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Evaluation of Coastal Protection Strategies in Respect of Climate Change Impacts

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Summary

The expected change of global climate will create impacts being an unknown challenge for coastal protection: Both, accelerated sea-level rise and stronger storms create higher set-ups of storm surges and stronger waves. Moreover, the adaption of intertidal areas in the coastal areas might be delayed providing larger water depths in front of coastal structures allowing again the occurrence of stronger waves. The question, if coastal lowlands could remain safe against the sea is of increasing importance. Alternatives to the presently exercised strategy of Keeping the Line of protection are discussed with reference to historical experience. For a quantitative comparison mathematical modelling of hydrodynamic loads for designing coastal protection structures is carried out for distinct scenarios of boundary conditions to be expected as consequence of climate change until the year 2100. As a final result protection by Keeping the Line is found to be the most favourable strategy in respect of both, safety and effectiveness. Based on these findings the adaptation strategy for coastal protection to climate change effects until 2100 was implemented by the State Government of Lower Saxony in 2013.

Keywords

coastal protection strategies, climate change impacts, accelerated sea level rise, storm surges, design

Zusammenfassung

Die zu erwartenden Folgewirkungen des globalen Klimawandels werden an den Insel- und Küstenschutz erhebliche Anforderungen von bisher nicht erlebtem Maß stellen: Beschleunigter Meeresspiegelanstieg und stärkere Sturmintensität führen zu höheren Staus bei Sturmfluten mit größeren Wassertiefen vor Schutzwerken, mit denen wiederum eine stärkere Seegangsbelastung einhergeht. Darüber hinaus wird es eine verzögerte und abnehmende Anpassung von Watten an beschleunigte Anstiegsraten des Meeresspiegelanstiegs geben, die zu einer weiteren Vergrößerung der Wassertiefen und damit auch zu verstärkten Seegangsbelastungen führen. Es stand daher zur Debatte, wie künftig der Insel- und Küstenschutz auszurichten sei, um den zu erwartenden Herausforderung erfolgreich und zugleich effektiv begegnen zu können. Deshalb wurden Alternativen zu der bisher traditionell seit Jahrhunderten angewandten Strategie linienhafter Schutz untersucht. Mit vergleichbaren Randbedingungen wurden in quantitativer Form die Konsequenzen alternativer Strategien im Vergleich zum linienhaften Schutz mit dem Maßstab gleicher Sicherheit für die zu schützenden Niederungsgebiete aufgezeigt, um eine objektive Evaluierung zu ermöglichen. Diese vergleichenden Untersuchungen mit alternativen Strategien haben eindeutig belegt, dass die Strategie linienhafter Schutz optimal hinsichtlich Sicherheit und Kosteneffizienz ist. Daher ist die

Strategie linienhafter Schutz Grundlage der in Niedersachsen von der Landesregierung eingeführten Anpassungsstrategie an Klimaänderungsfolgen bis 2100 geworden.

Schlagwörter

Küstenschutz-Strategien, Klimaänderungsfolgen, beschleunigter Meeresspiegelanstieg, Sturmfluten, Bemessung

Contents

1 Introduction

Changes in global climate and the consequently resulting acceleration of sea-level rise require a thorough re-evaluation of coastal protection strategies in many parts of the world. This yields also for the lowlands at the southern North Sea coast which are protected by a line of dykes since about 1,000 years. The anticipation of an accelerated sea-level rise due to global warming has raised the question if this strategy of Keeping the Line will still be appropriate or if alternatives should seriously be taken into consideration. This yields the more since furthermore a number of secondary effects of climate change will lead to stronger loads on coastal protection structures: increasing intensity of storms and consequently higher set-ups of storm surges (WOTH 2005) create as well larger water depths in front of coastal structures as the delayed adaption of tidal flat levels to an accelerating sea-level rise (MÜLLER et al. 2007). Since wave heights and periods on tidal flats are strongly depth-controlled (NIEMEYER 1983; NIEMEYER and KAISER 2001) any increase of local water depth is accompanied by corresponding higher wave loads on coastal structures.

