Assess adapted sediment management in the Elbe through use of new numerical model

June 2022

''This study was supported as part of the IMMERSE project- Implementing Measures for Sustainable Estuaries, an Interreg project supported by the North Sea Programme of the European Regional Development Fund of the European Union”

Assess adapted sediment management in the Elbe through use of new numerical model

Department: Hydraulic Engineering in Coastal Areas

Prepared by: M.Sc. V. Ortiz
Dipl. -Ing. H. Rahlf

Hamburg, June 2022

Bundesanstalt für Wasserbau

Postfach 21 02 53 · 76152 Karlsruhe
Tel.: (0721) 97 26 – 0

Wedeler Landstraße 157 · 22559 Hamburg
Tel.: (0 40) 8 19 08 – 0

Abstract

In this study, two aspects relevant for the sustainable sediment management in the Elbe estuary are addressed: adaptive sediment management and largescale river engineering measures that positively influence the tidal dynamics.
The estuarine characteristics of the tidal Elbe and historical interventions in the estuary are introduced as well as natural and man-made estuary pressures that challenge at present-day the sediment management. Particularly, the pressures tidal amplification and intensification of tidal pumping are regarded as they contribute to increase the transport of fine sediments upstream.

The concept of adaptive management is reviewed in view of relevant environmental factors in the Elbe estuary that affect sediment management actions as well as the development of measures and solutions. Potential river engineering measures that positive influence the tidal dynamics are discussed, in particular those that create additional tidal volume in the estuary. A largescale measure planned to counteract tidal pumping by reconnecting additional tidal volume in the tidal Elbe is evaluated, and the hydrodynamic modelling system UnTRIM-Sedimorph employed for the assessment is briefly described. The evaluated measure of reconnecting the cut-off anabranch Dove Elbe into the Elbe estuary was developed within the IMMERSE-project in BBS Greuner-Pönicke et al. (2020) and BAW (2021) by integrating social and technical constrains in the measure design. Different from BAW (2021), a new module in the modelling system is employed in the assessment presented here to simulate in more detail the sluice gate operation at the reconnection.

The effect of the anabranch reconnection on reducing tidal amplification, tidal asymmetry and suspended particle concentration are shown. The results depicted that the measure effectiveness reducing the upstream sediment transport was local and, considering the whole estuary, low. The measure effectiveness was constrained mainly by the limitation on the high water level within the Dove Elbe, as shown by BAW (2021), and to a minor degree also by the narrowed cross-section in the weir and riverbed geometry downstream the weir. That showed that the restriction to lower the potential measure impacts of higher water levels for the locals played a crucial role in the measure design and effectiveness.

That case of study evidenced also that one measure alone cannot bring the tidal Elbe back into balance as the current hydromorphological condition of the Elbe is the result of 150 years of hydraulic engineering measures, port constructions, fairway adjustments and coastal protection. The combination of several measures that create additional flood space at different locations in the estuary could have in total a major effect reducing the tidal range and the net transport of sediments upstream. Also, a more adaptive management on the practices for maintenance dredging and relocation is necessary to improve not only the dynamics and sedimentation patters in the estuary but also the sustainability of the use and management of the estuary ecosystem services.

Content

List of Figures

1 Introduction

The Elbe estuary comprised the tidal influenced low reach of the river Elbe. The entire trajectory of the Elbe extends 1094 km from its source in the Giant mountains in the Czech Republic, 1.386 m above the sea, being the fourth largest river in Middle Europe (see Figure 1). The drainage basin comprehends 148.268 km² (Boehlich and Strotmann 2008). Along its large trajectory to the North Sea, the Elbe collects sediments, nutrients and pollutants that determine the quality of the estuarine water and sediments.

The Elbe estuary is a valuable natural area, protected by European environmental laws, which has a significant relevance for the economic development of the region: it is the artery of the Metropolitan Region of Hamburg with Germany's largest seaport and the most important shipping route for international maritime traffic in Germany. The shore areas of the estuary are densely populated and intensively used by smaller ports, industry, agriculture, power stations, fishery as well as for recreation and tourism.

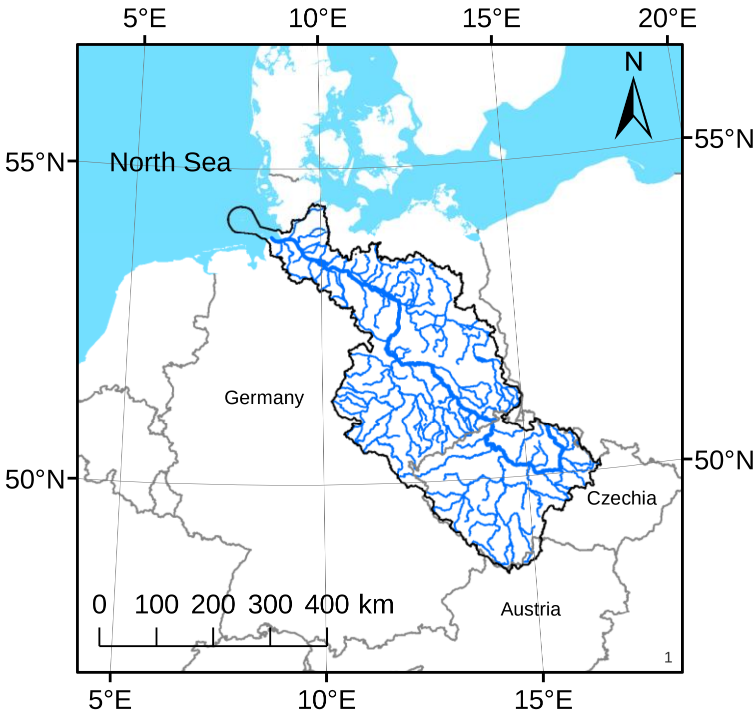

Figure 1. Elbe river catchment

To further the economic development in line with the environmental policy in the tidal Elbe, authorities and managers must guarantee both: safe water depths for navigation and sea port access, and a positive environmental performance of the estuary system. An adaptive, more sustainable management that considers the tidal Elbe system as a whole is an approach to address these requirements as discussed in HPA and WSV (2008), Entelmann et al. (2013), Winkel (2020) among others, which will be followed up in this report.

Subsequently, the estuarine characteristics of the tidal Elbe and the historical management activities are briefly addressed. Following, natural and management pressures that recently challenge the sediment management in the estuary are introduced, as well as the framework for the development of measures according to the present-day concept of sediment management. In chapter two, potential measures and concepts to advance in developing the estuary sustainably are reviewed. In chapter three, the practical assessment of estuary measures through advanced numerical methods is addressed, highlighting a case of study in the Elbe estuary about the reconnection of a cut-off area into the tidal Elbe.

1.1 Driving forces in the Elbe estuary

Figure 2. Mouth of the Elbe estuary (Satellite image from 2017, source: EOMAP, provided by the BAW).

The estuarine dynamics at the tidal Elbe are primary dominated by the semi-diurnal tide that predominates in the North Sea and propagates along the estuary. Tidal currents are the dominant driving force that shapes the geomorphology of the estuary. In addition, waves and wind-forced currents might induce now and again large transport of sediments particularly in the mouth of the estuary. At the mouth, the averaged tidal range is approx. 2.9 m (at Cuxhaven, see Figure 3), upstream into the upper estuary the tide wave reflects and amplifies, so that the tidal range arises to 3.87 m at St. Pauli in Hamburg (HPA 2022).

The tidal limit landwards is determined by a weir nearby the city of Geesthacht (see Figure 3). The weir separates the lower reach influenced by the tide from the fresh water inflow, as long as no storm-tide conditions prevail. Seawards from the weir within Hamburg, the tidal Elbe branches out into the Northern and Southern Elbe. Western Hamburg, both sidearms join again and form from here until the mouth, one main navigation channel surrounded by several islands, side channels as well as sand bars visible by low tide. The shape of this formations is in many cases the result of river training measures carried out in the past to improve the conditions in the fairway. By the transition to the North Sea, a major part of the funnel shaped mouth falls dry during low tide (see Figure 2), this area makes up part of the wadden sea; it is also a nature reserve and one of the most morphologically active regions in the German Bight.

The wide entrance of the funnel-shaped mouth contains extensive tidal flats and sand banks that significantly damps the wave and tidal energy that enters the estuary landwards. Morphological changes there, caused for instances by meandering tidal channels, can significantly affect the estuarine dynamics and impact tidal dissipation. In particular since 2008, a partial opening of a secondary tidal channel called Medemrinne increased the hydraulic capacity of the tidal inlet and the incoming tidal energy into the estuary (see chapter 1.3)
Besides this natural morphological development, variations in deposition and erosion patterns are also strongly influenced by a training wall of approx. 10 km in Cuxhaven, named Kugelbake (between Elbe-km 720 -730, see Figure 3). Its construction began in the 1970s to stabilize the former multichannel-system in the mouth and secured the main navigation channel.
Until the Cuxhaven-Kugelbake, the length of the tidal Elbe is 141.8 km starting from its tidal limit at the weir (IKSE 2005). According to Boehlich und Strotmann (2008), the seawards limit of the estuary is defined in the South by the tidal flats of the Scharhörn-riff and in the North by a lateral separation formed by drained sandbanks at low tide close to the great beacons A und Z (approx. 10 km seawards from Scharhörn).

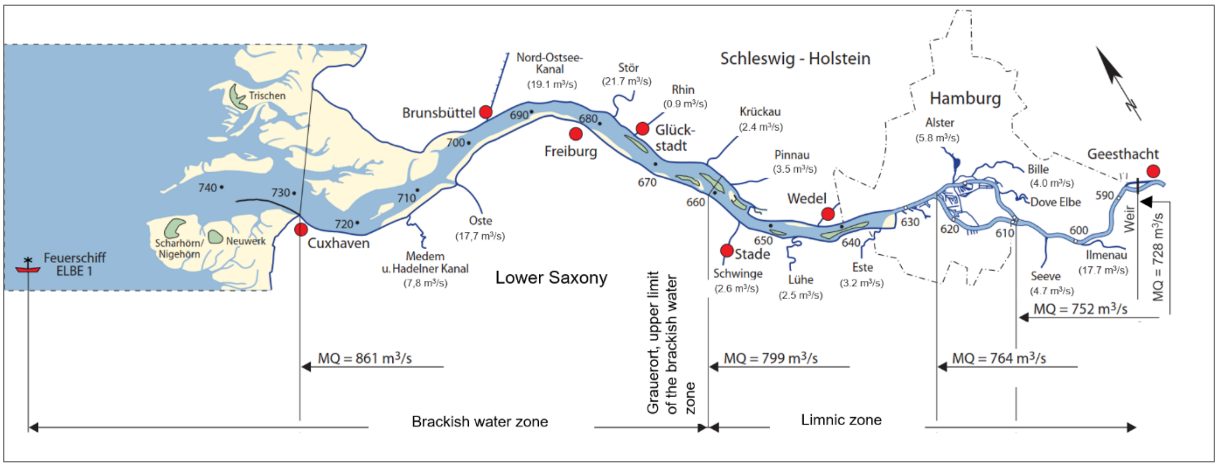

Figure 3. The Elbe estuary (IKSE2005modified): most important tributaries and channels of the Elbe estuary with the average annual discharges; calculated mean outflows (MQ) at selected cross-sections; distance marking (Elbe-km) starting by 588 at Geesthacht.

