ANALYSIS OF HYPOXIA IN BALTIC SEA

Oxygen dissolved in oceans and seas are critical for marine life. It is the one of the basic chemical compounds that structures the aquatic ecosystem. Low levels of dissolved oxygen also called hypoxia, is a well-known phenomenon which is rapidly increasing due to natural and anthropogenic reasons. One well known region which experience hypoxia is in the Baltic Sea. This report will focus on when, where, and why hypoxia occurs in the Baltic Sea. Individual analysis and modelling will be performed to further understand its occurrence. Furthermore, the report will talk resilience shown by the environment towards hypoxia.

Hypoxia in the aquatic ecosystem occurs when the dissolved oxygen in the water body falls below 2ml of oxygen per litre. Dissolved oxygen concentration of 2ml/L was chosen as the threshold as benthic organisms are strongly affected by this low oxygen concentration. Once the dissolved oxygen level declines below 0.5 ml/L mass mortality occur. With such low concentrations of oxygen, these bodies of water fail to support aquatic life creating areas called Dead Zones. Hypoxic zones are naturally found in deep waters for decades. But the number of dead zones has rapidly expanded in recent decades. Doubling every decade since the 1960s from 20 to 400 in the 2000s.

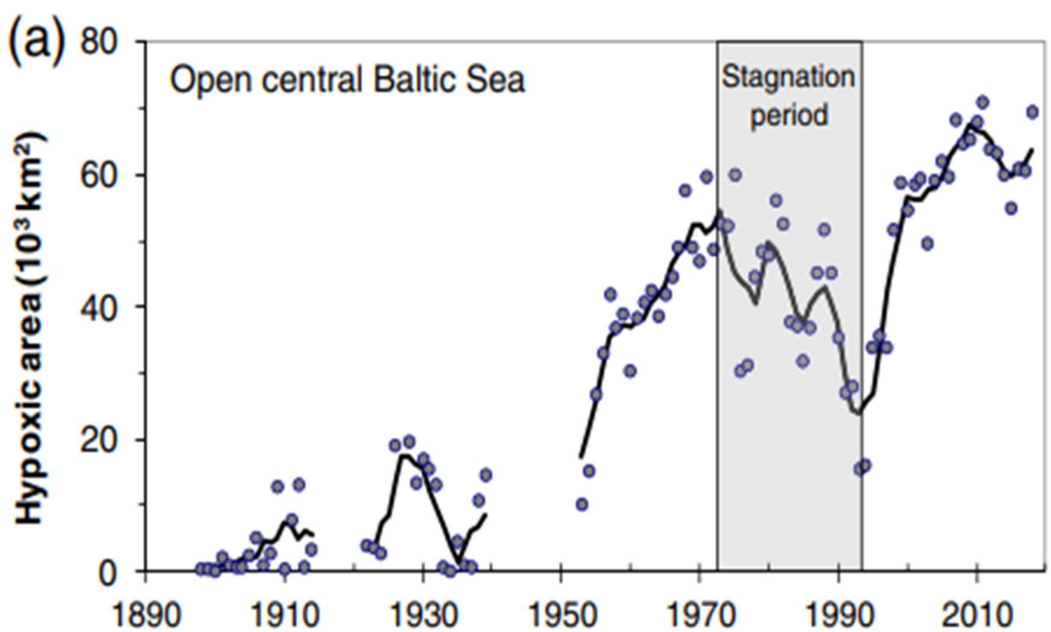

Figure 1: Time Series of Hypoxic Area (Source: CCICED special report)

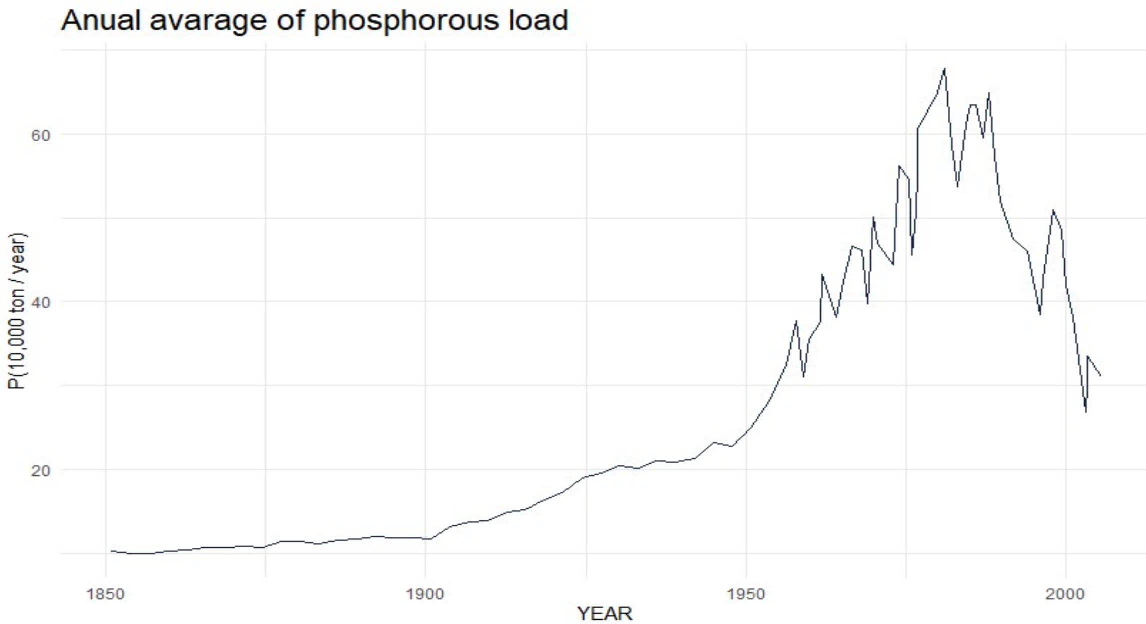

Figure 2: Annual average of phosphorous load (Data: HELCOM Project)

There are two major conditions for hypoxia to occur.

1. Huge influx of organic matter.
2. Stratification of water (causing lack of oxygen renewal)

One of the major causes of hypoxia is the presence of excess organic matter in the ocean and the main contributor to this excess matter is Eutrophication. Eutrophication is the process in which excess nutrients, mainly nitrogen and phosphate, are added to water bodies. This increases the number of nutrients available for algae. The increase in nutrient concentration increases the growth of aquatic plants both macrophytes and phytoplankton. This process is called nutrient-induced phytoplankton productivity. A common visible effect of this is algal blooms. These algae once they die off sink to the bottom and become organic matter. The organic matter gets decomposed by bacteria, during which oxygen is consumed thus depleting the oxygen level of the sea potentially generating an anoxic condition. The nutrient influx occurs due to human activities like **agriculture, transportation, and industrial and municipal waste.** Sewage-treatment plants, farming and industry activities have poured 20 million tonnes of nitrogen and 2 million tonnes of phosphorus into the Baltic Sea over the past 50 years, with a Major influx in organic matter occurring between the 1950s and late 1980s. From figures 1 and 2 we notice a common pattern between the nutrient loading and the total area in the Baltic which is hypoxic. From the year 1950 to 1980 the area under hypoxia increased from 20,000 km^2 to 60,000 km^2. This is the same period with the largest influx in phosphorous. Figure 3 Shows the clear areal mapping of hypoxic area during these periods.