This contribution provides results on the evaluation of coastal protection strategies gained within the research theme A-KÜST in the framework of the KLIFF program for the German Federal State of Lower Saxony. KLIFF focuses on adaptation to climate change effects and covers the topics agriculture, forestry and water management. A-KÜST is targeted at the evaluation of distinct coastal protection strategies like the historically practiced ones as well as those being discussed in earlier research projects (NIEMEYER 2005a, 2005b, 2010).

Major aim of the project is to compare alternative strategies with a methodical approach being in tune with the design practice due to the Lower Saxon Dyke Act. The alternative strategies are on the one hand the ones being already practiced in history like Retreat and Accommodation and on the other hand variations of Protection such as Set-Back or Combined Protection (Fig. 1). They have been compared with Keeping the Line as the traditional execution of the strategy Protection (NIEMEYER 2005a, 2005b, 2010).

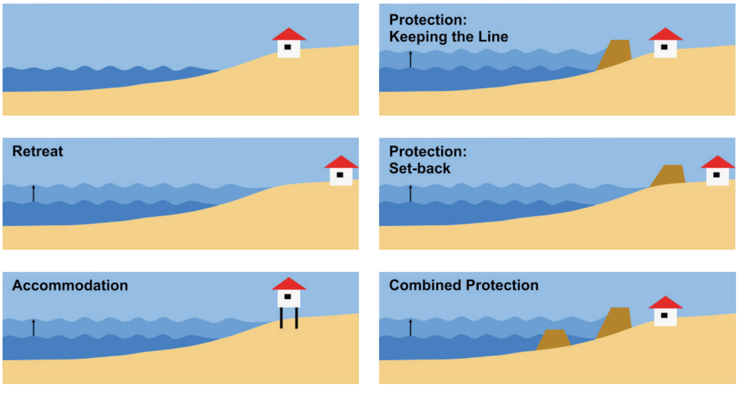

Figure 1: Alternative coastal protection strategies in response to sea-level rise (IPCC 1990) and adapted from COMCOAST (2007); (NIEMEYER 2005a, 2005b).

2 Chosen boundary conditions for the evaluation

As boundary conditions for the evaluation of coastal protection strategies design water levels and wave climate have been simulated for the southern North Sea for the present design conditions and for scenarios being both reliable and pessimistic for future climate change effects. On that basis hydrodynamic loads on coastal protection structures have been analysed by mathematical modelling for the test region Ems-Dollard estuary. The evaluation of hydrodynamic loads has been exercised with the same methodology and spatial resolution as applied for the actual design procedure for coastal protection structures in Lower Saxony.

2.1 Scenarios

Three scenarios for the development of hydrodynamic loads in the Dollard region till the end of the century were established (Fig. 2): the first one represents the actual design conditions with a safety measure for the design water level of 0.5 m created by a static water level rise of 25 cm – corresponding to measured one of MHWL at the southern North Sea coast during the last centuries – and an additional set up of 25 cm of storm surges due to higher gale forcing. For the second scenario the safety measure for the design water level has been increased to 1.0 m by a combination of a static water level rise of 65 cm, which is in the same order of magnitude as the upper limit of sea level rise by IPCC (2007). Furthermore an increase of the set-up of storm surges of 35 cm due to stronger forcing by wind has been added in accordance with earlier investigations (WOTH et al. 2006) and recent ones in the framework of the research theme A-KÜST by the HZG Institute for Coastal Research (WEISSE et al. 2012). The third scenario is a pessimistic one with an increase of the safety measure for the design water level of 1.5 m due to an increase of the static water level of 100 cm and a heightening of the surge set-up of 50 cm by stronger storms. Since water depths as well as wind forcing increases for all three scenarios a corresponding growth of wave heights and periods is implemented.

