

Wadden Sea Board

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At the 11th Wadden Sea Conference (Sylt, Germany 2010) it was *inter alia* decided to

Initiate a trilateral study on sustainable solutions to balance the expected sediment deficits on the basis of research questions specified by the CPSL. [Sylt Declaration §23]

In 2011 a trilateral research project, addressing the above questions, has started under the responsibility of coastal protection authorities in Denmark, the Netherlands and Germany.

In the attached document, prepared by some members of the TG-C and the CWSS an overview is given of the geomorphological background of the study, results of the first phase, as well as the contents of the next phase of the project.

Proposal

The meeting is invited to note the report and to discuss the option of presenting it in the form of a brochure at the Tønder Conference.

Trilateral knowledge paper: Sediment and sea level rise in the Wadden Sea

Summary

The Wadden Sea is highly dynamic ecosystem that has evolved as the result of a combination of sediment availability (local, North Sea, rivers and biogenic) and a regime of tides, wind, waves and storm surges under a moderately rising sea level. The Wadden Sea is structured into 39 adjacent tidal inlet systems (Figure 1) each of which with its characteristic morphologic elements (salt marshes, tidal flats, tidal gullies, barriers and ebb-tidal deltas; see Figure 3).

Tidal inlet systems (tidal basins) can be regarded as sand-sharing systems in which all elements are coupled and which are in or move towards a dynamic equilibrium with the hydrodynamic conditions. Changes in any part of a tidal inlet system will primarily be compensated by sediment transport to or from the other parts of the same system. When changes are temporary and limited, the old dynamic equilibrium will eventually be restored. If changes are more permanent or intense a new dynamic equilibrium will establish. Especially in this situation sediment may be imported from or exported to areas outside the sand-sharing systems. The reaction time for a new dynamic equilibrium to occur depends on the magnitude of the perturbation. For example, effects of large-scale interventions such as the closure of the Zuiderzee and the Lauwerszee are still observed today.

From large-scale sediment budget analyses for complete tidal inlet systems conducted throughout the Wadden Sea, some general conclusions can be drawn:

- Under the influence of sea-level rise (in the order of 1.5 mm/a) and man-induced coastal interventions in the past the Wadden Sea captures sediment. Hence, the Wadden Sea is an important long-term sediment sink of the coastal system. It is generally assumed that the import of sediment to the Wadden Sea causes erosion along the North Sea coasts.
- The current sedimentation rate in most of the Wadden Sea tidal inlet systems is higher than the observed sea-level rise.
- The majority of ebb-tidal deltas show an erosive trend over the last decades. The causes seem to vary regionally and are not known in detail.
- Possibly due to varying local sediment availability, there are differences in the developments of the Wadden Sea barrier islands. Some islands tend to migrate landward and/or in a down-drift direction, others are rather stable or even accreting. The morphological development of the islands is significantly influenced by artificial measures such as sand replenishments and hard constructions at the shorelines.
- Most tidal gullies, especially in the tidal inlets, seem to underlie a long-term erosive trend.
- Apart from local exceptions, tidal flat areas and salt marshes show accreting trends in exceedance of or balancing SLR. Sedimentation on most salt marshes is enhanced by management techniques.

The Wadden Sea seems robust and resilient with respect to morphological response to hydrological changes but accelerated sea level rise (SLR) may lead to a situation in which too little sediment is available to balance the higher sea level. Consequently, water depths may increase and eventually lead to a “drowning” of tidal flats and salt marshes. Because tidal basins have different geomorphological characteristics the SLR tipping point or threshold at which drowning will occur, will differ (see Figure 2). First results of modeling exercises indicate a complete disappearance of tidal flats under a long-term SLR in the order of 7 to 8 mm/a. The value of 8 mm/a was underpinned by geological investigations in the western Netherlands. One important parameter (apart from sediment availability) for the stability/resilience of tidal flat areas seems to be the size of the tidal inlet systems, i.e., the larger the system, the earlier the tipping-point is reached.

Although a wealth of data and knowledge is available, many questions still need attention. Examples of main research themes are:

- Exact critical rate of SLR (tipping-point):
What is the critical rate of SLR per basin and what factors influence this critical rate?
- Coastal nourishment and other forms of nourishment in the future.
The morphological, ecological and hydrological impact of coastal nourishments has to be determined in response to their design, dimensions and location.

