

# Climate Change and Closure of Thyborøn Channel

- An inconvenient truth on the closure of Thyborøn Channel

by

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## Summary

The matter of Thyborøn Channel is the culmination of the coastal engineering in Denmark. Many hundreds of man-years have been spent by engineers and scientists on the planning and evaluation of the complex of problems briefly outlined in the following.

After having been separated for more than 700 years the connection between the North Sea and the Limfjord was established by a storm surge in 1825. The opening drastically changed the salinity and ecology in the fjord. In the first part of the 20<sup>th</sup> century a fear of flooding of the city of Thyborøn became greater. In 1946 the Danish Parliament passed the so-called Thyborøn Act after which the Thyborøn Channel should be closed by a dam including a ship lock and a sluice for water exchange. Because of lack of money and professional disagreement the works progressed very slowly and in 1972 the act was repealed without finishing the final closure of the channel.

The coasts in the Limfjord are most sensitive to flooding and the climate changes will call for many types of precautions for the rising sea level. The closure of Thyborøn Channel should be understood as an alternative to many local solutions especially in the western part of the fjord. In general, the public conceives the channel as a preservation-worthy piece of nature but the inconvenient truth is that the channel exists only because of human intervention in the nature.

At suggestion of Jørgen Bülow Beck and the author the matter was reopened in 2005 because of the discussion of the consequences of the global warming and the rising sea level.

## The Limfjord – Some key data

The Limfjord is the largest estuary in Denmark with a length of 150 km, a surface area of 1500 square kilometers and a volume of 6,8 cubic kilometer. The water depths go up to 20 m but the average is only 4,5 m. The estuary consists of shallow broads and more deep sounds and the topography should be understood as the results of the glacial processes during earlier glacial periods.

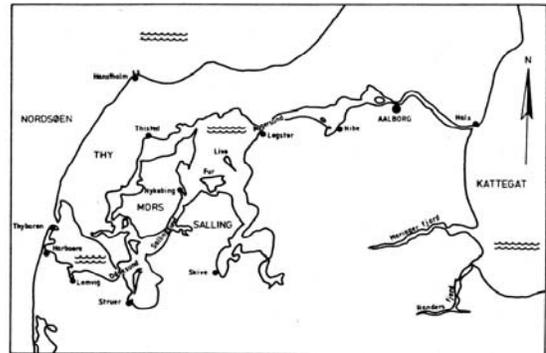


Figure 1. The Limfjord

The Limfjord is unique because it is open to the sea both to the east and the west. For reason of the dominant westerly wind an east-going net-current drives approximately 3,2 cubic kilometer per year through the system at Løgstør. Accordingly, the salinity is high and only slightly lower than the salinity in the North Sea. The catchment area is 6600 square kilometer and the annual fresh water supply is about 2,5 cubic kilometer per year. The estuary is highly eutrophicated because of the load nutrients coming with the freshwater originating primarily from the agriculture.

## The History of Thyborøn Channel

Since the Stone Age 6 – 7000 years ago there was an open connection between the Limfjord and the North Sea. Around year 1100 the connection was interrupted by the long-shore sediment transport which formed a continuous bar. At the seaside of the bar the wind created range of dunes which worked as an efficient natural dike against storm surges.

In the seventeenth century the bar consisted of fields and marshes. The population lived in a number of small villages. The highway between Ribe and Thisted of that time passed over here.

In the beginning of the eighteenth century a regression of the coastline began and the North Sea broke through a few times without forming persistent passages. But on 3<sup>rd</sup> and 4<sup>th</sup> February 1825 during a severe storm surge in the North Sea which also caused drastic damage in the

Netherlands and in Germany a permanent channel, named the Agger Channel, was formed. The new channels caused major changes in the morphology of the coast. The new opening acted as a so-called tidal inlet where stability was remained because of the tidal currents capability of removing the sand from the long-shore transport. The sand from the coast migrated through the channel and created the shallow grounds on the eastside of the bars. The coastline went back with up to 10 – 20 meters per year. Already in 1834 the channel was navigable and the new connection led to a boom in the trade between the provincial towns (especially Thisted) in the western Limfjord to Norway and England.