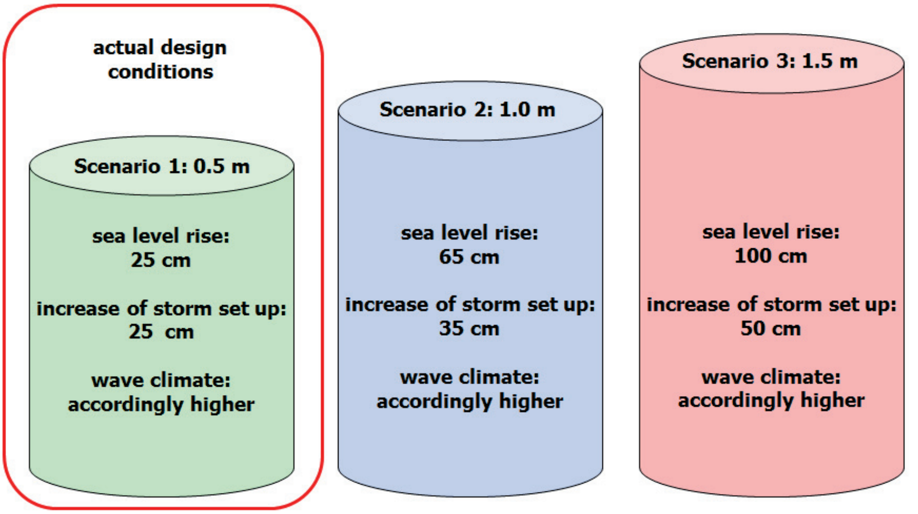

Figure 2: Scenarios for increasing design water levels.

2.2 Modelling

Modelling of the water level in the area of the Ems estuary was carried out by using a hierarchical cascade of three nested 2D-hydrodynamic models applying DELFT-3D with increasing resolution: the coarse Continental Shelf Model covering the whole North Sea and adjacent parts of the Atlantic, a model of the German Bight and a model of the Ems-Dollard estuary with a resolution of about 120 m (Fig. 3). The increase of sea level was implemented by adding the value respectively to the scenario on the water levels. The increase of surge however was effected by an increase of the respectively wind speed over the whole model cascade on the basis of a real storm surge from November 9th 2007 and adjusted for each scenario to the gauge Borkum at the entrance of the estuary.

Waves in front of the dykes were calculated applying the mathematical wave model SWAN coupled to the tidal model Delft-3D in two nested models considering the increased water levels of the scenarios and according wind conditions. The resolution of the inner model was 30 – 10 m. As offshore boundary of the outer model a JONSWAP spectrum with H_{m0} = 10 m, T_P = 15 s and a mean Dir = 315° was applied according to actual design practice in Lower Saxony (NIEMEYER 2001).

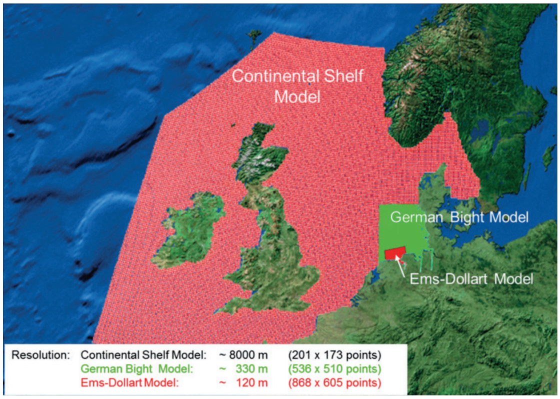

Figure 3: Model cascade.

2.3 Resulting loads on the dykes

Modelled peak water levels ascend considerably from the North Sea into the Ems-Dollard estuary (Fig. 4). For the chosen scenarios the increase intensifies the more the higher the absolute levels: e.g. for scenario one the safety measure of 0.5 m for the design water level at the gauge Borkum cause an increase of the design water levels of approximately 0.6 m in the inner part of the estuary.