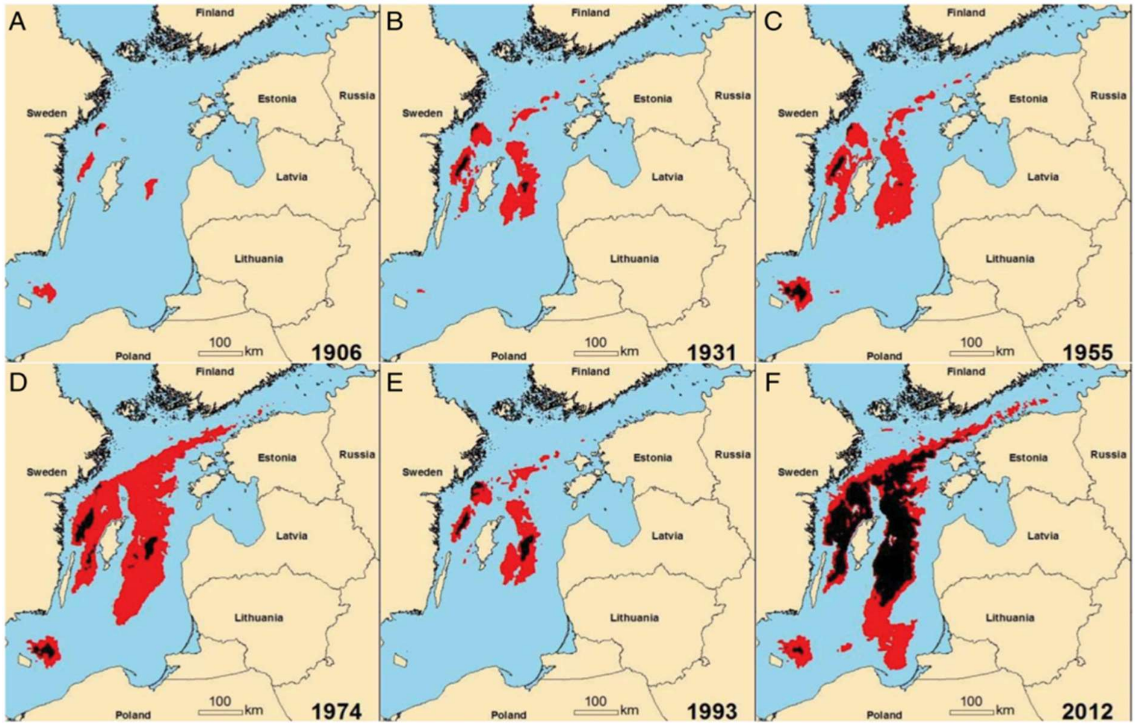

Figure 3: Areal Hypoxic map (Source: Jacob Carstensen, 2014)

The other major factor influencing hypoxia is stratification. The hypoxic area can become oxygenated by incoming oxygenated water from the open sea. The major area where hypoxia is affected is the bottom of the sea. Hypoxia persists here when incoming oxygenated water cannot replenish the oxygen lost during organic matter decomposition at the bottom of the sea. Stratification hinders this oxygen input into the bottom water by reducing the vertical mixing of oxygen to the bottom water reducing the mixing of oxygen-poor bottom waters with oxygen-rich surface water. The process of stratification occurs due to the change in the density of the water. This can be due to temperature difference, salinity or circulations. One of the reasons why Major saltwater inflows which are supposed to bring in oxygen are considered to increase hypoxia is due to their property to enhance stratification. Stratification also causes the presence of Halocline which are discontinuities in ocean salinity that separate waters of different saline concentrations.

Other factors which cause hypoxia include fishing. As in the case of the Baltic sea, where fishing Cod has caused hypoxia. Codfish eat sprats, which are small species that eat microscopic zooplankton, which in turn eat algae. Therefore, fewer cod means more sprat which in turn means more algae. Algae increase organic matter on dying and reduce oxygen concentration during its decomposition. Another factor that causes hypoxia is the increase in temperature caused by global warming. Warm water not only carries less oxygen but also causes stratification causing layers of hot and cold water to be formed creating a barrier for oxygen to reach the bottom of the sea. Warmer water also promoted the decomposition of algae and reduces the rate of water surface aeration.

The largest human-induced hypoxia in the world is found in the Baltic Sea. As of 2020 hypoxia in the Baltic Sea has extended to about 70,000 km2 which is more than the land area of Denmark. The Baltic Sea is one of the largest inland bodies of brackish water (part saltwater and part freshwater). The Baltic Sea receives seawater from the North Sea and the remaining from other rivers and streams. The Baltic sea is isolated from the rest of the Atlantic and the North Sea with the Danish Straits the only passing point. The geography of the Baltic Sea is very important as it has a large influence on the hypoxic state of the sea. Due to its geography, the Baltic Sea has limited connectivity and has always been prone to hypoxia, but this was restricted to a small area for many years. The inflow of water from the North Sea through the Danish straits is important for the hypoxic state of the Baltic Sea. Dense, salt water comes into the Baltic Sea and flows along the bottom bring in oxygen into the depths. This inflow of seawater is very irregular and occurs at a 10-year interval with the last one occurring in 2014.

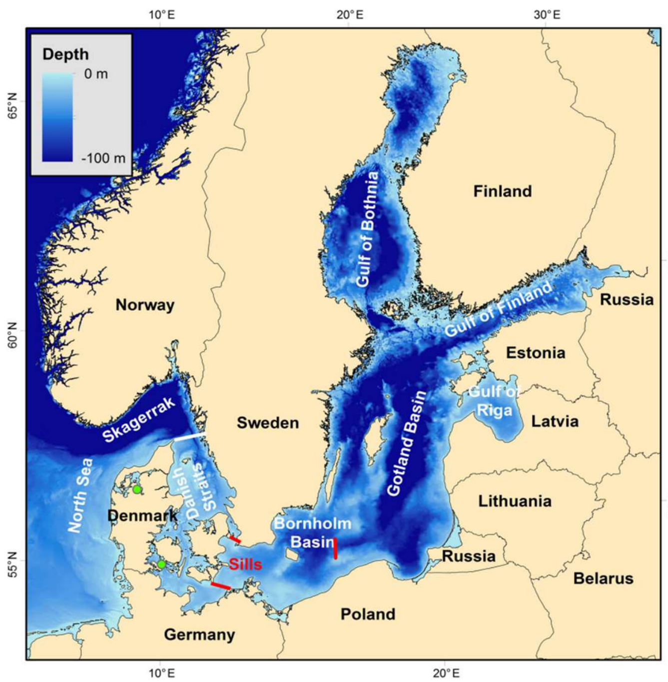

Figure 4: Baltic Sea's 7 Sub basins with depth (Source: ASLO)

The Baltic Sea is a huge area and can be analysed more easily by dividing it into 7 sub-basin as in figure 4. These are divided further into 17 sub-basin. Each area has its own specific characteristics. The areas range from the coastal region having hypoxic development for a few weeks to a few months, to the open central Baltic Sea observing perennial hypoxia. The majority of the Dead Zone occurs in the Eastern and western Gotland Basin. These are the deepest basins over 100 meters deep with a large repository of organic matter which is not decomposed. Irrespective of the area-specific effects in general the major cause of hypoxia is the increased influx of nutrients into the sea.

