sluices having an effective cross section of 80, 50, 25, 20, 15, 10 and 5% of the original cross section. The results are illustrated in figur B.1.

Figure B.1: This figure shows the relation between the cross section of the sluice and the average net flow in m^3/s over a year.

The figure illustrates that the effect of increasing the effective cross section area is

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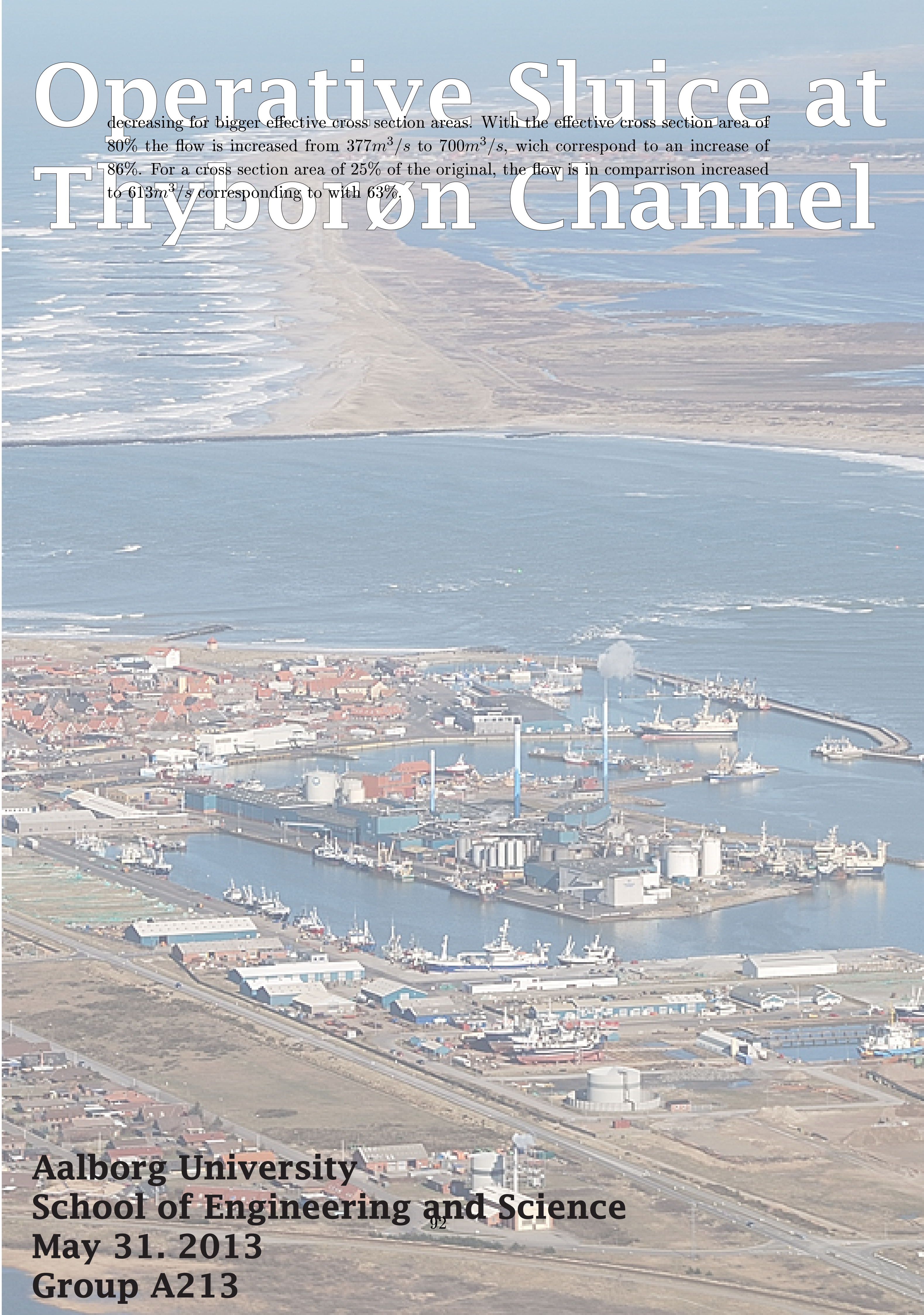

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decreasing for bigger effective cross section areas. With the effective cross section area of 80% the flow is increased from $377 m^3/s$ to $700 m^3/s$, wich correspond to an increase of 86%. For a cross section area of 25% of the original, the flow is in comparrison increased to $613 m^3/s$ corresponding to with 63%.

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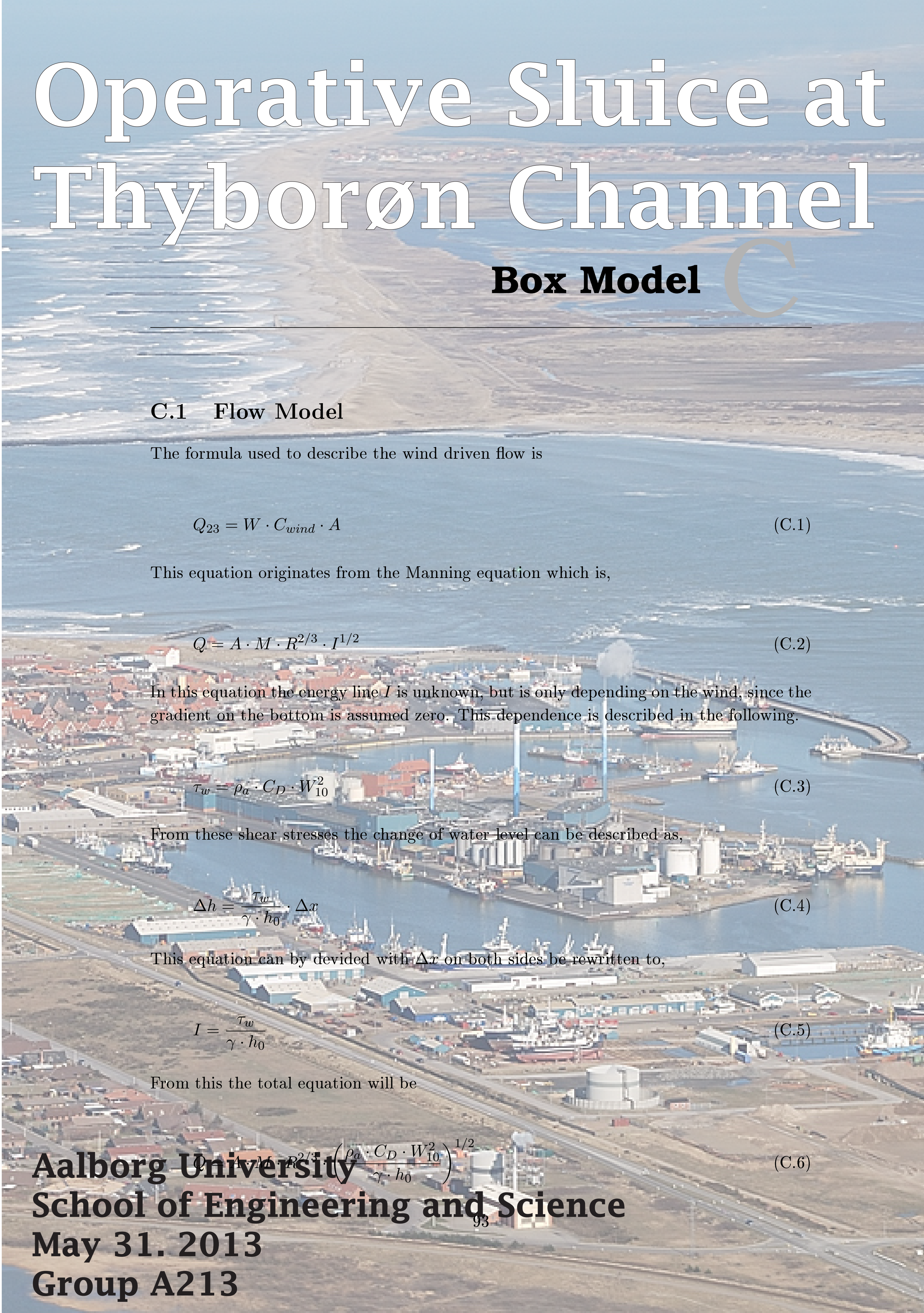