Because the Wadden Sea is one coherent coastal ecosystem subject to the same basic geomorphological processes, cooperation on a trilateral level with regard to increasing our knowledge of the impacts of climate change provides high added value with respect to the use of data and knowledge, the use of human expertise, dissemination of results and the comparison of regional differences. Acknowledging this, Dutch, German and Danish coastal administrations have since 2011 cooperated in a trilateral project to establish possible future sediment budgets (trends) for tidal inlet systems by applying different hydrological scenarios and models to tidal basins in Denmark, Germany and the Netherlands. In 2014, it is planned to test the established models by simulation of the observed developments over the last decades. If the models are able to reproduce the past development in the selected basins, modeling of possible future morphologic developments will be carried out. First results may be expected by the end of 2014. In the following years, it is planned to substantiate these preliminary results by simulation of other tidal basins.

1. Introduction

The Wadden Sea stretches over a distance of 450 km from Den Helder in the Netherlands to the peninsula of Skallingen in Denmark. It is a coastal sediment sink that developed in the course of the Holocene transgression. This highly dynamic ecosystem is the result of a combination of sediment availability (local, North Sea, rivers and biogenic) and a hydrodynamic regime of tides, wind, waves and storm surges under a moderately rising sea level. As a result, the Wadden Sea ecosystem is structured into 39 adjacent tidal inlet systems (tidal basins; Figure 1).

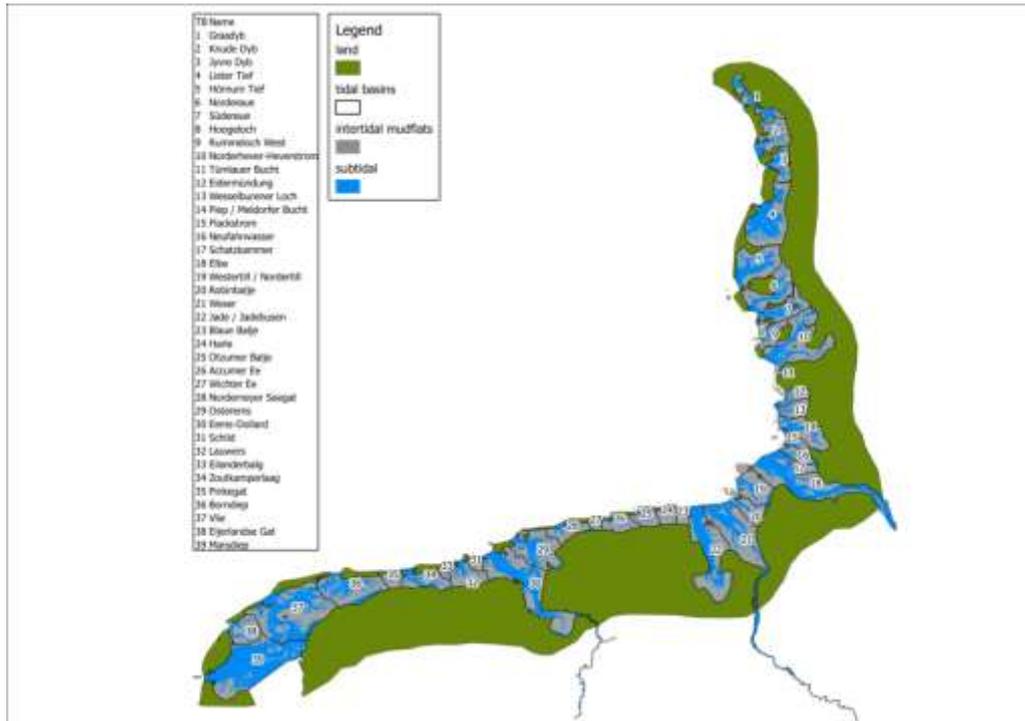


Figure 1. Wadden Sea tidal basins

Although the Wadden Sea seems robust and resilient with respect to morphological response to hydrological changes, it must be accounted for that accelerated sea level rise (SLR) may lead to a situation in which too little sediment is available to balance the higher sea level. Consequently, water depths may increase and eventually lead to a “drowning” of tidal flats and salt marshes. Because tidal basins have different geomorphological characteristics the SLR tipping point, or threshold at which drowning will occur, will differ (see Figure 2).