Gradually, the Agger Channel was closing and around 1850 the navigation stopped. To compensate for this loss a local channel near Løgstør, the so-called Frederik the 7<sup>th</sup> Channel was built in order to give the ships a way eastward out of the Limfjord. But already in 1862 a storm surge broke through some kilometers south of Agger Channel and the Thyborøn Channel was now a reality.

The first director of the newly established Department of Hydraulic Engineering (Vandbygningsvæsenet) stated that the channel probably would close again if just the coast was left to itself. But on the political scene strong forces augmented for a preservation of an open channel.

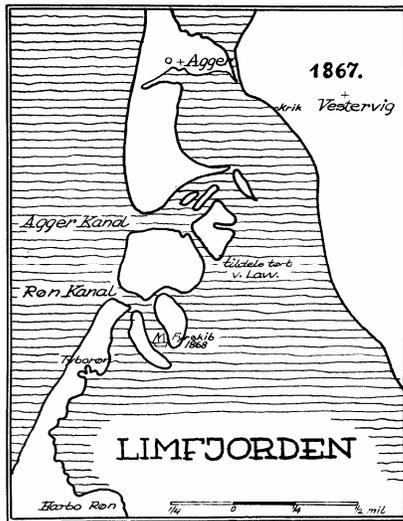


Figure 2 Thyborøn Channel and Agger Channel 1867

Figure 2 shows the situation in 1867 where both channels were open but now only Thyborøn Channel was navigable.

The political forces for keeping the connection open was still the strongest and in 1874 the building of groins on the southern bar (Thyborøn Tange) started in order to reduce the supply of sand to the channel. By successive steps both the north and the south bars became protected by groins as can be seen in figure 3 where also the original coastline before 1825 is shown.

Since the formation of Agger Channel in 1825 the situation was heavily debated both politically and technically. The shipping trade, the fishery, and the local communities had each their viewpoints and special interests to watch over. Several commissions were appointed by the parliament during the years. A culmination of the discussion was the appointment of the so-called Thyborøn-commission of 1937. The background was an increasing fear of a collapse of the bars capability of flood protection because of the rather extreme regression of the shoreline. The hypothesis was denoted the catastrophe theory. The report from the commission came in 1942 and recommended a closure of the channel. World War II impeded the further progress some years but in 1946 the parliament passed *Act number 454 on Measures for the Protection of the Limfjord Bars, Thyborøn Harbour and Thyborøn Channel*.

The act implied that the following works should be implemented

- recessed dikes along the bars and that
- a dam across the channel including a ship lock and a sluice for water exchange
- jetties for protection of the entrance plus building of various smaller works.

The dimensions of the act are shown in figure 3.

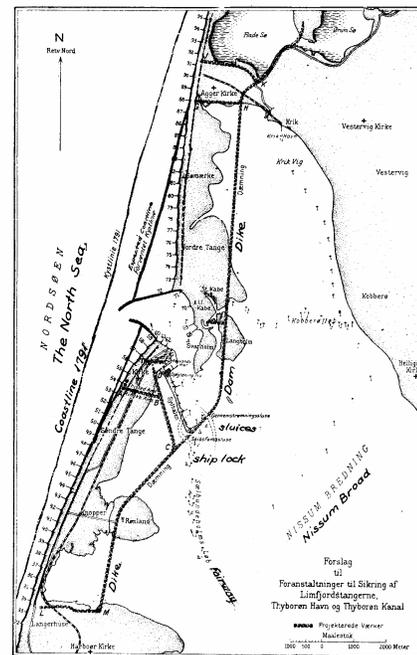


Figure 3 The Thyborøn Act of 1946

Because of the economical difficulties in the post-war era the construction works only slowly progressed. The recessed dikes were almost finished in 1954 where the political and technical debates once more broke out. The direct occasion was the appearance of the doctoral thesis "Coast stability" by the former engineer in the Hydraulic

Engineering Department Per Bruun, who later became a world-famed professor in coastal protection. The thesis in principle rejected the scientific basis of the conclusions in the Thyborøn Act (the so-called *catastrophic theory*). With this background Professor Helge Lundgreen, from the Danish Technical University in Copenhagen, suggested to the Minister of public works that new and complete investigations should be started in order to consider the eventuality of keeping the Thyborøn Channel open. Rumors tell an important informal argument was that the money could be given better to finish the fishing harbour in Hanstholm which had been under construction for many years.

