Report

The sluice model for Ringkøbing Fjord.

A contribution to the work of the coastal water boad (Kystvandrådet)

Date:	19 December 2023
Author(s):	Morten Holtegaard Nielsen
Prepared for:	Ringkøbing-Skjern Kommune
Client's rep.:	Lene Moth
Client's project no.:	
Client's project:	Kystvandråd Ringkøbing Fjord 2023
Version:	Final
Status:	Open

Marine Science & Consulting ApS
Peder Lykkes Vej 8, 4. th.
DK-2300 Copenhagen S
Denmark

P: +45 5369 0888
E: info@msandc.dk
W: http://www.msandc.dk
CVR/VAT no.: DK39987082

Summary

In this project an existing model describing the conditions in Ringkøbing Fjord in terms of water level, salinity and stratification has been brought up to date and revised to account for alterations in the harbour of Hvide Sande, which have had an impact on the exchange between the fjord and the North Sea since the model was first established. Although progress was considerably hampered by erroneous observations of water level in the North Sea at Hvide Sande, the project has resulted in a well-working and reliable sluice model for both 2017 and 2019. In the project the sluice model has been used to study a number of scenarios, subject to both the current conditions and possible future conditions, the latter expected to be concerned with an increased water level in the North Sea and an increased run-off of freshwater from the catchment area of the fjord. The model has shown that if a pump is used to increase the flow from the fjord to the sea, it is possible to both reduce the water level and to increase the salinity in the fjord. However, it was not considered to which extent a pumped solution could be feasible from practical and economic points of view. Also, the model has shown that by way of a different operation of the sluice it was possible to increase the salinity in 2019, a year that was characterized by an extraordinarily low salinity during much of the time. This model run has pointed to a way in which to achieve a relatively high and stable salinity in the fjord with little risk of oxygen depletion. Finally, the model was used to investigate the response of the conditions in the fjord in various climate scenarios. The model showed both that the water level in the fjord is going to respond quickly and almost equally to the changes to the water level in the sea and that the salinity in the fjord is going to decrease significantly only if the freshwater run-off is increasing a lot. Adding a pumped flow to one of the climate scenarios showed that it will be possible to counteract the effects of climate changes in the future. It is very possible that operating the sluice differently will be able to counteract the effects of climate changes, but it was outside the scope pf the project to carry out such an investigation.

Resumé (in Danish)

I dette projekt er en eksisterende model, som beskriver forholdene i Ringkøbing Fjord mht. vandstand, saltholdighed og lagdeling, blevet opdateret og revideret, så den nu tager højde for ændringer i havnen i Hvide Sande, som har haft en indflydelse på udvekslingen mellem fjorden og Nordsøen, siden modellen blev opstillet første gang. Selvom arbejdet blev vanskeliggjort af fejlbehæftede observationer af vandstand i Nordsøen ved Hvide Sande, har projektet resulteret i en velfungerende og pålidelig slusemodel for både 2017 og 2019. I projektet er slusemodellen blevet brugt til at undersøge en række scenarier, under både eksisterende forhold og fremtidige forhold, hvor sidstnævnte forventes at være forbundet med en forøget vandstand i Nordsøen og en forøget afstrømning af ferskvand fra fjordens opland. Modellen har vist, at hvis en pumpe anvendes til at øge udstrømningen af vand fra fjorden, er det muligt både at reducere vandstanden og øge saltholdigheden i fjorden. Det blev dog ikke undersøgt, om en sådan pumpe-løsning er mulig set fra økonomiske og praktiske synspunkter. Endvidere har modellen vist, at ved at ændre på brugen af slusen var det muligt at øge saltholdigheden i fjorden i 2019, et år som var præget af usædvanlig lav saltholdighed i fjorden i en stor del af tiden. Denne modelkørsel har vist en metode til at opnå en relativ høj og stabil saltholdighed i fjorden med en lille risiko for iltsvind. Endeligt er modellen blevet brugt til at undersøge, hvordan forholdene i fjorden ændres i forskellige klima-scenarier. Modellen har vist både, at vandstanden i fjorden vil ændre sig hurtigt og næsten på samme måde som vandstanden i havet, og at saltholdigheden i fjorden kun vil falde betydeligt, hvis ferskvandsafstrømningen øges meget. Hvis man anvender en pumpe til at øge udstrømningen fra fjorden, vil det være muligt at modvirke de klima-betingede ændringer af forholdene i fjorden. Det

er meget sandsynligt, at en ændret brug af slusen vil kunne modvirke effekterne af klimaforandringer, men en sådan undersøgelse var ikke en del af projektet.

1. Introduction

This report describes and documents the contribution to the work of the coastal water board (“Kystvandrådet” in Danish) for Ringkøbing Fjord carried out by Marine Science & Consulting, in agreement with the contract with Ringkøbing-Skjern Kommune dated 23 August 2023. In short, the purpose of the coastal water board is to suggest locally based solutions in order to reduce the load of nutrients on and to improve the environmental conditions in Ringkøbing Fjord.

Ringkøbing Fjord is a so-called strongly modified estuary, the connection between the fjord and sea being controlled by a sluice. The operation of the sluice is influencing both the water level, the salinity and the stratification in the fjord. This is having an impact on the biota in the fjord in terms of determining the living conditions, but may also lead to oxygen depletion and the death of the biota if stratifiation occurs for long enough periods.

Some changes that have been dicussed in order to improve the environmental conditions in the fjord are increasing the salinity in the fjord, using pumps to allow for additional outflow from the fjord or allowing low-lying areas around the fjord to become flooded. These suggestions are not easily implemented as they are having an impact on the terrestrial part of the system, such as breeding birds in the adjacent Natura-2000 areas, farmland or people's living spaces.

The sluice model is run for two separate years, i.e. 2017 and 2019. These were selected as being, respectively, a year of general conditions and a year of somewhat low salinity in the fjord, the latter having caused some wondering as to the reason why.

The purposes of the work with the sluice model are these: 1) To provide boundary conditions for the 3-dimensional model run by Longline Environment (LLE) in terms of outflow of fjordwater or inflow of seawater through the sluice for both 2017 and 2019. 2) To investigate various pumped scenarios. 3) To investigate the capacity of the sluice especially for 2019, which was a year of low salinity in the fjord. 4) To investigate various scenarios related to climate changes.

A few introductory remarks on the dynamical properties of Ringkøbing Fjord as a system could help in understanding the results to be presented in this report. It is noted that the capacity of the sluice, being about 1000 $m^3 s^{-1}$, is an order of magnitude bigger than the freshwater run-off from the catchment area. This implies that by way of the sluice relatively quick changes to the general water level in Ringkøbing Fjord may be obtained. I.e., if the sluice is fully open, a change of the water level in the fjord of, say, 0.10 m can typically be obtained in less than 24 hours. In contrast, for considerable changes in the salinity in the bulk part of Ringkøbing Fjord to take place, several weeks are required, depending on the degree to which the sluice is open. Thus, it will become apparent that changes to water level in Ringkøbing Fjord, resulting primarily from the operation of the sluice and the variation of the water level in the North Sea, are relatively quick whereas changes to the salinity, detemined by both the freshawater run-off and the exchange through the sluice, are rather slow. These circumstances must be taken into consideration when attempting to influence the conditions in the fjord, e.g. by way of operating the sluice.

2. Model description

The sluice model for Ringkøbing Fjord is a simplified model describing the prominent properties of the fjord, i.e. the water level, the salinity and the stratification, as a function of the external forcing. Since the fjord is characterized by small horizontal salinity gradients, an important simplification is to consider the vertical stratification only. The external forcing, which is varying in time, includes the freshwater input from the catchment area, the wind and the water level at the sea-side at Hvide Sande. Driven by the water level difference between the North Sea and the fjord at Hvide Sande, the model includes calculation of the flow through the sluice, which is also a function of the operation of the sluice. Detailed information on the model, including the underlying physical processes, the validity of the assumptions and the strengths and weaknesses of the model, are described and discussed in Nielsen et al. (2005), which also includes a large number of references of relevance.

