CHALLENGES FOR COASTAL PROTECTION IN MECKLENBURG-WESTERN POMERANIA FOR THE 21ST CENTURY

Ulrich Floth. Marcus Siewert and Lars Tiepolt

With 14 figures

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Summary: In 2020, the German Working Group on water issues of the Federal States and the Federal Government represented by the Federal Environment Ministry (LAWA) introduced the precautionary measure of 1.0 m for the expected sea level rise due to climate change for the next 100 years. As a result, the framework of tasks for the coastal protection in Mecklenburg-Western Pomerania and other coastal federal states changed significantly. The most relevant consequences are the increase in mean water levels and the associated expansion of permanently inundated zones. In addition, rising mean water levels are accompanied by an expected analogous increase in extreme water levels during storm surges and, therefore, a further extension of potentially flooded areas in these cases. Moreover, sea level rise or a change in meteorological and hydrodynamic conditions is expected to lead to profound changes in coastal morphology and its rate of development. Due to the intense use of widespread lowland areas, changes in mean and extreme water levels as well as coastal morphodynamics can be assumed to have a considerable impact on existing forms of land use. The associated number of potentially concerned inhabitants and the existing property values lead to a considerable rise in the potential for flood-related damages. Increasing requirements, especially with regard to design events, will force the state coastal protection in Mecklenburg-Western Pomerania to adapt to a new (natural and socio-economic) framework and to align with other spatially relevant interests. This is accompanied by an increased need for the state coastal protection administration for the most reliable long-term projections, advanced design approaches and efficient adaptation strategies in order to meet these challenges. The purpose of this paper is not a presentation of new scientific data, but to identify and explain foreseeable challenges and knowledge deficits for state coastal protection taking the perspective of the public administration based on experience, measurements, third party scientific studies and definitions by expert committees.

Keywords: Coastal protection, coastal erosion, coastal flooding, climate change, Mecklenburg-Western Pomerania, sea-level rise

1 Introduction – coastal protection in Mecklenburg-Western Pomerania

1.1 The geomorphological framework

The coastal morphology of Mecklenburg-Western Pomerania is mainly a product of the Pleistocene glaciation cycles, but also to a large extent of postglacial morphodynamic processes, especially since the end of the Littorina Transgression about 6000 years ago (Schwarzer et al. 2019). West of the Wustrow Peninsula we find large bays that follow the formation of earlier glacial lobes and are characterized to a moderate extent by longshore sediment transport and spit and barrier formation. Eastward of Wustrow Peninsula to the beginning of the Fischland, the course of the coast is considered to be highly equalized and no longer has any significant headlands or embayments. Quite different conditions are present from the Fischland east to Usedom (Fig. 1), where the reworking of Pleistocene island cores and the formation of spits and hooks in between led to a series of semi-enclosed basins (bodden) in their hinterland forming an interior coast. At the same time, on the exterior coast (adjacent to the open Baltic Sea), equalizing processes are dominant along wide areas which are largely determined by long term wave-regime, local relative sea level and marine flood events (Weiss 1992, Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2009). Regarding the latter, the knowledge of extreme events is restricted to those having taken place approximately since the 19th century and of which the storm surge of 1872 is the most outstanding one. Its return period is estimated to be more than 200 years (Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2022c). The morphodynamic effects of major events e.g. in 1320 or 1625 (Kolp 1955, Weiss 1992) remain largely unclear since historical reports on them are brief and address only few areas.

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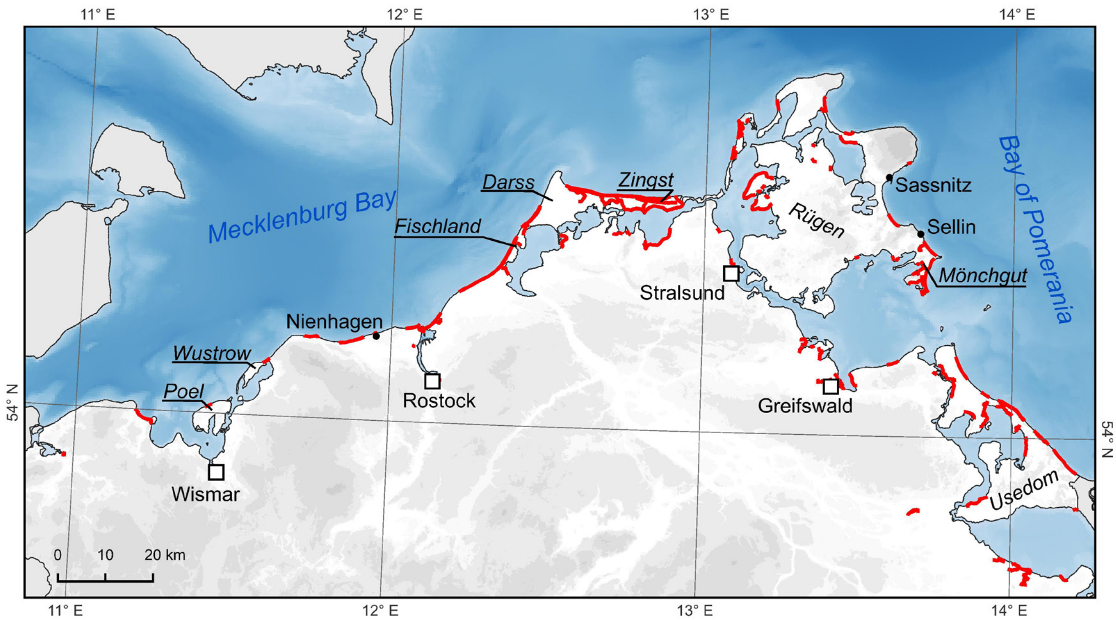