Hypoxic Condition in the Gotland Basin.

In the open central part, the Gotland Basin, hypoxia observed is perennial. This means the region remains hypoxic most of the time. But due to sea water inflows, there are shifts in hypoxic region. The Baltic Sea observer's irregular inflow from the North Sea. During which large saline dense inflow penetrates the inner bottom deep at specific wind condition (Figure 4). Even though this major inflow brings oxygen into the basin depth it further increases hypoxic area.

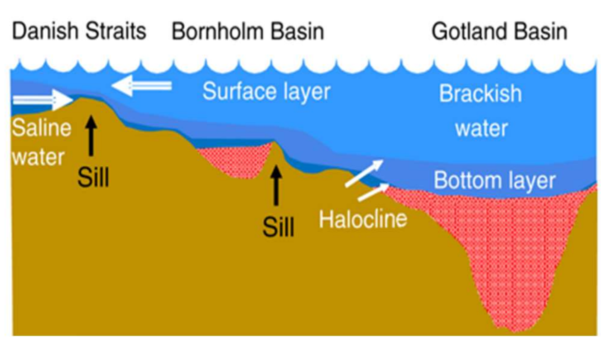

Figure 4: Inflow from North Sea

The effect of the saltwater inflow can be understood by taking the case of the 2015 major inflow. During this inflow, dense saltwater flowed deep into the basin carrying oxygen. From figure 5 (A) we see that on November 8th 2014 the Bornholm Basin is a Dead zone. During the major inflow in 2015 dense saltwater penetrated the basin and gets oxygenated as seen in February 2015 figure 5(B). This inflow also pushed the deoxygenated water from the Bornholm basin into the adjacent deeper basin. The same process occurs in the Gotland Deep. Where it gets oxygenated by pushing the anoxic water further away. The problem is that these areas have been without oxygen for decades and have a large quantity of biomass which is not decomposed due to the years of anoxic conditions. When oxygenated water penetrates this region rapid degradation of the organic matter consumes oxygen returning the basin into an anoxic state in a very short interval. It is observed that this process takes about 6 months to turn the area back into an anoxic state again. This results in further expansion of the dead zone region as the previous hypoxic water pushed further along still remains in hypoxic condition due to stratification.

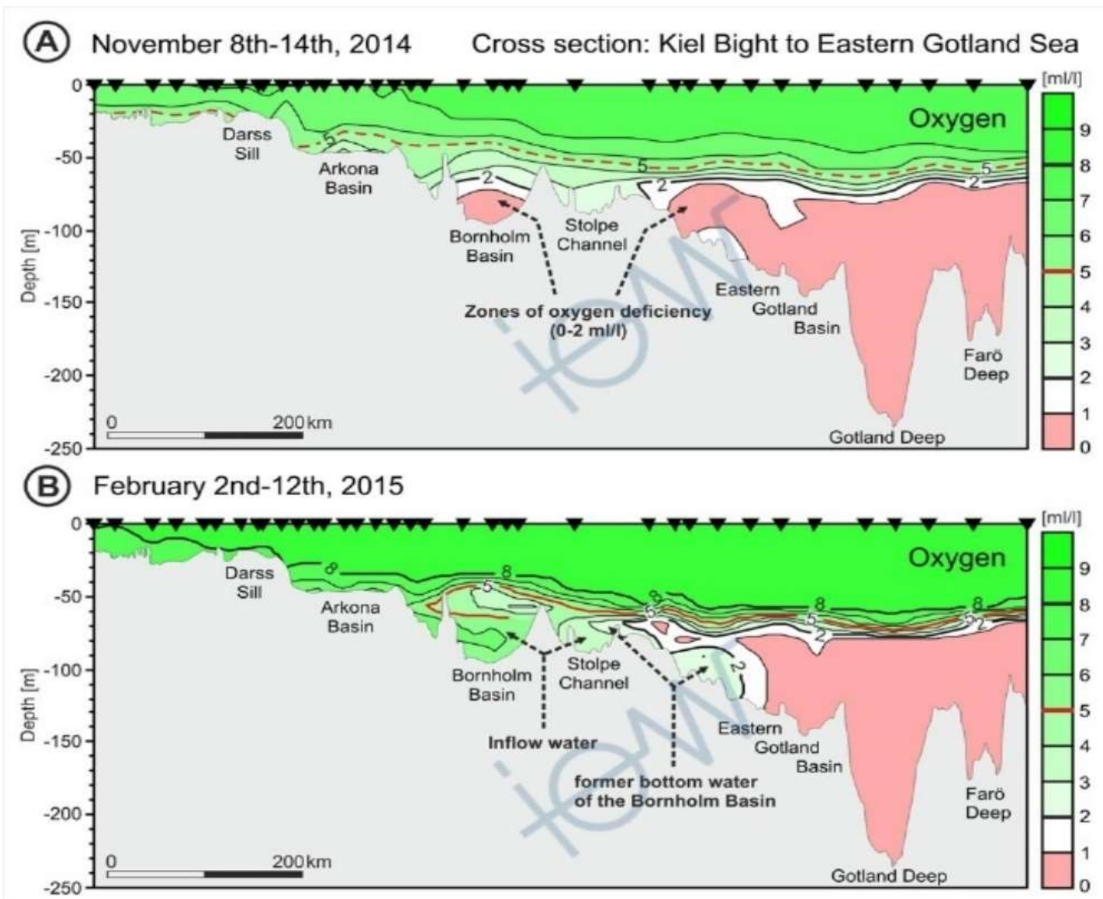

Figure 5: 2014 and 2015 oxygen dissolves area during major inflow

The other problem with the inflow is that as anoxic water is pushed forward by major inflow. The heavy water moves closer to the surface and this water is rich in nutrients like Phosphorus. This causes Cyanobacterial bloom which results in more Biomass being produced which act as a medium for further decline in the dissolved oxygen. This follows a cyclic pattern increasing the hypoxic area and the process is called the “vicious circle of the Baltic Sea”.