A modified version of the model was used to investigate the conditions in Nissum Fjord, an estuary that is also located along the west coast of Jutland, is subject to much the same environmental challenges as in Ringkøbing Fjord and is also connected to the North Ses by way of a sluice. This version of the model is documented in Nielsen (2013).

The original version of the sluice model for Ringkøbing Fjord was established based on the conditions prevailing in 1999 (Nielsen et al., 2005). Since then the harbour of Hvide Sande has been subject to a number of alterations, which have had an impact on the exchange of the fjord. These alterations are as follows, the information obtained from former sluice master Henning Yde (personal communication). Construction of a new breakwater to the north of the harbour and extension of the existing breakwater to the south of the harbour, carried out in 2012. Increase of the depth between the two breakwaters, in the entry area just west of the harbour and in the western part of the inner harbour to a minimum value corresponding to a seabed level of – 7.0 m DVR90, carried out in 2014. Increase of the distance by 10 m between the two jetties located at the north side and the south side in the inner part of the harbour, carried out in 2016. These alterations have led to changes in the energy losses in the flows between the fjord and the North Sea. Therefore the sluice model has been subject to modifcations to account for the conditions prevailing in 2017 and 2019. Due to the modifications, some calibration of the model was to be expected.

A pilot who is often bringing large vessels into the harbour of Hvide Sande reported that the depths in the vicinity of the entry to the harbour as well as between the breakwaters are highly variable in both space and time (personal communication). This is also apparent from information published regularly on the website of the harbour, showing that the depths in the area in question are mostly between levels corresponding to – 7.5 m and – 8.0 m DVR90. The pilot stated that he would abstain from bringing very large vessels into the harbour unless a bathymetric survey had been carried out very recently. Therefore maintenance dredging is taking place regularly in these parts of the harbour. However, the variability of the depths imply that the frictional losses for the flows through the harbour may be difficult to determine with certainty. In addition, the pilot pointed out that very strong along-shore currents in the vicinity of the harbour entrance made navigation into the harbour very difficult. Such along-shore currents have a substantial influence on the water levels at the entrance (see below).

In addition to the modifications owing to the alterations of the harbour, the functionality of the sluice model was extended to include a pumped flow from the fjord to the North Sea. This functionality was added in order to accommodate for the wish of the members of the coastal water board, wanting to find out to which extent a pump would be able to influence the conditions in the fjord. It was assumed that the pump provides a given flow, as prescribed, of water out of the fjord. For the sake of simplicity it was further assumed that the pumped flow is fully independent from the flow through the sluice and the harbour of Hvide Sande. However, if such a solution were to be implemented for real, it would probably be advantageous for both economical and practical reasons to place the pump and the piping near the sluice. This implies that the pumped flow cannot be expected to be fully independent from the flow through the sluice.

The model was implemented in LibreOffice Calc, a free and open source spredsheet software. The coding language used to write macros in LibreOffice Calc is Apache OpenOffice BASIC, which corresponds almost fully to Microsoft BASIC, the coding language of macros in Microsoft Excel.

Water temperature was disregarded throughout as this has very little influence on the physical properties of the fjord in terms of water level, salinity and stratification.

The model is disregarding the internal baroclinic dynamics in the fjord. One exception to this is the inflow of saline water through the sluice, which is modelled as a dense bottom current until it reaches the deepest part of the fjord. Due to entrainment the inflowing seawater is subject to a considerable dilution. This and other model details are discussed thoroughly in Nielsen et al. (2005).

3. Observations

In order to establish the boundary conditions for the model and to validate the model results the observations listed in the table below were used. The locations where the observations were made and the source of the observations are noted in Table 1.

Table 1: Observations used to establish the boundary condition for the sluice model and to validate the model results. Where applicable, the numbers of the measuring stations are mentioned, cf. the data sources.

Variable(s)	Location	Source
Water levels	North Sea at Hvide Sande (5203), Thorsminde (5101) and Esbjerg (6401)	Danish Coastal Authority (website)
Water levels	Ringkøbing Fjord at Hvide Sande (5210), Ringkøbing Harbour (5212) and Bork Harbour (5213)	Danish Coastal Authority (website)
Wind speed and direction	Hvide Sande (5200)	Danish Coastal Authority (website)
Sluice operation	Hvide Sande	Danish Coastal Authority (personal communication)
Freshwater run-off	Entire catchment area of Ringkøbing Fjord	Longline Environment (personal communication)
Salinity and temperature (vertical profiles)	One station in the North Sea near Hvide Sande (91330001)	Environmental Portal of Denmark (Danmarks Miljøportal, website)
Salinity and temperature (vertical profiles)	Seven stations in Ringkøbing Fjord (91320012, 91300002, 91320023, 91320018, 91320001, 91320014, 91320019)	Environmental Portal of Denmark (Danmarks Miljøportal, website)

Adding to the information in the table, it is noted that water levels in the North Sea at several stations have been used in order to be able to fill out gaps or missing data in the time series. This is explained below. Also, it is noted that the data for the sluice operation comprise the times of opening or closing and also the opening heights of the sluice gates. Information logged by the sluice operator, such as the motivation for operating the sluice, was also provided by the Danish Coastal Authority. Erroneous or missing data are discussed below. For the sluice data, it is noted that usually either several or all gates are fully open, one or two gates are slighly open, or all gates are fully closed.

4. Hypsometric data

In order to take into account changes in the fjord since the model was first established, a new bathymetric data set was used, provided by Longline Environment and used in their 3-dimensional model of the fjord. The bathymetric data were provided in terms of hypsometric data, i.e. the volume and the area as a function of the vertical level.

If the effects of relatively high water levels and/or flooding of low-lying areas in the vicinity of the fjord are to be investigated, hypsometric data for water levels above 0 m DVR90 are necessary. These data were provided by Ringkøbing-Skjern Kommune based on the Danish Elevation Model.

5. Boundary data

The boundary conditions that are required to run the sluice model include the water level in the North Sea at Hvide Sande, the wind speed and direction, which is assumed to have no spatial variablility over the fjord, the operation of the sluice, the run-off of freshwater from the catchment area, and the salinity in the North Sea at Hvide Sande, which may be assumed to be constant. As much data as possible were taken directly from the observations listed above, so that no or little modification of the raw data was necessary. The water level in the North Sea at Hvide Sande, however, turned out to require considerable efforts, as described below. Apart from that only short gaps in the data were found, which were filled by way of linear interpolation.

The boundary data were imported into a number of separate files in LibreOffice Calc, which were read by the model code. Note that the code was written in a way so that the observations could be used as boundary data with as few modifications as possible. However, as discussed below, holes in the time series had to be filled by way of either interpolation or data from other locations. Apart from these changes it is not known if the observations have been modfied by the Coastal Authority prior to publication on their website.

5.1 Water level in the North Sea at Hvide Sande

Although observations of the water level at Hvide Sande were available, it turned out that these data were erroneous to an extent that made them unsuitable as boundary conditions for the model. Unfortunately, this was not clear until rather late in the course of the project. Until that point in time it was clear that the model results did not agree satisfactorily with the observed water levels in Ringkøbing Fjord for 2017, the period that was being modelled at first. Many attempts were made to locate possible errors, including the exchange through the sluice and the harbour, the freshwater run-off and the hypsometric data, but there was no or only limited success. When focus was finally put on the observations of water level at Hvide Sande, the Danish Coastal Authority admitted that these data were, in fact, associated with considerable errors. This had been known by the technical personnel of the Coastal Authority since 2012. The technical personnel reported that the measurement gauge was located in an inconvenient place at the southern breakwater and had not been calibrated regularly. The substantial currents reported by the pilot (see above) may possibly have contributed to the erroneous observations. Subsequently the observations were removed from the website of the Coastal Authority.

