Mitigation of sea level rise in Denmark

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Great efforts have been made by Danes to become world leaders in sustainability. Unfortunately, they still must address challenges brought forth by climate change. As a country almost completely surrounded by water, Denmark is vulnerable to any increase in sea level. It is essential that a proactive approach be taken to implement protective measures. This article explores the risks that communities face and possible solutions to mitigate flooding.

Introduction

Denmark is considered a pioneer in promoting and implementing green sustainable policies (Ministry of Foreign Affairs of Denmark, 2022) and is often ranked as one of the most sustainable countries in the world (*Denmark Is Once Again*…, 2022). While these efforts should be celebrated, Danes make up only 0.07% of the global population; therefore, their achievements are far too small to have an impact on the overall trend of the world's climate change. However, Danish citizens still have to manage the consequences of greenhouse gasses emitted from other countries. Among the many challenges caused by climate change and global warming, one consequence that will affect Denmark in particular is sea level rise (SLR).

Denmark is almost completely surrounded by water. It borders the Baltic and North Seas, and no part of Denmark is more than 67 km (32 miles) from the sea. Water is also integrated into the major cities by complex networks of canals used by locals for recreational purposes like swimming, diving, kayaking, and boating. The canals not only are key tourist attractions, making Denmark a charming and attractive country to visit, but also dangerous, making the cities more susceptible to water damage that could arise from flooding. It is imperative that Denmark take a proactive approach to protect its cities from water level rise, just as it has done with greenhouse gas emissions. The sea level will rise in upcoming decades, and it is vital that Denmark start making adjustments to its infrastructure to minimize losses in the long term.

Climate change challenges

The two biggest consequences of climate change for Denmark are rising sea levels in general and an increase in extreme weather events that can lead to higher water levels and flooding in the short term. Although there is considerable uncertainty about the actual level of the SLR in the next few decades, it is generally accepted that the sea level will increase (Hallegatte et al., 2010). Demark is creating strategies to adapt to an SLR of 0.1 to 0.5 m (5–20 in) by 2050 and 0.2 to 1.4 m (8–55 in) by 2100 (*Coastal Flood Risk Denmark,* 2022). Danish cities can adapt to a slow water level rise through urban planning, which they have done successfully in the past. Some examples of this urban planning include climate-resilient buildings, flood mitigation strategies camouflaged as skateboard parks or gardens, and new coastal protection.

The greatest challenge is the increase in frequency and magnitude of storm surges. According to the National Hurricane Center, a storm surge is an abnormal rise of water generated by a storm over and above the predicted astronomical tide (National Hurricane…, 2022). Hurricane Katrina's impact on the US in 2005 is an example of how catastrophic a storm surge can be when it coincides with normal high tide. Denmark suffered a similar disaster in 2013, making clear the need to plan and prepare for these extreme weather situations that will cause the most damage and devastation.

Storm Bodil

In December 2013, northwestern Europe, including the United Kingdom, Netherlands, Belgium, Germany, Denmark, Sweden, Norway, and Poland, suffered a severe winter storm. Each country gave the storm a different name, with Denmark choosing Storm Bodil, after a vote in the Danish Meteorological Institute. The precipitation from Bodil and the high winds caused storm surges across the country. Specifically in Copenhagen, water levels rose as much as 2 m in some areas and 1.68 m in the harbor. The

storm took the country by surprise; the unavoidable damage became greater than expected; and the rebuilding period dragged on. One of the major problems during this time was a lack of awareness that flooding damage was not covered by private insurance companies. Since 1991, flooding caused by a storm surge has been considered a disaster, therefore not included in general homeowner's insurance. It is instead covered by the disaster program managed by the Danish Storm Council. This differentiation was not clear at the time of the storm and caused much confusion and stress, with the general public not aware of this second entity and the Council not quick to respond. Since then, the Danish Storm Council has educated the public on the difference in coverage due to fire damage (covered by general homeowner's insurance) or water damage caused by a storm surge (covered by the Danish Storm Council) (Baron, 2020).

Another change that emanated from Storm Bodil was the development of Copenhagen's Storm Flood Plan, released in 2017. This plan emphasized the importance of additional flood protection for low-lying areas in the south of Copenhagen and in the north, which were found the most susceptible to flooding. The plan estimated that if no additional protection was installed, the city was at risk of losing $0.94B to $1.61B over the next 100 years in direct costs of water level rise (*Klimasikring og kystlandska*, 2022). With climate continuing to evolve, extreme weather events will occur more often and in larger magnitude. Copenhagen's Storm Flood Plan was a good first step, but it is imperative that Denmark continues to make conscious efforts to adapt and prepare for the challenges that it will face in the future.