Consequently, the minister appointed a committee in 1957 for further action on this proposal. The report appeared in 1968 and was building on a number of thorough investigations. The professional contributions by especially Helge Lundgren and Torben Sørensen (later director of DHI) stand as the culmination of Danish hydraulic engineering.

In the report it was concluded that there was no acute risk of a collapse of the bars the first 30 to 50 years. Accordingly the Thyborøn Act was repealed in 1972. In a contrast to the former 150 years of disputations all professionals agreed in this decision.

When the decision was made in 1942 the key methods for the protection of the coast were the establishment of groins, dikes, dams and plantation of dunes. With these measures the recession of the coastline on the bars was reduced from 10 – 20 m per year to 1 – 2 m per year. But it is obvious that these passive methods could not stop the erosion completely. In the recent decades the method of *coast nourishment* has been the main principle for coastal protection on Danish West Coast and the Limfjord Bars. The technological development has made it economical possible simply to replace the sand on the shore with sand dredged from the sea bottom some kilometers away from the coast. With this active principle the recession of the coast can be stopped and controlled completely. With few words we can say that in 1942 the key point was life and safety whereas the problem today has changed to a question of economy and priority.

### ***Climate change***

It is important to realize that certain climate changes already have been registered. In the recent 100 years the water temperature in the Limfjord has increased with 1,1 degree Celsius and the precipitation has increased with 15 %.

#### *Rising sea level*

The recent 100 year the sea level around Thyborøn has raised about 12 cm because of the level changes coming from the decompression after the last Glacial Age. Globally, the temperature has increased with a little less than 1 degree Celsius and it is expected that the

temperature will increase further at least 2 degrees. The increasing temperature will lead to an expansion of the water in seas and to a melting of the ice caps on Antarctic and Greenland. The maximum (potential) rise in sea level is 70 m if the ice caps melted totally. The expected level rise the next 50 -100 years is 19 to 58 cm.

In respect to coast and flood protection also the changes in storm surge and wave run-up are very important. Both effects depend on the wind speed in the hurricanes. ATV, 2003, mention that the 50-year storm surge level in the Danish Watten Sea will increase with 25 to 40 cm but more precise results are expected to appear in the near future. The increase in the wave run-up will depend highly on the local conditions eg. the orientation of the actual coastline.

#### *Water quality*

It is already well examined that the global warming will increase the oxygen depletion in the Danish estuaries significantly. The increasing precipitation will increase the discharges of nutrients and the increasing temperature will speed up the algae growth and degradation.

### ***The frequency of Storm Surges seems to increase in the Limfjord***

The water level in the westerly Lim Fjord depends strongly on the water level in the North Sea. Regarding the question on flooding in this area it is relevant to look whether the frequency of storm surges has changed in period since the discussion on closure of the Thyborøn Channel started.

The water level has been measured in Thyborøn Harbour since 1931 and the evaluation covers the period 1931 to 2005. The 20 highest storm surges are shown in Tabel 1 in rank order.

**Tabel 1 The 20 largest events**

Rank	date	water level Cm
1	09.01.2005	189
2	24.11.1982	187
3	27.02.1990	178
4	21.01.1976	174
5	04.01.1984	173
6	14.01.1984	173
7	17.01.1954	169
8	20.12.1991	169
9	06.11.1985	167
10	26.01.1990	167
11	12.01.1993	165
12	02.11.1965	157
13	19.11.1982	157
14	28.02.1990	157
15	29.12.1955	155
16	18.01.1983	154
17	01.01.1984	154
18	06.11.1996	154
19	26.10.1998	153
20	23.01.1993	153

During storm surges the water level in Thyborøn Harbour lies lower than the water level in the North Sea because of the head loss in the inflow from the sea to the estuary. Nevertheless, it seems acceptable to evaluate the frequency of storm surges in the North Sea on the basis of frequency of high water in Thyborøn Harbour.