Neither the nature nor the magnitude of the errors could be clarified by the Coastal Authority. Judging from the modelling results using the erroneous boundary data it seemed that apart from a constant offset the observations were correct for long periods of time. In addition, no drift of the observations was apparent. A constant offset during a period of time indicates that the measurement gauge was working well, but that a physical movement of the measurement gauge or an adjustment of the observations, applied at the time of measurement or after collection of the observations, had taken place. The Coastal Authority was unable to provide further information on the issue, apart from stating that a better location for the measurement gauge was needed.

Due to the late point in the course of the project that this was realized it was decided to make some simple adjustments to the observed water levels at Hvide Sande in order to obtain a reasonably well operating sluice model for 2017. The changes that seemed to be necessary were an offset adjustment of about 15 cm from 1 January to 9 May (interestingly, at this point data were lacking completely from all stations for a period of about 10 hours) and about 20 cm from 6 October to 22 November. In the period between 9 May and 6 October, there did not seem to be any significant and constant offset error. The observations of water level from the North Sea at Hvide Sande were adjusted accordingly. It is noted that erroneous water levels were not found to be a problem as the sluice model was first developed (Nielsen et al., 2005), possibly because the design of the outer part of the harbour was much simpler at that time.

To establish a complete set of water level boundary data, periods of missing observations had to be filled somehow. If the gap was shorter than 60 minutes, linear interpolation was carried out. Gaps longer than 60 minutes were filled with observations from either Thorsminde or Esbjerg, located about 40 km to the north and 60 km to the south, respectively. By way of visual inspection (data not shown) it was found that the tidal waves at Thorsminde were delayed by roughly 30 minutes relative to Hvide Sande, but that the amplitude was roughly the same. For Esbjerg it was found that the tidal waves arrived about 1 hour earlier than at Hvide Sande and that the tidal amplitude was roughly twice as big. When filling the gaps in the time series for Hvide Sande, these conditions were taken into account.

During a period of a few days at the end of June 2017 observations were missing at all three stations, possibly due to a server error somewhere. For this period there was no other alternative than linear interpolation. However, due to a large water level in the North Sea during this period, the sluice was open for a short time, and so the missing observations have had only a small influence on the model results.

Filling gaps by way of observations at other stations is not without problems. As can be seen, one can easily and to some extent take into account the speed as well as the dampening or the amplification of the tidal waves. However, a setup or a setdown of the water level due to a blowing wind may increase as the disturbance is travelling along the coast in the form of a so-called Kelvin wave. This can lead to nonsystematic errors. Luckily, the sluice is normally closed during periods of large water level differences between the fjord and the sea, and so this kind of error is expected to have only a very little influence on the model results.

For 2019 there seemed to be no easy way of obtaining reasonable water level boundary data. In fact toward the end of 2019, it seemed that the measurement gauge had been taken out of the water completely and was measuring atmospheric pressure only. Therefore it was decided to use the observations made at Thorsminde, subjected to the same adjustments that were used when filling gaps in the time series of 2017. In 2019 all gaps except for one were shorter than 1 hour, and so these were filled by way of linear interpolation. The only exception from this was a gap of a little less than 2 hours, which, for convenience, was also filled by way of linear interpolation.

Due to the distant location of Thorsminde a vertical offset of the observed water level was expected. Judging from the initial model results (data not shown) this offset was about 10 cm, which was applied to the water level boundary data of the model.

Finally, it should be noted that observations of water level were carried out inside the harbour of Hvide Sande at a point close to the sluice (station number 5201). Since the exchange between Ringkøbing Fjord and the North Sea is much influenced by the frictional loss taking place between the sluice and the entry of the harbour, these observations could not be easily used as boundary data for the sluice model.

5.2 Initial conditions

The intial conditions of the model included the water level and the salinity in Ringkøbing Fjord at the beginning of the model runs (1 January 2017 at 00:00 and 1 January 2019 at 00:00). The initial water levels were gathered from the observed water levels at the three stations in the fjord (see Table 1). The initial salinities were guessed from the observations made at one or more of the stations in the fjord (see Table 1) before and after the beginning of the model runs. This could lead to small discrepancies between the model results and the observations although only at the beginning of the periods being modelled. As mentioned above, the water temperature was disregarded throughout.

6. Calibration

The alterations of the harbour between 2010 and 2014 imply substantial changes to the energy losses in the flow between Ringkøbing Fjord and the North Sea due to both friction and conversion. Thus, some need for recalibration was to be exptected. However, setting the cross-sectional flow area in the harbour at 900 m^2, which is well in agreement with the actual physical measures (the average values of the depth and the width being about 120 m and 7.5 m, respectively) in much of the harbour from the entry to the west to the sluice to the east, no additional calibration of the model appeared to be necessary. Thus, a Manning Number of 18 $m^{1/3}$ s^{-1} was used to determine the friction loss in the harbour. Other parameter values can be found in Nielsen et al. (2005).

It is noted that the total energy loss in the flow between the fjord and the sea is divided into roughly equal parts pertaining to the sluice and the harbour. This implies that an accurate determination of the energy loss in the harbour is crucial for an accurate calculation of the exchange between Ringkøbing Fjord and the North Sea.

7. Model baseline results

When running the model in the two baseline scenarios 2017 and 2019, i.e. subject to the boundary conditions described above, the results shown in Figures 1 and 2 are obtained. The results that are shown include the water levels at the three stations in Ringkøbing Fjord, i.e. at Hvide Sande, Ringkøbing Harbour and Bork Harbour, and the mean salinity in the bulk part of Ringkøbing Fjord. Also shown are the observations of water level at the three stations as well as the median, the maximum and the minium of the vertical profiles of salinity, cf. Table 1. The observations of salinity were oftentimes carried out at three stations or less and at a varying frequency. Thus, if stratification in the fjord were present, it is not certain that the vertical profiles of salinity would show this fully. The model forcing and the model results, including the exchange between Ringkøbing Fjord and the North Sea, for the baseline scenarios are shown in full detail in Appendices 1 – 6.