Rising sea level risks

Rising sea levels create risks that are only com-pounded by extraordinary storm surges. These risks vary depending on the size of affected communities and include maritime operations as well as infrastructure and human losses. Understanding these distinctions can assist with preparedness planning.

Sea level rise in large cities

Denmark is largely urbanized, with 88% of the Danish population living in urban areas or cities (O'Neill, 2023). The two largest cities in Denmark are Copenhagen and Aarhus, making up 40% of the total population (*Copenhagen, Denmark Metro*…, 2022). Both cities have adequate resources and, through strategic urban planning, could improve plans to mitigate and adapt to the challenges that climate change will surely bring.

Current flood protection in Copenhagen is based on a water level 150 cm above the mean sea level; this protection level is associated with a return period of 120 years. This means that Copenhagen is currently protected from a storm that has a 1 in 120 chance of happening every year, equivalent to an 0.83% chance of occurrence every year. However, if the mean sea level were to increase by 25 cm with no additional flood protection installed, the protection level would decrease to the level of a 1- in 10-year storm, increasing the probability of flooding to 10% every year (*Coastal Flood Risk Denmark*, 2022).

For a case study in Copenhagen, six professors from international backgrounds designed a model to predict the relationship between economic losses, SLRs, and protection level. Economic losses include the direct and indirect costs of flooding in Copenhagen. The researchers defined direct losses as the cost of repairing damaged buildings and infrastructure along with the goods and jobs lost. Indirect costs are defined as the reduction in the production of goods and services across the economy due to the disaster, which includes business interruption and the loss of production of goods and services. In other words, the cost of the disaster is the sum of what is not produced plus the sum of the things that are produced but are not consumed and all the damage done to physical property (Hallegatte et al., 2010).

Estimates vary for how much SLRs will cost the city. In the case study mentioned previously, researchers estimated the current protection level of Copenhagen to be 200 cm above the mean sea level. Denmark is expecting an SLR in the range of 25 cm in the next 50 years. Their model suggests that the increased annual probability of flooding due to an SLR of 25 cm would cost the city of Copenhagen an average of almost €1M per year in direct and indirect costs (Hallegatte et al., 2010).

The estimation of the protection in Copenhagen in this study is slightly above other assessments, which indicate that the current protection level is only 150 cm above the sea level, not 200 cm (*Coastal Flood Risk Denmark*, 2022). Predicted costs rise rapidly with reduced protection. The case of protection at 150 cm would correspond to annual losses of almost €100M on average, a hundred-fold more than with protection at 200 cm. Clearly, serious consideration of protection against SLR is in order given the potential for catastrophic loss.

Sea level rise in small cities

Aside from the two main cities of Copenhagen and Aarhus, the other 60% of the Danish population resides in smaller cities. Many of these towns

are coastal and do not have the same resources or long-term plans as Copenhagen in terms of flood mitigation. They cannot afford to invest billions of dollars in water level mitigation and protection and therefore must take advantage of other alternatives that can be implemented on a small scale and are less costly. One of the options smaller cities often choose to take advantage of is dikes, structural barriers that act like small dams and contain water on one side of the structure.

Three climate researchers from the University of Potsdam conducted a study on Kalundborg, a medium-sized Danish coastal city with about 16,000 citizens (Boettle et al., 2013). In this study, they compared the damage the city would incur with and without dike protection. Figure 1 summarizes the estimated costs at various SLRs with and without dikes.