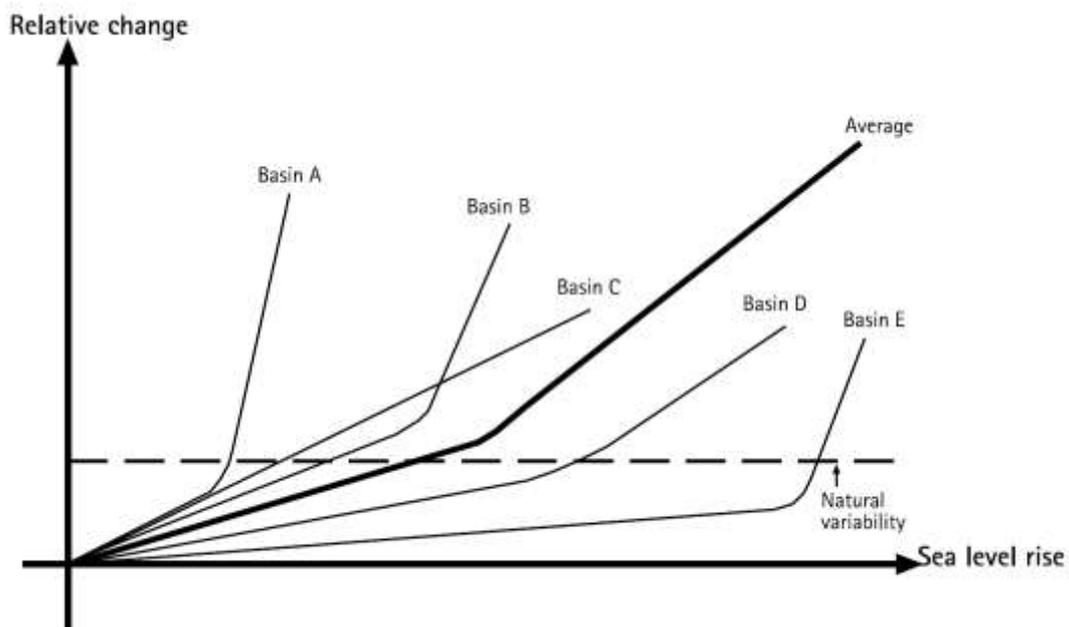


Figure 2. Response of various hypothetical tidal basins to sea level rise.

Exceeding the SLR-thresholds will have serious implications for ecological functions and resources of the Wadden Sea. Furthermore, the functionality of the Wadden Sea with respect to dissipating storm wave energy and, therewith, reducing the energy-impact on coastal flood defenses will deteriorate. Hence, profound knowledge about the morphological development and processes under different SLR-scenarios is indispensable for managing the impacts of sea level rise.

2. Rationale for a trilateral approach

Because the Wadden Sea is one coherent coastal ecosystem subject to the same basic geomorphological processes, cooperation on a trilateral level with regard to increasing our knowledge of the impacts of climate change provides high added value with respect to:

- Use of data and knowledge. A large number of national and regional institutions gather, store and analyze Wadden Sea data. Without cooperation and the appending exchange of information, it is impossible to achieve a complete overview of and access to these data and the generated knowledge.
- Use of human expertise. While gathering and analyzing Wadden Sea data, administration and research institutes produce and maintain skilled personnel. As with data and knowledge, trilateral cooperation secures an optimal use of available human expertise.
- Dissemination of results. Products that are established in trilateral cooperation will automatically be disseminated in a trilateral context, thereby optimizing its degree of attention in the Wadden Sea region as well as its cost-benefit ratio (avoiding double work).
- Consideration of regional variability. Due to varying geomorphologic and physiographic characteristics, both the challenges of climate change and optimal adaptation may differ in the 39 tidal inlet systems. For example, a northward shift in storm wind direction may lead to higher storm surges in the Netherlands and Lower-Saxony, but to lower storm water levels in Denmark and Schleswig-Holstein. Trilateral cooperation secures optimal consideration of this variance.