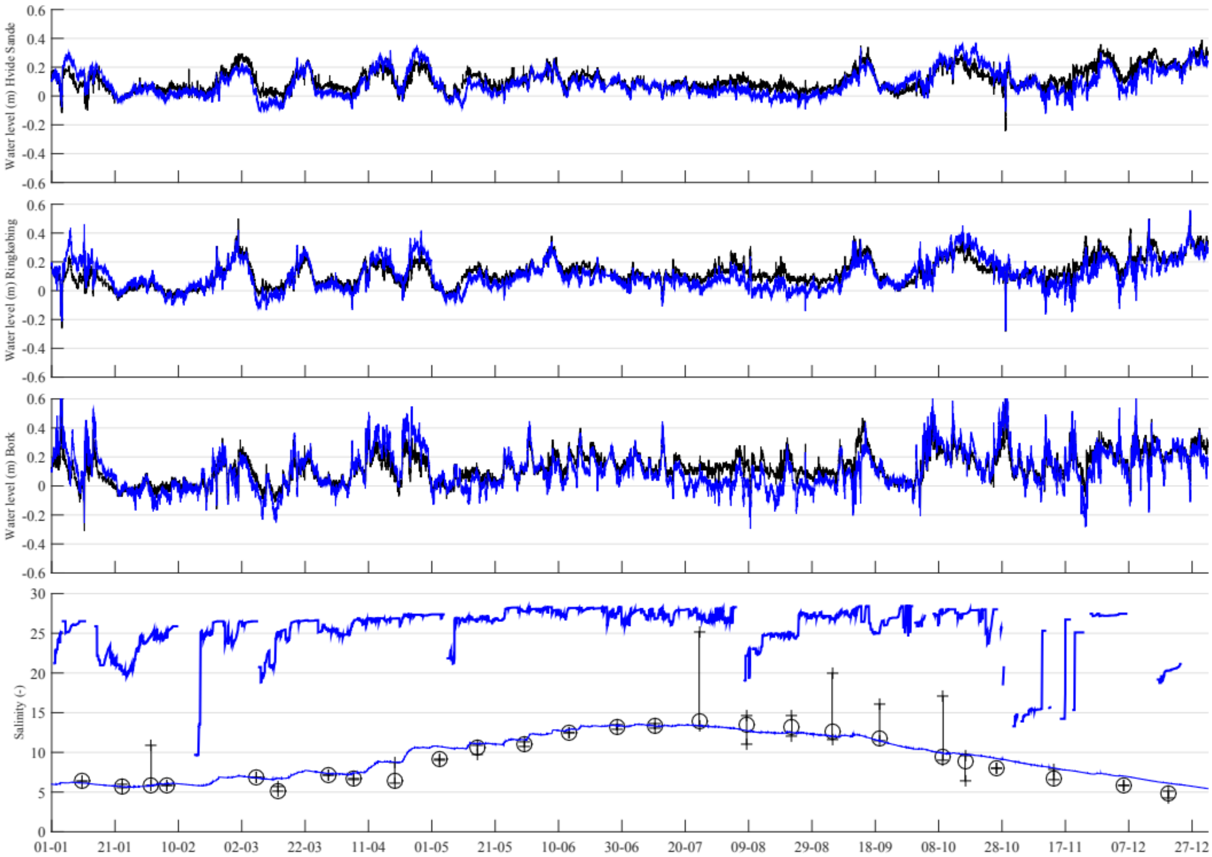

Figure 1: Model results and observations for the baseline scenario 2017. The upper three panels show in order the water levels in Ringkøbing Fjord at Hvide Sande, at Ringkøbing Harbour and at Bork Harbour. The blue curves indicate variables calculated by the model wheres the black curves are observations. In the lower panel the salinity of the upper layer of the water masses in Ringkøbing are shown (thin line) and, if present, the salinity of the lower layer is also shown (thick line). Observations of salinity on a given date are shown by plusses, indicating the maximum and the minimum values, and by a circle, indicating the median value of the observations. See Appendix 3 for more details.

Figures 1 and 2 show that in both baseline scenarios the water levels in Ringkøbing Fjord are satisfactorily reproduced on both short time scales, which is due to wind events, and long time scales, which are due to prolonged flow into or out of the fjord. The best agreement between the model and the observations are found at Hvide Sande. This is essential as the exchange between the fjord and the sea is driven in part by this water level. At the other two stations the agreement between the model and the observations is less good, especially for short-term wind events. This is expected since the model is not built to study the barotropic currents within Ringkøbing Fjord and so does not include a detailed, two-dimensional bathymetry. Still, it is encouraging to know that the model is capable of reproducing the barotropic dynamics in much of the fjord by means of a simple approach.

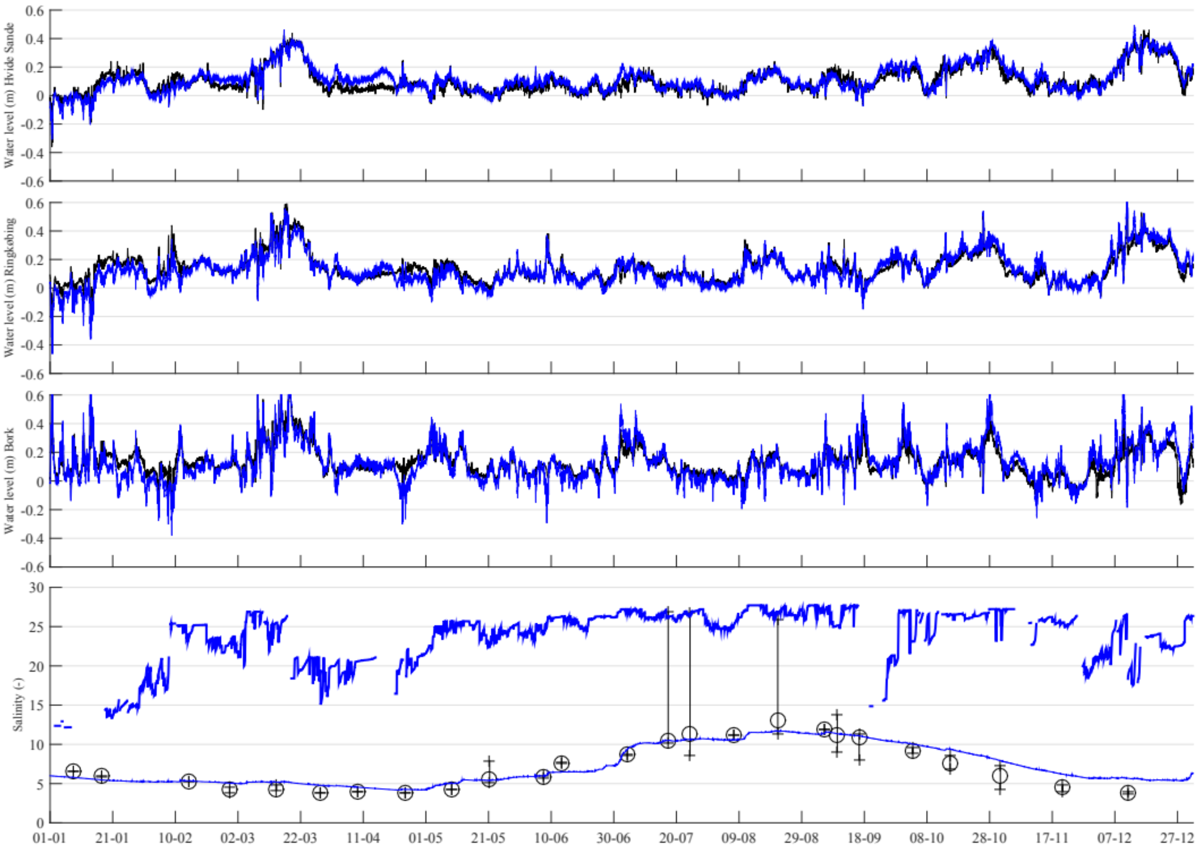

Figure 2: Model results and observations for the baseline scenario 2019. See the caption of Figure 1 for a description of the plots. See Appendix 6 for more details.

Figures 1 and 2 also show that in the two baseline scenarios the model is very well at reproducing the salinity in the bulk part of the fjord. This includes being able to describe the temporal variability of the salinity, which are tightly connected with the exchange between the fjord and the sea as calculated by the model. Thus the relatively abrupt increase in the salinity observed at the beginning of July 2019 are connected with a considerable inflow of seawater. This is apparent from Appendix 5. Similar, but smaller increases are clearly seen on a few occasions during the first half of 2017. This ability of the model is important to realize and appreciate since an incorrect calculation of the exchange would probably have had little influence on the water levels in the fjord, discussed above, but a strong influence on the salinity.

For the baseline scenario 2019 it is of interest to point out that during the period January through May the salinity is rather low and that as of June the salinity is subject to a substantial increase. This is in full agreement with the calculated exchange between the fjord and sea, shown in Appendix 5. However, knowing that according to the existing regulations a relatively high and stable salinity is desired, it is striking that very little seawater has bin let into the fjord between January and May. Judging from Appendix 5 it has certainly been possible to let in seawater without running the risk of getting a relatively high water level in the fjord. So it could well seem that keeping a low salinity in the fjord during the period in question has been a conscious decision. In one of the scenarios to be discussed in the following the sluice model is used to investigate what the salinity in the fjord could have been if the sluice had been operated differently.