Local wave conditions are strongly fluctuating according to coastline exposition to wind direction. Due to increasing wind velocities and growing water depths significant wave heights mount up by a magnitude of up to some decimetres and a gain in wave energy periods of up to approximately 0.5 s.

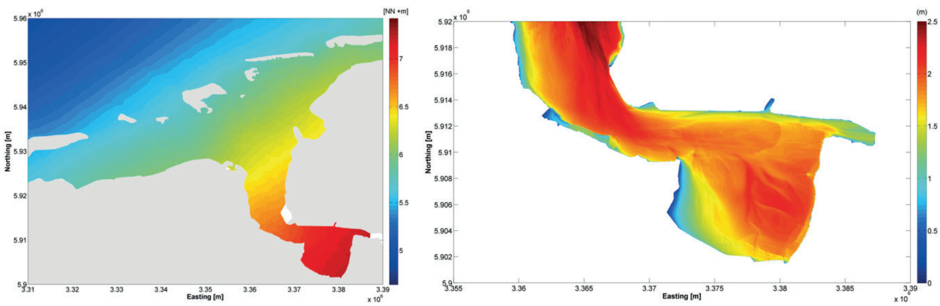

Figure 4: Left: Peak water levels for scenario 2. Right: Significant wave heights H_{m0} [m] for scenario 2.

3 Evaluation of alternative strategies

The present strategy for coastal protection in Germany is specified as Keeping the Line: In response to increasing hydrodynamic loads strengthening of the existing line of protection structures is performed (Fig. 5). The extension of the protected lowlands covers 14 % of the state and is inhabited by about 1.200000 people (REGIERUNGSKOMMISSION KLIMASCHUTZ 2012). Moreover, the safety against storm surges for a large number of people living in the neighbouring federal states of Bremen and Hamburg and in the Dutch province Groningen depends on coastal protection. Without any protection they all would lose their homes and economic basis. The question in respect to climate change is, if the actual exercised strategy of Keeping the Line will remain feasible and if other strategies would be preferable. The results of that evaluation are presented here.

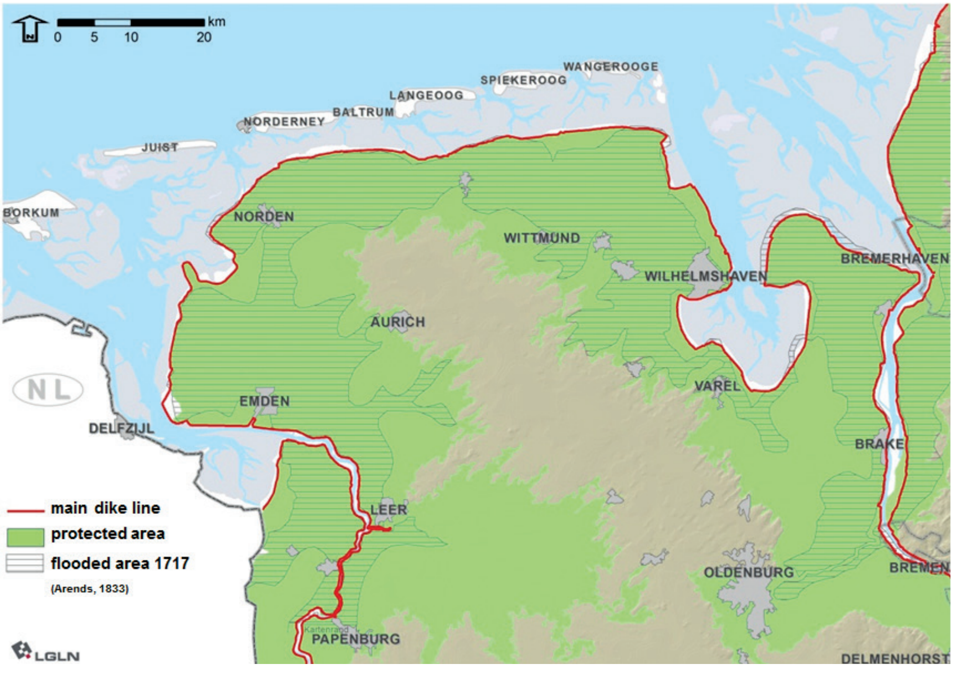

Figure 5: Protected lowlands in the western part of Lower Saxony (RITZMANN and NIEMEYER 2011).