Fig. 1: Overview map of the coastal regions of Mecklenburg-Western Pomerania with adjacent areas. The red lines indicate sections which are protected by coastal structures against erosion and marine flooding described in section 1.3 (Base of map: Baltic Sea Bathymetry Database https://www.bshc.pro/data/, Digital Terrain Model by the Landesamt für Innere Verwaltung Mecklenburg-Vorpommern)**.**

1.2 Duties, tasks and objectives

Coastal protection in Mecklenburg-Western Pomerania is characterized by technical standards and recommendations, past experiences, measurements and results of numerical modelling, as well as national and international legal bases. Its purpose has always been to protect coherently developed areas from coastal erosion (Fig. 2) and flooding (Fig. 3). It should be emphasised that a statutory duty of protection extends only to these areas and that unoccupied zones are generally left to natural coastal dynamics (Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2009).

In addition to technical aspects (cf. section 1.3), this paradigm is strongly influenced by the HELCOM (Helsinki Commission) Recommendation 16-3 from 1995, which has been incorporated into the guidelines for the coastal protection of Mecklenburg-Western Pomerania. Another fundamental objective of coastal protection in Mecklenburg-Western Pomerania is the adaptation to the challenges of climate change with

Fig. 2: Developed area atop a cliff section in Sassnitz (Rügen) endangered by coastal erosion processes (Photo: L. Tiepolt)

Fig. 3: Flooded parts of Greifswald-Wieck and at the mouth of River Ryck during the storm surge event of 2002 and before the construction of the Greifswald flood barrier (Photo by courtesy of Technisches Hilfswerk, local chapter Greifswald)

the greatest possible conservation of marine sand resources as laid down in the current coalition agreement for the government of the federal country (Sozialdemokratische Partei Deutschlands Landesverband Mecklenburg-Vorpommern & DIE LINKE Landesverband Mecklenburg-Vorpommern 2021).

1.3 Technical instruments of state coastal protection

Coastal protection systems along lowland sections of the exterior coast often consist of a sequence comprising a groyne field to stabilize the shoreline, a subsequent coastal protection dune maintained through regular nourishments and a dike further inland as a second line of protection (Fig. 4).

Specific local and regional features and challenges are responded to by the use of breakwaters, seawalls, geotextile structures, revetments or mobile protective structures. This list is by no means to be considered as exhaustive and the toolkit is generally open to expansion. In order to be prepared for future increasing challenges, 'hard' structures (e.g. seawalls) are constructively and functionally designed according to valid technical standards for long-term design water levels. At the same time, regular safety checks are carried out to determine whether existing structures meet current requirements (e.g. reference water level with a return period of 200 years) (Weichbrodt et al. 2013).

Concerning the choice of building materials, the focus for their utilization is set, however not exclusively, on natural options (e.g. stone, wood) in accordance with the contents of the aforementioned HELCOM recommendation.

1.4 Organization

The Ministry for Climate Protection, Agriculture, Rural Areas and Environment in Mecklenburg-Western Pomerania is the central responsible authority for issues of coastal protection due to its role as supreme water authority in this federal state. The coastal department within the State Agency for Agriculture and Environment of Central Mecklenburg (StALU-MM) fulfils tasks of basic issues of coastal studies, monitoring, safety assessment, conceptual and technical planning as well as technical examination. Its responsibility stretches along the entire coast of Mecklenburg-Western Pomerania and ensures the implementation of equal standards.

2 Challenges for coastal protection in Mecklenburg-Western Pomerania by changes of the natural framework

2.1 Climate change-induced sea level rise and design water levels

It was already clear from past projections by the IPCC (Intergovernmental Panel on Climate Change) that the sea level rise caused by climate change would have a profound impact on coastal protection in Mecklenburg-Western Pomerania. However, the contents of the Special Report on Oceans and Cryosphere in a Changing Climate (Oppenheimer et al. 2019) indicated a drastic acceleration of sea-level rise in the 21st century. As a result, in 2020 the LAWA agreed on the basis of the projection of the RCP5-8.5 scenario to introduce the precautionary measure which foresees a sea-level rise of 1.0 m over the next 100 years since its introduction (LAWA-AK 2020). This