8. Investigation of pumped scenarios

In order to improve the environmental conditions in Ringkøbing Fjord, one idea that was brought about by the coastal water board was to use a pump to increase the outflow of water from the fjord, making the outflow less dependent on the water level in the North Sea being sufficiently low. By way of the sluice model this solution was investigated in two different ways using the baseline scenario for 2017 as the starting point.

The first pumped scenario was based on a constant rate of pumping of 40 $m^3 s^{-1}$ throughout the entire year. The other scenario was based on a rate of pumping of 80 $m^3 s^{-1}$ only during the winter half of the year. In both cases the model was initialized using a salinity equal to the value found at the end of the year in order to avoid a long period of adjustment. These values were 6.6 and 8.5 PSU. The pumping rates have been selected arbitrarily, but at values that are comparable to the run-off of freshwater to the fjord. All other boundary conditions as well as the operation of the sluice remained unchanged, cf. Appendices 1 and 2.

The results of the two pumped scenarios are both shown in Figure 3. For comparison the results of the baseline scenario are also shown. It is apparent how both pumping scenarios lead to substantial reductions in the water level in the fjord. It is also apparent that once the pump is stopped at 1 April in the second scenario the water level in the fjord is quickly returning to the baseline situation, owing to the relatively fast barotropic response of the system. Likewise, as the pump is turned on again at 1 October, the water level in the fjord is descreasing quickly.

Correspondingly, the salinity in the bulk part of the water masses in the fjord is increasing in both scenarios. This is due to the fact that pumping water out of the fjord allows more seawater to be let into the fjord. Whereas the constant rate of pumping leads to a mostly constant increase of 1 – 2 PSU throughout the year, the pumping during the winter half of the year results in a considerable increase during early spring. This increase appears to last for much of the summer, owing to the residence time of the system. This implies that if the salinity can be raised during the winter time, e.g. by increased exchange through the sluice, then this is going to result in a substantially higher salinity throughout much of the rest of the year.

It should be stressed that the purpose of this investigation was to examine to what extent a pumped flow would be able to influence the conditions in the fjord. It was not the purpose to assess if such a solution would be feasible from practical and economic points of view.

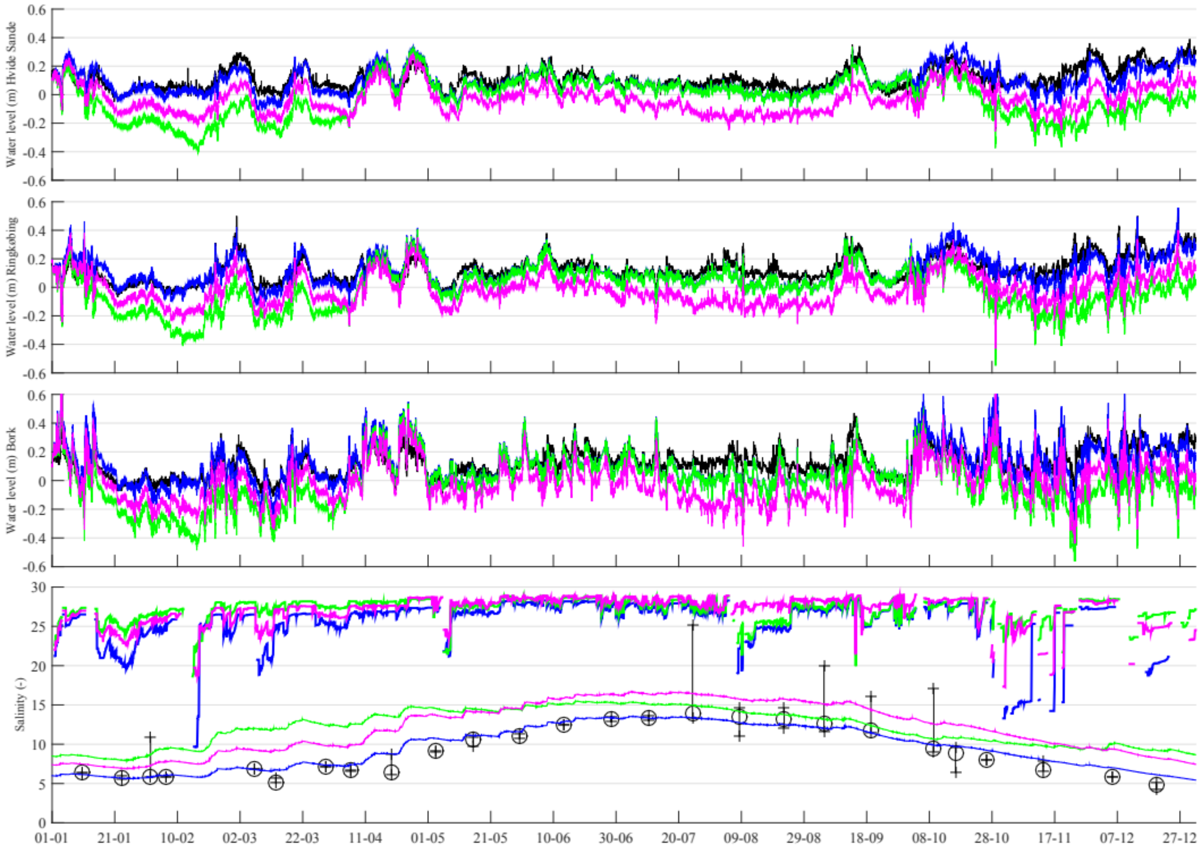

Figure 3: The results of two pumped scenarios involving a constant rate of pumping of 40 $m^3\ s^{-1}$ throughout the entire year (green lines) and a rate of pumping of 80 $m^3\ s^{-1}$ during the winter half of the year only (magenta lines). The two pumped scenarios are based on the baseline scenario of 2017, shown by the blue lines. See the caption of Figure 1 for further information on the plots.

9. Investigation of the sluice capacity in 2019

Since the salinity in Ringkøbing Fjord in 2019 was rather low, especially during the first part of the year, cf. Figure 2, the coastal water board expressed a wish to see if operating the sluice differently could lead to a higher, more stable salinity. By way of the model this was studied in two steps. First, knowing that an increased outflow from the fjord leads to some increase of the inflow, cf. the pumped scenarios discussed in the previous section, it was attempted to open the sluice fully at the times of operating the sluice in the baseline scenario. Second, the sluice was opened fully in periods during which inflow from the sea was possible due to the water level difference between the fjord and the sea. Focus was put on periods during which the sluice could stay open for long periods of time, typically of a duration of a few days, to allow both outflow and inflow, a wish that was also expressed by the coastal water board.

It was attempted to follow this procedure during the periods between January and April and between September and December since the salinity in the baseline scenario was either low or decreasing. In addition, as mentioned above, from the baseline study it could seem that during these periods focus had been put on letting fjordwater out and not letting seawater in. In fact, it would appear that not until May substantial amounts of seawater had been let into the fjord.

Figure 4: Results of the two model runs investigating the sluice capacity based on the baseline scenario of 2019. See the caption of Figure 1 for an explanation of the plots. The blue curves show variables calculated by the model in the baseline scenario, cf. Figure 2 and Appendices 4 – 6. The green curves show the results of the first part of the sluice scenario, i.e. opening the sluice fully at the times of operating the sluice in the baseline scenario. The magenta curves show the results of the full sluice scenario.