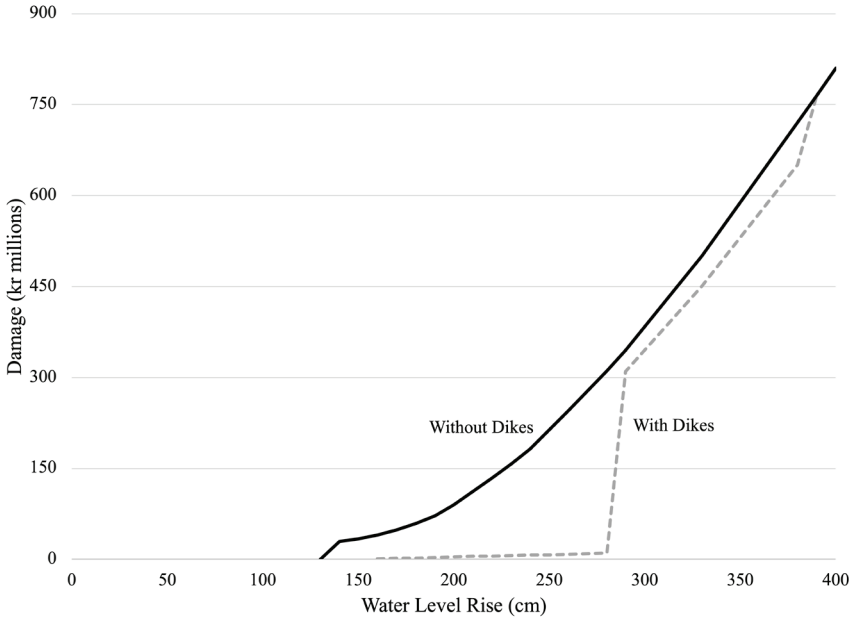
Dike installation as a mitigation system for flooding in larger cities has been common, and this study concludes that it is especially beneficial in smaller-scale cities. The study assumes that the current water protection level in Kalundborg is around 135 cm above the mean sea level. As Figure 1 shows, dike protection would keep damage costs near zero up to SLRs of 275 cm above the current water level. Without this protection, costs could be as high as 250Mkr ($35M). But dikes would not add much cost to risk mitigation. Events where flooding would be 300 cm (10 ft) would be almost equally detrimental with or without flood protection. At this level, dikes would be overtopped and protection would fail (Boettle et al., 2013). Clearly, dike protection makes sense for smaller Danish cities.

Maritime operations

Denmark has a small open economy and is very dependent on foreign trade. Annually, Denmark exports goods and services valued at more than 1Tkr ($142B). The Danes have a trade surplus; maritime transport, pharmaceuticals, and machinery are among the major commodities and service exports (Statistics Denmark, 2022). Most of this trade takes place in ports, as Denmark is the world's fifth largest maritime shipping nation (American-Danish Business Council, 2022). With a large percentage of the GDP coming from sea trade, it is crucial for Denmark to avoid interruptions of its maritime operations. At the same time, these operations are vulnerable to SLRs and storm surges, which could cause severe economic losses.

Economic losses arising from both direct damage to infrastructure and operational disruptions and delays across interconnected global supply chains can add up to large sums. The global supply chain has been undergoing extensive difficulties since COVID-19 and is set to face many more challenges from climate change. Enhancing and building more climate-resilient seaports is one of the main points in the United Nations *2030 Agenda for Sustainable De-*

Figure 1
Estimated damages with and without proposed dike protection, Kalundborg



Source: Boettle et al., 2013.

velopment. It was highlighted in the Second Global Sustainable Transport Conference as one of the priorities and challenges that all nations will face in the near future (United Nations, 2015).

Inundation due to sea level rise and storm surges can lead to both temporary and permanent flooding, especially in seaports. According to the global mean sea levels and storm surges projected by the Intergovernmental Panel on Climate Change (2012), 64% of seaports are expected to be inundated at some point. According to another study conducted by researchers from the European Commission Joint Research Centre, the risk of ports becoming inundated is expected to increase at least 80% from 2030 to 2080. This trend is stronger in the North Sea, which the west of Denmark borders (Christodoulou et al., 2019). Because of their unique situation and economic importance, port facilities require special attention as Denmark seeks to avoid the most adverse outcomes of SLRs.

Solutions

Adaptation to SLRs is not an issue that Denmark is facing alone; countries around the world are trying to create infrastructure that is climate change resilient. The common challenge has allowed for solutions that communities could implement, but it is essential to keep in mind that not one solution is right for all communities.

Lynetteholm Island, Copenhagen

Copenhagen, the nation's largest city, presents a special case. To increase the protection level, Copenhagen is planning to build a 1-mi^2 artificial island called Lynetteholm that will act as a high-tech dam and cost $3.2B (Beyer, 2021). A solution of this magnitude is only economically feasible if it has an alternative use. Thus, the island not only will serve as a water level controller but also will house 35,000 people and a variety of businesses. Copenhagen is currently undergoing a housing crisis, and this new development near the city center will aid in mitigating this crucial problem (Olsen, 2022).