Operative Sluice at Thyborøn Channel

C Box Model

C.1 Flow Model

The formula used to describe the wind driven flow is

$$Q_{23} = W \cdot C_{wind} \cdot A \tag{C.1}$$

This equation originates from the Manning equation which is,

$$Q = A \cdot M \cdot R^{2/3} \cdot I^{1/2} \tag{C.2}$$

In this equation the energy line I is unknown, but is only depending on the wind, since the gradient on the bottom is assumed zero. This dependence is described in the following.

$$\tau_w = \rho_a \cdot C_D \cdot W_{10}^2 \tag{C.3}$$

From these shear stresses the change of water level can be described as,

$$\Delta h = \frac{\tau_w}{\gamma \cdot h_0} \cdot \Delta x \tag{C.4}$$

This equation can by devided with Δx on both sides be rewritten to,

$$I = \frac{\tau_w}{\gamma \cdot h_0} \tag{C.5}$$

From this the total equation will be

$$Q = A \cdot M \cdot R^{2/3} \left(\frac{\rho_a \cdot C_D \cdot W_{10}^2}{\gamma \cdot h_0} \right)^{1/2} \tag{C.6}$$

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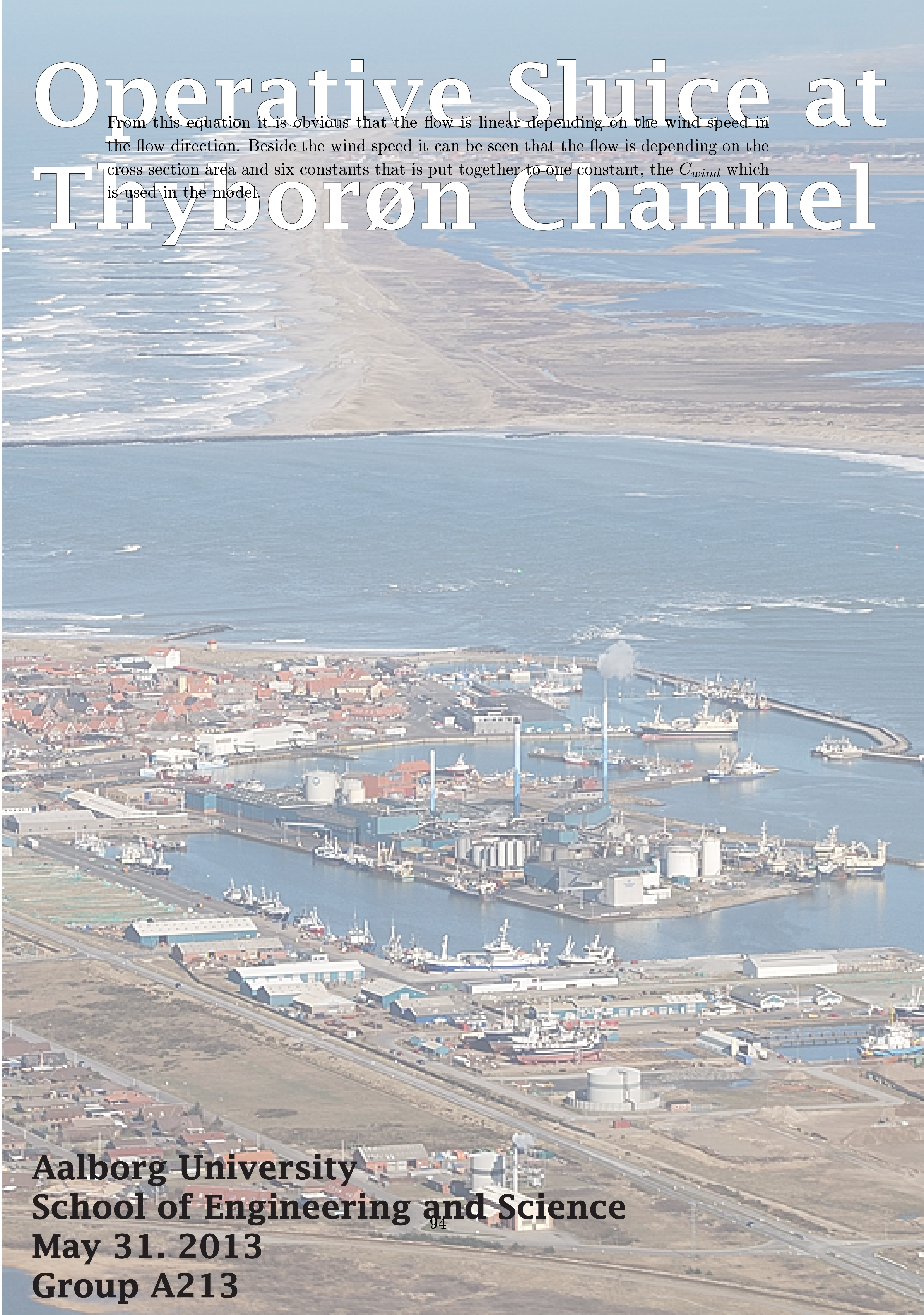

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From this equation it is obvious that the flow is linear depending on the wind speed in the flow direction. Beside the wind speed it can be seen that the flow is depending on the cross section area and six constants that is put together to one constant, the C_{wind} which is used in the model.

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D Mike Zero

In this chapter the theory behind the Mike Zero models is described.