Figure 3 shows also the most important tributaries and channels along the Elbe estuary that contribute to approx. 85% of the drainage flows from the estuary basin area. Their annually mean contribution (MQ) to the tidal Elbe sum up 112.73 m^3/s (without the Rhin river).

The fresh water inflow from the head of estuary significantly influences the dynamics and transport capacity of the well-mixed estuary, especially due to its large range of variability (see chapter 2.1.1), the long term mean discharge is 695 m^3/s (HPA 2022). Very high discharges enhance the water volume flowing during Ebb and can alter resonance and reflection patterns especially in the upper estuary. Boehlich et al. (2008) depicted the effect of high discharges on the tide duration and showed a notably increase on the tide ebb duration and decrease on the flood duration upstream from Elbe-km 665, when comparing feasible riverine inflows of 2,000 m^3/s and 300 m^3/s. High discharges enhance the flushing capacity of the estuary leading for instances to an increased residual transport of particulate matter to the mouth, as showed by Weilbeer (2015). On the other hand, very low fluvial inflows boost the import of marine sediments into the upper part of the estuary. In this case, also fluvial loads are barely transported downstream from Hamburg. In general, such natural variations on the fresh water inflow influences estuarine processes on the tidal Elbe system like barocline processes, salinity intrusion, trapping effect of the turbidity maximum (ETM), as well as biogeochemical processes. Holzwarth's investigations (2018) depicted, how the natural variability in fresh water discharge affects the riverine water age within the estuary, and the implications of this on degradation of riverine organic matter and oxygen depletion.

1.2 Long-lasting adaptation for human activities

Major adaptations in the estuarine environment for human activities began approx. in the 13th century at the Elbe estuary. For agriculture purposes, foreshore areas were diked and the hinterland drained to gain land. This resulted in soil subsidence in hinterland areas that are today below the mean sea level. For flood risk protection, extensive areas were also diked and floodplains drastically diminished. Specially after the severe storm surges events in 1962 and 1976 major flood protection measures cut off the tidal influence in the foreshore areas, tributaries and sidearms. Since 1900, the Northern foreshore areas in the state Schleswig-Holstein, have decreased 50 % and the Southern foreshore areas in the state Lower Saxony 75 % (Elbe estuary working group 2012).
The construction of the tidal weir in the city of Geesthacht in 1956/1960 was also a significant intervention in the estuary that fixed a tidal limit 20 km upstream of Hamburg causing a partly reflection of the tidal wave and an increase in the tidal amplitude in Hamburg (Freitag et al. 2008)

For navigation and port accesses the river channel has been deepened and widened several times. Until 1868 the tidal channel downstream Hamburg was maintained to a water depth of 5.30 m (Boehlich and Strotmann 2008), today, container vessels with a regular draft of 13.5 m can leave the Port of Hamburg without restrictions to tidal water level. A draft up to 14.10 m is possible for larger container vessels (62.5 m wide or 400 m large) by using flood tide (WSA Elbe-Nordsee 2021). The strengthening of the river channel altered the tidal dynamics of the Elbe. The deepening of the channel reduces the effect of bottom friction on the flowing water mass, so that the incoming tidal wave is less dampened and more tidal energy moves upstream amplifying the tidal wave. In particular, it caused in the tidal Elbe a decrease of the low water.

The cumulation of these human interventions combined with natural changes on the geometry of the estuary led to an increase of 1.48 m in the tidal range from 1950 to 2021 in Hamburg, St. Pauli (HPA 2022), as depicted in Figure 4.

1.3 Present-day natural and man-made pressures for the Elbe estuary management

Tidal amplification, e.g. the increase of the range between high water and low water towards the inner estuary, is one of the pressures that has become intensified over the last decades in meso- and macrotidal estuaries like the Elbe, Weser, Scheldt and Humber (TIDE 2012, 2012). The intensification of the tidal amplification is associated with changes on the estuary geometry (e.g. after the construction of dykes and barriers, the deepening and widening of the main channel) and the removal of sandy sediments out of the system that reduced friction and dissipation of energy. In the Elbe, a progressive increase in the tidal range over the last 70 years is observable at the inner upper part of the estuary (see Figure 4), particularly the decrease of the low water levels has fostered the amplification of the tidal wave landwards.

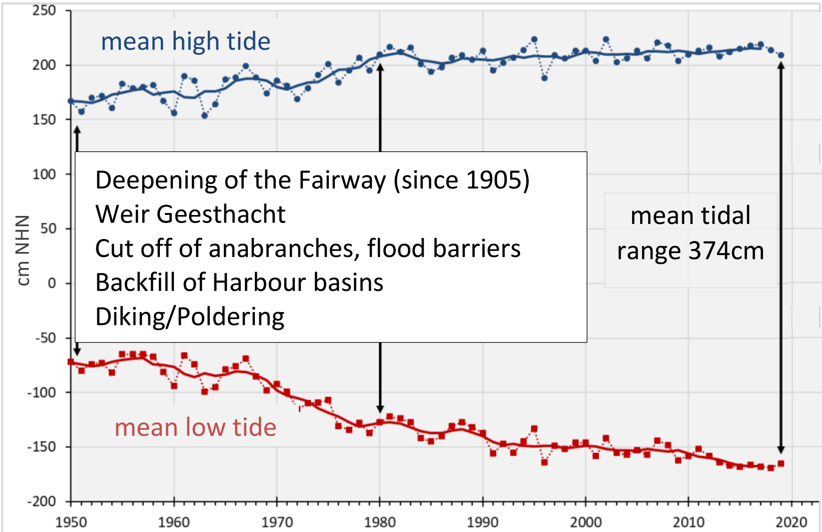

Figure 4. Water level at gauge St. Pauli, Hamburg (upper estuary) from 1950 until 2020. Source Hamburg HPA, 2020 (modified)

An increase on the tidal range is linked to changes on the propagation rates of the tidal wave, the transport regime of sediments and salt intrusion. Variations on the amplification of the tide might reflect shifting dynamics in the estuary system in response to natural processes or man-made interventions that could influence several uses of the estuary services. In the Elbe estuary, an accelerated increase in the tidal range was observed from 2013 to 2018 together with an increase in the current velocities and higher levels of turbidity. Here, the high morphological activity of the mouth of the estuary was found to be a major cause, in particular the meandering of the two side arms Medemrinne and Klotzloch (see black rectangle for 2010 and 2016 in Figure 5) which in 2018 intersected each other and partially joined into a wider branch with enhanced hydraulic capacity (Weilbeer et al. 2021). This meander migration caused the removal and deposition of large amounts of sediments, and an increase in the tidal energy entering the estuary (at least temporary), similarly to the morphological activity observed between 1998 and 2002 (Freitag et al. 2008). Weilbeer et al. (2021) concluded that the accelerated increase of the tidal range and sediment transport upstream after 2013 were caused by the combination of the recent morphological changes in the mouth of the estuary, a long period of low mean annual freshwater discharge and the recirculation of dredged material after relocation works around the port of Hamburg. An increment in the tidal energy, sediment availability and the long-lasting low mean annual freshwater discharge explained the higher amounts of dredged material (fine sediments) at highest in 2014 upstream the middle estuary (Weilbeer et al. 2021).

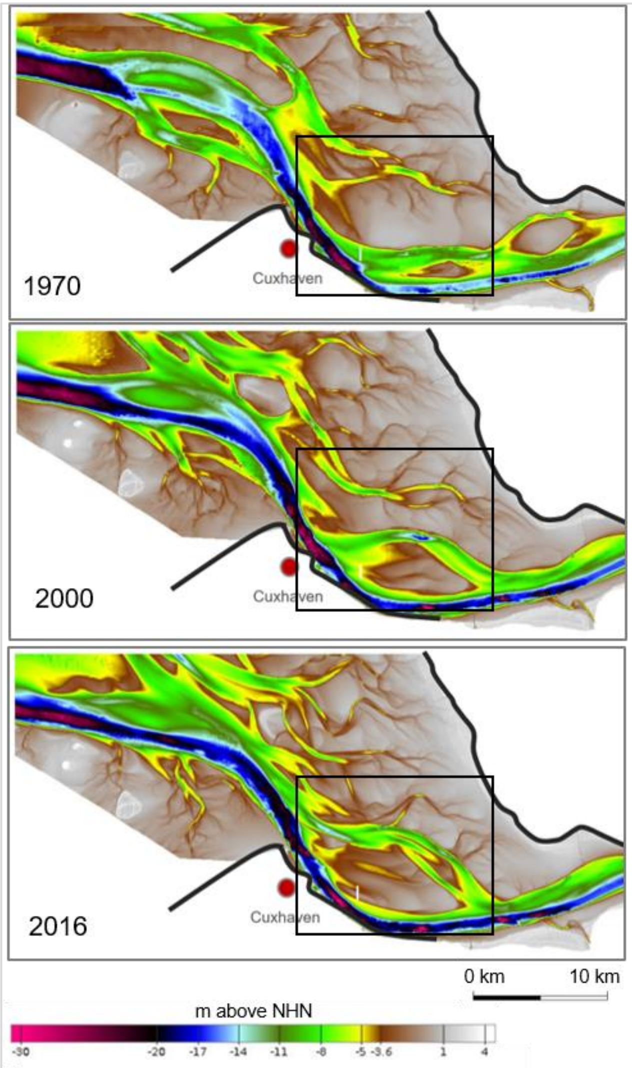

Figure 5. Morphological activity at the mouth of the Elbe estuary. Topography in 1970, 2000 and 2006 from DEM. Black rectangle shows the west-north displacement of the side arm Medemrinne.

Different studies showed the effects of tidal asymmetry on the net sediment transport in tidal systems (Ridderinkhof 1997; van de Kreeke and Robaczewska 1993) and in the Elbe estuary (e.g. (Freitag et al. 2008; Weilbeer 2015). The intensification of the net sediment transport upstream, so-called tidal pumping, is particularly a pressure of a matter of concern in the Elbe estuary due to the economic and ecological impacts of higher turbidity and increased dredging activities needed to maintain the waterway.

Tidal asymmetry typically refer to a deformation of the tidal curve along an estuary with tidal variations primary in channel depth, when the tidal wave propagates faster during high water than during low water due to the water depth difference between both phases (Boehlich and

Strotmann 2008; Friedrichs 2010). But different types of tidal asymmetry can be distinguished: the asymmetry mentioned above owing to a difference in the duration between rising and falling tides; flow asymmetries owing to differences in the duration and magnitude of flood and ebb currents (Song et al. 2011), and those owing to differences in the vertical mixing (Scully and Friedrichs 2003; Winterwerp 2011).