Lynetteholm Island will have a coastal landscape facing the Øresund section of Copenhagen (north of the city), and it will act as climate protection. The rocky and sandy beaches on the island will have a flat landscape, which will dampen storm surges by taking energy out of waves before they hit the city. The opening left between the existing Nordhavn port area and Lynetteholm is wide enough that boats can enter and leave the harbor and small enough that gates to control water flow could be installed (*Klimasikring og kystlandska*, 2022).

On June 4, 2021, a broad political majority of the Danish Parliament passed a law permitting the construction of Lynetteholm. This decision has been highly controversial for economic and environmental reasons. A total of 80 million tons of soil will be needed for this island (*Denmark Parliament Approves…*, 2021). Environmental groups are concerned about water quality and the effect on the quality of life of the residents of Copenhagen as the island will be constructed over the next 50 years. It is estimated that 350 truck journeys will have to take place daily throughout the start of the construction period to transport the soil. This will increase contamination, fossil fuel emissions, and traffic in the capital (Smithson, 2021).

Construction of Lynetteholm started in January 2022, with the installation of a road for soil transportation, which included two dams, a bascule bridge, and a navigable channel, all completed in early 2023. The construction of the island itself is expected to be conducted in two main phases. The construction of phase I has started and is expected to finish by the end of 2023. Phase II is a much larger project; construction there will commence once phase I is completed and most likely take three years to finish. This project is an example of water rise protection that large cities should be implementing. The city of Copenhagen found a way to mitigate the harmful effects of SLR, at the same time providing a solution to its housing crisis and enabling new businesses to become established. However, this is only one city in the country; it is essential that the other large cities in Denmark follow Copenhagen's steps, implementing plans that proactively address this challenge.

Dikes

Another popular solution that has been implemented both in small and large communities in Denmark are dikes. As discussed previously, dikes are structural barriers that act like small dams and contain water on one side of the structure. They are a good option to serve as the main infrastructure for densely developed, low-lying coastal communities with space constraints. Dikes also serve as accessible open spaces for outdoor recreation like walking, running, and cycling. They are a more affordable solution in the short term as they are mostly constructed from compressed soil, but the maintenance, upgrade, and inspection can become costly in the long run (*Dikes and Related Works*, 2022).

Copenhagen has used dikes for protection against flooding for decades; one of the most prominent is the Vestamager dike, built in 1943 for storm surge protection (*Climate Adaptation…,* 2013). The dike

has a length of 14 km and a height of 4 m and protects the south of the city. This dike underwent extensive upgrades in 2012; a new 5.8-m-high and 7-km-long dike was created behind the old dike. The old dike was reinforced to almost 6 m high and was renovated to serve as a recreational area for the people from the community (*Copenhagen Climate Adaptation Plan*, 2015). This example, although located in a major city, offers a good idea of what could be readily accomplished in smaller cities or constricted areas at reasonable cost.