The period of measurements is now split into two equal partial periods, one from 1931 to 1968 and one from 1969 to 2005. If we consider when the storm surges occurred we found that

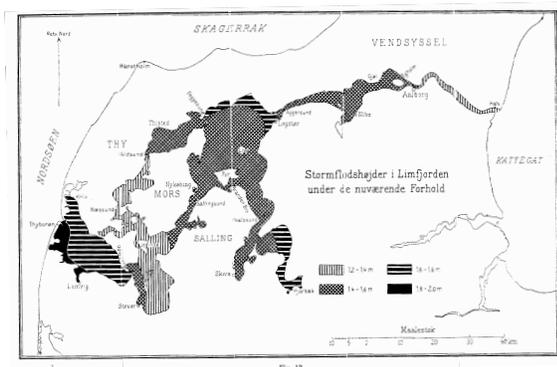
- The highest surge felt in the second period
- Among the 5 highest surges 0 felt in the first period and 5 in the second period
- Among the 10 highest surges 1 felt in the first period and 9 in the second period
- Among the 20 highest surges 2 felt in the first period and 18 in the second period

From this viewpoint it is obvious that considerably more storm surges have occurred in the latest period.

About the same subject DMI, 2007, writes:

*The latest 20 years have been characterized by many storm surges compared to the more than 100 years where the water level has been monitored. Where the events with water level above 2,5 m in Esbjerg Harbour in most of the recent century have lied on 5 to 10 per decade the 1980ties have had 16 events and the 1990ties even 20 events. The background for the large number of high water levels is not quite clear.*

If we now look at the data which were available for the 1942- report about closing the channel and the 1968- report about not closing the channel it is obvious that we today are facing storm surges that are considerably higher than earlier. Two examples follow:



Figur 4 Maximum storm surges in the Limfjord estimated in the 1942-report

In figure 4 we see the maximum storm surges as they were estimated in the 1942-report. If we look at the central Limfjord (Skive Fjord, Louns Bredning) the maximum storm surge is estimated to 1,4 to 1,8 m. But

twice, in 1981 and in 2005, the storm surges reached about 2,4 m.

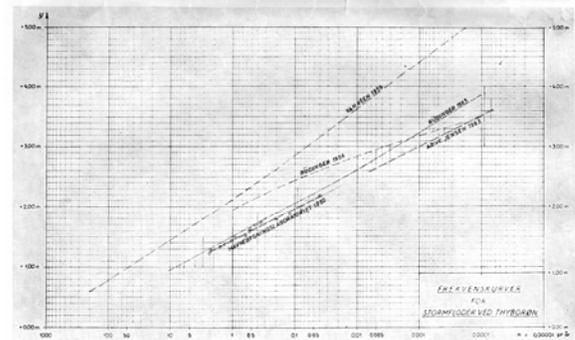


Figure 5 Exceeding frequency of water level in the North Sea near Thyborøn from the 1968report

As example number two we see in figure 5 that the water level in the North Sea exceeds 3.0 m with a frequency of 0.001 per year corresponding to once per thousand years. A water level here of 3.0 m was measured in 2005 as the highest ever. Whether this really was a thousand year event is anybody's guess, but it is unlikely that it was.

From the authors point of view it can be concluded that we probably has experienced a certain climate change in respect to storm surges. The reason for this and whether this is caused by the global warming can definitely not be found in this primitive analysis.

### Water exchange and water quality

As already mentioned the Limfjord is unique in the sense that it has open connections to both the North Sea and to the Kattegat (the sea between Denmark and Sweden). This plays a dominant role for the physical, chemical and biological conditions. The topography in the westerly part consists of rather shallow broads (5 – 7 m deep) and more deep straits (10 – 20 m deep). The easterly part has a narrower channel surrounded by broad shallow areas. The most important hydraulic resistance lies in the easterly part.

The hydrodynamics of the fjord is complex temporally as well as spatially. The driving forces are the wind, the tide and the fresh water supplies.

#### Wind-driven net-current

From the theory of hydrodynamics we know that the influence of the wind is inversely proportional to the water depth. As the average depth as mentioned is about 4,9 m the influence of the wind is large.

The shear stress from the wind on the water surface generates a wind-driven current in the direction of the wind. Furthermore, the wind also causes a wind-setup which results in differences in water level which again

generates currents. Because of the dominant westerly winds an east-going net-current in the order of 50 – 150 m<sup>3</sup>/s drives water from the North Sea through the fjord. Accordingly, the salinity in the Limfjord is higher than all other Danish estuaries and even higher than the salinity in the surface layer in the Kattegat.

### Tide

The tide in the surrounding seas is relative small with 0,5 m in the North Sea at Thyborøn and 0,3 in the Kattegat near Hals. Nevertheless, the tidal currents are the reason for keeping the connections to the sea open both at Hals and Thyborøn.