Mike Zero, which is the overall name for Mike 21 and Mike 3, uses Reynolds Average Navier Stokes equation to calculate the fluid motion. Navier-Stokes equation comes from Newtons second law and the momentum equation, which together result in equation D.1.

$$\rho \frac{dv_i}{dt} = \rho \cdot g_i - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right) \tag{D.1}$$

By time averaging Navier-Stokes equation, it can describe turbulent flows. The time averaged Navier-Stokes equation, also called the Reynolds Average Navier Stokes equation, is illustrated in equation D.2

$$\rho \frac{dU_i}{dt} = \rho \cdot g_i - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j} + \rho\overline{u_i u_j}\right) \tag{D.2}$$

In the time average Navier-Stokes equation, the left hand side $\rho\frac{dU_i}{dt}$ expresses the change of momentum over time; while ($\rho \cdot g_i - \frac{\partial P}{\delta x_i}$) defines the pressure on the body. The first part is the gravity forces and the second part is the change in force over distance. The viscous shear stress is denoted by ($\frac{\partial}{\partial x_j}\mu\frac{\partial U_i}{\partial x_j}$) and they are mainly taking out energy from the current close to the walls and bottom. The turbulence, which is the change of momentum due to fluctuation, is described by ($\overline{\rho u_i u_j}$), and is the strongest where the velocity is the largest.

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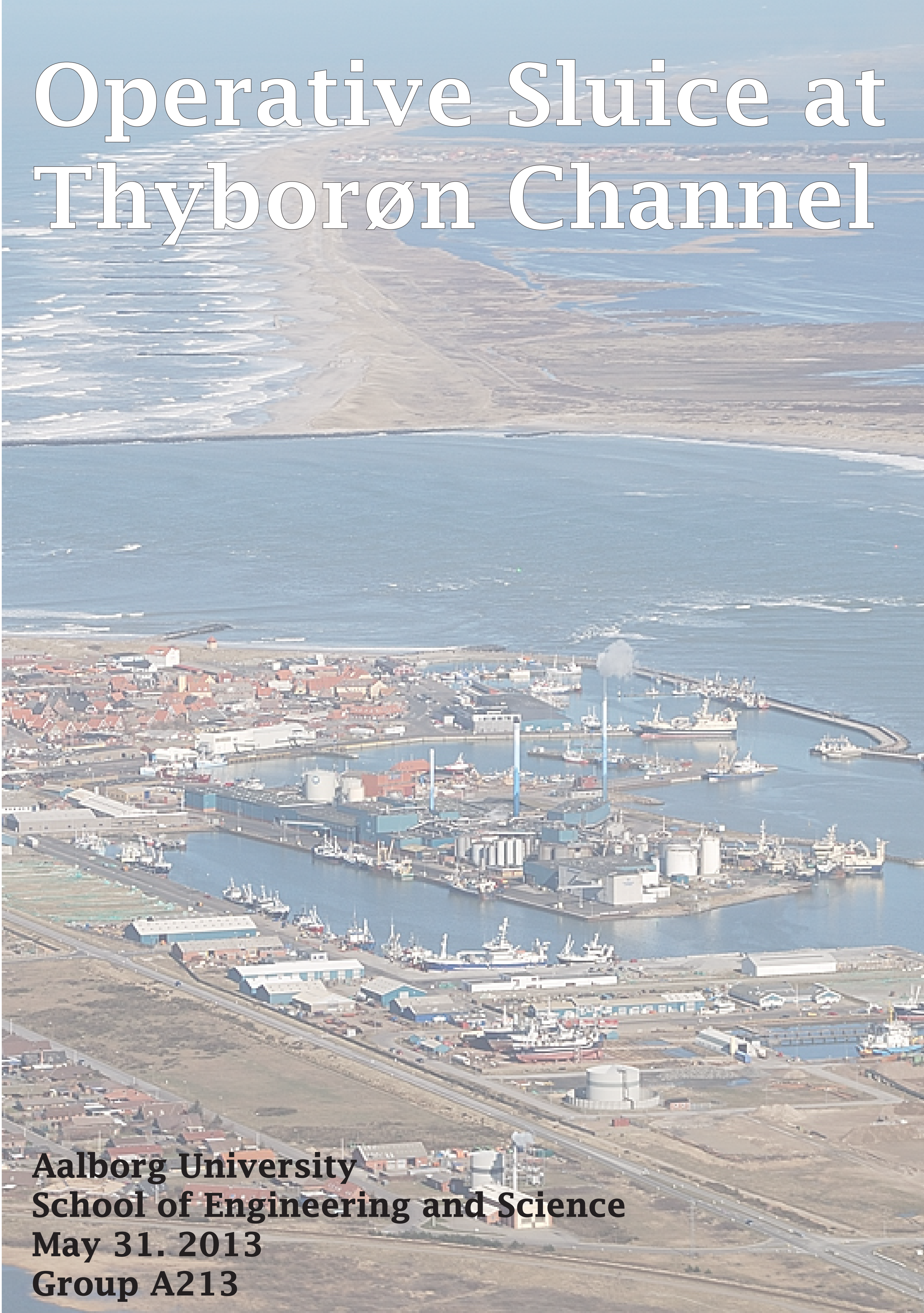

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E Mike 3

E.1 Salinity Calibration

In this section, the figures for the salinity calibration, which was calculated for different measurement stations from the hydrodynamic model in MIKE 3 FM, are shown.

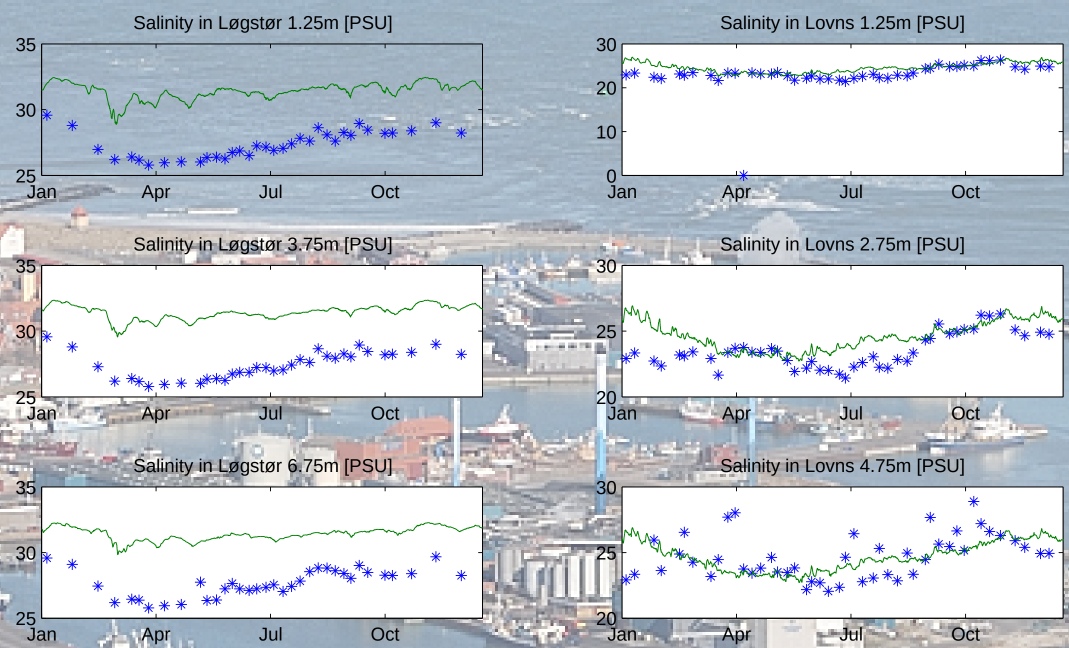

Figure E.1: Calibration of salinity for Lovns Broad and Løgstør Broad.