Following Song et al. (2011) and Gong et al. (2016), three tidal asymmetries can be evaluated by the skewness, for instances to obtain insights about the sediment transport patterns: The tidal duration asymmetry (TDA), which reflects the difference between the duration of rise and fall water levels, depicting whether a tidal phase lasts longer than the other one. The flow velocity asymmetry (FVA) which is the difference in the magnitude of the maximum velocity during ebb and flood tidal flow, and the flow duration asymmetry (FDA), which is the difference in the duration of the slack water going from flood to ebb and vice versa. FVA and FDA are relevant for the study of sediment transport (Gong et al. 2016). Figure 6 shows the evaluation of these three asymmetries for a validated model of the Elbe estuary in the reference scenario with the bathymetry of 2016 (including the fairway deepening that finished in 2022), within an analysis window of four weeks in May-June 2016 (see also reference Elbe estuary model in 3.2.1.1).

In Figure 6, positive (red) values depict a positive asymmetry: for the TDA (upper panel in Figure 6), the dominating positive asymmetry over the whole estuary means a shorter duration of the rising tide which is expected for a funnel-shape, hydromodified river as the tidal Elbe, where the tidal variations dominate in the channel depth (Friedrichs 2010). A decrease in TDA (blue in Figure 6) is observed in some sections with tidal flats and fringing marsh where the tidal variations in width might dominate so that the low tide propagates faster. Also the interactions of the semidiurnal tides (e.g. M2 and M4), which predominate in the Elbe estuary, are in favor of generating a positive tendency according to Gong et al. (2016).

The asymmetries in the flow velocity (FVA) and flow duration (FDA) can be used as a proxy for the direction of sediment and substance transport. The FVA gives insights about the direction of the bedload transport. It reflects whether the maximum magnitude of the current velocities in one tidal phase is higher than in the other one, considering the influence of the residual flow. It is positive when the flood current is dominant and negative when the ebb flow is dominant. In the middle panel in Figure 6, the modelled reference scenario shows to be ebb dominant up-estuary, where the estuary is shallower and the influence of the freshwater discharge is greater, but also in the mouth, where by lower water levels the ebbing flow is confined in the channel and less influenced by the tidal flats, so that it can reach higher velocities than the flood current velocities that are reduced by the extensive tidal flats (during rising tides).

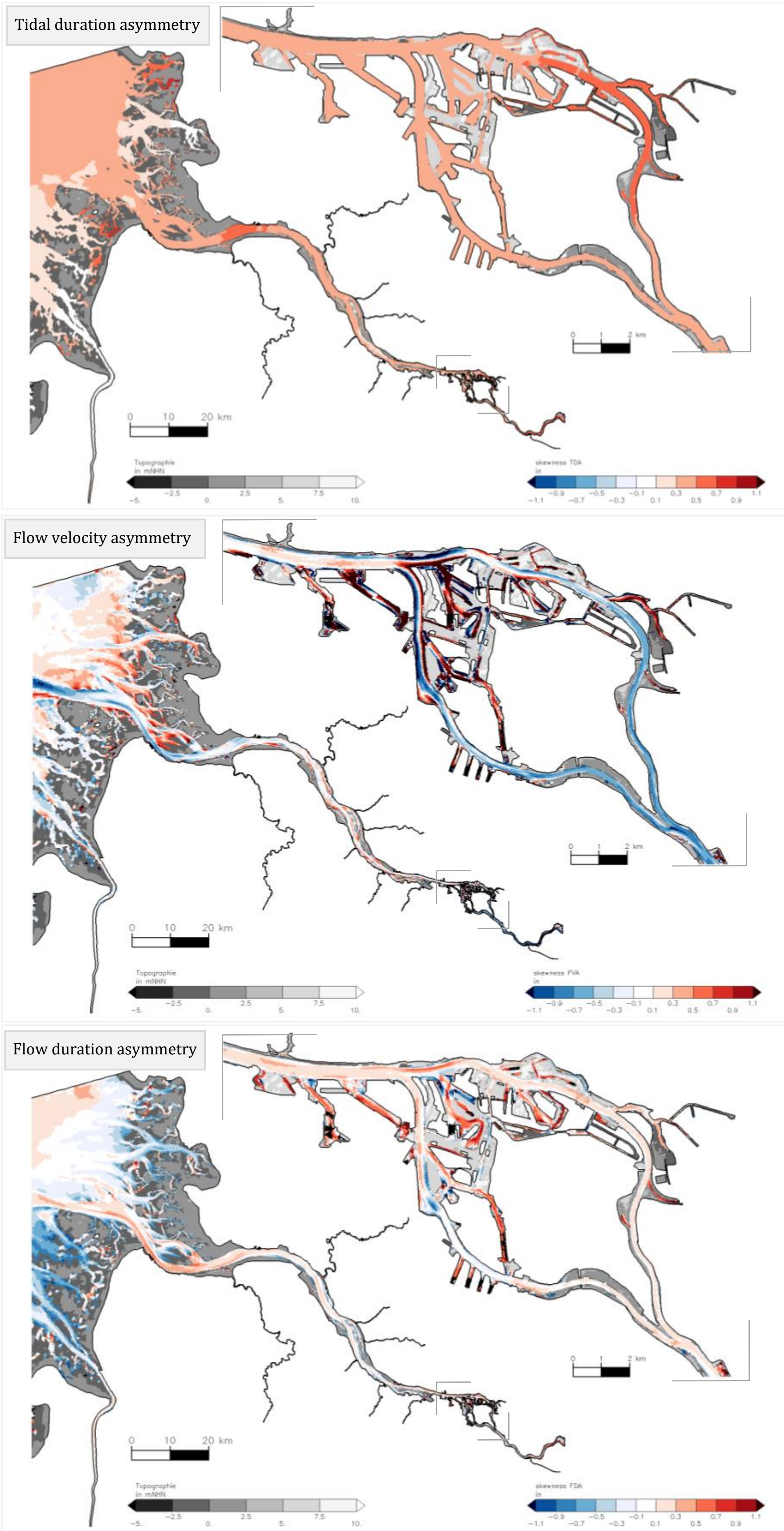

Figure 6. Tidal asymmetries, TDA (above), FVA (middle), FDA (bellow) after Gong (2016) for a reference scenario of the Elbe estuary with topography of 2016.

A positive asymmetry in the flow duration (FDA) reflects a shorter duration of low water slack and longer duration of the high water slack, which favors the landward transport of fine sediment, while a negative asymmetry favors the seaward transport of fine sediments (see lower panel in Figure 6). The reference scenario of the Elbe estuary exhibits in Hamburg a tendency of a positive asymmetry, which becomes predominant in the port basins in Hamburg. Downstream of the mouth, the tidal creeks in the tidal flats show a negative asymmetry, whereas the navigation channel shows primarily a positive tendency of the FVA. In Figure 6, it is also observable that FVA and FDA are opposite to each other in some estuary regions as they are in favor of different sediment transport patterns.

Besides tidal pumping, other pressures of concern at the Elbe are sediment-bound pollution and recirculation of dredged material. These (exclusively) man-made pressures exacerbate the impacts of tidal pumping on the sediment management measures.

1.4 Framework for the measure development in the Elbe sediment management

Measures for the maintenance of the tidal Elbe as a federal waterway are in the competence of the Federal Waterways and Shipping Administration (WSV), except for the Harbour area, where the Hamburg Port Authority is responsible for the water and landside infrastructure. Besides, the implementation of measures for example for flood risk protection and monitoring are principally in the competence of the federal states of Hamburg, Lower Saxony and Schleswig Holstein within their territory, in coordination with the monitoring coordinating group FGG, *Flussgebietsgemeinschaft Elbe*, which is in charge of the national surveillance monitoring of the Elbe catchment. The estuary management is therefore a join task of different governmental or federal authorities with different competences.

Since 2008, the management of the estuarine sediment has followed a concept developed in discussions with the federal states of Hamburg, Lower Saxony and Schleswig Holstein, and agreement between the Federal Waterways and Shipping Administration (*WSV*) and Hamburg Port Authority. The River Engineering and Sediment Management Concept for the Tidal River Elbe - *Strombau- und Sedimentmanagementkonzept Tideelbe* (2008) aimed to contribute to the long-term sustainable development of the tidal Elbe by developing and implementing measures at short, medium and long term. It considered measures of three kinds: river engineering measures to modify the unbalanced sediment budget and the intensified tidal pumping; measures to optimize the maintenance practices and relocation strategies; and measures to reduce the polluted dredged material (see Figure 7). Towards implementation, suitable locations for both, relocation of dredged material and river engineering measures were discussed with the stakeholders and interest groups of the estuary region and forward concretized (Dialog Strombau- und Sedimentmanagement Tideelbe 2015). In that consultation process, more than 20 locations were preselected for the forward development of river engineering measures that might reduce the tidal amplitude (i.e. tidal range), influence the erosion and siltation patters in the estuary system and so modify the unbalanced sediment budget.

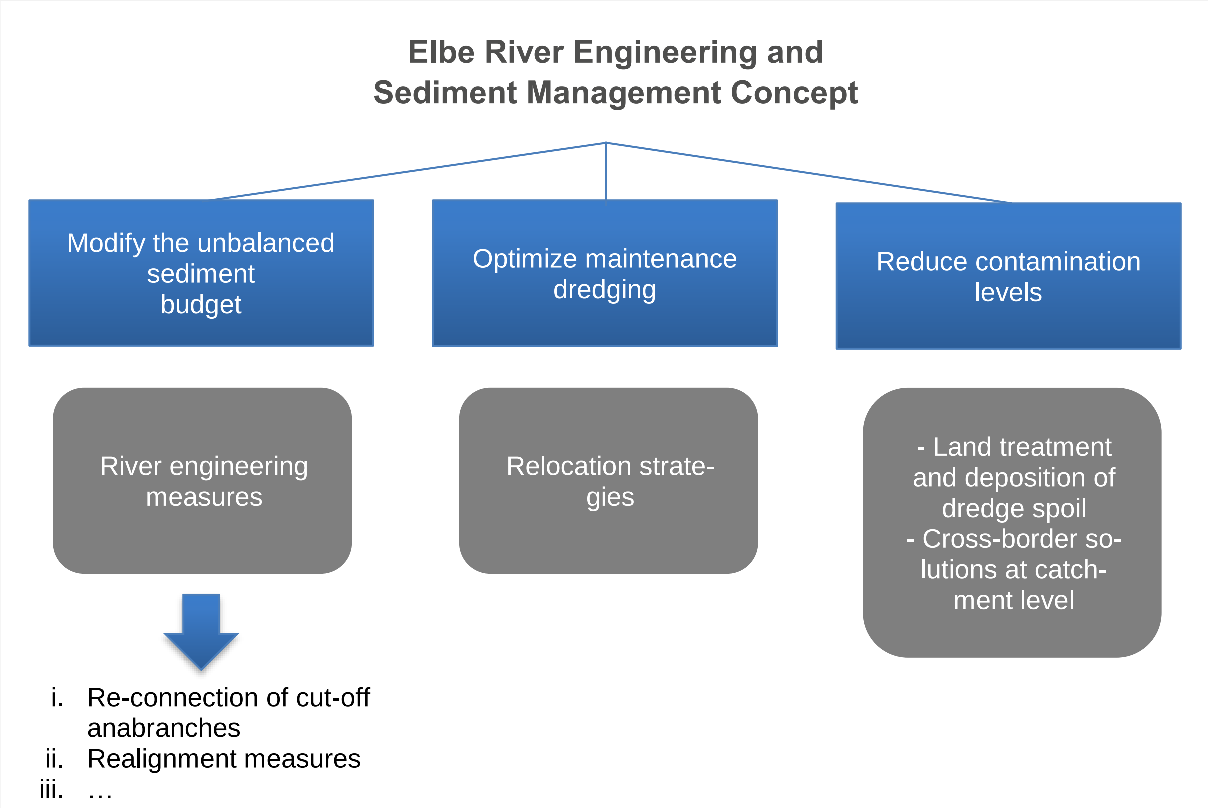

Figure 7. Measure categories intended in the Elbe River Engineering and Sediment Management Concept (2008)

Since 2016, the estuary partnership *"Forum Tideelbe"* has continued this process in discussion with interest groups and stakeholders of the estuary to give a recommendation to the responsible authorities about feasible locations for measure implementation considering the ecological and socioeconomical conditions. In chapter 2.2, this sort of largescale river engineering measures are discussed and in chapter 3.2, a case study is presented for the hydro-morphological assessment of one of the potential locations considered by the estuarine partnership for a detailed evaluation and feasibility study.