Acknowledging this, Dutch, German and Danish coastal administrations have since 2011 cooperated in a trilateral project to establish possible future sediment budgets (trends) for tidal inlet systems by applying different hydrological scenarios and models. The applied morphodynamic models are the semi-empirical¹ model ASMITA and the process-based² models DELFT-3D and GETM; all are freely available. First step of the project was the establishment of a common knowledge base with respect to the morphodynamics of the Wadden Sea. On the basis of a description of available empirical and modeling studies, knowledge deficits and research questions

¹ These models make explicit use of empirical relations to define the morphological equilibrium. An important assumption is that the morphological system after a disturbance (through natural evolution or by human interference) always tends to develop into a state satisfying the empirical equilibrium relations.

² Such models aim at the best possible description of the relevant processes by numerical solution of mathematical equations.

were formulated. Further, a set of common hydrological scenarios for the model studies was defined.

3. Common hydrological scenarios

In order to achieve comparable results, a common set of hydrological scenarios was defined during a trilateral workshop as basis for the modeling studies. The scenarios are in the table below. It was agreed that each partner is free to define complementary (sets of) scenarios (e.g., changes in wind direction).

	1990 – 2050*			2050 – 2100*		
	MSLR	MLWR	MHWR	MSLR	MLWR	MHWR
Moderate SLR	+0.15	+0.125	+0.175	+0.35	+0.30	+0.40
High SLR	+0.35	+0.325	+0.375	+0.85	+0.80	+0.90

*: linear SLR during the two periods

MSLR = mean sea level rise; MLWR = mean tidal low water rise; MHWR = mean tidal high water rise

These two SLR-scenarios are combined with two wind/wave scenarios:

1. No change in storm wind/waves
2. 5% linear increase in storm winds, meaning 10% linear increase in storm waves (2010 – 2100)

4. Common knowledge base and research needs

The Wadden Sea with its 39 sandy tidal inlet systems (tidal basins) constitutes one of the world's best investigated ecosystems. Numerous studies deal with the bio-hydro-morphological interrelationship and the resulting morphodynamics. Further research focusses on the establishment of the morphological development through sediment budget analyses. Here, a short synthesis of common (trilateral) findings is presented based on state-of-the-art reports from the partners and a recent publication (Wang, *et al.*, 2012³). Research questions are formulated at the end of the chapter.

³ Wang Z.B., P. Hoekstra, H. Burchard, H. Ridderinkhof, H.E. De Swart and M.J.F. Stive (2012). Morphodynamics of the Wadden Sea and its barrier island system. *Ocean & Coastal Management*, Vol. 68, pp. 39–57, Special Issue on the Wadden Sea Region.