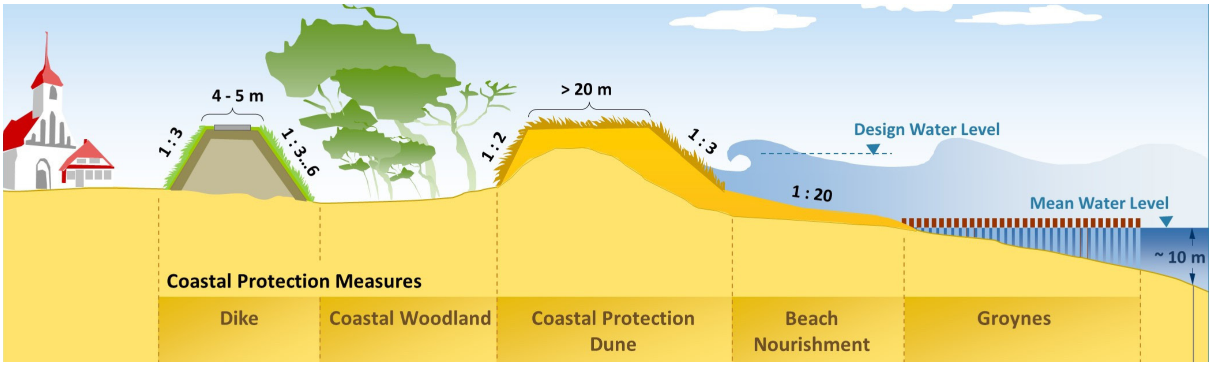

Fig. 4: Traditional and general coastal protection system along exterior lowland coastal areas in Mecklenburg-Western Pomerania (Graph: A. Klee, modified)

serves as a further basis for national coastal protection strategies. This definition was confirmed by the projections of the IPCC's Sixth Assessment Report for the SSP5-8.5 scenario (Fox-Kemper et al. 2021).

It is worth noting that the regional projections, similar to the global projections, show a concave trajectory, with sea-level rise expected to accelerate towards the end of the century (Fig. 5, Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2022a). Rising mean water levels and thus the precautionary measure result in a long-term increase of design water levels (in the case of very severe storm surges with a statistical return period of 200 years) for state coastal protection structures.

The past trend for a potential increase in magnitude and frequency of storm surges seems to be inconclusive for the southwestern Baltic Sea (The BACC II Author Team 2015). Based on our own preliminary analyses of long-term time series of the evolution of mean and extreme water levels, there has been no apparent increase in relative storm surge water levels over the past few decades. Going forward, there will be regular reviews of the evolution of extreme water levels for relevant return periods (cf. Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2022b).

2.2 Development of hydro- and sediment dynamics

Studies on the evolution of sea-state conditions during the course of the 21st century seem to be ambiguous. An increase in wind speeds and thus of significant wave heights as well as mean wave periods is indicated by Dreier et al. (2013, 2021). Based on a regional RCP5-8.5 scenario an increase of up to 4 % for significant wave heights until 2100 (compared to 1971-2000) is projected. Slight changes in the dominant wave directions are also to be expected with a shift of +2° by 2100, but a fundamental change in wind and sea state patterns in the area of the southwestern Baltic Sea cannot be assumed. Dreier et al. (2015) furthermore pointed out, that an increase of up to 0.5 m for extreme wave heights in the southwestern Baltic Sea is possible by the end of the 21st century due to a change of wind speeds. However, no clear trend could be detected. The results of Bonaduce et al. (2019) considering the RCP5-8.5 scenario suggest a slight decrease of average wind speeds and significant wave heights towards the end of the 21st century (compared to the period 1980-2005) for the southwestern Baltic Sea. On the basis of the IPCC A1B and B1 scenarios Groll et al. (2017) determined a slight increase (<5 %) of median significant wave heights towards the end of the century (2070-2100) compared to the period 1961-1990, while the results for maximum wave heights were indecisive. Nevertheless, effects on the prevailing natural sediment transport regimes are generally to be expected in case of modified future average and extreme sea-state conditions with potentially accelerated morphodynamic development at least along the exterior coast of Mecklenburg-Western Pomerania. Further research is certainly needed on this last aspect.

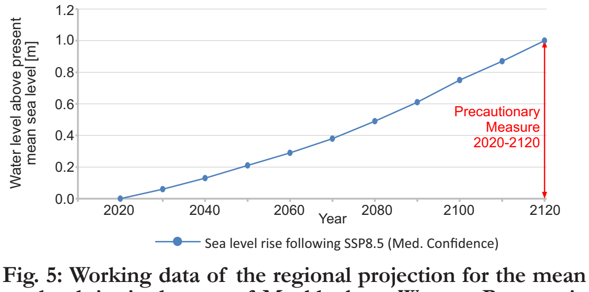

Fig. 5: Working data of the regional projection for the mean sea level rise in the area of Mecklenburg-Western Pomerania following the SSP5-8.5 scenario of the 6th Assessment Report by the IPCC and in accordance to the precautionary measure (Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt Mecklenburg-Vorpommern 2022a)

2.3 Large-scale evolution of the coastal morphology

Closely linked to the issues raised in sections 2.1 and 2.2 is the future large-scale evolution of the exterior coast of Mecklenburg-Western Pomerania. For example, at a mean water level rise of 0.5 m (corresponds to an absolute level of approx. 0.6 m above the vertical datum Normalhöhennull NHN, Fig. 5) approximately 550 km² are at risk of being permanently flooded, while in the case of a mean water level rise by 1.0 m (approx. 1.1 m above NHN) this figure increases to 850 km² (Fig. 6). These values are derived from in-house evaluations using high-resolution digital terrain models.

Furthermore, in the long term, the projected rise in water levels is expected to result in far-reaching flooding of river lowlands. Above all, those of the River Warnow, the River Recknitz and the River Peene are worth mentioning in this context (Fig. 6).