3.1 Retreat

A retreat from all coastal areas being endangered by storm surges would induce enormous losses. A resettlement of the coastal population into areas being safe from inundation due to storm surges without any requirement of protection against storm surges would furthermore create a large burden for both, individuals and society. The extension of those areas becoming uninhabitable without protection against storm surges is enormous which is clearly demonstrated by those areas being nowadays designated by the Lower Saxon Dyke Act as protected coastal protection structures (Fig. 5). The vulnerability against very high storm surges in case of a non-effective coastal protection scheme is highlighted by the flooding due to the catastrophic Christmas Surge in 1717 as documented by ARENDS (1833) and edited by Hans Homeier (FORSCHUNGSSTELLE KÜSTE 1980) (Fig. 5). A storm surge with a similar gale forcing would nowadays flood even larger areas since the MHWL is about 0.75 m higher due to sea level rise (Fig. 6).

Abandoning coastal protection for the lowlands of Lower Saxony would not only affect the loss of homes and economic basis of the people living here, but also endanger an almost equal number in neighbouring states being indirectly dependent on the Lower Saxon coastal protection system. Furthermore, the cultural heritage of the lowlands like e.g. medieval churches or prehistoric stone graves would be lost forever. Comparing the cost saving aspects due to a total withdrawal from coastal protection with the implicit enormous economic and cultural losses, this alternative is regarded as highly unfavourable. The effect of Retreat in respect of corresponding losses is sufficiently highlighted by the coastal flood prone areas as designated by the Lower Saxon Dyke Act. The impacts of future climate change simply evaluated by adding anticipated higher sea levels of 0.5 m and 1.0 m above present design water level (Fig. 6).

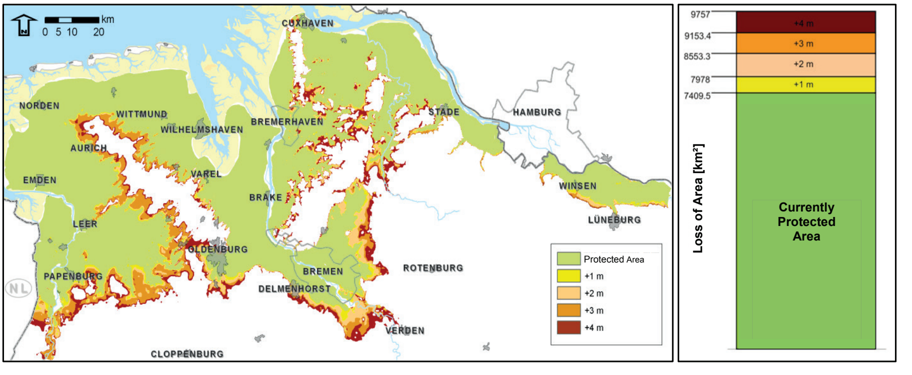

Figure 6: Abandoned land due to execution of the strategy Retreat from storm surge endangered areas (RITZMANN and NIEMEYER 2011).

3.2 Accommodation

Accommodation in the lowlands requires the creation of numerous protected islands with settlements and industrial areas in the lowlands along the coast and tidal estuaries. The use of the former dwelling mounds is deficient for safety against storm surges since the level of their surface is nowadays too low in respect of storm surge levels due to the sea-level rise which has taken place since their erection. A further heightening is only possible for a few ones without settlements and buildings. Most of the dwelling mounds are densely covered with buildings (Fig. 7).