It is known that the tide generates a net-current because of non linear effects in the line of propagation but compared to the wind-driven current this is of no significance.

Inside the Limfjord the tide varies from 0,5 m down to about 0,1 m in the central part. Although the tide seems quite low the tidal currents are important in respect to mixing and water exchange especially in the critical high pressure situations in the summer.

### Freshwater supplies – Salinity, Stratification and Oxygen depletion

The east-going net-current of water from the North Sea is gradually diluted with the freshwater on its way towards Kattegat. Tabel 2 gives the mean salinities along the fjord.

Tabel 2

Location (see figure 1)	Salinity per thousand (or PSU)
North Sea	33
Oddesund	30
Aggersund	25
Aalborg	25
Kattegat (Aalborg Bay, surface layer)	22

A further analysis of the distribution of the salinity and freshwater supply gives a rather precise picture of the water exchange in the system. For example it can be seen that despite the east-going net-current a considerable part of the freshwater passes out of the Thyborøn Channel as a dispersive transport caused by the fluctuations in the currents.

The main environmental problem in the Limfjord originates from the discharge of freshwater. Most important is the eutrofication and the derived oxygen depletion near the bottom caused by the discharges of nutrients (nitrogen and phosphorus) originating from the agriculture around the fjord. The nutrients stimulate the growth of the planktonic algae. These algae have a

short life-cycle (a few days) and when they die they sediment to bottom, where degradation takes the oxygen from the water masses near the bottom.

In the summer high pressure weather frequently occurs. In these periods the temperature is high and the wind speeds are low leading to a stabilization of the water column where the vertical diffusion of oxygen is restrained.

Because of the combination of the degradation of organic matter and the stratification of the water column larger parts of the sea bottom area are damaged by the oxygen depletion almost every year. It is important to remember that most species of fish find their feed on the sea bottom. Accordingly, the fishery in the estuary has in practice disappeared during the last 30 years.

The problem with oxygen depletion was mentioned already in the 1942-report as seen in Figure 6. In the newest report “The Limfjord in 100 years” from DMU, 2006, the development of the environmental conditions is described in more detail.

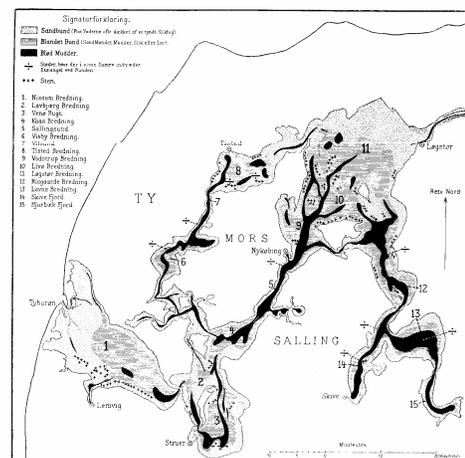


Figure 6 Plan showing the bottom conditions and oxygen depletion in the western and central part of the Limfjord (from the Thyborøn commission of 1942)

### Closing the Thyborøn Channel and controlling the water exchange

The increase in the water level in the oceans plus the increase in the size of the storm surges make the question of closing the Thyborøn Channel relevant again. As discussed here the basis of decisions in 1942 and 1968 has already changed considerably and more precise estimates on climate changes will occur in the years to come.

In the 1942-report about closing the channel it was estimated that a salinity of 15 per thousand in Nissum Broad (just east of Thyborøn) could be achieved with a sluice for water exchange with a cross-section area of

200 m<sup>2</sup> under the condition that the sluice only is open for in-going currents. With the eyes of today this would have been nothing less than a catastrophe for the water environment in the estuary because of the reduced water exchange and the subsequent influence on the water quality.

The tidal current in Thyborøn Channel is approximately sinusoidal with a period of 12,42 hours and an amplitude of 4000 m<sup>3</sup>/s. If we imagine a sluice which only allows east-going currents and the resistance in the flow is negligible the potential net-current is about 1500 m<sup>3</sup>/s, which is the absolute maximum net-current the tide can drive. Besides the wind-generated currents can contribute significantly to the flow, but during period with high pressure and low winds the tide is the main factor for water exchange.