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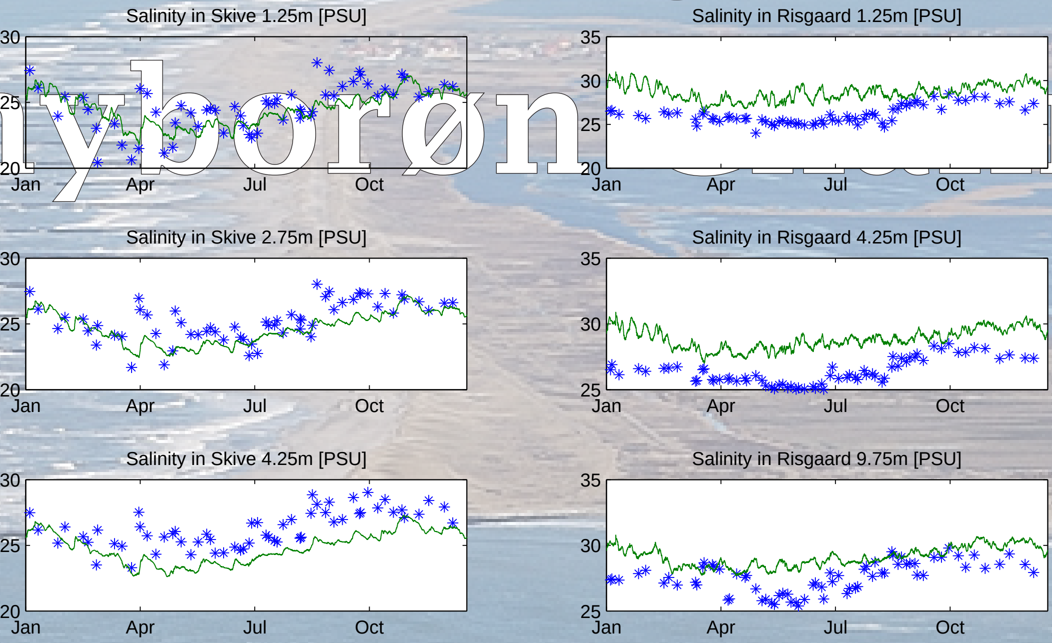

Figure E.2: Calibration of salinity for Risgaarde Broad and Skive Fjord.

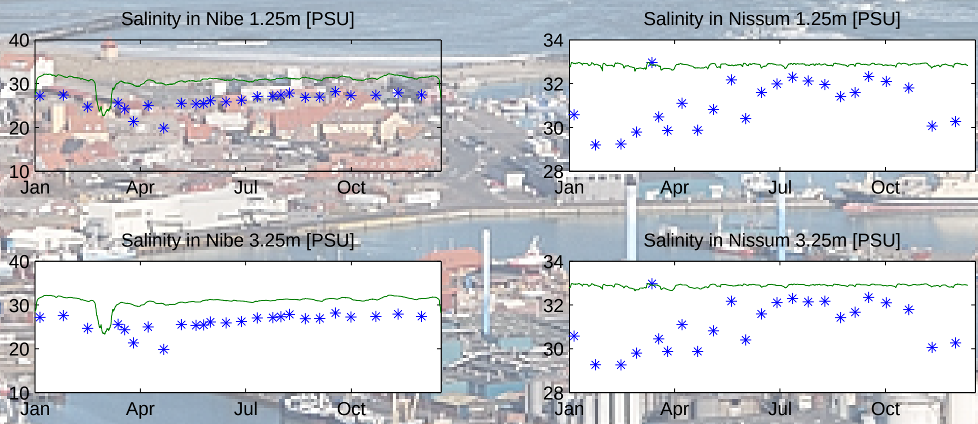

Figure E.3: Calibration of salinity for Nissum Broad and Nibe Broad

E.2 Ecolab Data

In the following table, the data used as input for all the fresh water sources are shown.

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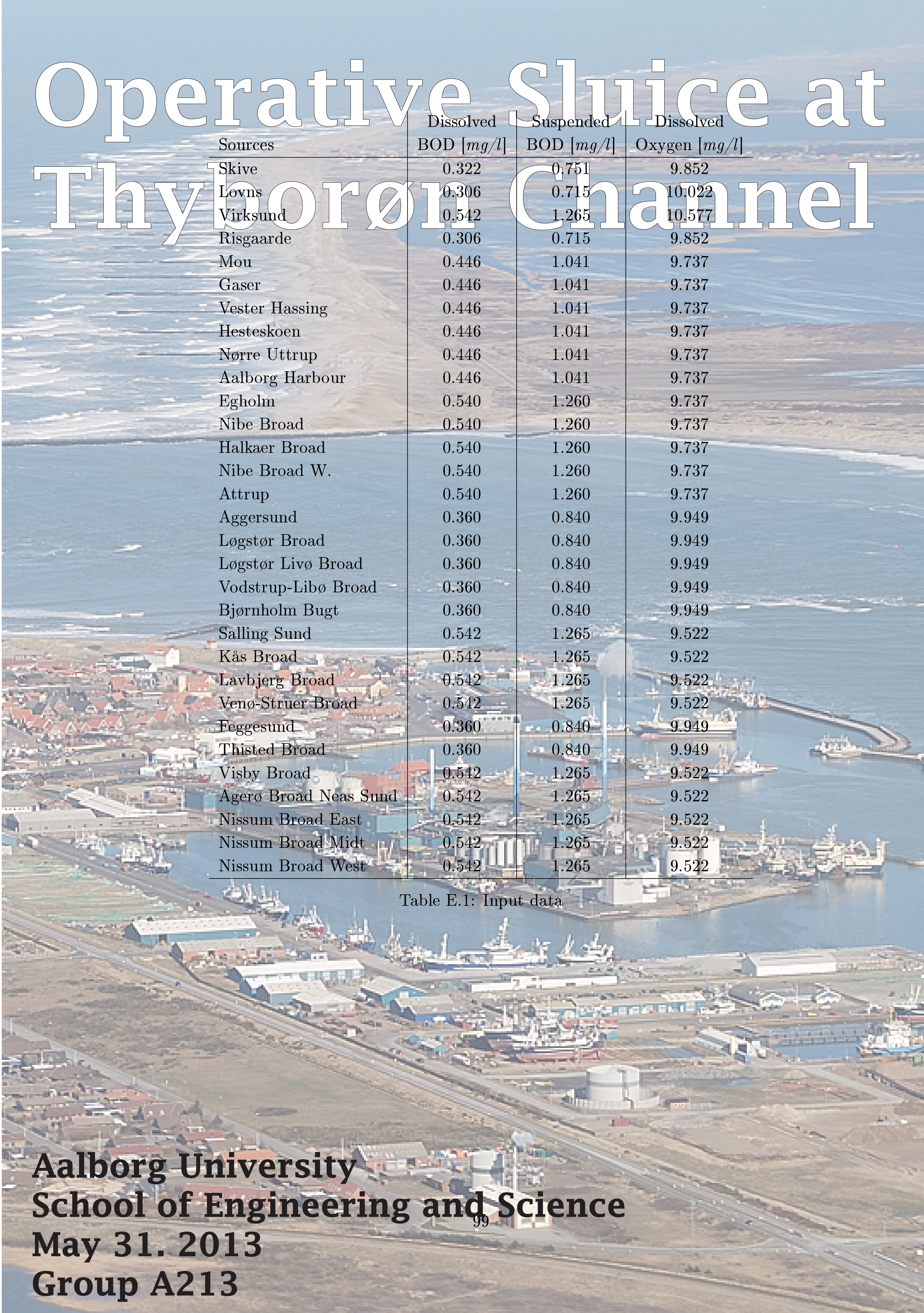