2 Management measures for the sustainable development of Elbe estuary

In the advancement of measures for a sustainable development of the Elbe estuary, two aspects are here emphasized: adaptive sediment management and long-term measures that positively influence the tidal dynamics. At the following, the concept of adaptive sediment management and long-term measures proposed in the River Engineering and Sediment Management Concept for the Tidal River Elbe are discussed.

2.1 Adaptive sediment management

The Elbe estuary is a diversely and intensively used environment located at the intersection of different federal states, delimiting geographic borders. Whereas sediment-related transport

processes act on the estuarine environment at a system-scale, the administration and management of the estuary is shared between federal states and governmental authorities with different jurisdictions and competences. A coordinated sediment management can be challenging, since a common understanding between several estuary players is required in view of the functioning of the estuary system. A joint fact-finding regarding present-day pressures and potential cross-borders solutions is needed, so that management actions can react flexible and adaptively to natural or anthropogenic estuary pressures.
From a higher level, at catchment-scale, hydrological and sedimentological processes prescribe the fluvial sediment loads and particle-bound pollutants that enter into the estuary. At the estuary-scale, those fluvial discharges mix with marine loads and with those trapped, exiting loads within the estuary. Transport and settling rates of both sediments and particle matter undergo high dynamic mixing processes along the entire estuary. Thus, joint responses and adaptive actions in response to pressures like tidal pumping, recirculation of dredged material or sediment pollution must build on a common understanding of the system and clear collective objectives followed by the estuary stakeholders towards the sustainable development of the estuary. On this basis, sediment strategies can be continuously adjusted and improved following an adaptive sediment management that facilitate decision-making.

Adaptive management was proposed by CEDA (2015) as a decision framework that can facilitate decision-making by allowing management actions to be progressively adjusted in response to outcomes from monitoring and evaluation. Different than the usual execution of a fixed management plan, the flexibility of this approach should allow management actions to be periodically adjusted to meet sustainable objectives and goals, by intensifying monitoring and correcting when needed, to response to uncertain variables (e.g. sea level rise and its impact on tidal pumping). This flexible approach can improve strategies in sediment management and in the collective use of the estuary services at the Elbe estuary, as decision-making is continuously supported by monitoring and through a stepwise reduction of uncertainty of environmental effects at each revaluation of monitoring outcomes. For that, estuary managers should commit on the overall goals and objectives that steers management actions in line with monitoring outcomes.

From a practical perspective, adaptive management and flexible practices in sediment relocation can improve the efficiency of maintenance works at the tidal river Elbe, when considering intensive monitoring and forecast of the freshwater discharge. At the Elbe estuary, freshwater discharge is a variable factor that determines the flushing capacity of the river flow and can boost sediment transport in both ways in the tidal stream. A flexible strategy to decide where and when the relocation of the sediments is effective can allow managers to react ad-hoc to changes on meteorological and hydrological conditions that might increase or decrease the freshwater discharge and plan maintenance works making use of favorable conditions and minimize wasting resources or unfavorable depositions.

Adaptive activities can lead also to a more sustainable and efficient management where the effects of engineering and maintenance measures are uncertain or predicted with low confidence. Climate change scenarios, changing environmental regulations and new technologies are factors that impact long-stablished human activities and uses, and challenge managers in planning the future development of the estuary. As the severity of the impact for future activities might be not accurate for planning at long term, management measures require a vision to follow and a cyclic evaluation, where uncertainties are renewed estimated with new findings and within an updated context (EMOVE 2015; CEDA 2015)

2.1.1 Freshwater discharge forecast

The freshwater discharge at the head of the Elbe estuary (gauge station Neu Darchau) varies significantly; in the past 96 years from 1926-2021, the mean discharge was 695 m^3/s, whereas the lowest discharge was 145 m^3/s (LQ) and highest 4050 m^3/s (HQ) (HPA 2022). The MLQ and MHQ derived from 01.11.1874 - 31.12.2020[1] were 270 m^3/s and 2000 m^3/s, respectively.
This variation of the river discharge influences the flux of suspended material transported downstream. Such very high or very low river discharges flush with a very different strength towards the sea, regulating the residual energy of the tidal current (net energy of the current integrated over one tidal period). Therefore, the reach of the sediments and settling rates along the estuary vary in interaction with the magnitude of the freshwater discharge. Following that, the need of dredging in the fairway or in the harbour entrances is boosted by long dry periods and small discharges, and it is lowered by high water events. In 2013, the summer high-water event at the Elbe (HHQ = 4070 m3/s in June) lowered the dredging need to minimal values during Winter and still in 2014 the dredged volume hold very low to 2.1 million m^3 (Weilbeer et al. 2021). On the other side, the low river discharge observed on average between 2014 and 2019 (MQ lower than 500 m^3/s) intensified the need of dredging works and in combination with other factors lead in 2016 in Hamburg to 14.3 million m^3 of dredged volume (Weilbeer et al. 2021).
Given that variability on the natural sediment transport, flexible strategies to plan dredging activities are more effective, when they consider the freshwater discharge. Estimations able to forecast, for instances, high freshwater discharge within days can provide relevant information to optimize dredging and reduce maintenance works. Also, when very low discharges are expected for long periods, it might be useful to recognize inefficient relocation and disposal on-time, and avoid dredging cycles that increase maintenance works. These dynamic actions following an adaptive strategy require coordinated, inter-jurisdictional reactions estuary-wide. Hereby, hydrological and hydrodynamic operative models are useful technologic tools in addition to monitoring, for example to estimate the likely run-off and expected freshwater discharge, and calculate the hydrodynamics and expected transport of SPM and bedload in the tidal reach.

First approaches have been started in the Elbe to develop operative models that provide ad-hoc decision-making data. For instances, a hydrological six-weeks forecast for the freshwater discharge at the head of estuary (Neu Darchau station) was initiated by the National Meteorological Service, the Deutsche Wetterdienst (DWD), and Federal Institute of Hydrology (BfG) of Germany (Frielingsdorf et al. 2018).

[1] Data source: https://undine.bafg.de/elbe/pegel/elbe_pegel_neu_darchau.html

The BAW started the development of OPTEL-C, an operational tidal model for the tidal Elbe, using the hydrodynamic numerical model UnTRIM (BAW 2011). The model has been extended for the German Bight (German Bight Operational Model, GBOM) and is employed at present-today to calculate daily forecasts of water levels and current velocities in 2D. Also, a conceptual model used by the port of Hamburg to estimate the dredging needs has been advanced in its efforts to correlate low freshwater discharges with dredging cycles (Weilbeer et al. 2021).

Open questions for further development regard modelling frameworks that operatively simulate the potential transport and deposition of sediments (within days/weeks) using climatological-hydrological forecast-models and hydrodynamic operative models. Those might be particularly useful for the ad-hoc planning of maintenance works in waterways. Developments to meaningfully integrate non-deterministic data from forecast-models with deterministic hydrodynamic models are required, as well as suitable approaches to quantify the uncertainty of such combined prediction models.

2.1.2 Integrated estuary management

2.1.2.1 Interplay between abiotic and biotic parameters in transport process

The understanding of the physical processes related to abiotic parameters like water levels and current velocity have played a significant role in coastal engineering and in sediment management measures. For many engineering problems, advances in describing the transport phenomena related to fluid dynamics and estuarine circulation has been imperative to develop engineering measures by means of numerical modelling.

New findings and a better understanding about the biological effects on sedimentological processes have encouraged scientific efforts in developing process-based models that better represent interconnected mechanisms between abiotic and biotic parameters in sediment transport; process like for example bioresuspension, flocculation or seasonal biomass-sediment interactions. For instances, the role of the biologically mediated flux in the water-sediment interface and its effect on the SPM-dynamics has been demonstrated (Graf and Rosenberg 1997; Le Hir et al. 2007). Here, benthos-organisms are responsible for influencing erosion and sedimentation patterns of fine particulates. This could be demonstrated near-bed at the shallow North Sea shelf and quantified by means of numerical modelling (Graf and Rosenberg 1997; Le Hir et al. 2007; Nasermoaddeli, Mohammad Hassan et al. 2014; BAW 2016). These advances in understanding the influence of biotic parameters on sediment transport process can reduce the uncertainty of processes usually neglected in the modelling systems, and improve the reliability of model-based sediment management assessments.

On the other side, the influence of abiotic parameters on biotic parameters is crucial for the functioning of diverse ecosystems in the estuary. Physical factors as the flow current, substrate (e.g. sediments and SPM), temperature and oxygen are major factors of importance to the biota (Allan 1995). Sediment management practices cause changes on those physical factors, at different scales; dredging, relocation or deposition of sediments can pose challenges for the biota to adapt to alterations in the habitats, but also opportunities to improve the ecological conditions through purposeful designed engineering measures. Thus, potential environmental effects of the uses of estuarine resources should be integrally assessed wherever the state-of-the-art approaches allow it. Integrative methods including biogeochemical interconnections in 3D numerical models have been developed with this purpose and employed, for instances at the Elbe estuary, to assess the implications of man-made bathymetric modifications on the dissolved oxygen (Holzwarth 2018). Following the later, good practices in an adaptive sediment management might emerge from integrative approaches that employ interdisciplinary knowledge and technologic tools like numerical models that help to quantify approaches to achieve a more sustainable and cost-efficient estuary management. The less uncertainties about the interplay of abiotic and biotic factors in estuarine processes (e.g. bioresuspension, flocculation, seasonal biomass-sediment interactions), the more accurate and proper are measures and strategies that aim the sustainable development of the estuary region. Nonetheless, appropriate methods to assess the development of the estuary are essential to fulfil the requirements of the EU legislations (e.g. WFD, MSFD).

2.1.2.2 Integration of estuarine ecosystem services and sediments

Estuarine environments provide direct or indirect contributions to human well-being in form of natural resources, so-called ecosystem services. Their correct functioning builds in many ways the sustainability of economic systems (TEEB 2010). Ecosystems in estuarine environments provide food sources, water for navigation, sand provision, as well as regulating services like the dissipation of tidal and wave energy that regulates the flow current, mitigates storm surges, river peak discharges and allows i.e. safety navigation (Liekens et al. 2013).