Any rising of the level of inhabited dwelling mounds would require the dismantling and reconstruction of the existing infrastructure. The creation of well-chosen areas being protected by rings of surrounding dykes is therefore regarded as more appropriate for economic reasons. This yields the more since adaption of level heights of dwelling mounds to rising water levels would become repeatedly necessary in the future and would be again more costly than strengthening of dykes.

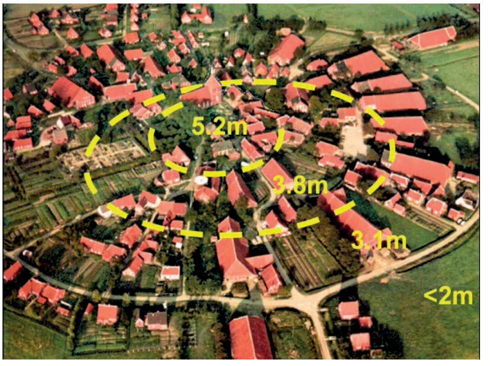

Figure 7: Dwelling mound village of Rysum in East Friesia with marker lines for existing levels above German datum; actual design water level in the area is about 6.5 m above German datum (RITZMANN and NIEMEYER 2012).

A schematic example of an area with low population density highlights the enormous efforts being necessary to create those safe havens against storm surges in the lowlands (Fig. 8). Major advantage of the strategy Accommodation is the anticipation of a significantly reduced length of the dyke line. In the investigated area of western East Frisia in Lower Saxony this would be only achieved if solely the settlements with more than 20.000 inhabitants experienced a protection against storm surges by surrounding dykes. But compared to the size of the protected area the economical aspect is not given (Fig. 9).

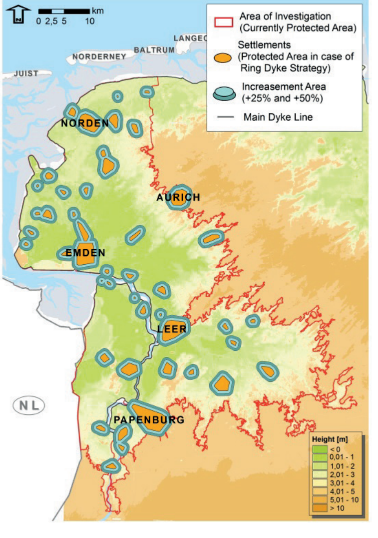

Figure 8: Dyke rings for large settlements and commercial sites (RITZMANN and NIEMEYER 2012).

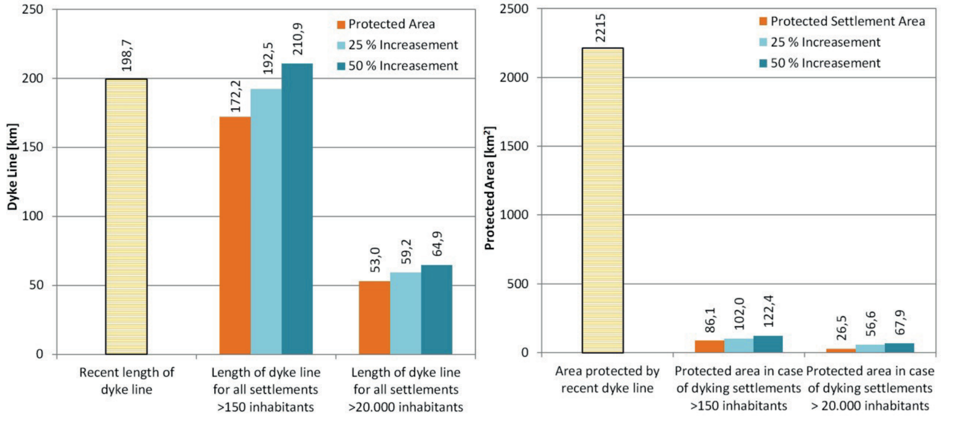

Figure 9: Comparison of the strategies Accommodation by dyke rings and Protection by Keeping the Line. Left: Length of the necessary dyke line. Right: Protected area (RITZMANN and NIEMEYER 2012).