Approximate calculations with a sluice with a passage of 1000 to 1500 m<sup>2</sup> show that the tide can generate a net-flow of 3 – 400 m<sup>3</sup>/s, which is 3 to 4 times the actual value. This will increase the salinity in most of the estuary to about 30 – 31 per thousand unless in the “blind” branch (Louns Bredning, Skive Fjord), where also a certain increase will occur. Such a solution will increase the water exchange and the water quality in the whole estuary considerably. The results of such estimates are shown in figure 4.

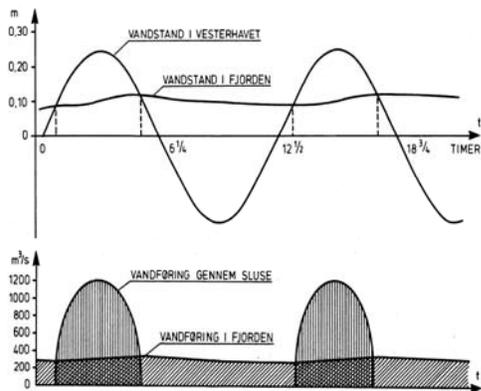


Figure 4 Estimated water level and flow through the fjord (at Oddesund)

As seen in figure 4 there is an in-going current when the water level in the North Sea stands higher than in the fjord. Inside the estuary the water level is higher than the average in the North Sea because of the flow resistance between Thyborøn and Hals.

Totally seen, it can be concluded that by means of the tide and an adequate sluice it is possible to improve the water exchange, the salinity and the water quality significantly. Additionally, the condition will be more constant than today where the meteorological variations can induce pronounced variations in the hydrographic conditions.

Figure 7 shows a rough draft of the presentation of a closure of the channel including such a sluice for water exchange, a navigation lock plus jetties for protection of the entrance to the harbour and the channel against sanding up.

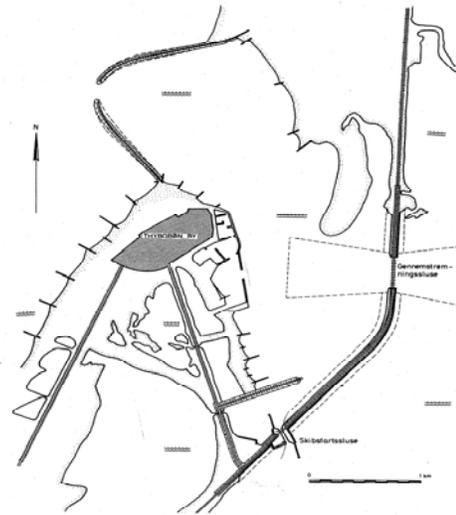


Figure 7 Draft of dam, sluice and lock

It is obvious that extensive studies and modellings with the entire Limfjord will be necessary in order to find the correct size of the passage in the sluice and the optimal control strategy. These modellings have to build on long historic time series of hydrographic and meteorological data.

### Advantages and disadvantages by closing the channel

In the following the most important advantages and disadvantages on closing the channel will be listed. It should be possible to produce economical estimates of most points in order to present a cost-benefit analysis.

Only advantages and disadvantages directly related to closing the channel are mentioned. The general disadvantages which follow from the climate changes are not included.

#### Advantages

- Floods in the westerly estuary will be reduced significantly. The value of the properties of the areas near the coast will rise.
- The coast protection on the bars can be reduced
- The up-filling of the grounds east of Thyborøn in the estuary will stop
- The water quality will improve significantly
- Condition for fishery and farming of shellfish will improve
- The amenities and the tourist value will improve

- Traffic over the channel will improve. Ferry can be discontinued.
- Extreme low water levels can be avoided (advantage for navigation)

#### **Disadvantages**

- Costs for the establishment of dam, sluice and lock take here as a disadvantage
- Sanding of the entrance shall be removed regularly
- The storm surge level in the channel outside the dam will increase slightly
- The planning of Thyborøn Town and Harbour will be restricted
- Ice conditions in the estuary can grow worse
- The navigation will be delayed by the lock
- The dam and the sluice will by the public be conceived as having a lower aesthetic and natural quality

#### **Decision-making about flood protection and environmental disasters**

The intention of this paper is to focus on the changes we need to take as consequence of the climate changes. An interesting point is how the decision-making in this respect will take place. The decision about flood protection in the Limfjord will probably not be taken in the near future. In the following a short review of the process has been in some well-known examples.