Rising mean water levels also bear a general risk of island formation or further fragmentation of existing islands due to rising mean water levels. This is especially true in areas such as Zingst,

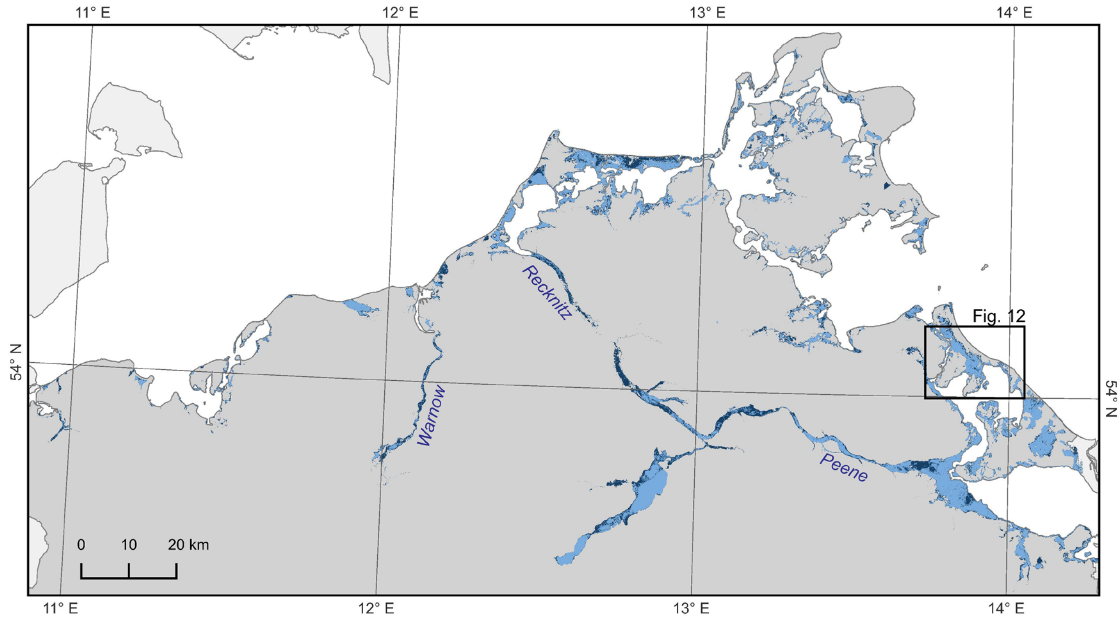

Fig. 6: Potentially permanently flooded areas in Mecklenburg-Western Pomerania in case of a mean sea level rise from 0.1 m above NHN (approx. mean water level 2010-2020) to 0.6 m above NHN (expected by ca. 2085, light blue) and to 1.1 m above NHN (expected by ca. 2120, dark blue). The base map is a digital terrain model with a spatial resolution of 1.0 m² (Base of map: HydroGis GmbH)**.**

Mönchgut (Rügen), but also in the interior coastal areas of Usedom (Fig. 1). With probably accelerated coastal morphodynamics, however, such a development is not necessarily guaranteed, since a genesis of new spits and tombolos between formerly separated land is conceivable as well. More detailed estimates, which also include small-scale morphodynamic processes and possible silting-up processes in the area of interior coasts are not yet available.

3 Requirements, options and uncertainties for adaption

3.1 Basic assumptions regarding the possible adaptation of technical measures

The adaptation of coastal protection systems to increasing requirements can be met in principle with the assumption that these structures can be extended in their dimensions to increase their functional capacity. Thus, generally, dikes can be raised and widened, while seawalls can also be raised to counter an increasing risk of flooding. Dunes can also certainly gain in their capacity to avert storm surges through shorter nourishment intervals and supplementary rigid structures such as internal geotextile container structures. Coastal sections particularly at risk of retreat and preservable cliffs can, in principle, be additionally secured by means of breakwaters or revetments.

It should be emphasized, however, that the possibilities of enlarging technical flood defences are not infinite. Therefore, especially in the face of profound environmental changes caused by anthropogenic climate change, it is necessary to understand adaptation not only as technical, structural adaptation, but also to take into account a possible need for a fundamental strategic and conceptual reorientation of state coastal protection.

3.2 Protection of coastal lowlands

Along lowland coastal areas sand dunes are the dominant coastal protection instrument in Mecklenburg-Western Pomerania. Although they are often accompanied by other installations, the focus here shall be set on their need and ability for adaption towards future requirements.

It certainly can be assumed that rising mean sea levels and thus rising design water levels for coastal defences will translate into a significantly larger required cubature of dunes (Newe 2016). Basic strategies for the adaption towards sea level rise are known for more than 30 years. The comprise, among others, approaches of accepting a lower degree of safety ('do nothing'), preserving the present routes of coastal protection structures ('hold the line'), even extending them further seawards (move seawards') or a managed realignment ('retreat') (Dronkers et al. 1990, Fröhle 2012). So far, it is not generally decided which strategy is most efficient, cost-effective and resource-conserving to respond to rising water levels in the federal state.

If the existing routes of coastal protection dunes are to be maintained, it is foreseeable that not only an increase in the dune itself is required but, analogously, an increase in the level of the beach and surf zone to levels of the closure depth (the seaward boundary of significant morphodynamics and sediment transport by waves) is also necessary (Fig. 7a). In addition to the foreseeable immense amounts of sand required for this adaptation measure, there is also the risk of bastion formation should neighbouring areas recede in an uncontrolled way. As a result, a morphodynamic load would be placed on the section to be maintained and a correspondingly higher maintenance expenditure would be expected.