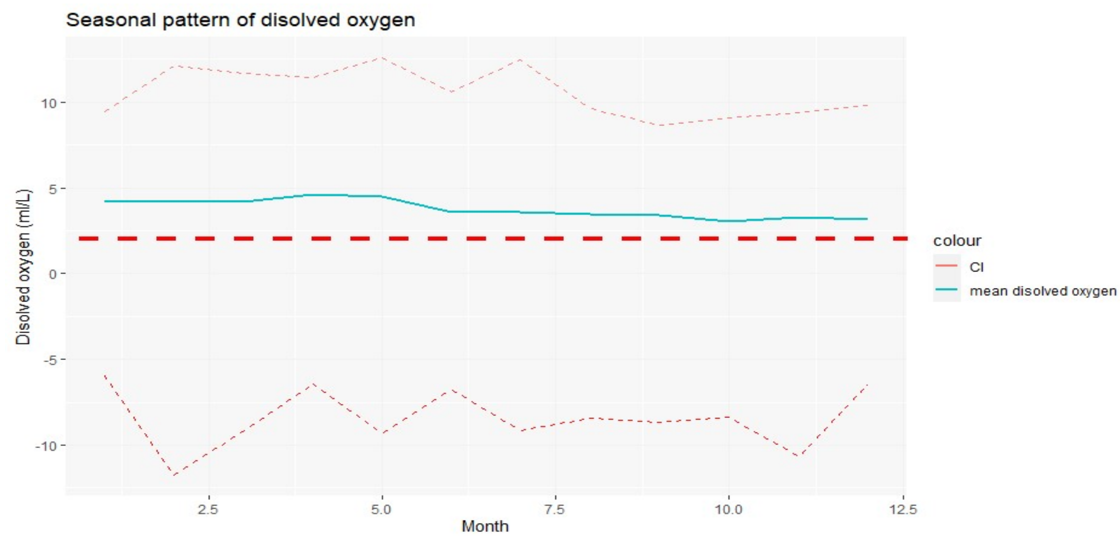

Figure 6: Average monthly Dissolved oxygen (1969 to 2921) (Data : ICES data repository)

Figure 6 shows the monthly pattern averaged across the year 1969 to 2021, the data was extracted from the ICES data repository. This analysis was done to check for any seasonal pattern. No pattern is observed with the same level of hypoxia observed all month. The red dotted line represents the hypoxia line of oxygen level 2ml/L. We can see a large variation from the mean as shown by the Confidence interval (CI).

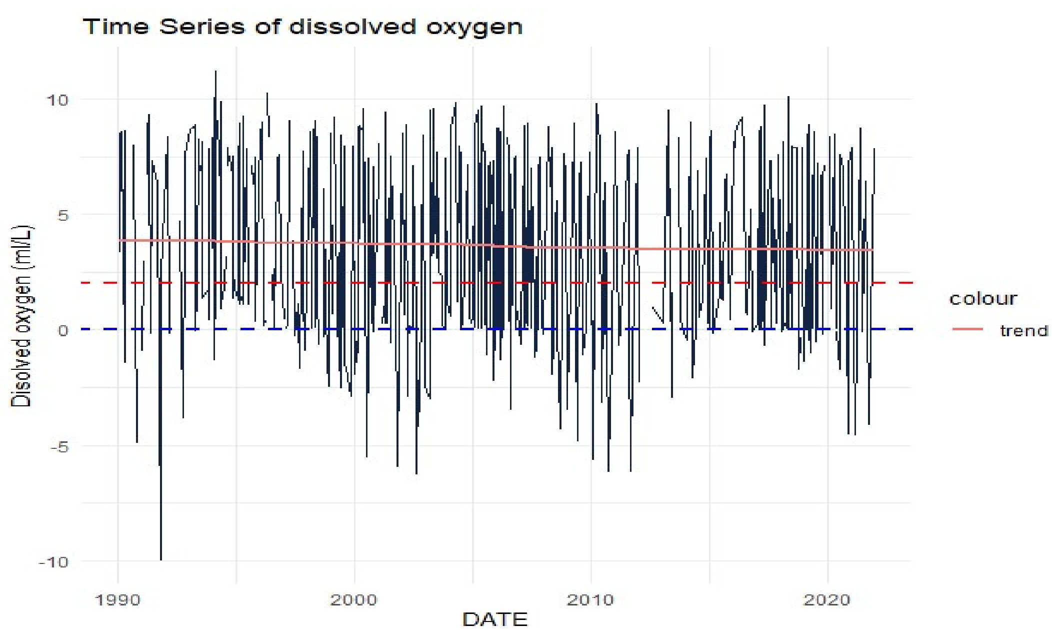

Figure 7: Time series analysis (1969 to 2921) (Data : ICES data repository)

Two things from the time series analysis are observed (Figure 7) . One is that the amount of dissolved oxygen is negative. The Baltic Sea is the only water system that shows negative dissolved oxygen. This is due to the presence of Hydrogen sulphide (H2S). The negative oxygen is the amount required to oxidise H2S. In the data used to plot the time series, H2S was given in micromoles, therefore, cannot be used to directly compare dissolved oxygen. To convert it into the oxygen required for H2S oxidation we convert it into ml per litter. 10ml/L of oxygen is required to oxidise 213 micro-Mole of H2S. The Red dotted line represents the oxygen level of 2ml/L and the blue dotted line is 0ml/L. The second thing observed is that when modelling for trends using the gam model it is noticed that there is a trend of a slight decline in dissolved oxygen from 1990 to 2021. This analysis gives us a further understanding that at the Gotland deep hypoxia observes perennial hypoxia and is increasing as time passes.

Hypoxic Condition Near Danish Straits.

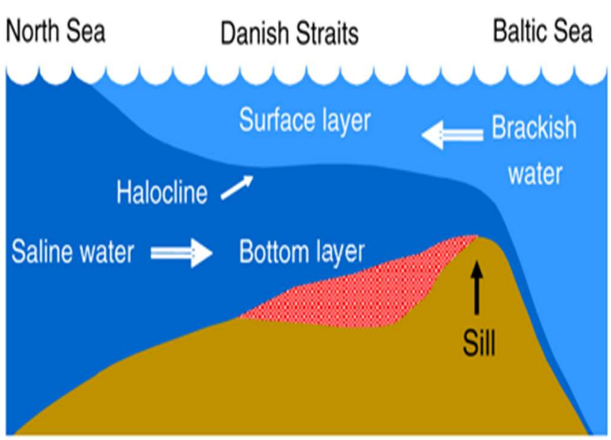

Figure 8: Inflow in the Danish Straits

Danish Straits which connect the Baltic Sea to the Northern Sea is the entrance of the Baltic. The bottom layer here is well oxygenated by the Northern Sea. This occurs by High-density saline water from the North Sea penetrating the Brackish water outflowing from the Baltic Sea. There are many Estuaries located near the Danish Straits and hypoxia is common near them. This is due to the influx of nutrients sustaining algal growth and the strong stratification caused by differences in surface and bottom water salinity. Estuaries in this area also create an enclosed area which hinders the mixing of water.

The hypoxia occurred in this region is seasonal and occurs during the summer. Three factors have been identified as the main drivers of this seasonal hypoxia. bottom water transport.

(1) Bottom water transport,

During summer bottom water transport is reduced due to freshwater surplus and lower wind speed from a south-easterly direction. The water resides in the bottom layer for a few months and becomes stagnant near the estuaries.

(2) Nutrient input,

Due to the presence of estuaries nutrient-rich bottom water is moved up into the surface layer. Resulting in the growth of algae and sedimentation of organic matter which reduces the oxygen concentration during its decomposition.