Sediment management activities make use of ecosystem services related to the flow current, and natural fluxes of particle matter. For example, the flush capacity of the freshwater discharge is a natural service, on which dredging strategies in the tidal Elbe relies (e.g. on the typical, historical time series of freshwater discharge). Also, morphological features like sand bars or intertidal areas, exert a natural damping function of tidal and wave energy through friction, which regulates water levels and the amount of sediment transported into the estuary, diminishing tidal pumping. According to the studies in the TIDE-project (Sander et al. 2012; Liekens et al. 2013; TIDE 2012), the ecosystem services with the highest demand in the estuaries Elbe, Weser, Scheldt and Humber are the supply of water for navigation (i.e. presence and use of water for shipping purposes), regulating services of the water quantity for transportation (i.e. river discharge and tidal characteristics that lower dredging) and biodiversity (Sander et al. 2012).

Sediment management activities can alter the functioning of these natural benefits as they interfere in the natural evolution of the morphology and sediment drift across the estuary. The interference might be temporal, positive or negative and to a minor or major degree. The high demand and followed intensive use of ecosystem services for shipping and port access suggest that sediment management actions require flexible, resilient practices to safeguard both, the proper functioning and sustainable supply of the natural estuary services: the functioning of the estuarine habitats can be impacted for example by dredging works due to enhanced turbidity or direct impact on benthic communities (Sander et al. 2012) and the sustainable supply of the regulating benefits for navigation like riverbed friction, river discharge and tidal forcing can be impacted for example by to sea level rise, i.e. climate change.

The integration of estuarine ecosystem services into an adaptive sediment management requires measure assessments regarding the performance of the estuarine habitats present in the estuary. Methodologies to determine the ecosystem services were suggested for example by TIDE (2012), and an evaluation tool developed and applied in the Scheldt estuary (Boerema et al. 2020). Hereby, the quantification of the physical interactions is also essential, for example to evaluate sediment management activities and engineering works and their impact on the estuarine habitats. Advanced physical-mathematical models are therefore an important basic tool to assess estuary measures. Based on measure assessments, cost-benefit analysis of possible scenarios can be compared, and so, decision-making in sediment management strategies supported.

2.2 Long-term positive influence on tidal dynamics

Tidal pumping has become a matter of concern at the Elbe estuary due to the increased need of dredging to secure safety navigation in the Elbe waterway to Hamburg. The entities that administrate the waterway and are responsible for its maintenance (WSV and HPA) decided to further river engineering measures that positively influence the tidal dynamics at long-term and counteract the unbalanced regime of the sediment transport (HPA and WSV 2008). Largescale river engineering measures were foreseen to reverse, or at least to lower a further intensification of tidal pumping.

Largescale river engineering solutions like realignment measures, and those conceived to activate new channels or polders in the estuary can positively influence the estuary dynamics by increasing the local tidal volume (tidal prism). To increase the tidal volume, measures can be differently implemented, for instances by widening and excavating silted up areas (see e.g. pilot at the Sea Scheldt in IMMERSE WPA 5.4) or by reconnecting cut-off estuary areas like assessed for the Elbe estuary by the (BAW 2021). The main aim of this type of measure is to damp tidal (wave) energy by spreading it over a larger cross-section and so reduce tidal amplification and tidal pumping. Other benefits of allowing the tide to run over larger flood areas relate the decrease of the high water levels which helps to reduce the storm surge flood risk, or the improvement of the ecological conditions by creating intertidal areas where estuarine habitats can develop (Knüppel 2012; Boerema et al. 2013).

According to the investigations of the BAW (2014; BAW 2021; 2021), three key factors are important to obtain the largest possible hydraulic effect reducing tidal amplification and tidal pumping by this type of river engineering measure (e.g. realignment measures or reconnecting cut-off areas):

- Location along the estuary, where tidal volume is reconnected or re-created for tidal flooding. Since the Elbe estuary is funnel-shaped (narrower and shallower upstream), the increase of the tidal volume next to the wide mouth (up to approx. 17 km wide) has a lower local effect on the water levels than the same tidal volume would have in the upper estuary or within the Hamburg harbour, where the cross section of the tidal Elbe is smaller (e.g. the anabranch Northern Elbe in Hamburg is approx. 300-500 m wide and 5-20 m deep below German Datum NHN).

- Tidal prism: the water volume created in the connected areas above mean low tide level is determinant. Water volume under mean low tide is neither filled, nor drained by the tidal wave (within average tidal level) and thus, it does not influence the flow conditions of the main river. The larger the tidal prism (tidal volume between MLT and MHT) connected to the main river the greater is the effect on the water levels and velocities in the main river.

- Flow cross section: the depth and width of the cross section that connects the main river to the new flooding area can change the expected effect of a certain tidal volume. A small cross section can turn into a bottleneck and reduce the effectiveness of the measure.

The physical response to a specific re-activation of a cut-off area of the estuary is in general well known, however the real effectiveness of a measure has to be evaluated for every different place of implementation because of differences on the morphology and hydrodynamics, and the non-linearity of the tidal dynamics. Detailed studies, for instances by means of numerical modelling, are required to calculate the effective influence of a specific location on the estuary dynamics, the effective estuary volume connected, and the design of the cross section between the main river and the connected area.
Besides the physical and technical considerations, uses and potential impacts in the concerned area play a crucial role in the measure design. This was evidenced in the assessment of reconnecting the former anabranch Dove Elbe to the Northern Elbe at the Elbe estuary, in which at the end of stakeholder involvement the potential tidal volume for the reconnection was reduced 54% from approx. 5 million m^3 to 2.7 million m^3 to lower the measure impact for the local stakeholders (BAW 2021). That constrained the measure effectiveness in reducing tidal pumping and tidal amplification (see chapter 3.2).

3 Assessment of estuary measures through numerical methods

The flow conditions of an estuary are typically subject to dynamic processes that result in a slow, but continuous change of the estuary shape. The river bed, tidal flats and shoal areas are subject to non-steady and in many cases high active hydrodynamics caused by the sum of astronomic forces, meteorological conditions, riverine discharges, as well as anthropogenic interventions. These combined processes ongoing in an estuary are difficult to track or classify based on observations. Especially, natural and man-made induced changes appear undistinguishable in measurements of hydrodynamic parameters (e.g. water level, flow velocities or sedimentation rates) and cannot always be differentiated by means of measurement analyses, particularly, when it comes to understand the trigger of a certain change in the dynamics or to estimate the effects of an engineering measure on the estuary. Numerical models have been used in the scientific scene to fill that gap. They model processes and mechanisms at a defined scale observed in nature, solving mathematical equations numerically that cannot be resolved through analytical methods.

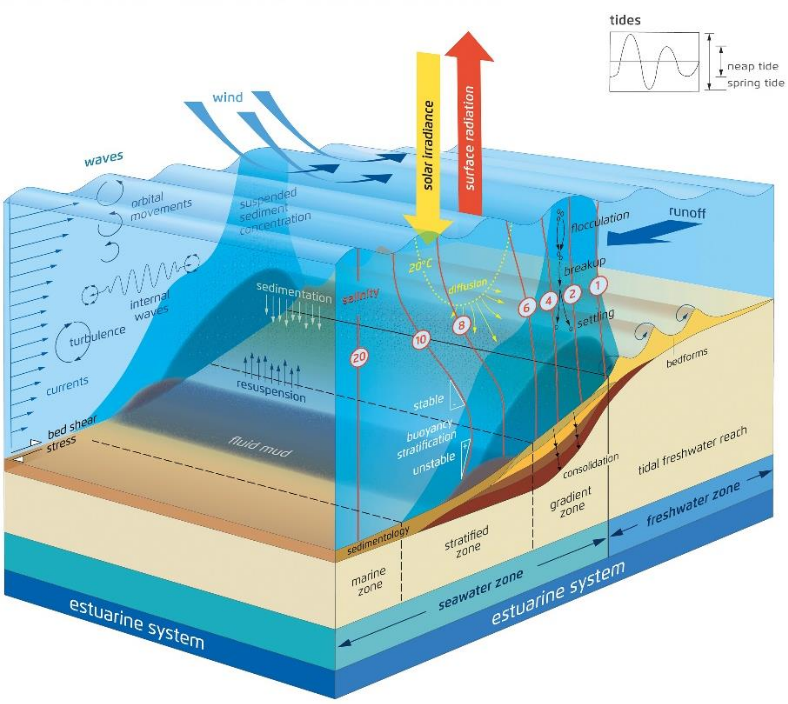

Figure 8. Estuarine physical processes

Figure 8 depicts important process that characterize an estuary in a physical system. The most relevant of them are considered in the hydro-morphological model system UnTRIM –Sedimorph employed at the BAW to investigate engineering measures in the German estuary systems.

3.1 Hydro-morphological model system UnTRIM –Sedimorph

The BAW uses spatially detailed three-dimensional modelling to simulate the morpho-hydrodynamics at the Elbe estuary. The modelling suite is based on the mathematical numerical method UnTRIM (Casulli 2009) and the morphological model Sedimorph (Malcherek et al. 2005). The hydrodynamic model UnTRIM solves time-dependent, non-linear differential equations related to free-surface flow and transport problems on an unstructured orthogonal grid (see Figure 9). Sedimorph is a software package that models two or three-dimensional fractioned sediment transport in the river bed and the related morphological process like for example the bed evolution. Details about the numerical methods can be found in the validation documents by Casulli and Lang (2004), and Malcherek et al. (2005).

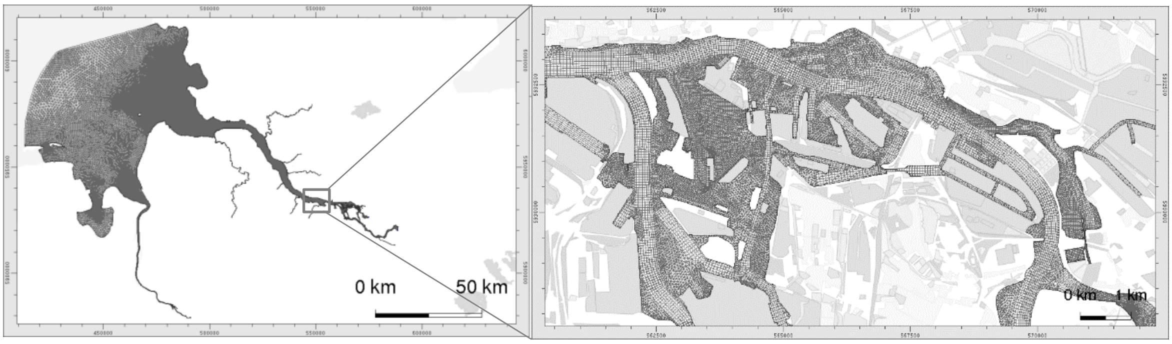

Figure 9. Unstructured orthogonal grid, with complex bathymetry of the Elbe estuary model domain (left), zoomed in to Hamburg harbour (right)

UnTRIM computes a system of differential equations that represent the physical conservation laws for water volume (continuity equations), linear momentum (Reynolds-average Navier-Stokes equations), and transport mass for salt, heat (temperature), suspended sediments or conservative tracers (advection-diffusion equation). Those equations are solved numerically within a model domain defined by an unstructured orthogonal horizontal grid (combination of triangles and quadrilaterals) and vertical z-layers that discretized the topography of the investigated area and can model complex geometry and bathymetry (Figure 9). Also, full drying and wetting zones like tidal flats are part of modeled area. The model domain is also determined by certain boundary conditions, for instances, unsteady tidal water levels at the sea boundary and unsteady river inflows at the head of the estuary. Details about the governing equations, discretization methods and numerical approaches can be found in the works by Casulli and Zanolli 1998), Casulli 1999), Casulli and Walters 2000), Casulli and Zanolli 2002), Casulli and Zanolli 2005) Casulli 2009).