The results of the investigation of the sluice capacity are shown in Figure 4. In Appendix 7 the details of the operation of the sluice in this scenario as well as the calculated exchange between the fjord and the sea can be found. All other forcing was kept as in the baseline scenario, cf. Appendix 4.

From the results it is seen that simply opening the sluice gates to their full extent at the times of operating the sluice in the baseline scenario does not lead to a substantial change of the salinity in the fjord. Most certainly this has to do with the fact that the sluice in the baseline scenario was operated to let fjordwater out and to not let seawater in. However, the effect of opening the sluice fully is not completely insignificant. More seawater does appear to flow into the fjord, and when doing so a higher salinity in the lower layer is obtained. Due to the small volume of this lower layer, though, it does not lead to a substantial increase of the salinity in the bulk part of the fjord.

Opening the sluice fully at times when inflow is possible does, however, appear to have a very big influence. The salinity in the upper layer, i.e. the bulk part of the fjord, shows this clearly. As exchange between the fjord and the sea is allowed to take place fully, even for just some periods of a few days here and there, so much seawater can be let in that a substantial increase of the salinity can be obtained. This can be seen on at least four notable occasions during the first part of 2019 and three or more occasions during the last part of 2019.

Since these periods of opening the sluice fully for a few days also imply that considerable amounts of fjordwater can be let out, this practice does not lead to any substantial increase of the water level in the fjord. An exception to this is in the first half of January where a net inflow of water from the sea is taking place, raising the water level in the fjord to more than 0.2 m. At the same time, though, strong winds are acting, and so it is difficult to see how much the mean water level has increased. However, it would seem that the water level in the fjord does not exceed the limit of 0.25 m by much.

Although it was attempted to follow the rules of operation of the sluice, i.e. closing the sluice for water level differences exceeding 1.0 m, little attention was paid to the stratification in the fjord and the ability of the wind to break down this stratification quickly. (Note, however, that since reliable observations of water level at the seaside in Hvide Sande are not available it may not have been possible to follow the rules of operation fully.) Focus was put on investigating to what extent some big inflow events could raise and maintain the salinity in the fjord. It can be concluded that the capacity of the sluice is large enough that only some periods of full exchange between the fjord and the sea are required to raise the salinity substantially. This implies that if attention is paid to the weather forecast then it should be relatively easy to let enough seawater into the fjord as well as avoiding the presence of a strong stratification in the fjord. A close inspection of the sluice data and the exchange between the fjord and sea shown in Appendix 7 show that many, short periods are found during which seawater could be let into the fjord. Also, it should be kept in mind that if a relatively high salinity can be achieved during the winter or early spring it is relatively easy to maintain this salinity during the summer and much of the fall. In doing so the salinity can be raised when the water temperature is low and the risk of oxygen depletion near the bottom is at a minimum.

10. Investigation of various climate scenarios

Using the sluice model a number of different climate scenarios have been investigated. The details of these scenarios, which are based on projections for the future years of 2050 and 2100, are listed in Table 2. Following the UN's Intergovernmental Panel on Climate Change (IPCC) it was decided by the project management to investigate two scenarios, referred to as IPCC 2050 and IPCC 2100, that were charactized by increases of both the water level in the North Sea and the total freshwater run-off to Ringkøbing Fjord as shown in Table 2. In addition, two scenarios assuming linear trends of the water level and the freshwater run-off were investigated. These two scenarios are referred to as Linear Trend 2050 and Linear Trend 2100, assuming the values as shown in Table 2.

Table 2: The climate scenarios that were investigated with the sluice model, showing changes to both the water level in the North Sea and the total freshwater run-off to Ringkøbing Fjord.

Scenario	Water level in the North Sea	Total freshwater run-off
IPCC 2050	+ 0.25 m	+ 3.5%
IPCC 2100	+ 0.50 m	+ 7.0%
Linear Trend 2050	+ 0.045 cm	+ 12.5%
Linear Trend 2100	+ 0.11 cm	+ 25%

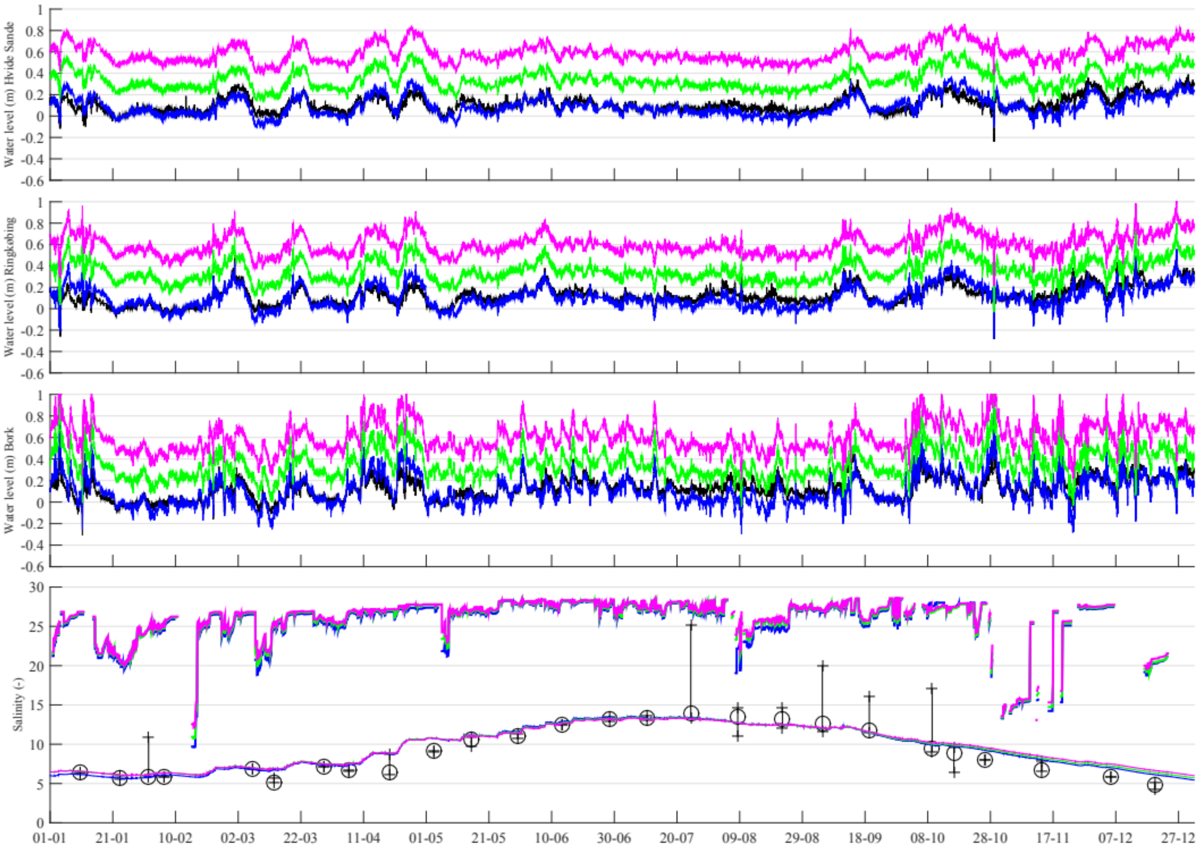

Figure 5: Results of the two climate scenarios IPCC 2050 (green lines) and IPCC 2100 (magenta lines), cf. Table 2. See the caption of Figure 1 for an explanation of the plots. Note the scale of the y-axes in the three upper panels.

The scenarios were investigated based on the baseline scenario of 2017. Thus the boundary data were adjusted according to Table 2, and the remaining boundary data, including data for the operation of the sluice, were not subject to any changes, cf. Appendices 1 – 3. The initial water levels were adjusted accordingly, but the initial salinities were kept as in the baseline scenario.