(3) Temperature,

The increase in temperature in summer further increases the oxygen consumption and reduce the oxygen-carrying capacity of the bottom waters. These factors together create a 20-week hypoxic period in the Danish Straits.

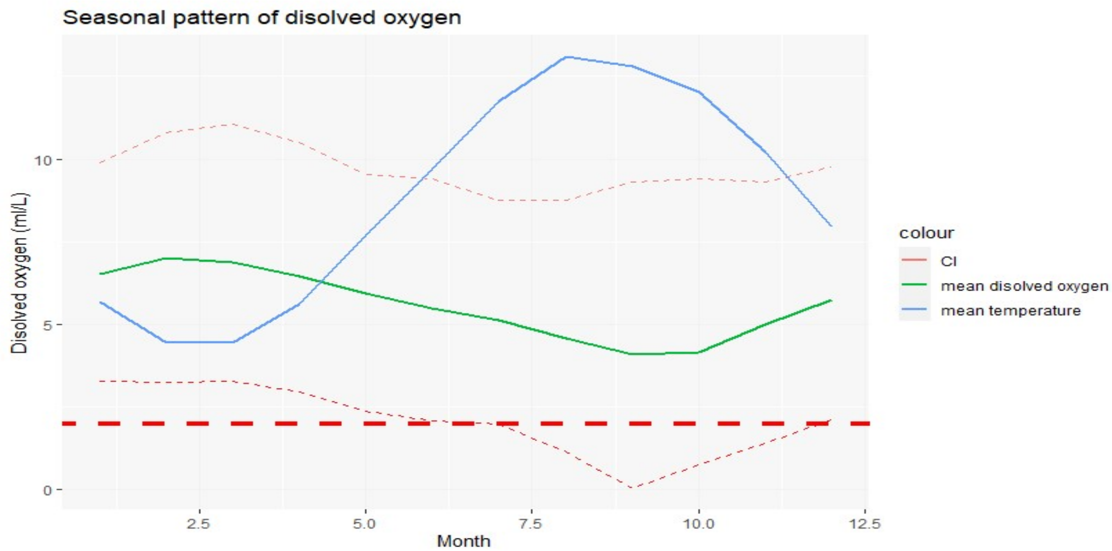

Figure 9: Seasonal pattern analysis (1969 to 2921) (Data : ICES data repository)

For the analysis of hypoxia near the Danish Strait data from the W Landskrona station was extracted. This is a region in the Danish Strait. The monthly average throughout the year 1969 to 2021 in the Danish Strait shows a clear seasonal pattern in the summer with the month from August to September observing the highest hypoxia(Figure 9). The blue line represents the average temperature measures and this clearly shows that during the hypoxia phase the temperature is high. The variation from the mean as shown by the CI is large showing signs of great fluctuation from the mean being close to 0ml/L in the year 2000.

<u>Hypoxia in Coastal region:</u>

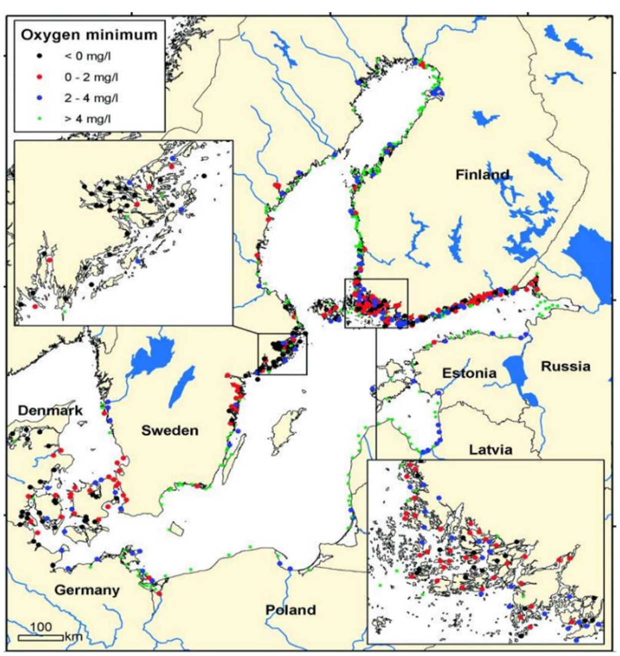

Figure 10: Coastal Hypoxia

216 regions out of 613 coastal units have experienced hypoxia in the Baltic Sea in the period from 2000 to 2009. With 63 per cent of the coastal regions not experiencing hypoxia, 1.5% experience Persistent or perennial hypoxia, 4% observe seasonally and 30% observe Episodic hypoxia. From Figure 6 we can see there is little to no hypoxia along the coast of Poland, Latvia, Estonia, and Russia. This is because of a lack of stratification and enclosed areas resulting in good mixing of waters. But the regions of Bothnian bay have observed hypoxia. This is due to the presence of estuaries and organic matter. Estuaries and many complex topographies around the Bothnian bay restrict the mixing of bottom water. The large flux of organic matter is explained by the presence of many paper mills in this area which

dumping fibre into the water. This presence of organic matter will remain here and sustain hypoxia for several decades.

Hypoxia in coastal areas is mainly episodic-like Limfjord in Denmark. It had several estuaries experiencing hypoxia in the 2nd week of July in 2009. A week later it spread out rapidly and 2 weeks later completely disappeared in most places due to strong wind. This is because Occasionally, water from the open waters spills into topographical depression due to stratification and intense internal waves as shown in figure 11. The coastal systems become hypoxic episodic, seasonal or even perennial based on the stratification and residence time of bottom water in these depressions. We can observe the same in the Stockholm archipelago where we have strong episodic cycles with high oxygen concentration during winter and get depleted in the summer. The hypoxia here are also influenced by the nutrient inflow from urban and agricultural sources.