Sedimorph computes, coupled to UnTRIM, the bedload transport in the undermost z-vertical layers, balancing both: the mass movements of different grain classes within the bottom layer, and the vertical load exchange between the water column and the river bed resulting from deposition and resuspension. It computes the bed roughness resulting from grain and form roughness, bottom shear stress, bed load transport rates, bed evolution, sediment distribution and porosity prediction. Details about governing equations can be found in Malcherek et al. (2005); approaches and improvements recently implemented into the Sedimorph model can be found in BAW (2020b).

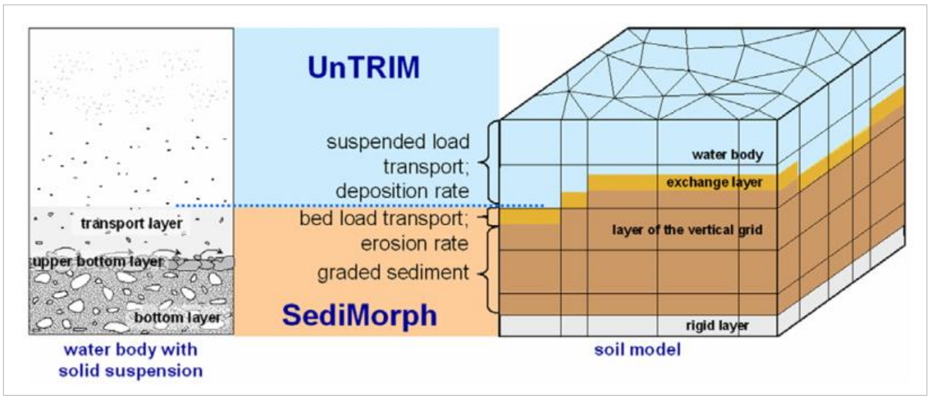

Figure 10. Model system for sediment transport in UnTRIM-Sedimorph

Complementary modules have been incorporated to the hydrodynamic model system UnTRIM-Sedimorph to improve the process-based descriptions of physical phenomena related to coastal dynamics and parameters that are characteristic for tidal waters (see Figure 11). Advances in this field from the scientific community are continuously implemented in the modelling suite, as well as improved methods for computational efficiency, numerical treatment and postprocessing analysis and visualization (Lang 2017).

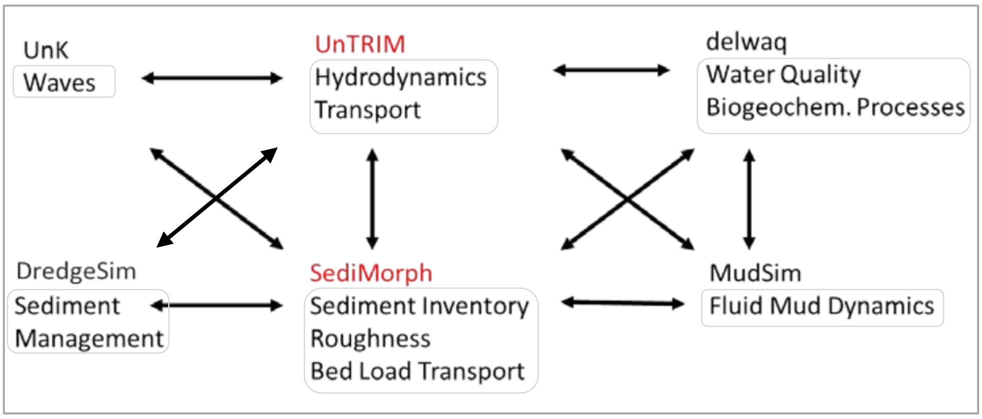

Figure 11. HN-Modelling system

3.1.1 New feature: Operational Weir

An important characteristic of the architecture of UnTRIM is its modular setup. This property allows developers to integrate complementary modules coupled to the hydrodynamic computations, for instances, to simulate alterations in the flow regime and sediment transport resulting from management works like for example the package DredgSim does by modelling dredging and dumping of sediment.

During this investigation the feature “Opweir" was programmed and incorporated in the suite model to simulate the operation of hydraulic structures like sluice gates at runtime and control weir sections in the model domain depending on the model results. This feature steers the weir height according to user-defined thresholds for the flow conditions, enabling a more efficient simulation for the operation of weirs since the modeler doesn’t need to know or estimate the exact times of changes on the weir height. Opweir proofs the flow conditions at observation points in the model domain (see Figure 12) and determine whether the weir height should change. For example, when the water level exceeds or falls below a given threshold at an observation point, the weir height is modified at runtime, simulating the closing or opening operation of a weir gate. Besides the water level, control conditions can be defined based on a threshold for the magnitude or direction of the flow velocity and the speed of water level change. The difference of the water levels and current magnitudes between two given observation points can be also used to define control conditions. The control conditions can be specified for certain dates, times or weekdays and different conditions can be combined logically (AND or OR connections) to build chain of rules for the weir operation that might be close to reality (OP_WEIR.DAT 2021). The application of this feature for a measure assessment is shown in the following section.

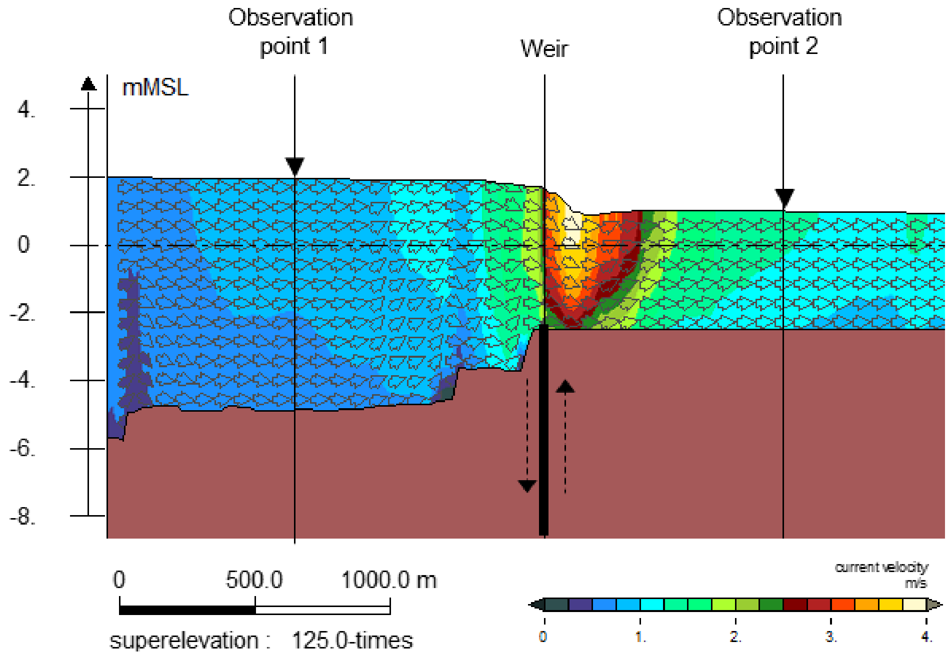

Figure 12. Flow velocities in a longitudinal profile, downstream and upstream of a weir. The velocities at both observation points (together with thresholds) can be used to steer the weir height.

3.2 Case of Study: reconnection of cut-off estuary areas

One of the long-term solutions formulated in the River Engineering and Sediment Management Concept for the Tidal Elbe River (2008) bears on the creation of additional flood space in the estuary. Through an increase of the tidal volume (tidal prism) at a suitable location along the estuary, this type of measure could reduce tidal pumping and, thus, the amount of sediments transported towards the upper estuary (see chapter 2.2).

Three locations to reconnect former estuary areas to the tidal Elbe were preselected by the estuarine partnership Forum Tideelbe (2020): at the former anabranches Dove Elbe and Alte Süderelbe, and in the diked wetland Haseldorfer Marsch. Within the IMMERSE-project, a measure layout for the reconnection of the Dove Elbe has been developed, which integrates social and technical constrains (BAW 2021) .

The present case of study shows the use of the modelling system UnTRIM-Sedimorph for the assessment of the Dove Elbe reconnection and the application of the feature Opweir simulating the weir operation. In the measure layout, specifications to control the water levels in the anabranch Dove Elbe were considered to reduce the impact of the current uses for the locals and improve the ecological state: for instances, a restricted tidal exchange was planned which lowers the tidal wave upstream the anabranch. In BAW (2021) this measure layout has been assessed with the same modelling system but using a simplified approach at the weir. In that approach, the water flux in and out the Dove Elbe to the tidal Elbe was simulated, so that the maximal tidal water volume achievable in the reconnected area was computed, for instances, assuming pumps installations that drain the reconnected flood area by ebb (BAW 2021). In the approach presented here, the feature Opweir models the actual opening and closing of sluice gates at the reconnection as an obstacle constricting the flow downwards. Thus, potential limitations due to the flow constriction at the weir are here examined.

The method of investigation consists in the analysis of the Elbe model simulated in two scenarios: a baseline scenario in the initial state without the reconnection, and an alternative scenario that includes the reconnected area in the Dove Elbe and the operation of sort sluice gates that control critical water levels within the Dove Elbe. In both simulations, baseline and case scenario, forcing and modelling parameters as well as boundary conditions are kept the same (same method and setup of the study by BAW (2021).