The results of the two IPCC scenarios are shown in Figure 5. Since the two IPCC scenarios are involving large increases in the water level in the North Sea and only modest increases in the freshwater run-off, the results show that the primary effect is an increase of the water level in Ringkøbing Fjord by the same amounts. The influence on the salinity is small, but not one-sided. The increased amount of freshwater run-off implies a decreasing salinity in the fjord, but the increased water level in the North Sea implies an increased exchange and thus an increased salinity. This means that the climate scenarios are resulting in slightly higher salinities in the winter time and slightly lower salinities in the summer time.

The results of the two scenarios based on the linear trends are shown in Figure 6. In comparison with the IPCC scenarios, the two linear trend scenarios are concerned with small increases of the water level in the North Sea, but large increases of the freshwater run-off. The water level in the fjord is responding by increasing by the same amounts as the water level in the sea, owing to the fact that the system is responding quickly to barotropic forcing. In contrast, though, the increasing amounts of freshwater run-off are now leading to a significant reductions of the salinity in the fjord. Thus, even though an increased water level in the sea implies an increased exchange between the fjord and the sea, the increased freshwater run-off is now the dominating influence.

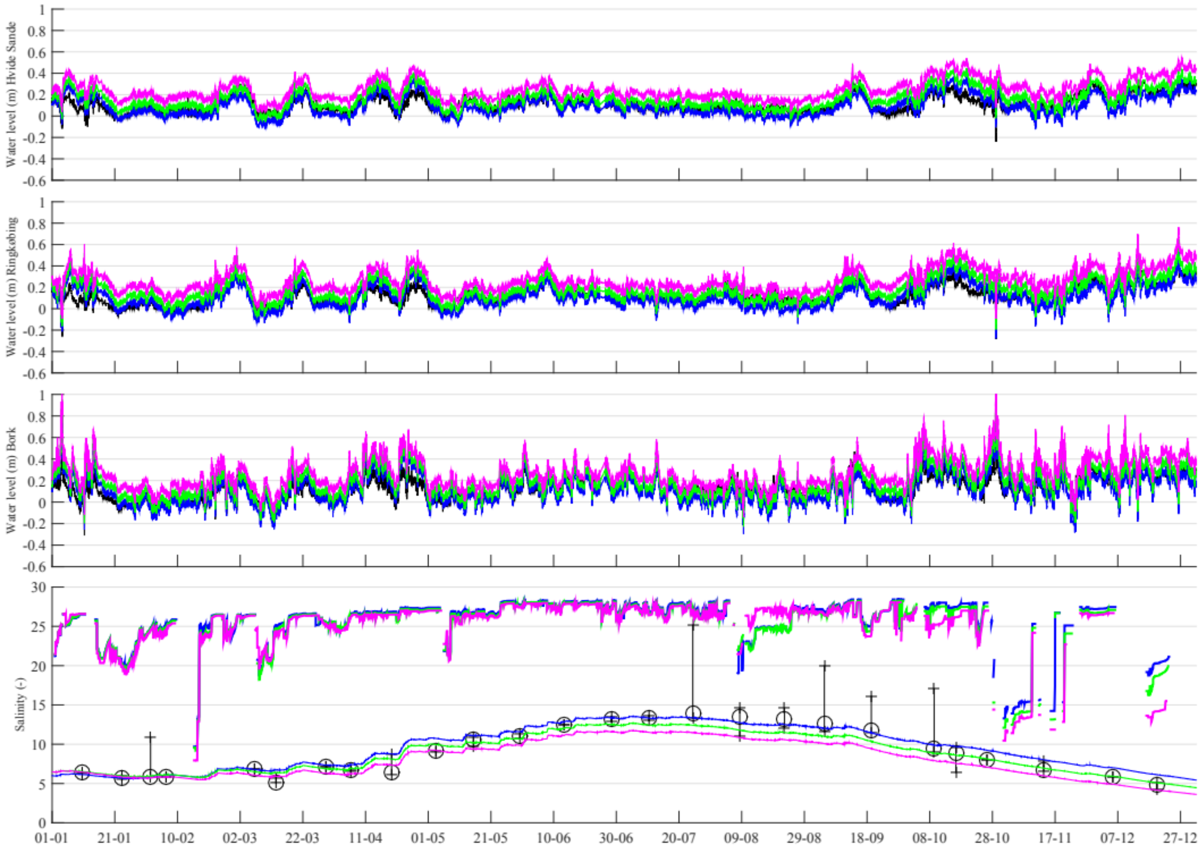

Figure 6: Results of the two climate scenarios Linear Trend 2050 (green lines) and Linear Trend 2010 (magenta lines), cf. Table 2. See the caption of Figure 1 for an explanation of the plots. Note the scale of the y-axes in the three upper panels.

It is important to point out that this approach to studying future climate scenarios is perhaps somewhat too simplified. One important thing that is not taken into account in this way is the wind, changes of which can also be expected in the future. Changes in the wind, or, more generally, the short-term meteorological conditions, are influencing not only the water levels and the stratification in Ringkøbing, but also the water level in the North Sea. However, investigating climate scenarios to their full extent is a task that exceeds the scope of the present project. Therefore, the purpose of the model simulations presented here is to provide both some indication of what the future for Ringkøbing Fjord could likely be and point to questions that need to be addressed in the future.

For instance, knowing what kind of challenges are going to take place, one could use the model to find out to which extent operation of the sluice is able to counteract these challenges. This task is also beyond the scope of the present project as it requires much work adjusting the operation of the sluice and observing the effects on the fjord. However, one thing that can easily be studied with the present version of the model is if a pumped flow from the fjord to the sea could counteract some of the climate-related challenges.

To that end two combined climate and pump scenarios have been investigated, both based on the IPCC 2050 scenario. The two climate and pump scenarios both involved constant pumping, the first at a rate of 80 $m^3 s^{-1}$ and the second at a rate of 40 $m^3 s^{-1}$. The results of the two climate and pump scenarios are shown in Figure 7.