As a counterproposal to this, a landward displacement of the dune body can be considered (Fig. 7b). This would only require a raise of the dune crest, whereas an increase of beach and surf zone could be compensated by the landward displacement. This strategy would correspond to a retreat of coastal protection structures and thus result in the possibly necessary abandonment of previously used areas. Therefore, in order to enable such a retreat, preferentially, a suitable spatial provision of land would have to be implemented (cf. section 4).

It is, however, not easy to quantify the extent of the required relocation. The first prominent, purely geometric approach to the response of dune-backed lowland coasts to changing sea levels was undertaken by Bruun (1962). On the one hand it has since been further developed (Rosati et al. 2013, Dean & Houston 2016), on the other hand it has always been subject to general criticism (e.g. Cooper & Orrin 2004). Despite a number of relevant approaches, no generally accepted way for a quantitative assessment has emerged to date.

Since the early 1990s approx. 21 million m^3 of marine sand were spent for repeated beach and dune nourishments along the exterior coast of the federal state. While the need for these sands is certainly not decreasing, it is of fundamental importance for the long-term maintenance of coastal dunes that the sand for nourishments is considered a resource worth preserving (Mangor et al. 2017). The marine reserves and storage areas identified in the federal state development programme (Ministerium für Wirtschaft, Infrastruktur, Tourismus und Arbeit Mecklenburg-Vorpommern 2016) for coastal protection contain explored (with regards to quality and quantity) approx. 130 million m^3 of sand. These ensure a supply of coastal dunes for the 21st century even for increased requirements. However, it is necessary to assess the order of magnitude of the amounts of sand necessary in the intermediate and far future (see section 3.3) as a base for conceptual and strategic

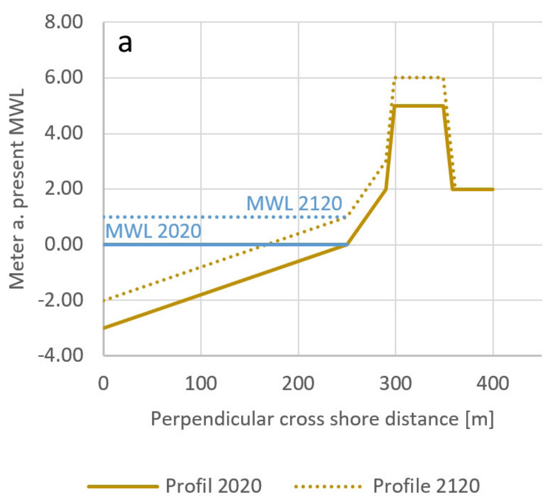

Fig. 7a: Idealized sketch of a possible long-term adaption of surf zone-to-dune cross sections corresponding to a "move seaward/hold-the-line" strategy with regard to a rise of mean water level (MWL)

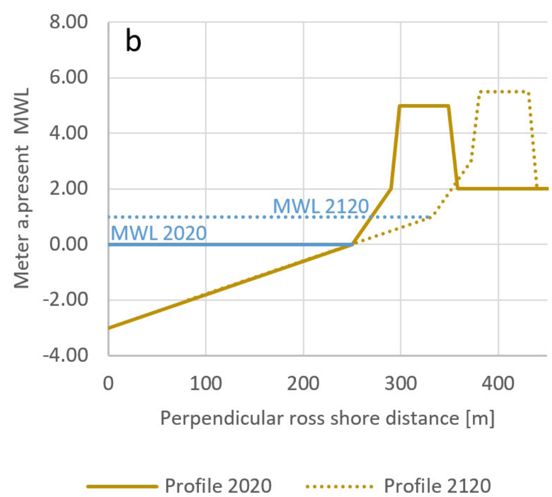

Fig. 7b: Idealized sketch of a possible-long term adaption for coastal protection dunes corresponding to a "retreat" strategy with regard to a rise of mean water level (MWL)

planning. In order to preserve existing marine sand resources and to reduce costs, it is sensible to aim to minimise sand loss in the area of coastal protection dunes and to extend nourishment intervals. The establishment of sand circulation systems can help to achieve these goals. With clear prevailing net sediment transport directions, nourished sands can be trapped (possibly with the aid of additional structures) after their longshore transport along protected stretches of coastline and returned in parts to the point of origin to become part of the sediment dynamics again. Such an approach can be pursued both at the local level (Fig. 8a), i.e., within quasi-closed embayments, and at a regional level (Fig. 8b) along larger coastal sections without significant bays and headlands.

Of course, circulation systems can never be fully closed. Thus, a loss of sand by cross-shore transport and suspension has to be taken into account. The establishment of a cycle management, therefore, is not a solution to permanently make an additional supply of external sand unnecessary. Nevertheless, it has the potential to reduce the need for sand from exterior sources significantly and represents a promising approach that is already being applied at a municipal level.