Operative Sluice at Thyborøn Channel

Sources	Dissolved BOD $[mg/l]$	Suspended BOD $[mg/l]$	Dissolved Oxygen $[mg/l]$
Skive	0.322	0.751	9.852
Lovns	0.306	0.715	10.022
Virksund	0.542	1.265	10.577
Risgaarde	0.306	0.715	9.852
Mou	0.446	1.041	9.737
Gaser	0.446	1.041	9.737
Vester Hassing	0.446	1.041	9.737
Hesteskoen	0.446	1.041	9.737
Nørre Uttrup	0.446	1.041	9.737
Aalborg Harbour	0.446	1.041	9.737
Egholm	0.540	1.260	9.737
Nibe Broad	0.540	1.260	9.737
Halkaer Broad	0.540	1.260	9.737
Nibe Broad W.	0.540	1.260	9.737
Attrup	0.540	1.260	9.737
Aggersund	0.360	0.840	9.949
Løgstør Broad	0.360	0.840	9.949
Løgstør Livø Broad	0.360	0.840	9.949
Vodstrup-Libø Broad	0.360	0.840	9.949
Bjørnholm Bugt	0.360	0.840	9.949
Salling Sund	0.542	1.265	9.522
Kås Broad	0.542	1.265	9.522
Lavbjerg Broad	0.542	1.265	9.522
Venø-Struer Broad	0.542	1.265	9.522
Feggesund	0.360	0.840	9.949
Thisted Broad	0.360	0.840	9.949
Visby Broad	0.542	1.265	9.522
Agerø Broad Neas Sund	0.542	1.265	9.522
Nissum Broad East	0.542	1.265	9.522
Nissum Broad Midt	0.542	1.265	9.522
Nissum Broad West	0.542	1.265	9.522

Table E.1: Input data

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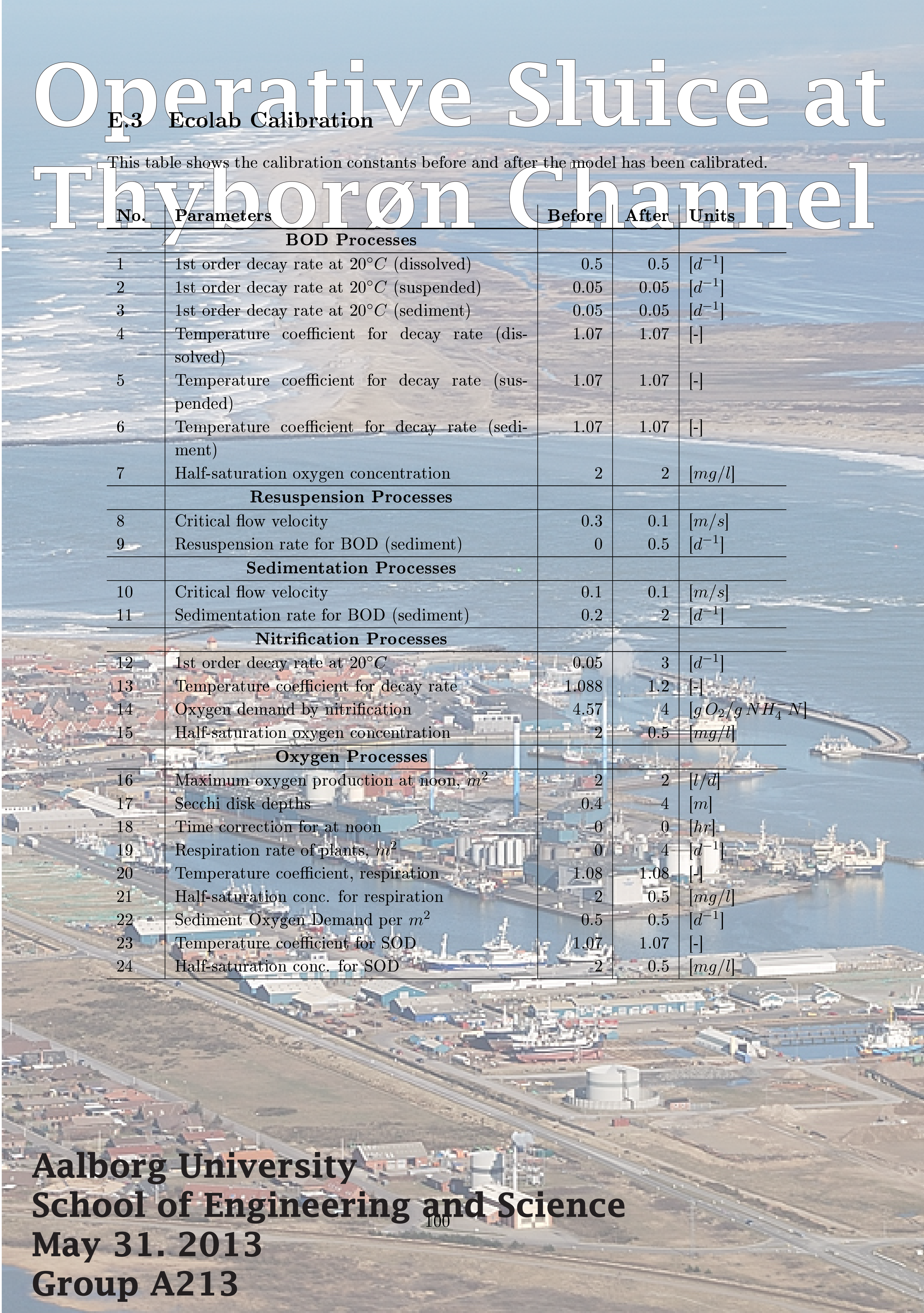

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E.3 Ecolab Calibration

This table shows the calibration constants before and after the model has been calibrated.