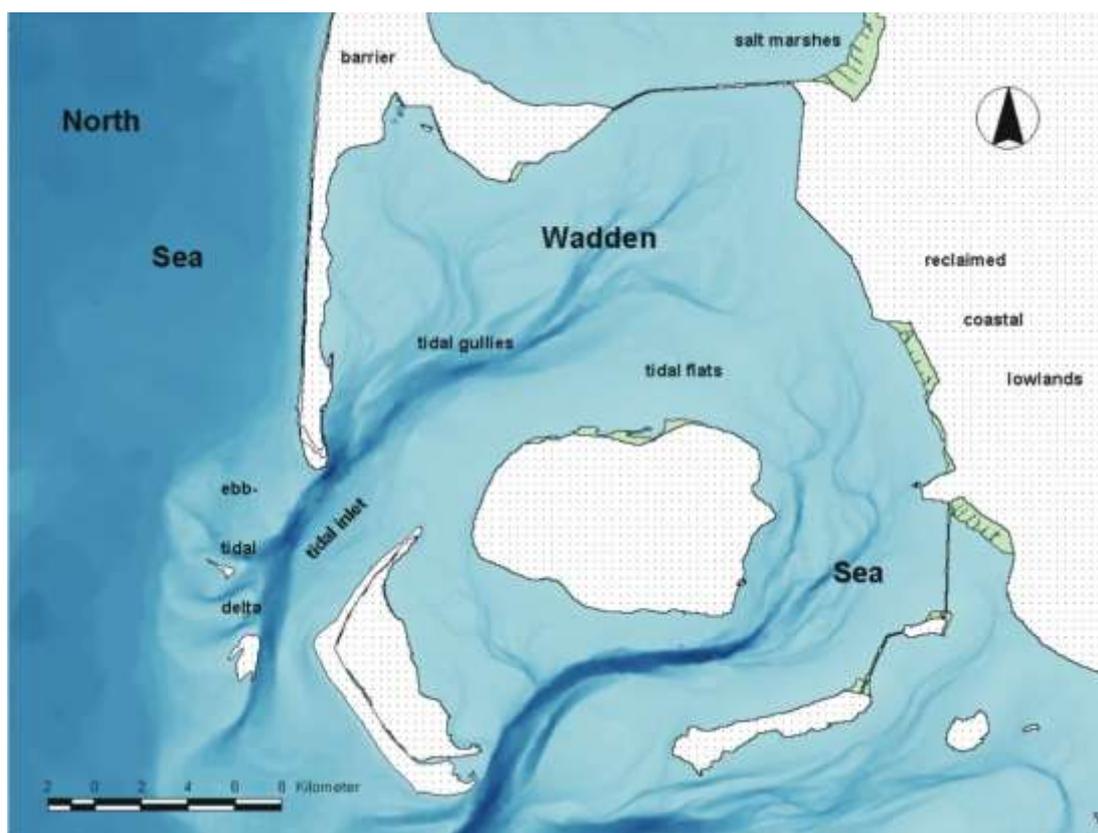


Figure 3. Tidal basin with typical morphological elements

Each tidal inlet system with its morphologic elements (salt marshes, tidal flats, tidal gullies, barriers and ebb-tidal deltas; see Figure 3) can be viewed upon as a sand-sharing system. All elements of the system are coupled and can be in, or strive towards, a dynamic equilibrium with the hydrodynamic conditions. Changes in any part of a tidal inlet system will primarily be compensated by sediment transport to or from the other parts of the same system. When changes are temporary and limited, the old dynamic equilibrium will eventually be restored. For example, a moderate increase in sea level rise induces a stronger accumulation on tidal flats and salt marshes as a result of longer tidal inundation (i.e., the sediment having more time to settle). As a result, the elevation of the flats and salt marshes increases and the time of tidal inundation decreases again until the old dynamic equilibrium is restored. An indication for this is that the morphological state of the system correlates well to the hydrodynamic conditions. This is exemplarily illustrated by the following relations:

- the area of inter-tidal flats in a tidal basin relates to the size of the basin,
- the total channel volume and the volume of the ebb-tidal delta both correlate to the tidal prism of the basin, and
- the average level of tidal flats measured relative to low water relates to the mean tidal range.

If changes are more permanent or intense a new dynamic equilibrium will establish (e.g. reduction in the cross section of tidal channels caused by a permanent

reduction in tidal prism⁴ due to land reclamation). Especially in this situation sediment may be imported from or exported to areas outside the sand-sharing systems. The reaction time for a new dynamic equilibrium to occur depends on the magnitude of the perturbation. For example, effects of large-scale interventions such as the closure of the Zuiderzee and the Lauwerszee are still observed.

From large-scale sediment budget analyses for complete tidal inlet systems conducted throughout the Wadden Sea, some general conclusions can be drawn:

- Under the influence of secular sea-level rise (in the order of 1.5 mm/a) and man-induced coastal interventions in the past the Wadden Sea captures sediment. Hence, the Wadden Sea is an important long-term sediment sink of the coastal system. It is generally assumed that the import of sediment to the Wadden Sea causes erosion along the North Sea coasts.
- The current sedimentation rate in most of the Wadden Sea tidal inlet systems is higher than the observed sea-level rise.
- The various tidal inlet systems cannot be considered as separate systems with fixed boundaries. Transports occur across the natural watersheds and, subsequently, the watersheds tend to migrate in time.

Sediment budget analyses covering morphologic elements within tidal inlet systems allow for the following general conclusions:

- The majority of ebb-tidal deltas show an erosive trend over the last decades. The causes seem to vary regionally and are not known in detail.
- Possibly due to varying local sediment availability, observed barrier development is heterogeneous. Some tend to migrate landward and/or in a down-drift direction, others are rather stable or even accreting. Morphologic development on the barriers is significantly influenced by artificial measures such as sand replenishments and hard constructions at the shorelines.
- Most tidal gullies, especially in the tidal inlets, seem to underlie a long-term erosive trend, possibly due to increasing tidal prisms.
- Apart from local exceptions, tidal flat areas and salt marshes show accreting trends in exceedance of or balancing SLR. Sedimentation on most salt marshes is enhanced by management techniques.