Furthermore infrastructure like e.g. roads, railways or transmission links of energy between the safe havens would be more vulnerable against the impact of storm surges and would require much higher maintenance costs than in protected areas. Already a rough comparison makes it evident that Accommodation as an alternative coastal protection strategy for dealing with an accelerating sea-level rise will require high investments corresponding with enormous economic losses due to the abandonment of smaller settlements and agricultural revenues on the one hand and increasing maintenance costs of infrastructure after flooding due to storm surges. For areas like the lowlands at the Lower Saxon coast the strategy Accommodation is therefore extremely unfavourable in comparison to protection of the areas in total.

3.3 Set-Back

Other options which are discussed as alternative strategies are modifications of protection like Set-Back or realignment by erecting a new protection line in a larger distance from the coastline creating a belt of salt marshes with the aim of a stronger attenuation of waves (COMCOAST 2007). But that concept neglects that in embanked areas no longer sedimentation could take place after earlier embankments of salt marshes. Whereas the salt marshes in front of the dykes could grow furthermore, the embanked ones remained at the level before their embankment. Therefore the gradient of the surface level is declining from the present coastline inland leading to lower surface levels the more away from the sea. After a Set-Back of dyke line water depths in front of a dyke in a certain distance from the present coastline will increase. Consequently, wave loads on the dyke will be higher than at the present coastline. An example of a Set-Back of 3.5 km at the Dollard Bay makes evident by wave modelling that for design conditions significant wave heights increase by approximately 15 % and energy periods by approximately 8 % (Fig. 10) which furthermore results in an increase of wave run-up of approximately 20 %.

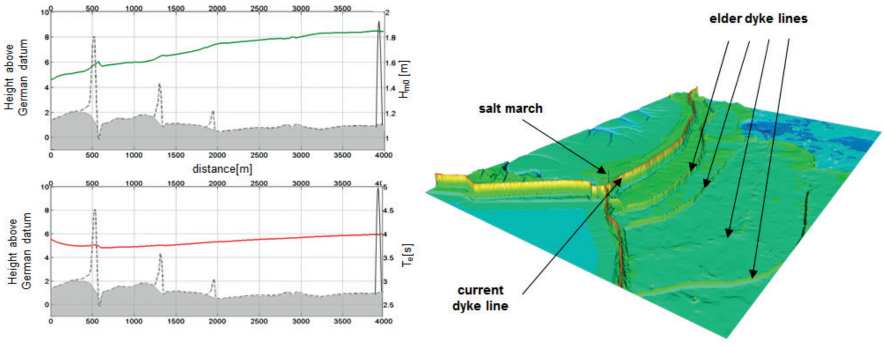

Figure 10: Left: Increase of significant wave height (top) and energy period (bottom) after Set-Back of a dyke. Right: Set-Back of dyke lines in the past (KAISER et al. 2010).

Already this simple example highlights that the Set-Back of a dyke line in coastal lowlands has no advantages: wave loads are higher and require a higher structure for protection against storm surges than at the present coastline. Furthermore, that strategy would demand enormous efforts for the construction of a totally new dyke line landward of the existing one and the necessary compensation of the private land owners according to existing law. An unquestionable advantage being achieved by a Set-Back of a dyke line would be the creation of large areas of salt marshes which are regarded as highly valuable with respect to ecology. But in respect of coastal protection a Set-Back of dyke lines is unfavourable in regard of safety and economics.