3.2.1.1 Elbe estuary model

The domain of the Elbe model extends from the tidal weir in Geesthacht at the head of the estuary until Helgoland, beyond the sea limits of the estuary (see Figure 13). The horizontal resolution of the mesh grid varies gradually from large grid cells in the North Sea (2 km) to finer grid resolution in small channels upstream (20 m), with 1 m resolution for the z-layers. The heights were interpolated from the digital elevation and bathymetry model based on an estuary-wide survey in 2016 (WSV 2016). For this year, also the dataset required for the forcing, calibration and validation of the model was available. The forcing data used at the sea boundary (water level, temperature and salinity) bear on the results of a validated North Sea model computed with the model system UnTRIM-Sedimorph-UnK (BAW 2020a). At the head of the estuary, hourly freshwater discharge measurements from the gauge Darchau located 20 km upstream of the weir are used with one day time lag. Suspended particulate matter, temperature, and conductivity measurements from the monitoring station at weir Geesthacht (provided by The Federal Institute of Hydrology, BFG) are also imposed for boundary forcing. The main tributaries of the tidal Elbe are included, here freshwater discharge measurements are imposed. For the atmospheric forcing (wind, atmospheric pressure and air temperature), area-wide data from the Global Modell ICON provided by the German Meteorological Service (Reinert et al. 2021) is used. The initial sediment load at the river bed (superficial, erodible soil layer) corresponds to the distribution of the measurement-based functional soil model “AufMod” (Heyer and Schrottke 2013). The sediment distribution is represented in Sedimorph by 10 fractions of different particle sizes from very fine silt to gravel.
Further initial conditions and model parameters are setup according to the extensive sensibility analysis and model calibration carried on for the planning of the waterway deepening and widening works that started in 2019 (BAW 2006b, 2006a). The calibrated model for the year 2016, set up with the dataset above described, depicted a RMSE for the water levels smaller than 0.15 m in all 25 gauges stations along the tidal Elbe. This model was employed here as the baseline scenario including the expected bathymetry after fully implementation of the deepening, widening and the compensation measures started in 2019. Thus, the reference scenario of the Elbe estuary used to evaluate the effect of the following river engineering measure (i.e. reconnecting additional tidal volume to the estuary) represents the hydrodynamic conditions expected in the near future.

The simulation period covers three spring -neap cycles from 19th April to 02th June 2016. For the analysis and postprocessing, only the last two spring-neap cycles (04.05.-19.05.2016) are considered. The period between (04.05.-19.05.2016) is characterized by high tidal energy that causes

large tidal ranges, and by rather low freshwater discharge (between 609 - 320 m3/s against the 30-years mean discharge of 700 m3/s). As these two conditions enhance the import of sediments upstream (tidal pumping), this period represents the most unfavorable but realistic conditions of the year to assess the effectiveness of a river engineering measure under a “worse-case” scenario in terms of tidal pumping.
A longer analysis period (04.05.2016 -02.06.2016) was employed for a tidal harmonic analysis to evaluate the measure effect on the tidal asymmetry (see chapter 3.2.1.3).

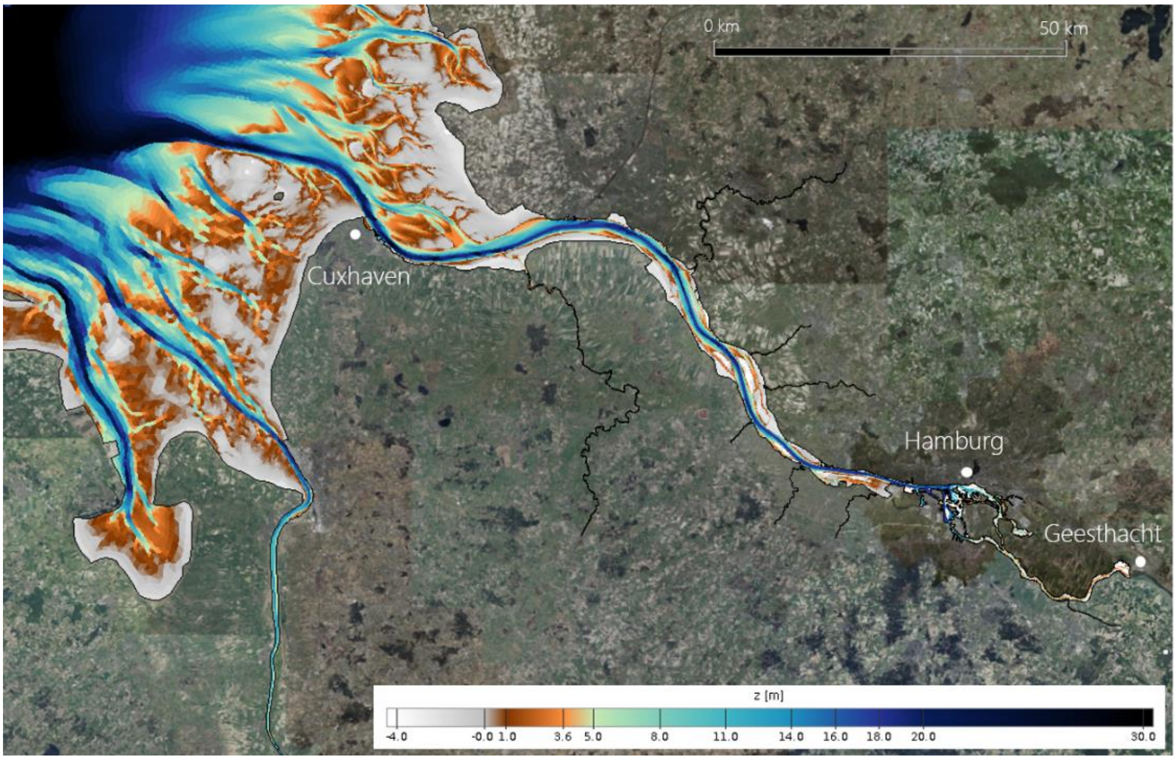

Figure 13. Spatial extent and bathymetry of the Elbe Modell 2016 (here including the Dove Elbe reconnection upstream Hamburg).

3.2.1.2 Alternative case scenario

The measure layout in the case scenario extends the tidal influenced areas along 6.3 km into the cut-off anabranch Dove Elbe, which is today an inland waterbody (see Figure 14). The depth of the channel next to the weir Tatenberger Siel is planned 3.5 m under NHN, (*NHN* is the german vertical datum for the standard elevation zero). Further upstream of the anabranch, the case scenario reflects the current bathymetry, which reaches until -13 m NHN. Some shore areas are planned deeper as today to create intertidal areas (134 ha). The measure layout foresees a conditional tidal exchange, so that the low and high tide are moderated within the reconnected area. The water levels should be regulated around 0.9 m NHN and -1.2 m NHN. The weir is so operated that the time of weir closure and the periods of no water movement are minimized and the sediment deposition in the reconnected is reduced. The slow, but continuous movement of water in both ways in the tidal stream should also further habitat creation in the intertidal areas. To get the greatest hydraulic effect of the measure, the tide control should steer a tidal range of approx. 2.1 m.

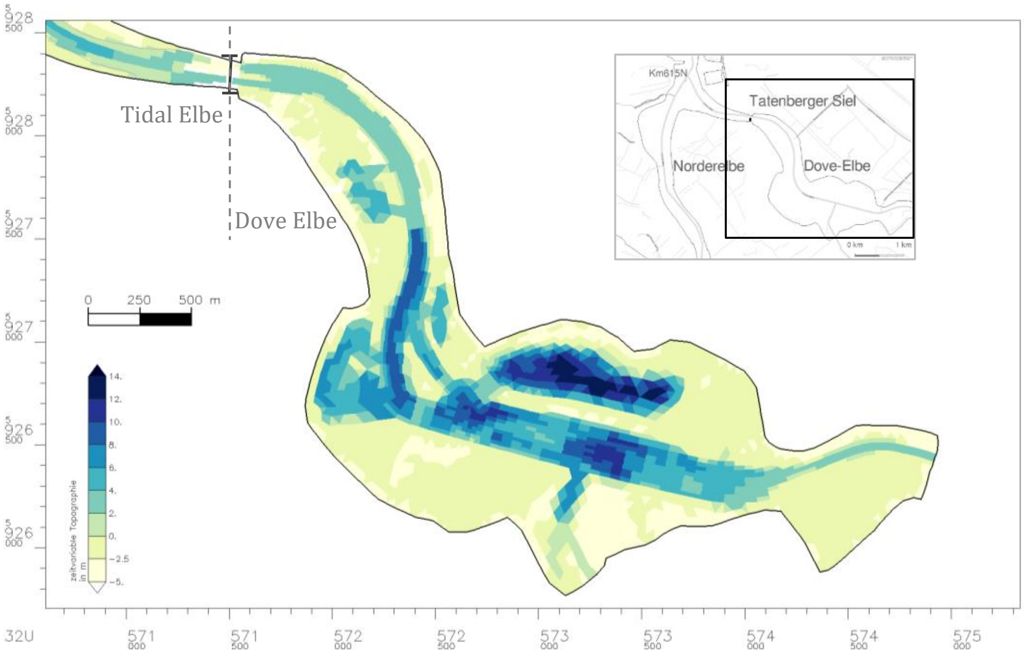

Figure 14. Topography of the additional estuary area to be reconnected to the tidal Elbe at the former anabranch Dove Elbe, today separated by the Tatenberger Siel

3.2.1.3 Results

The measure effectiveness on flow conditions and sediment transport at large-scale was determined by the sluice operation to regulate the high water within the Dove Elbe. In average within a 2-week analysis period, the high water in the Dove Elbe was 0.9 m NHN, regulated by the sluice gate, whereas the mean high water in the Northern Elbe was 2.4 m NHN (see Figure 15). For the falling tide duration within the Dove Elbe induced by the sluice, the low water was hydraulic limited by the narrowed cross-section of the weir and riverbed geometry downstream the weir; the mean low water resulted in -1.0 m NHN, less than the target value of -1.2 m NHN. Figure 15 shows the different mean low water levels downstream and upstream the sluice.
The mean tidal range resulted in 1.9 m upstream the sluice. In the Northern Elbe, at the mouth of the Dove Elbe, it was 4.2 m. This significant reduction of the tidal range in the reconnected area lowered the water volume (i.e. tidal prism) that could potentially pass through the reconnection. As a result, the additional tidal prism connected from the Dove Elbe to the estuary caused principally a local effect in the flow dynamics that within few kilometers seawards subsided: next to the mouth of the Dove Elbe, the reduction reached approx. 10 cm and the average tidal range in the Hamburg area was 2 to 3 cm (see Figure 16).