In synthesis, long-term sediment redistribution from the ebb-tidal deltas and tidal gullies to the tidal flats and salt marshes seem to prevail. This redistribution pattern may be the result of moderate SLR combined with an increase in tidal range. In result, the gradients in the tidal inlet systems increase.

The former trilateral working group on coastal protection and sea-level rise – CPSL (now TG Climate) estimated a mean tipping-point in the order of 5 mm/a. It was assumed that higher rates of SLR would, in the long-term, lead to significantly diminishing tidal flat areas. First results of modeling exercises indicate a complete disappearance of tidal flats under a long-term SLR in the order of 7 to 8 mm/a. The value of 8 mm/a was underpinned by geological investigations in the western Netherlands. One important parameter (apart from sediment availability) for the

⁴ Tidal prism is the volume of water in a tidal inlet system between mean high tide and mean low tide.

stability/resilience of tidal flat areas seems to be the extension of the tidal inlet systems, i.e., the larger the system, the lower the tipping-point.

Although a wealth of data and knowledge is available, many questions still need attention. Formulated main research themes are:

- Exact critical rate of SLR (tipping-point). The present sedimentation rate in the Wadden Sea is, overall, larger than the rate of SLR. However, if SLR accelerates it can reach a critical threshold value. Important questions are:
 - What is the critical rate of SLR per basin?
 - What factors influence this critical rate?
- Character and effect of mitigation. It is insufficiently known what measures can be effective in controlling undesired developments such as local drowning of shoals and tidal flats in response to accelerated SLR.
- Coastal nourishment and other forms of nourishment in the future. The morphological, ecological and hydrological impact of coastal nourishments has to be determined in response to their design, dimensions and location.
- Morphological significance of changes in wind (strength and direction). The tidal process-response mechanism is obscured by wave and storm surge currents, e.g., stronger storm waves induce erosion on tidal flats. Further, a change in wind (and wave) direction may alter alongshore and onshore sediment transport.
- Sediment budget per sediment fraction. Until now, sediment budget studies only determine the total amounts of sedimentation and erosion. Little is known about which sediment fractions have caused the changes. In fact a budget is needed per sediment fraction and at least a distinction is required between mud and sand.
- Transport field. Purely based on the sedimentation and erosion rates in the tidal basins it is very hard to determine the net sediment transports through the various inlets, between the basins and along the North Sea coast.
- Uncertainties in the results of the sediment budget studies. Based on the bathymetric data, sedimentation and erosion volumes are determined for various areas. However, this information is subjected to errors and uncertainties, e.g., in collecting, preparing and evaluation of data. Future research has to address these errors and uncertainties.

5. Monitoring

It is clear that improvement of our knowledge about the morphological development and processes under SLR and other climate change effects such as wind velocities is strongly dependent on the collection of monitoring data. Data concerning the topography, hydrodynamics, salt marsh and dune development and other relevant field parameters including information on sand nourishment and sediment dumping in the Wadden Sea area, as well as sediment extraction sites and, if relevant, changes in spatial extent of the backbarrier basins have to be collected, processed and made available by the participating countries. Cycles of monitoring and input of fresh data into the modeling activities are expected to support the adaptive climate change management that the countries need to develop. An important step is to create a

data-base in the public domain, allowing research groups to join the modeling studies.

6. Next steps

As stated in the introduction and described above, a “common knowledge base morphodynamics Wadden Sea” and a “set of hydrological scenarios” has been established as a basis for the modeling studies.

The work presently concentrates on building models (configuration, calibration) for the first set of tidal inlet systems to be investigated. In Schleswig-Holstein, the two tidal inlet systems: “Lister Tief” and “Meldorf Bight” are investigated. The cross-border Danish-German “Lister Tief” tidal inlet will be investigated together with the Danish partner. In the Netherlands the “Borndiep” and “Marsdiep” will be investigated.

In 2014, it is planned to test the established models by simulation of the observed hydro-morphological development over the last decades. If the models are able to reproduce the past development in the selected basins, first modeling exercises looking at possible future morphologic developments for defined hydrological scenarios will be conducted. Hence, by the end of 2014, first results may be expected. In the following years, it is planned to substantiate these preliminary results by simulation of other tidal basins.

With the trilateral work described above as a solid basis, initiatives for proposals for EU-projects are highly welcomed and will certainly contribute to future understanding of the hydro-morphological development of the Wadden Sea area.