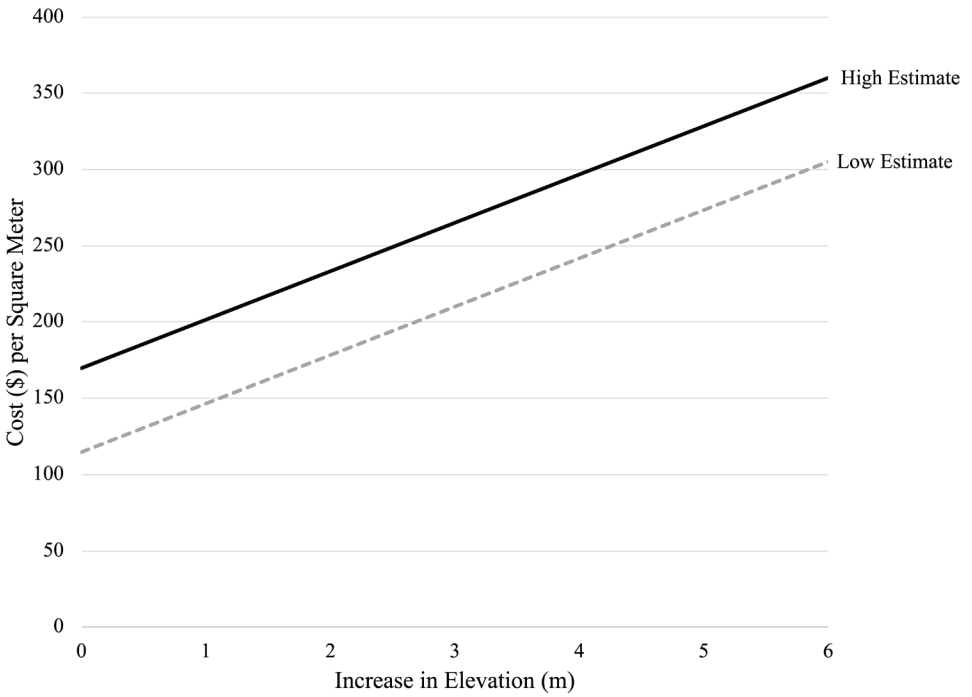
Seaport protection

Seaports present a special case regarding risk mitigation. They have long been designed to be resilient to stresses, because they are particularly exposed to a wide range of natural hazards due to their location. However, they are still susceptible to impacts of climatic hazards, such as SLRs, storm surges, waves, and strong winds. The most commonly used method to increase the protection of a port against long-term SLRs is to elevate the entirety of the port by placing layers of gravel and asphalt to elevate the ground level (Asariotis, 2021).

The cost of elevating a port is difficult to approximate, given the many location-specific variables involved. Stanford University tackled the challenge in in 2015, estimating how the total costs (per square meter) for elevating a port rise with increases in elevation (Fig. 2). Although this cost estimation was done for ports in the US, for the purpose of estimating costs in Denmark, the same assumptions can be used for a preliminary analysis.

The largest port in Denmark is in Aarhus, the second largest city in the country. The Port of Aarhus is Denmark's leading container port, with a market share of 56%. The port handles approximately 9 million tons of cargo annually and is considered among the most efficient container handling ports in Europe. The port itself covers a surface area of 2,500,000 m^2. If the port were elevated by 1 m, Figure 2 indicates the cost would be \$150/m^2 in a low estimation and \$200/m^2 in a high estimation (Hippe et al., 2015). Therefore, given the total area of the Port of Aarhus, it would cost between \$375M and \$500M to elevate by 1 m. No substantial planning has been done to protect the Port of Aarhus in recent years, making it vulnerable to potential inundations and other extreme weather events. While costly to raise the level of large areas, such as those utilized in this port, doing nothing could prove even more costly in the long run. To secure the future of the Danish economy, it is essential that the main sources of its financial stability be protected against climate change; to do that,

Figure 2
Estimated cost per square meter to elevate a port



Source: Hippe et al., 2015.

port cities must take action to prepare and adapt to the conditions that will come.

Conclusions

Denmark is an environmentally conscious country. Its citizens have gone to great lengths to reduce their carbon footprint and be more sustainable. However, despite this progress, because of its small size and unique geography, Denmark is still exceptionally susceptible to climate change. The country is almost surrounded by water and is vulnerable to SLRs. In the upcoming decades, not only the mean SLR but also more extreme weather events will lead to an increased number of storm surges.

There are some interesting projects that Denmark has initiated to deal with the SLRs that will occur in the future, like the Lynetteholm Island in Copenhagen. However, smaller cities that do not have the capital to invest in new infrastructure are not making it a priority to protect themselves against SLRs. By investing in dikes (a less significant capital investment than Lynetteholm Island), small cities could benefit in the long run as costs of flooding and other damages would be significantly reduced.

Because of its unique geographical location, Denmark's economy is based on the export of goods by sea. Most of this business takes place in the Ports of Aarhus and Copenhagen, in the two largest cities in Denmark. In past decades, there has not been an emphasis on the protection of these ports that are vulnerable to flooding. Inundation of either of these ports would lead to significant international supply chain problems. Denmark needs both short- and long-term plans that address these issues to minimize the cost of climate change in the future. The responsibility to prepare for the future conditions must be addressed at multiple levels; one group or organization alone cannot be expected to take full responsibility.

In the recent past, Denmark has focused on greenhouse gas emission reduction, resolving as a country to address a cause in which it wholeheartedly believes. With Denmark set to reach its reduction goals in the upcoming decade, a shift must be made in what it considers its utmost priority. The people of Denmark need to come together to address SLRs, which bring a complex set of challenges resulting from climate change.

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