No.	Parameters	Before	After	Units
	BOD Processes			
1	1st order decay rate at 20°C (dissolved)	0.5	0.5	$[d^{-1}]$
2	1st order decay rate at 20°C (suspended)	0.05	0.05	$[d^{-1}]$
3	1st order decay rate at 20°C (sediment)	0.05	0.05	$[d^{-1}]$
4	Temperature coefficient for decay rate (dissolved)	1.07	1.07	[-]
5	Temperature coefficient for decay rate (suspended)	1.07	1.07	[-]
6	Temperature coefficient for decay rate (sediment)	1.07	1.07	[-]
7	Half-saturation oxygen concentration	2	2	$[mg/l]$
	Resuspension Processes			
8	Critical flow velocity	0.3	0.1	$[m/s]$
9	Resuspension rate for BOD (sediment)	0	0.5	$[d^{-1}]$
	Sedimentation Processes			
10	Critical flow velocity	0.1	0.1	$[m/s]$
11	Sedimentation rate for BOD (sediment)	0.2	2	$[d^{-1}]$
	Nitrification Processes			
12	1st order decay rate at 20°C	0.05	3	$[d^{-1}]$
13	Temperature coefficient for decay rate	1.088	1.2	[-]
14	Oxygen demand by nitrification	4.57	4	$[g\,O_2/g\,NH_4^-N]$
15	Half-saturation oxygen concentration	2	0.5	$[mg/l]$
	Oxygen Processes			
16	Maximum oxygen production at noon, m^2	2	2	$[l/d]$
17	Secchi disk depths	0.4	4	$[m]$
18	Time correction for at noon	0	0	$[hr]$
19	Respiration rate of plants, m^2	0	4	$[d^{-1}]$
20	Temperature coefficient, respiration	1.08	1.08	[-]
21	Half-saturation conc. for respiration	2	0.5	$[mg/l]$
22	Sediment Oxygen Demand per m^2	0.5	0.5	$[d^{-1}]$
23	Temperature coefficient for SOD	1.07	1.07	[-]
24	Half-saturation conc. for SOD	2	0.5	$[mg/l]$

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No.	Parameters	Before	After	Units
	Ammonia Processes			
25	Ratio of ammonium released by BOD decay (dissolved)	0.3	0.01	$[g\,NH_4^-N/g\,BOD]$
26	Ratio of ammonium released by BOD decay (suspended)	0.3	0.01	$[g\,NH_4^-N/g\,BOD]$
27	Ratio of ammonium released by BOD decay (sediment)	0.3	0.01	$[g\,NH_4^-N/g\,BOD]$
28	Amount of NH3-N taken up by plants	0.066	0.02	$[g\,N/g\,DO]$
29	Amount of NH3-N taken up by bacteria	0.109	0.03	$[g\,N/g\,DO]$
30	Halfsaturation conc. for N-uptake	0.05	0.3	$[mg/l]$
	Nitrate Processes			
31	1st order denitrification rate at $20°C$	0.1	0.1	$[d^{-1}]$
32	Temperature coefficient for denitrification rate	1.16	1.3	[-]
	Phosphorus Processes			
33	Phosphorus content in dissolved BOD	0.06	0.06	$[g\,P/g\,BOD]$
34	Phosphorus content in suspended BOD	0.06	0.06	$[g\,P/g\,BOD]$
35	Phosphorus content in sediment BOD	0.06	0.06	$[g\,P/g\,BOD]$
36	Amount of $PO_4 - P$ taken up by plants	0.0091	0.0091	$[g\,P/g\,DO]$
37	Amount of $PO_4 - P$ taken up by bacteria	0.015	0.015	$[g\,P/g\,DO]$
38	Halfsaturation conc. for P-uptake	0.005	0.005	$[mg/l]$

Table E.2: Input data

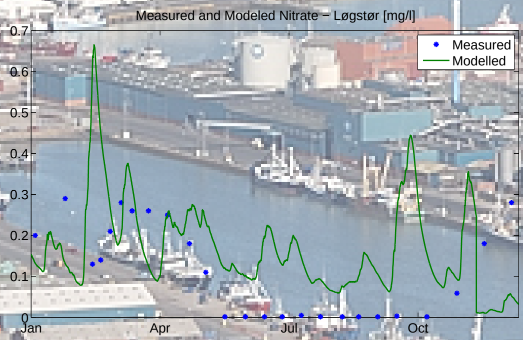

Figure E.4: Calibration of nitrate for Løgstør Broad

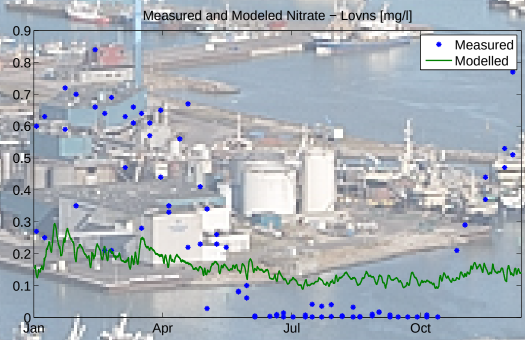

Figure E.5: Calibration of nitrate for Lovns Broad

E.4 Results

Results of the $4000m^2$ cross section sluice effect on nitrate concentration are shown in the following pictures.

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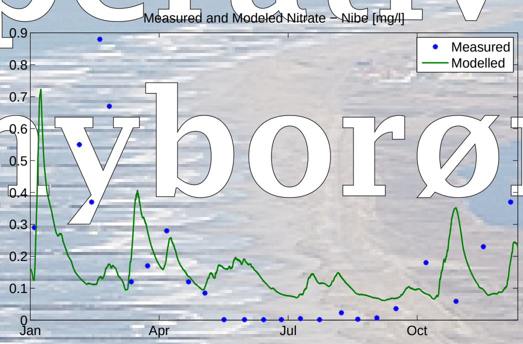

Figure E.6: Calibration of nitrate for Nibe Broad

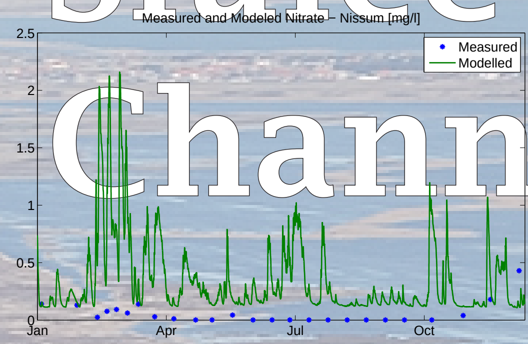

Figure E.7: Calibration of nitrate for Nissum Broad

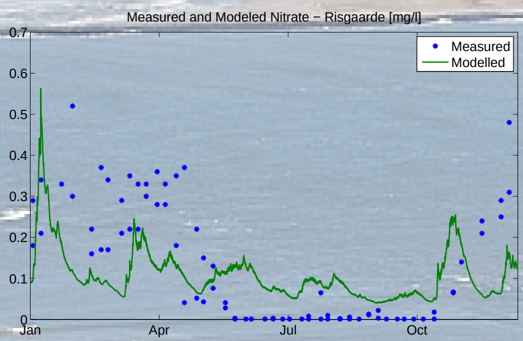

Figure E.8: Calibration of nitrate for Risgaarde Broad

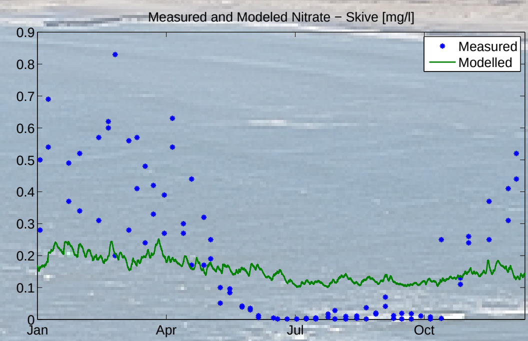

Figure E.9: Calibration of nitrate for Skive Broad

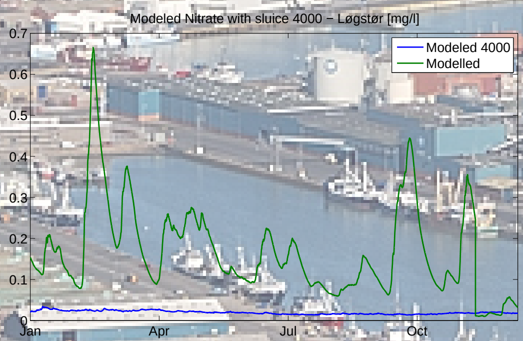

Figure E.10: Nitrate modelled values and nitrate values with the sluice of a cross section of $4000m^2$ in Løgstør