3.4 Combined Protection

Another alternative for protection of the hinterland is the two-line strategy: a combination of two structures for coastal protection: the most seaward one with the aim to act as a submerged breakwater and in a certain distance another one being sufficiently high to keep storm surges levels at bay. This assumption is mainly based on observations of wave damping in the shelter of summer dykes during lower storm surges. But observations during higher storm surges highlighted their decreasing effectiveness due to higher water levels (NIEMEYER and KAISER 1998, 2001). Mathematical wave modelling has proved this result to a much further extent (NIEMEYER and KAISER 1998, 2001): Even for present design conditions the effect of the existing summer dykes as submerged breakwaters are reduced to small insignificant numbers (Fig. 11) which are even insufficient to justify the maintenance of summer dykes.

In order to create submerged breakwaters being even effective for an accelerating sea-level rise, significantly higher efforts would be required than the maintenance or construction of structures with dimensions like the nowadays existing summer dykes: Investment costs will be very high since the construction must be strongly armoured in order to avoid its destruction by overflow during a storm surge leading to strong wave attack on the second dyke which is highly vulnerable against wave attack would then endanger the whole protected hinterland.

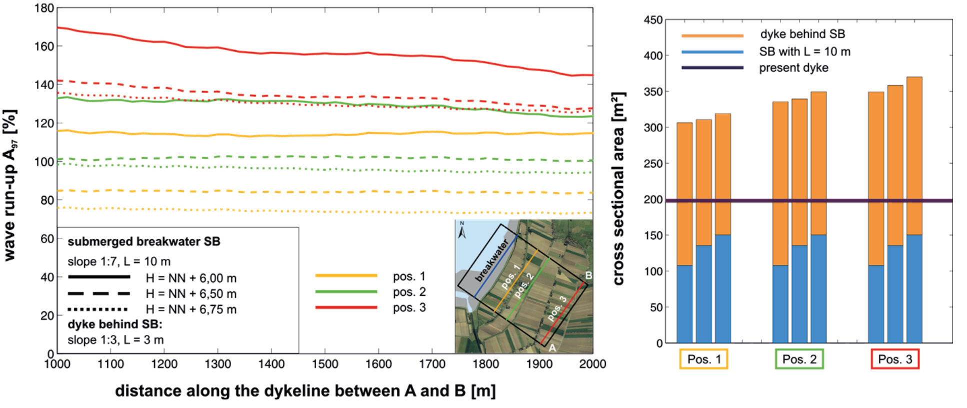

Figure 11: Left: Wave run-up at dykes behind a submerged breakwater. Right: needed cross sectional area for a conventional dyke due to Keeping the Line compared to Combined Protection (NIEMEYER et al. 2011b).

Combined Protection with two lines of structures is not expected being safer than the line protection with one single structure as practiced since 1000 years. Moreover, this alternative strategy will require higher investment costs and probably also an increase of maintenance costs in comparison with the traditional one.

4 Summary and Conclusions

Global climate change and its anticipated impacts like e.g. acceleration of sea-level rise or higher set-up of storm surges require a thorough and reliable evaluation of coastal protection strategies. This work provides investigation results carried out in the research theme A-KÜST being a constituent of the research framework KLIFF in the German Federal State of Lower Saxony. The evaluation is carried out by means of mathematical models and aimed at the reproduction of real world conditions both for hydrodynamic loads on structures and their design. The results are representative for the lowlands coasts at the southern North Sea and are transferrable for coasts with similar boundary conditions worldwide.

Since about 1000 years the lowlands at the Lower Saxon lowland coast is protected by a single dyke line which is also common practice at other lowland coasts at the southern North Sea. In the past, these protection structures have been strengthened in response to increasing hydrodynamic loads. The evaluation of distinct strategies has highlighted that these strategy will also be preferable in future, even for the enormous increase of hydrodynamic loads to be expected by climate change impacts until 2100.

Based on this results an adaption strategy for coastal protection has been developed and afterwards been implemented by the State Government of Lower Saxony in 2013.

5 Acknowledgements

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