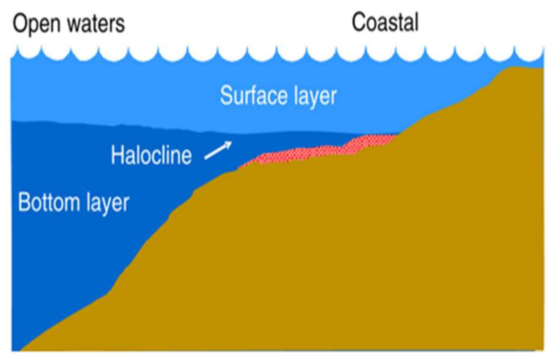

Figure 11: inflow

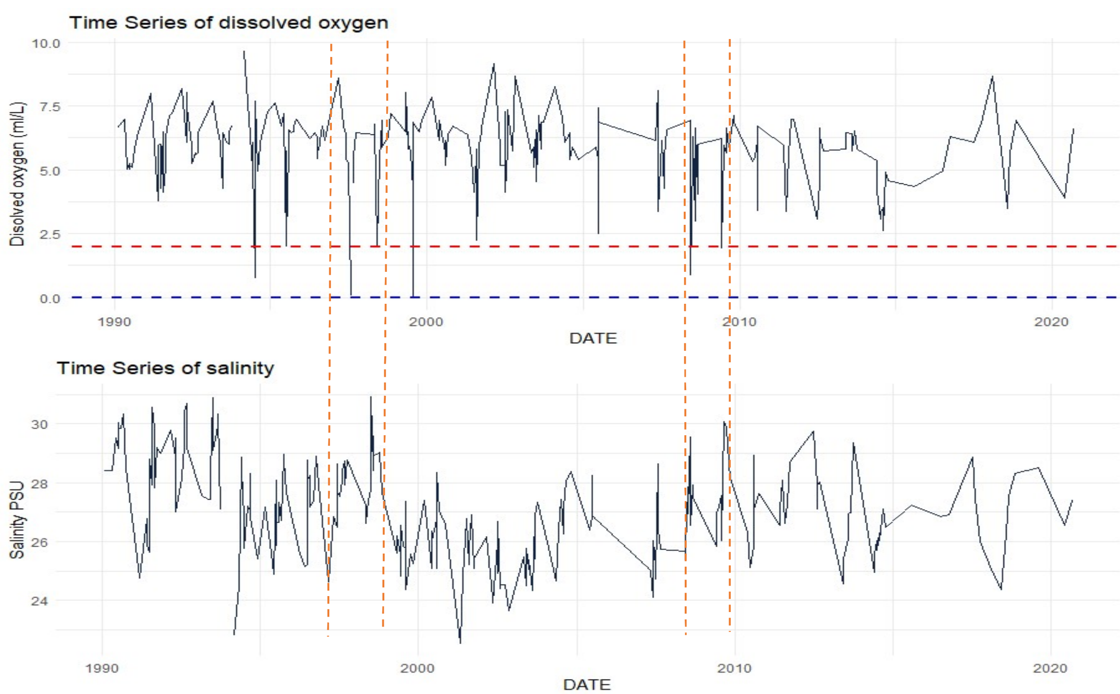

FIGURE 12 : Time series analysis

To analyse the dissolved oxygen condition of the Limfjord, data from the period 1990 to 2020 was extracted from the ICES data repository. Here we see a clear episodic cycle near the coastal region of Denmark (Limfjord). As mentioned we observe a hypoxic condition in 2009 and during which the salinity is high indicating an inflow of saline water. The same episodic pattern is observed in the year 1997 which had a similar high salinity condition.

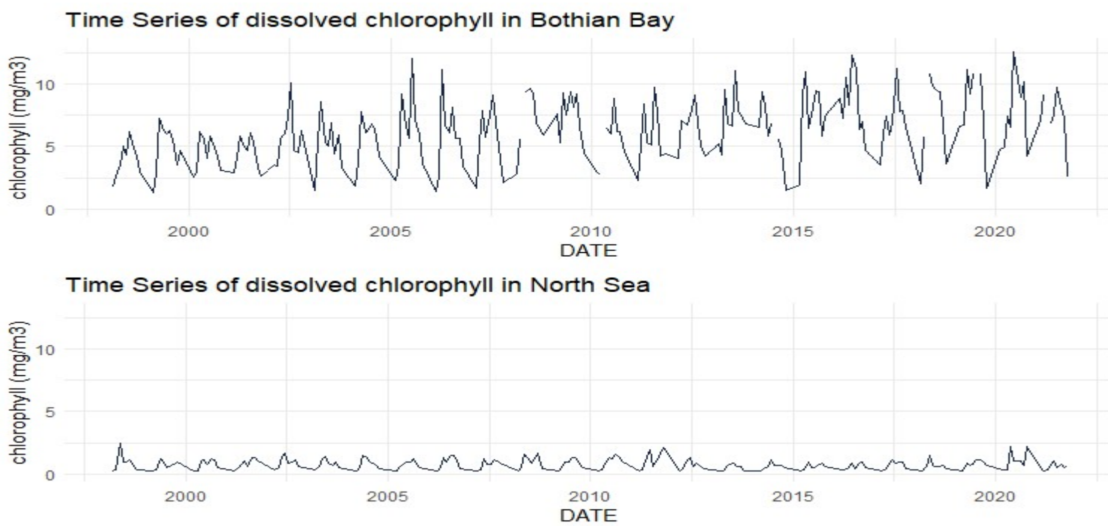

Figure 13: Time series analysis of chlorophyll

From observing the amount of Chlorophyll present in the North Sea and the Bothnian Bay we can clearly see a large amount of biomass being produced in the Bothnian sea. Which is at a magnitude of roughly 8.6 times the amount produced in the North Sea. This is caused by the continuous effect of the nutrient loading that has happened over the years like the effluent from paper mills.

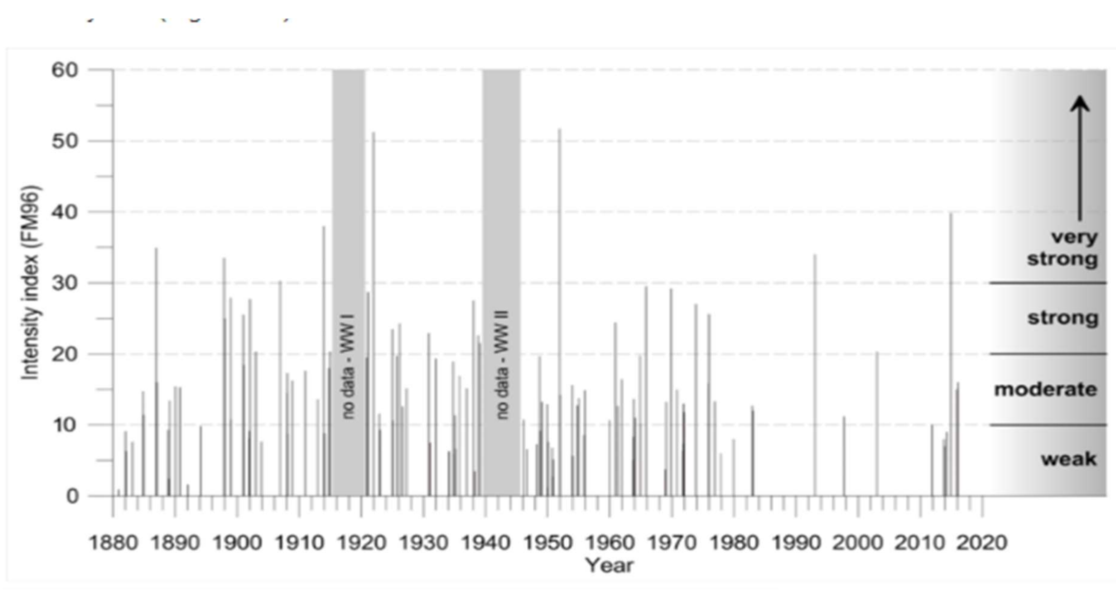

Figure 14: Major flows

The Lowest period of hypoxia was in 1990 this was a period which was called the great stagnation period. As the previous major inflow was in 1983.After that period Inflow didn’t occur for almost 10 years. We observe that the lowest hypoxia occurred when we didn’t have any inflows from figure14 and figure 1.