##### ***Lolland – Falster (south -east of Denmark) 1872***

A storm surge reaching a high water of more than 3 m in the western Baltic Sea flooded in November 1872 the coasts of the islands Lolland and Falster. 80 persons drowned and 50 ships were stranded on the east coast of Sjælland. A year later the Danish parliament passed an act on building around 63 km dikes along the south coast of Lolland plus a number of further works.

##### ***Zuider Zee, the Netherlands 1916***

A storm surge in 1916 flooded the coasts of the Zuider Zee and 20 persons drowned. The act concerning building the so-called *Afsluitdijk* crossing the Zuider Zee passed the Dutch parliament in 1918 with some delay because of the World War I. A large shallow freshwater area was formed and considerably environmental problems appeared.

##### ***The Rhine Delta, the Netherlands 1953***

In 1953 a storm surge in the North Sea flooded the southern part of the Netherlands and UK. More than 2000 people (1850 in NL and 300 in UK) lost their lives. Less a month after a commission was set up and the

following years the Dutch parliament step by step decided to establish the largest flood protection scheme ever seen in the World known as the Delta Plan.

##### ***Danish Watten Sea Coast 1976***

3<sup>rd</sup> January 1976 a storm surge in the North Sea hit the marshland near Tønder. 20.000 persons were evacuated but a serious flood was narrowly avoided. Already the day after the Danish prime minister inspected the location and about one year later the act on the advanced dike from the Hindenburg Dam (Germany) to Himmelev (Denmark) passed the parliament.

##### ***East Asia Tsunami 2004***

Probably the most serious disaster in the history followed the tsunami induced by an earthquake in the Indian Ocean near Sumatra. 230.000 people were killed. In general, no precautions have been decided primarily because of the size disaster and because of its low frequency.

##### ***Hurricane Katrina, Gulf Coast USA 2005***

The worst flood in the history of USA was the inundation of New Orleans in August 2005 caused by the hurricane Katrina. The storm surge reached more than 8 m. 1850 persons drowned and the damages were 84 billion USD. The disaster was the lesson of many years of negligence and political incompetence. Decisions regarding definite measure against a repetition are still under discussion.

##### ***Oxygen depletion and dead fishes, Kattegat 1986***

Oxygen depletion in Kattegat was the first time observed in 1981 and occurred several times in the 80ties and the problem penetrated gradually into the public opinion. In 1986 the finding of 5 dead lobsters north of Læsø (island in northern Kattegat) developed to an uncontrolled media event which forced the Prime Minister to make a proposal in the parliament about reducing the discharges of nutrients to the sea with 50 %. The act about this reduction passed the parliament in 1987 and the costs for the Danish society was 12 billion DDK (equivalent to 25000 DDK per inhabitant).

##### ***Total dead of organic life, Mariager Fjord 1997***

After a long and sunny summer the central part of Mariager Fjord experienced a total oxygen depletion which killed all organic life in the estuary. This has never been seen in Denmark before. A year after the parliament passed Water Quality Plan II, which for the first time deeply interfered in handling of nutrients in the agriculture.

From the authors point of view four main conclusions can be made from these examples:

- decisions are first taken after major disasters
- decisions are taken about one year after the provoking event

- solutions are exaggerated both in respect to safety and expenses
- solutions neglect more or less the environmental consequences

The climate changes will with certainty increase the risk of a disaster in the Limfjord in the coming years. For example a storm surge only slightly bigger than the event in January 2005 would generate considerable floods in the estuary, or an extreme warm summer a little warmer and with less wind than in 2006 would certainly more or less spoil the fisheries after blue mussels totally. In the light of the above mentioned experiences with the decision-making process the discussion of a closure of the Thyborøn Channel more or less automatically will emerge if such a disaster should happen.

In order to avoid bad and unnecessary expensive solutions it is necessary already now to produce a well worked plan for either a closure of the Thyborøn Channel or a total plan for the flood and coastal protection of the Limfjord area.

From EU a new directive concerning floods is under discussion and preparation in order improve the planning of coastal areas. One can hope that this directive will turn the decision-making in a more objective direction. It will be interesting to see whether the closure of Thyborøn Channel will pop up as an alternative to local solutions in the later implementation of the directive.

### **Earlier contribution**

The present contribution is an update of an earlier paper (Larsen, 1985) present on a conference in Aalborg on the future for the Limfjord in 1985.

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