3.3 Evolution of retreat rates along cliffed coastal sections

In the course of climate change-induced sea-level rise it can be expected that historical rates of coastal retreat are not easily transferable to the future. In addition to known uncertainties arising from geodetic inaccuracies of shorelines from historical maps and aerial images, the database for the long-term past development of cliffs is insufficient. However, it should be noted that even if a sound database was available in this regard, a simple linear projection of recession rates into the future is considered problematic. Rather, an acceleration of receding rates is to be expected, especially along exposed cliffed sections. Apart from approaches to extend the above-mentioned Bruun rule to cliffed coasts under full consideration of the sediment budget (Dean 1991), there has been a number of more elaborate approaches over the past decades that deal with the response of steep cliffs to changing sea levels (e.g. Sunamura 1992, Meadowcroft et al. 1999, Trenhaile 2000). In this context, however, the approach of Walkden & Hall (2005, 2011) which focuses on the response of unconsolidated cliffs or those with comparatively low morphological resistance (a basic assumption that applies very well to the marl- and sand-dominated cliffs of Mecklenburg-Western Pomerania largely formed by glacial and inter-/postglacial deposits as e.g. till or basin sands) is worth mentioning. Here, a cliffed coast is represented by profiles, where feedback pathways and interaction between cliffs, beaches and shore platform under marine forcing is simulated.

The ability to accurately estimate the expected rate of cliff retreat is particularly important in order to be able to evaluate the long-term safety of existing buildings and of whole developed areas (Fig. 9, Fig. 10), but also the basic usability of cliff sections for future projects. Being able to adequately assess the long-term usefulness and maintainability of coastal defences along critical cliff sections is another aspect of this complex of issues.

Unprotected cliffs in particular are an important source of sand to be available for nearshore sediment transport and are therefore also highly relevant for the natural evolution and the management of adjacent low-lying coastal sections. A precise knowledge of the proportion of relevant grain-size fractions (especially

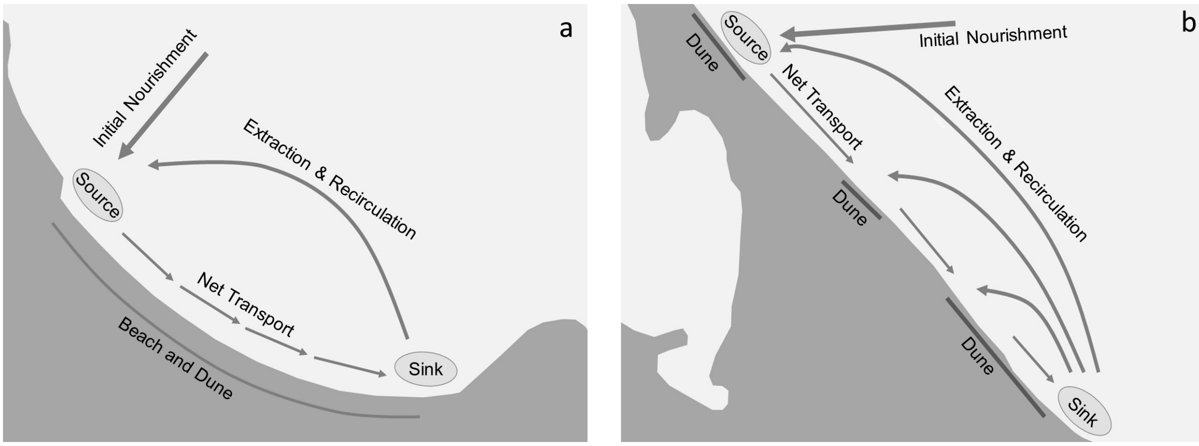

Fig 8: Schematic sketch of a possible establishment of a local (a) and regional (b) sand circulation system

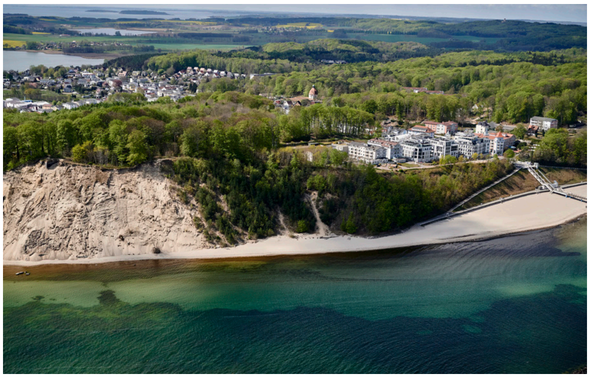

Fig. 9: Developed area atop a protected cliff section in Sellin (Rügen) (Photo: T. Häntzschel)

Fig. 10: Developed area atop a protected cliff section in Nienhagen (Photo: L. Tiepolt)

sand) as well as an accurate estimation of the rates of retreat are therefore important to be able to determine the contribution of partially and unprotected cliffs to the sand supply of coastal stretches. In this regard Kamphuis (1987), however, emphasizes, that the portion of sand in glacial till cliffs which is relevant for a natural sediment supply for beaches must not be estimated too high.

3.4 Future viability of coastal protection routes

Coastal protection routes often run close to the shoreline. In the face of long-term rising mean sea levels, the viability of national coastal defences can be called into question as most structures are generally not designed for sustained direct exposure to mean water levels. They are but designed only for a comparatively short period (hours-days) during episodic events with significantly raised water levels. This is particularly true for dikes and dunes which are separated from mean water levels by their foreshore.