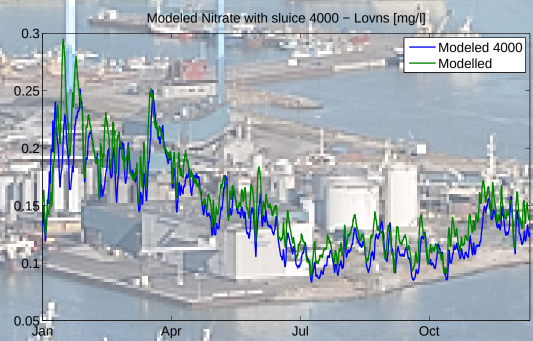

Figure E.11: Nitrate modelled values and nitrate values with the sluice of a cross section of $4000m^2$ in Lovns Broad

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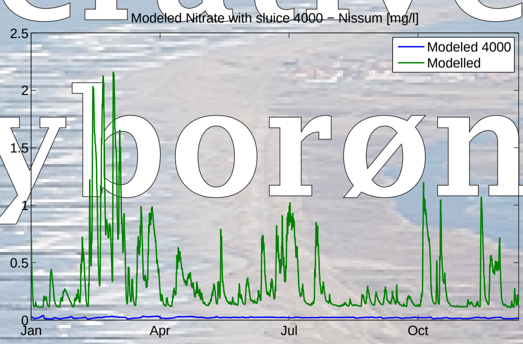

Figure E.12: Nitrate modelled values and nitrate values with the sluice of a cross section of $4000m^2$ in Nissum Broad

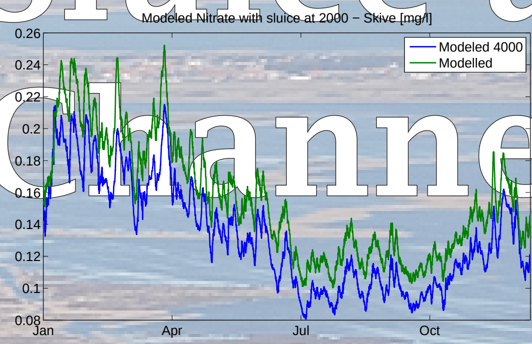

Figure E.13: Nitrate modelled values and nitrate values with the sluice of a cross section of $4000m^2$ in Skive

Results of the $6000m^2$ cross section sluice effect on nitrate concentration are shown in the following pictures.

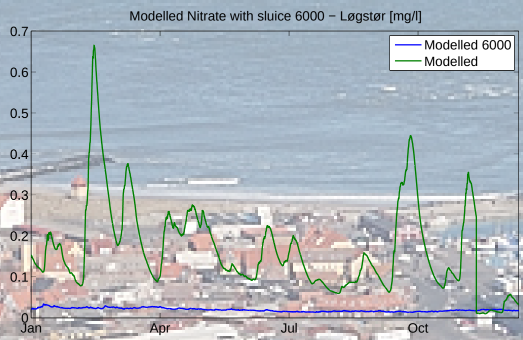

Figure E.14: Nitrate modelled values and nitrate values with the sluice of a cross section of $6000m^2$ in Løgstør

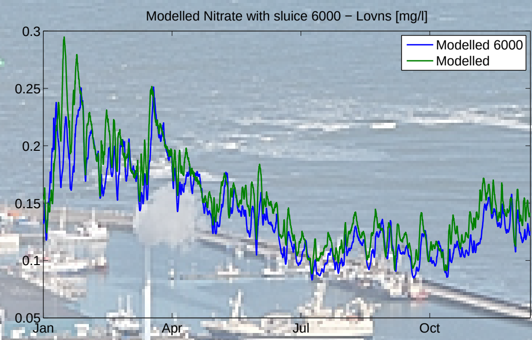

Figure E.15: Nitrate modelled values and nitrate values with the sluice of a cross section of $6000m^2$ in Lovns Broad

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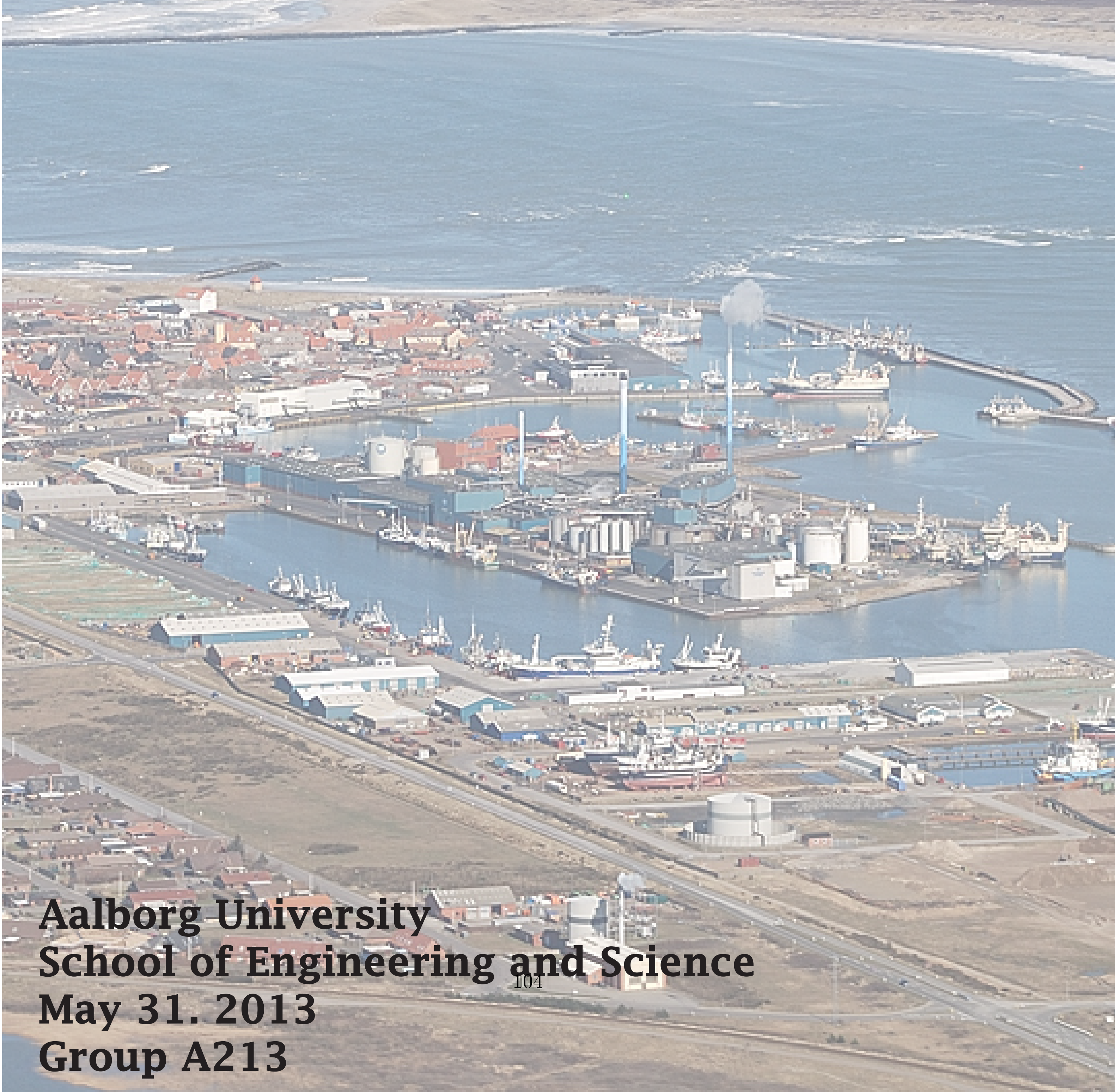
Operative Sluice at Thyborøn Channel