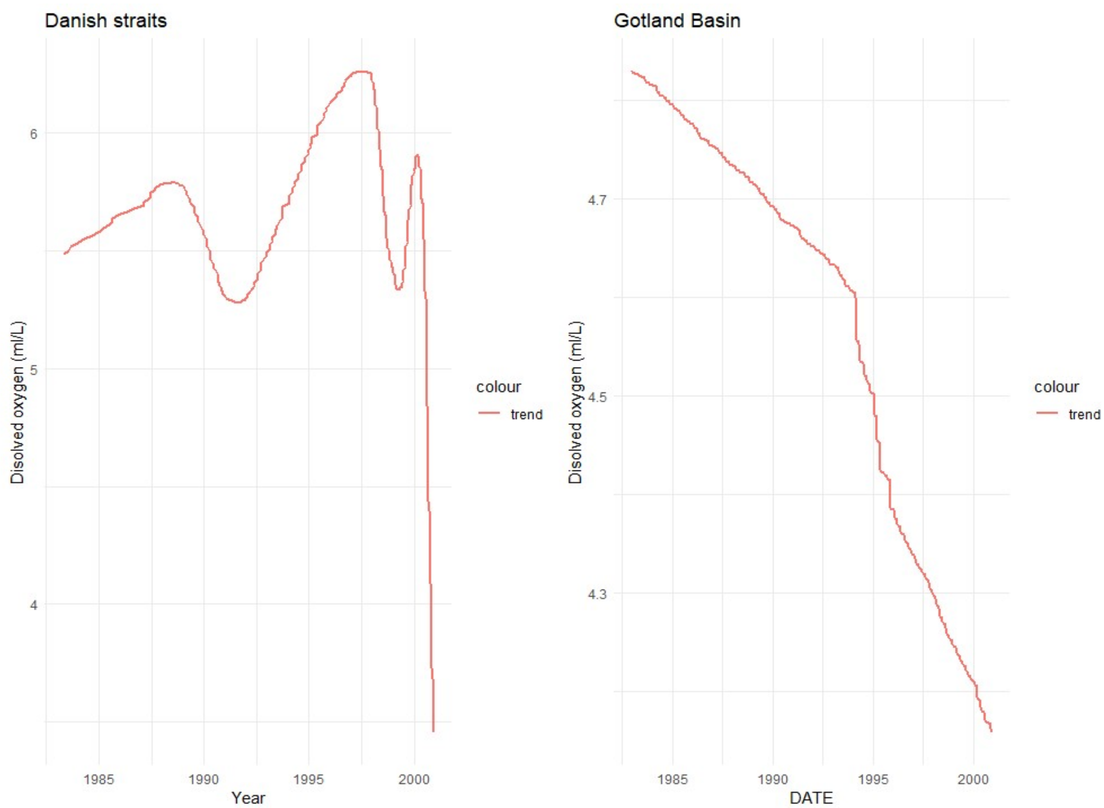

Figure 15: Trend of dissolved oxygen

One performing analysis in the region of Danish strait and Gotland Basin we see that the regions start becoming more hypoxic after the year 1993 during which an major inflow occurred. This makes sense, The stagnation period caused a reduction in the influx of saline water. This resulted in reduced stratification allowing oxygen to be diffused to deeper depths. These major inflows are just a small part of other inflows which occur intermediately. All these intermediate inflows do not the right temperature and salinity to replace the bottom water. But due to the stagnation period stratification weakened and the halocline deepened and the intermediate inflows oxygenated the Baltic sea during the stagnation period

A major effect that hypoxia has is the change in Biogeochemistry of the ocean. Oxygen deficiency influences biochemical processes that control nutrients and trace metal concentration. This includes occurrences like reduction in the ability to lose nitrogen through denitrification and increase in phosphorous due to iron phosphorous bonds being created. Which accelerated the rate of hypoxia by increased biomass being produced by the nutrient flux. This happens because during oxic condition sediments like phosphorous act as sinks and sources during hypoxic condition due to its interaction with iron.

On analysis, we see that dissolved inorganic phosphorous (DIP) presence is consistent with change in area of hypoxia. The DIP accumulation in the bottom water due to hypoxic area expansion is about the same as the DIP loss during shrinking of hypoxic area. This indicates phosphorous present in these basins can be reversed to reduced amounts with shrinkage of hypoxic area.

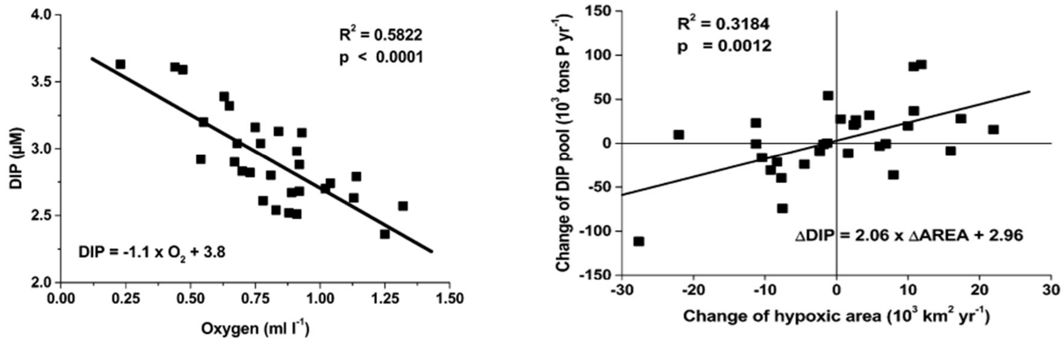

Figure 16 A) oxygen vs Dip B) change in DIP with hypoxic area

The Figures 16 A shows the relation between hypoxia and the level of dissolved inorganic oxygen as the oxygen level closes to 0 DIP peaks and vice versa can be seen. Showing the inverse relation between dissolved oxygen concentration and DIP. The Fig 16 B is obtained by taking an year as a standard in this case the year 1970 was taken as the standard and fluctuation of DIP and the total hypoxic area from the standard is plotted. As the hypoxic area from the standard year increases there is a visible increase in DIP.

Hypoxic environments also have many effects on the aquatic ecosystem and tolerance shown by marine animals to hypoxic conditions varies, with Fish and crustaceans being most sensitive. Even though fishes can swim to an area with more oxygen, some get trapped in the hypoxic area due to upwelling hypoxic water. Hypoxic condition in the Baltic Sea has also witnessed the reduced ability of cod to spawn in bottom waters. As high saline and oxygen concentration are required for Cod fry to develop. Only bacteria and fungi, along with some algal and other species can thrive in nutrient-rich hypoxic conditions. This causes structural and functional disruption to the entire aquatic ecosystem resulting in loss of habitat and species biodiversity (Daniel j. Conley, 2002).

Benthic organisms can normally tolerate low oxygen levels but struggle during long exposure to a hypoxic environment. These organisms carry out important functions such as bioturbation, bio irrigation and sediment nutrient cycling. They also have an important role in the marine food web and commercial fisheries. The loss of benthic fauna due to hypoxia is estimated to be around 3 million tonnes. Furthermore, the decomposition of these massive loss results in further hypoxia. The benthic organism also improves the flow of nitrate and oxygen across the sediment-water by building burrows and tubes, this process is called bio irrigation. This stimulates nitrogen removal and accumulation of iron-bound phosphate.