The focus here shall be on the interior coastal areas, where a large number of dikes have been erected in close proximity to the shoreline (to protect agricultural land or populated areas, Fig. 11). With expected rising mean water levels and low elevations of the already narrow foreshore, there is a risk of permanently flooded areas spreading from the interior coastal waters to these dikes in the long term (Fig. 12). As earthen structures, they are undoubtedly not designed to avert rising mean water levels, so they cannot effectively protect their hinterland against long term flooding by rising sea levels.

Fig. 11: Dike "Neuendorf" near Netzelkow (Usedom) towards the north in immediate proximity to reedy wetland bank of the Achterwasser (left). There is no real elevated foreshore to temporarily compensate rising mean water levels (Photo: U. Floth, see Fig. 12 for location).

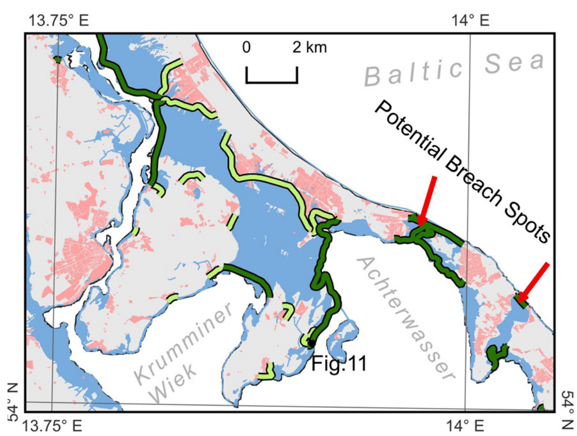

Fig. 12: Present dike routes (dark green) along the interior coast of Usedom and possible future inland substitutes (light green). Blue areas indicate the potentially permanently flooded area in case of a mean sea level rise to 0.6 m above NHN (expected by ca. 2085), reddish areas indicate populated areas (see Fig. 6 for overview). The base map is a digital terrain model with a spatial resolution of 1.0 m² (Base of map: HydroGis GmbH).

Rather, it is to be expected that the structural stability of dikes in the permanently flooded area will no longer be provided and thus their protective function in view of flood events will be eliminated to a considerable extent or even completely. For this reason, there are fundamental doubts about the viability of dike routes at a number of locations along the interior coastal waters.

Therefore, if dike routes are to be designed with rising water levels in mind, relocating routes from a future permanent flood zone to higher ground is an obvious and at some point inevitable measure (Fig. 12) if no other technical options are available. However, this requires the long-term abandonment of previously protected land and, possibly, a fundamental shift in coastal protection strategy away from a comprehensive area-protection approach towards local, site-specific measures.

Particularly serious are the consequences of rising water levels on coastal protection routes and their design in bottlenecks between the exterior and interior coasts, with (in some cases historically proven) increased risk of breach in the event of storm surges. This mainly affects areas on Fischland-Darss-Zingst and Usedom and thus primarily the more dissected coast of Western Pomerania. In these places, the lack of available space limits the potential for relocation of coastal protection systems to such an extent that suitable technical means to adapt to rising water levels must be readjusted. A general strategy or selection for new suitable technical instruments for this challenge is still lacking.

3.5 Potential use of flood barriers

Flood barriers such as the Thames Barrier in the UK, the Maeslantkering in the Netherlands or MOSE in Italy are designed to effectively protect large areas of the hinterland from marine flood events as a one-off measure (Linham & Nicholls 2010). The construction of the Greifswald flood barrier (completed in 2016) at the mouth of the River Ryck illustrates that the use of barriers does not necessarily always have to be of such magnitude as in the international examples (Fig. 13). This coastal protection structure, in conjunction with other installations, protects the Hanseatic town of Greifswald as well as other places within the lower reaches of the River Ryck from marine flooding. This location, as well as the second existing barrier in Mecklenburg-Western Pomerania at the Convent plain, however, is by no means the only plausible location in Mecklenburg-Western Pomerania for such a structure (Fig. 14).

Places which form a bottleneck for flood routes to large potentially threatened hinterland areas and/or areas with high damage potential exist in the federal state in significant numbers. Plausible locations for the construction of barriers would be the Meinigen strait of the Darss-Zingster Boddenkette, the mouth of the northern Peenestrom but also the access to densely populated areas such as the Bay of Wismar or the mouth of the Warnow River in Rostock-Warnemünde (Fig. 14). Flood barriers could help to prevent the necessity for a large number of coastal defences in their hinterlands or even make them redundant. They could also resolve potential

Fig. 13: The Greifswald flood barrier after its completion in 2016 (Photo: L. Tiepolt)

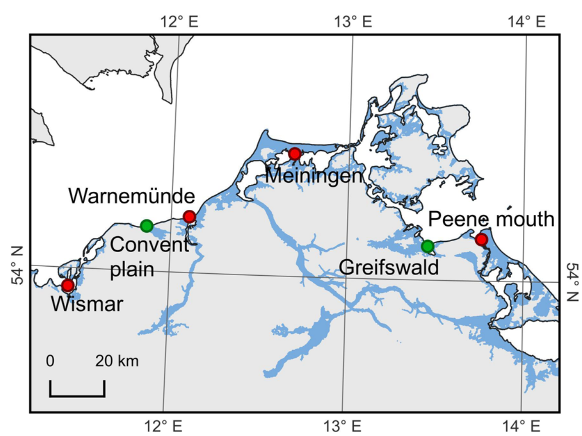

Fig. 14: Existing positions (green dots) of flood barriers and plausible positions (red dots) for a future realization. The light blue areas indicate the potentially flooded area in case of a very severe storm surge (in this case 2.0 m above NHN). The base map is a digital terrain model with a spatial resolution of 1.0 m² (Base of map: HydroGis GmbH).

conflicts between the interests of coastal protection and other uses (see section 4).