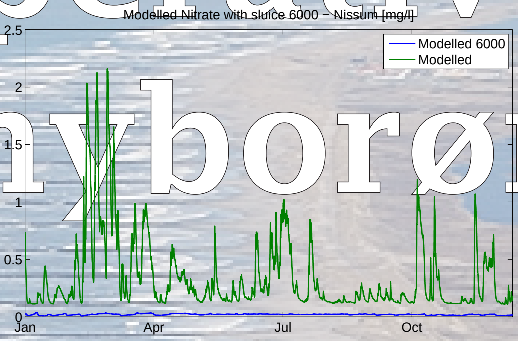


Figure E.16: Nitrate modelled values and nitrate values with the sluice of a cross section of $6000m^2$ in Nissum Broad

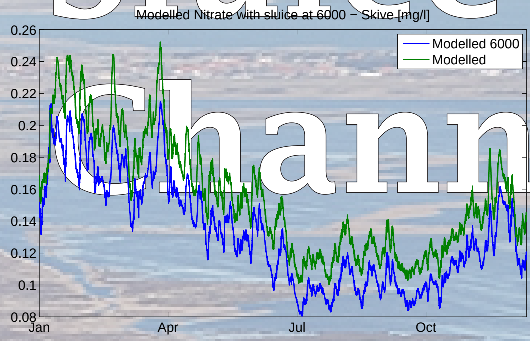


Figure E.17: Nitrate modelled values and nitrate values with the sluice of a cross section of $6000m^2$ in Skive

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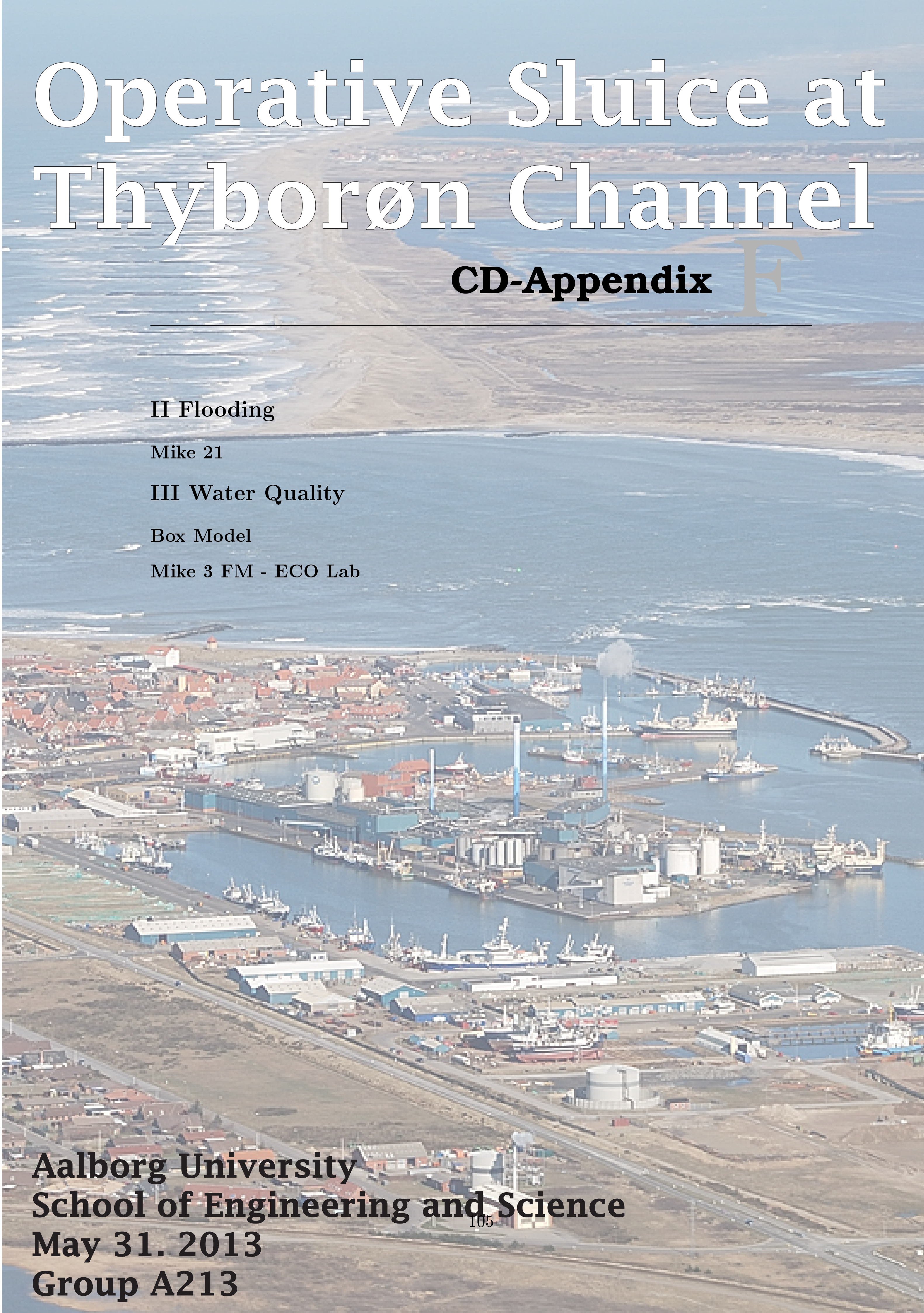
CD-Appendix F



II Flooding

Mike 21

III Water Quality

Box Model

Mike 3 FM - ECO Lab

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