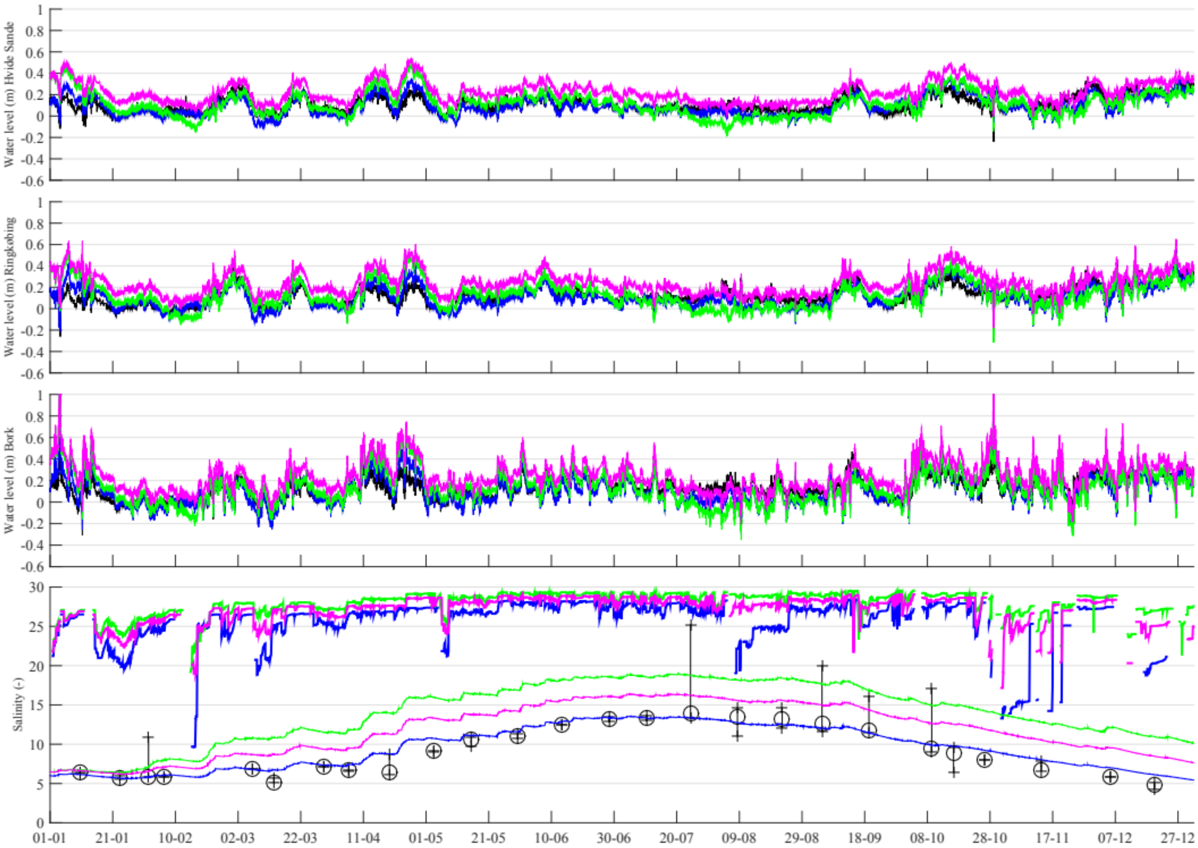

Figure 7: Results of the two climate and pump scenarios based on the IPCC 2050 scenario, cf. Table 2, and constant pumping rates of 80 m^3 s^{-1} (green lines) and 40 m^3 s^{-1} (magenta lines). See the caption of Figure 1 for an explanation of the plots. Note the scale of the y-axes in the three upper panels.

It appears that a pumping rate of 80 m^3 s^{-1} is roughly able to counteract the effect of the increase of the water level in the North Sea of 0.25 m, which can be seen in Figure 5. However, the increasing inflow of seawater, which is also a result of the pumping, implies that the salinity in the fjord is increasing by more than 5 PSU. When using a rate of pumping of only 40 m^3 s^{-1}, it is possibly to counteract a part of the increase of the water level in the North Sea. This pumping rate is contributing less to the exchange between the fjord and the sea, resulting in an increase of the salinity in the fjord of about 3 PSU.

11. Conclusions

Although progress was considerably hampered by the erroneous observations of water level in the North Sea at Hvide Sande, the project has resulted in a well-working and reliable sluice model for both 2017 and 2019. The model appears to be responding correctly to the external forcing, i.e. the water level in the North Sea, the wind and the freshwater run-off, as well as the operation of the sluice at Hvide Sande, resulting in a very good agreement between model results and observations in terms of both water levels and salinity in Ringkøbing Fjord. Although the baroclinic dynamics of the fjord is not accounted for explicitly, the model is able to describe the stratification satisfactorily and is in agreement with the observed profiles of salinity, even though these are limited in both time and space. A thorough discussion of the strengths, the weaknesses and the validity of the basic asumptions of the model can be found in Nielsen et al. (2005).

Adding a pumped flow of water out of the fjord of a magnitude comparable to the freshwater run-off, the sluice model has shown that the conditions in the fjord can be influenced substantially in terms of both a reduction of the water level and an increase in the salinity. However, it was not considered to which extent a pumped solution could be feasible from practical and economic points of view.

For 2019, which was characterized by an extraordinarily low salinity during much of the year, a different operation of sluice, focusing on letting seawater into the fjord, showed that the salinity in the fjord could easily have been significantly higher. This model run has also shown that if substantial amounts of seawater are let into the fjord during the winter or early spring, the salinity can be kept at a high and stable level for a long time subsequently without the need for much additional seawater. The model has shown that this can be achieved without increasing the water level significantly during the winter and early spring. As the risk of oxygen depletion in the stratified water masses is low during the winter and early spring, this implies that a relatively high salinity can be maintained with less risk of oxygen depletion during the summer.

Finally, the model was used to address the response of Ringkøbing Fjord to conditions to be expected in the future, i.e. an increased water level in the North Sea and an increased freshwater run-off, both due to climate changes. The model showed that the water level in the fjord is going to respond quickly and almost equally to the changes to the water level in the sea. The model also showed that the impact on the salinity in the fjord is subtle, as a consequence of both an increased run-off of freshwater and an increased exchange through the sluice, the latter being due to the increase of the water level in the sea. Thus, the salinity in the fjord is going to decrease a little only if the freshwater run-off increases substantially. Thus the system seems rather robust in terms of the salinity and easily influenced in terms of the water level. Adding a pumped flow to one of these climate scenarios showed that it is possibly to influence both the water level and the salinity in the fjord significantly. Again, it was not considered if a pumped solution could be feasible from practical and economic points of view.

It should also be noted that the operation of the sluice could probably be used to counteract the impact on the fjord due to the climate-induced changes to the forcing, but this was outside the scope of the project. However, the model is very well-suited to carry out such an investigation.

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Appendices

The following appendices are attached as a number of separate files

1. Model forcing (boundary data) for the baseline scenario of 2017. The data shown include the water level in the North Sea (upper panel), the total freshwater run-off (second panel), and the speed (thin line) and the direction (thick line) of the wind (third panel). In the lowermost panel the pumped flow is shown, which is zero everywhere in the baseline scenario. 12 pages in total.

2. Sluice data and flow between the fjord and the sea for the baseline scenario of 2017. The data shown include the number of sluice gates that are fully open (upper pannel), the flow through the sluice and the harbour, positive numbers indicating flow from the fjord to the sea (middle panel), and the water levels in the sea and in the fjord at Hvide Sande (lower panel). In the lower panel the water level in the sea is shown again, cf. Appendix 1, in order to be able to compare directly with the water level in the fjord at Hvide Sande, the difference between the two driving the exchange between the fjord and the sea. The blue curves indicate variables calculated by the model or data for the operation of skuice, which are to be modified when examining various scenarios. 12 pages in total.

3. Model results and observations for the baseline scenario of 2017. The data shown include the water levels in Ringkøbing Fjord at Hvide Sande (upper panel), at Ringkøbing Harbour (second panel) and at Bork Harbour (third panel). The blue curves indicate variables calculated by the model wheres the black curves are observations. In the lower panel the salinity of the upper layer of the water masses in Ringkøbing are shown (thin line), which comprise by far the most of the water in the fjord. If a stratification is present, which may be the case for some time subsequent to an event of inflow to the fjord, the salinity of the lower layer is shown (thick line). Observations of salinity on a given date are shown by plusses, indicating the maximum and the minimum values, and by a circle, indicating the median value of the observations. If all three symbols are coinciding, no stratification was observed. 12 pages in total.

4. Model forcing (boundary data) for the baseline scenario of 2019. See Appendix 1 for explanation of the plots. 12 pages in total.

5. Sluice data and flow between the fjord and the sea for the baseline scenario of 2019. See Appendix 2 for explanation of the plots. 12 pages in total.

6. Model results and observations for the baseline scenario of 2019. See Appendix 3 for explanation of the plots. 12 pages in total.

7. Sluice data and flow between the fjord and the sea for the scenario of 2019 in which the sluice is operated to a large extent. This scenario included, first, allowing the sluice to be fully open at the times at which the sluice was operated in the baseline scenario and, second, opening the sluice fully in some periods during which inflow of seawater was possible due to the water level difference between the fjord and the sea. See Appendix 2 for an explanation of the plots. The blue curves show variables calculated by the model in the baseline scenario, cf. Appendices 4 – 6. The magenta curves show variable calculated in the sluice scenario. 12 pages in total.