On the other hand, barriers are to be regarded as structures, which, in addition to their permanent need for operation, are accompanied by other potential and real limitations. For example, it is generally assumed that they have limited adaptability to rising water levels. This may result in shortened periods of use, in some cases, by the introduction of new design water levels. In addition, flanking structures (e.g. dikes, seawalls) may still be required to ensure sufficient protection against flood events. It also needs to be considered that a significantly higher number of lives and property values are tied to the functionality of a single building. Finally, it should be stressed that the use of barriers can only be considered to be sensible if there is a healthy balance between the benefits of protecting lives and property and the resulting costs, and there is an equal advantage over conventional protective measures. Potential conflicts with traffic, environmental protection concerns, landscape, water balance and other fields of interest have to be taken into consideration during a planning process. In conclusion, however, it should be noted that there are currently no concrete plans to further implement such a project in Mecklenburg-Western Pomerania.

4 Challenges in the adaptation process

Even though matters of coastal protection and their manifestation as coastal structures are prominent along the coast of Mecklenburg-Western Pomerania, they are not the only field of interest within this area. Worth mentioning are other public protection obligations (e.g. nature conservation) but also regional and local infrastructure (traffic, water supply and distribution, data infrastructure, energy supply, drainage) as well as the development of municipalities and housing. The enumeration can be extended towards the private and economic sector concerning agriculture, tourism, etc. Coastal protection concerns regularly intersect with one or several of these interests. Mostly, this is the case in terms of occupation of areas potentially subject to marine flooding and erosion (present or future), also concerning the expansion or redesign of coastal protection structures. The continued existence of coastal 'protection areas' of the GDR (German Democratic Republic) water law in the present water law of the federal state of Mecklenburg-Western Pomerania guarantees the priority of interests of coastal protection in 16 areas (which do not extend, however, to all current areas with coastal protection structures).

Facing the aforementioned challenges, the priority of state coastal protection is to follow a 'hold the line' strategy at the present scale as long as possible and tenable. The fact is, however, that this condition cannot be guaranteed and unconfined in the long term. The question how long this strategy can be pursued and when, where and if a paradigm shift towards a 'retreat' strategy has to be applied cannot be answered with the present state of knowledge. It is foreseeable, that competing and/or intersecting interests will potentially grow into more profound conflicts. In this context, the frequent competition between coastal protection and natural coastal dynamics has to be emphasized. Thus, in many cases coastal protection measures cannot provide indefinite safety but rather have to be regarded as a 'purchase of time' in terms of periods of use for existing protected property as well as future projects.

Therefore, it is even at a present stage of paramount importance to address present and future matters (cf. 1.2) and forcing terms (natural: e.g. preservation of coastal dynamics; technical: e.g. implementation of valid standards; or socio-economic: e.g. legal obligations) for coastal protection towards other interests. Apart from the technical measures described above, specifically, this means that these issues require mandatory implementation in planning processes at a regional and municipal level, however, with enough flexibility to be able to adapt towards an updated state of knowledge, future (natural and socio-economic) developments, etc. Suitable instruments to pursue this aim are e.g. an adequate provision of land and appropriate collateral clauses for the future realization of third-party projects in the coastal area. The fact, that these issues are not limited to terrestrial areas is e.g. illustrated by the increasing number of offshore lines (pipes and cables) in the area of the southwestern Baltic Sea and potential conflict with the provision of marine sand deposits for state coastal protection. For the present, however, these resulting conflicts are not of decisive importance for ensuring the objectives of state coastal protection.

5 Conclusion

The challenges for state coastal protection in the 21st century primarily result from the manifestations of climate change. The most prominent factor is the projected long-term rise of mean sea level, which is accompanied by an expected rise of extreme sea levels. However, future coastal morphological development, which, at the moment, can hardly be adequately estimated in detail, also comes with challenges for the responsible authorities in the adaptation process.

In view of the aforementioned challenges, more research is required towards the continued improvement of projections and design approaches for coastal protection structures that help to identify adaptation needs and select appropriate adaptation measures, pathways and strategies. A successful adaption towards the described challenges however can only happen in conjunction with other spatially relevant (i.e. socio-economic) interests. Primarily, the spatial provision of land to ensure any necessary retreat potential for coastal protection structures as well as consideration in development planning towards other prominent spatial use interests should be mentioned in this regard as essential aspects.

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Authors

Ulrich Floth
ulrich.floth@stalumm.mv-regierung.de
Dr. Marcus Siewert
marcus.siewert@stalumm.mv-regierung.de
Dr. Lars Tiepolt
lars.tiepolt@stalumm.mv-regierung.de
Staatliches Amt für Landwirtschaft und
Umwelt Mittleres Mecklenburg
Landesbehördenzentrum Rostock
Blücherstraße 1
18055 Rostock
Germany