To counteract hypoxia, the Baltic an inter-governmental organisation HELCOM has taken action. On 15 November 2007, the HELCOM Ministerial Meeting made a contract involving the nine countries close to the Baltic Sea. During this they adopted the Baltic Sea Action Plan (BSAP) and set 2021 as the target to achieve a good ecological status of the sea. The action plan introduced a scheme called the Nutrient input Reduction Scheme which gave a limit to the nutrient input into the sea, 792 209 for Nitrogen and 21 716 for Phosphorous. But the implementation has had its flaws. As per record, In the year 2019, the Nitrogen input exceeded 88 929 and 6 350 for Phosphorus from the BSAP set threshold. But if the BSAP maximum input is maintained over a period of time the current 80,000 km^2 area of hypoxia will be reduced to 50,000 km^2

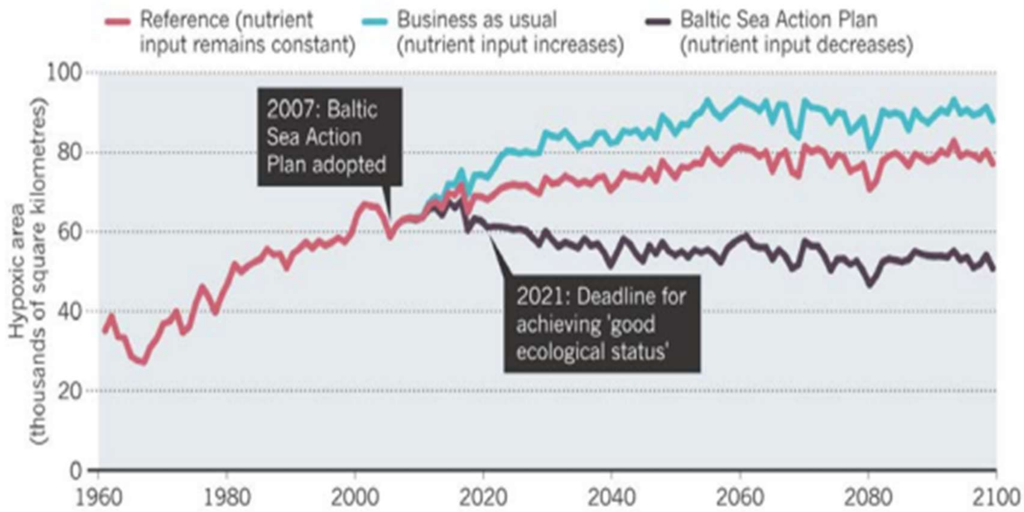

Figure 17: HELCOM action plan

Since this is slow process research on other alternatives was made with geoengineering being shown great interest. But geoengineering can cause negative effects on the Baltic Sea as rapid oxygenation into the sea through any mechanism has a risk of releasing different ecological problems. One such problem would be the shift in biodiversity. Such as attracting species into the oxygen-rich environment.

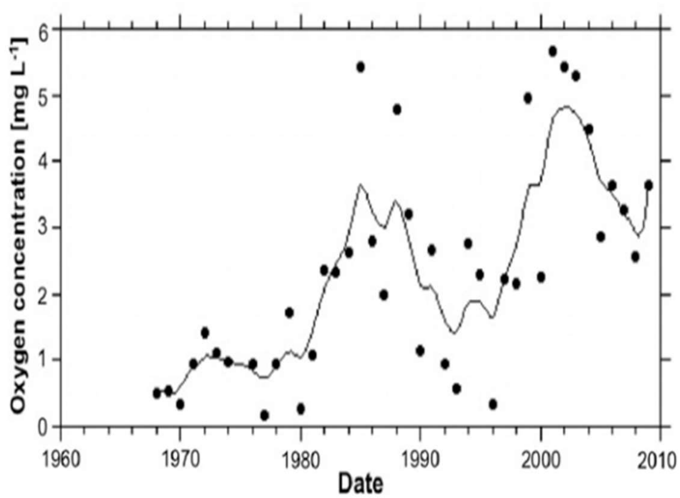

Figure 18: Oxygen concentration improvement

With all this, mitigating hypoxias seems impossible but there are instances showing hypoxia can be reversed and cases where the ecosystem shows resilience's. An example of this is the case of Stockholm Archipelago. After long-term dumping of sewage inputs oxygen condition in the inner Stockholm Archipelago were poor but gradually improved as inputs were reduced. This improvement allowed Benthic organisms to colonize and bioirrigate the sediments. Increasing the flow of sediments and oxygen, reducing the phosphate sediments in the bottom water allowing the ecosystem to recover over time. But this happens only if nutrient inputs are reduced to a level that ensures sufficient oxygen condition for Benthic organisms. From this we can understand that undisturbed marine ecosystems are resilient to handle natural fluctuations and can recover its original ecosystem with time but external influence have major impact on this resilience. The figure 18 shows the improvement in the oxygen level over time.

The recent eutrophication assessment made by HELCOM has shown deterioration in the eutrophication status of four out of 17 sub-basins in the Baltic Sea. This is partly due to natural climate change and hydrography and the long-term trend shows signs of improved eutrophication status in the westernmost Baltic. Although signs of improvement are seen in some areas, the effects of past and current nutrient inputs still influence the overall status. Some subbasins have shown a strong reduction in nutrient inputs. The waterborne nitrogen input to the Baltic Sea is currently at levels of that In the 1960s, and the phosphorous inputs of the 1950s.

When performing analysis and studies in the Baltic we face some limitations in the amount of data we can acquire. For example, it is shown that at the start of 1900 that there was only a few km of hypoxia, but this does not capture the entire data. As we check the sediment data there are some deep basins of the Baltic that has been hypoxic for a long period of time. Also, when analysing the global occurrence of hypoxia we lack systematic data collection. Also, there is a lack of availability of data to establish Historical trends which can be used to study the cause and pattern of hypoxia based on different regions. We also require deep water data taken from the bottom water which is taken routinely and does not represent concentration at the sediment-water interface at varying depths. This is because the presence of sediments cause fluctuation from the actual nutrient dissolved in the water.

In Conclusion the Baltic Sea has always observed hypoxia for many centuries but due to its geography, where it is surrounded by many well-developed countries, it experiences human interventions. These have caused a rapid expansion of hypoxia as mentioned in the report. We have also seen the result of reduced nutrient loading and how the environment responds. We have seen how hypoxia creates more hypoxia and how it spreads with Natural and Human intervention. Hypoxia in the Baltic Sea cannot be completely removed but can be managed to a small area. The Baltic Sea is on a Healthy path with good policies being made to counter the Anthropogenic effects. The problem comes when deviation from the set policies and plan. The impact of hypoxia is large and therefore is a serious matter that should be given its due importance. More analysis and data collection are required for a better analysis of hypoxia in the Baltic Sea.

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