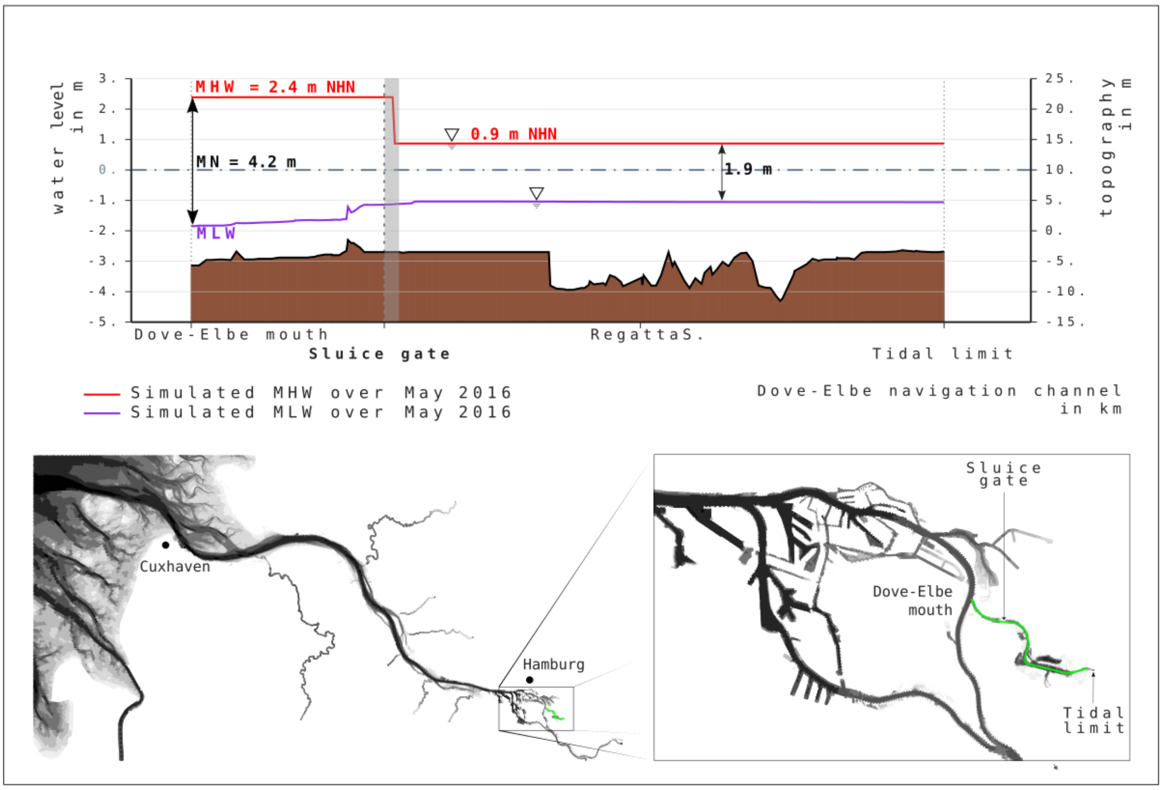

Figure 15. Tidal exchange controlled by a sluice gate along the navigation channel of the Dove Elbe (see upper panel). Location of the reconnected area in the Dove Elbe (see lower panel)

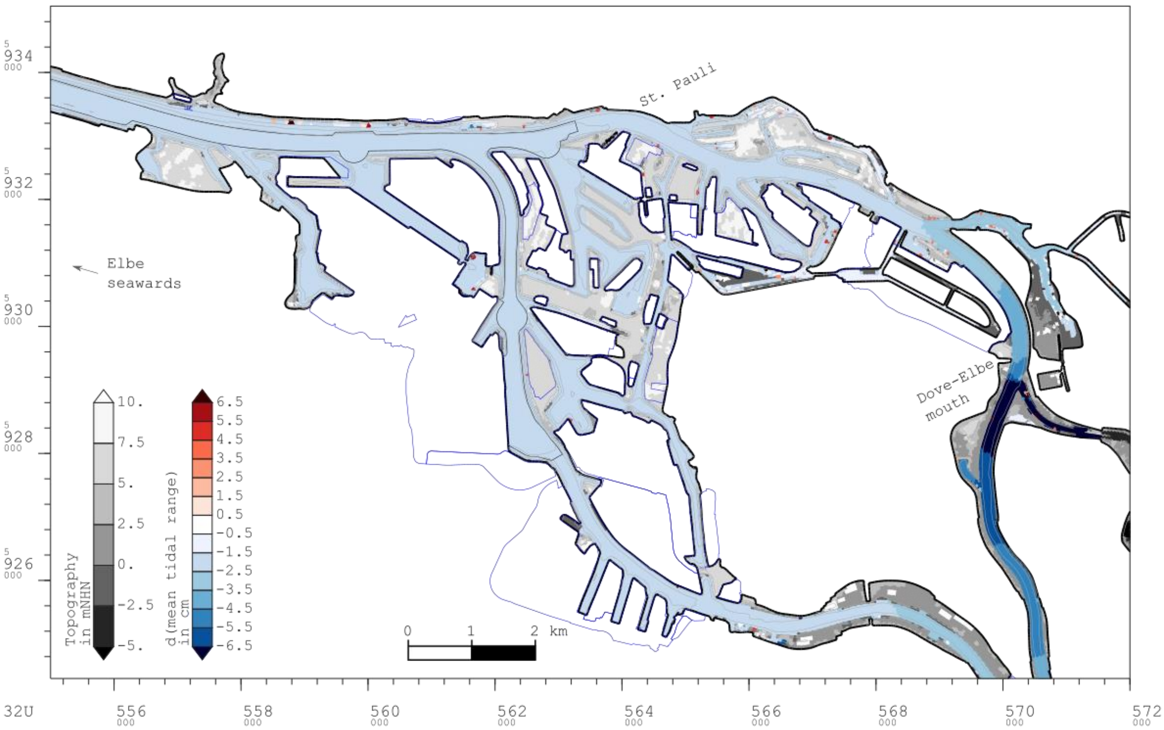

Figure 16. Reduction on tidal range in Hamburg due to the reconnection of the Dove-Elbe

For a 4-week analysis period (04.05.2016 -02.06.2016), the measure effect on the flow velocity asymmetry (FVA) and flow duration asymmetry (FDA) (see chapter 1.3) in Hamburg is depicted in Figure 17. Similar to the figures above, Figure 17 shows a difference: the results of the parameter FVA or FDA in the scenario with the reconnection of the Dove Elbe minus the results of the same parameter in the reference scenario without the measure. The flow velocity asymmetry FVA tends to be more dominant downstream the Dove-Elbe, which indicates that in that section the maximum flood velocity increases more than the maximum ebb velocity after the reconnection (but not necessary the mean flood and ebb velocities). Since this section of the tidal Elbe in the reference state is ebb dominant (see Figure 6) and the increase on the FVA is rather low, this area remains ebb dominant after the reconnection. The flow duration asymmetry (FDA) depicts a stronger tendency to a positive asymmetry also downstream of the Dove Elbe mouth. This area presents typically lower suspended loads in comparison to the typical loads downstream St. Pauli and it might be therefore less impacted by the positive dominance of FDA that the reconnection would induce. A tendency to positive FDA and FVA is also observable along a shallow and narrow channel section in the middle of the Port.

A slight tendency to a negative asymmetry for the FVA and FDA is caused by the measure in different sections at the branch Köhlbrand by the Elbe-km 625 (see km625 in Figure 17). The reduced asymmetry in the maximum flow velocity and the slack water duration (more ebb dominant) has an impact on the sediment transport, in particular in the river sections with high suspended particle concentration like for instances around the branch Köhlbrand by km625. This positive effect on the sediment transport extends downstream St. Pauli along the tidal Elbe (Figure 18). The suspended particle concentration becomes 1 to 9 mg/l lower due to the reconnection. The effect is stronger during the first depicted spring-tide (ninth spring-neap-cycle of the year) which is in general related to a high tidal energy import into the Elbe estuary. In the Northern Elbe downstream the mouth of the Dove-Elbe, the suspended particle concentration increases up to 11 mg/l as an initial morphological response to the locally changed flow behavior (in correspondence to positive tendency of FVA) that might be temporary, and subside in the medium term (Figure 18).

The positive effect on the sediment transport showed in the study BAW (2021) could be confirmed in the approach presented here by using the module Opweir to simulate the weir control at the sluice Tatenberger Siel. The measure effectiveness on the upstream sediment transport was low, constrained mainly by the limitation on the high water level within the Dove Elbe since the less amount of water flowing through the connecting sluice, the less influence had the transport of this additional water on the tidal dynamics of the Elbe. To a minor degree, the tidal volume was also constrained by narrowed cross-section of the weir and riverbed geometry downstream the weir.

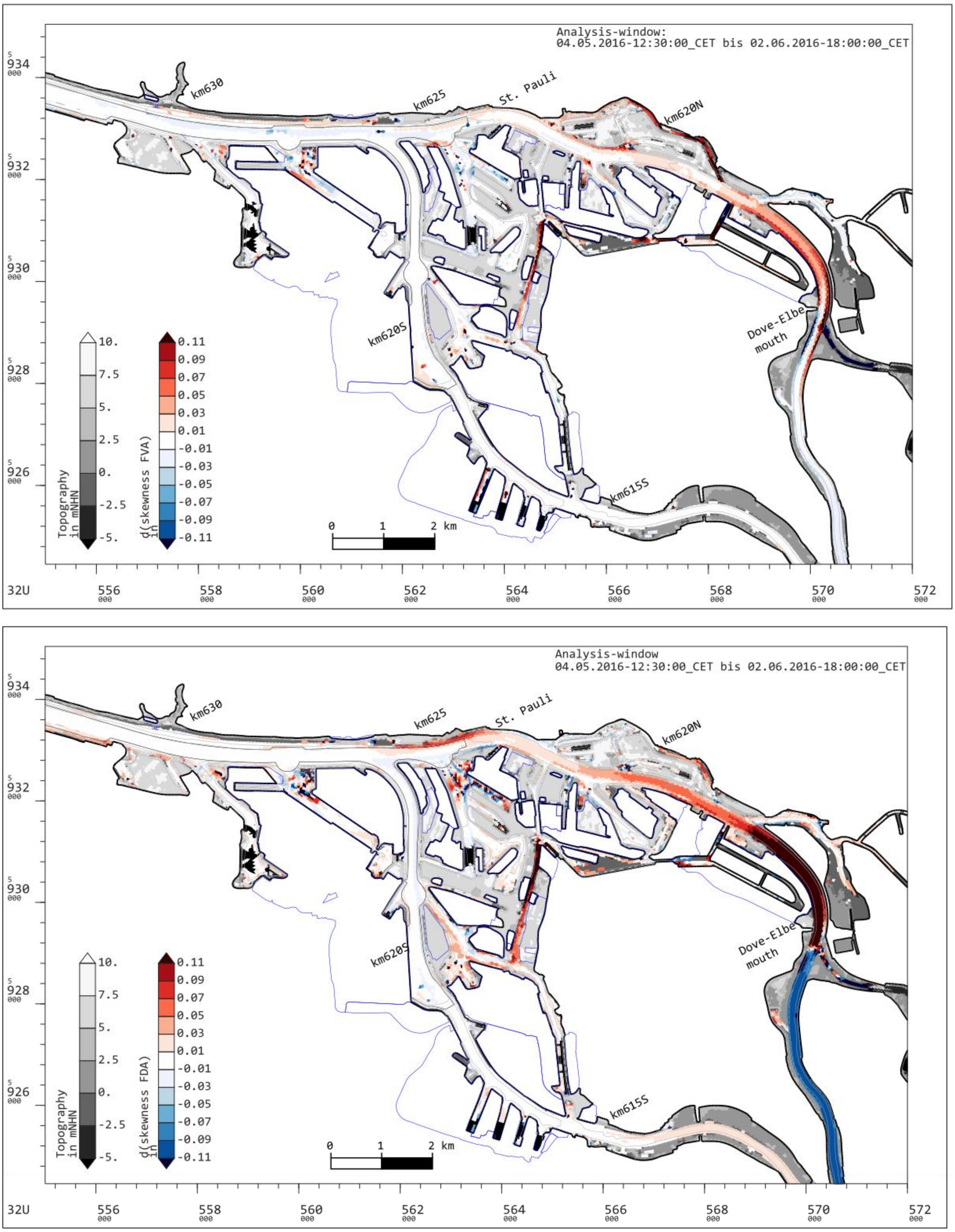

Figure 17. Difference in the tidal asymmetry during 4 weeks analysis time between the reference and study case scenario. Difference of the flow velocity asymmetry FVA (above), difference of the flow duration asymmetry FDA (bottom).

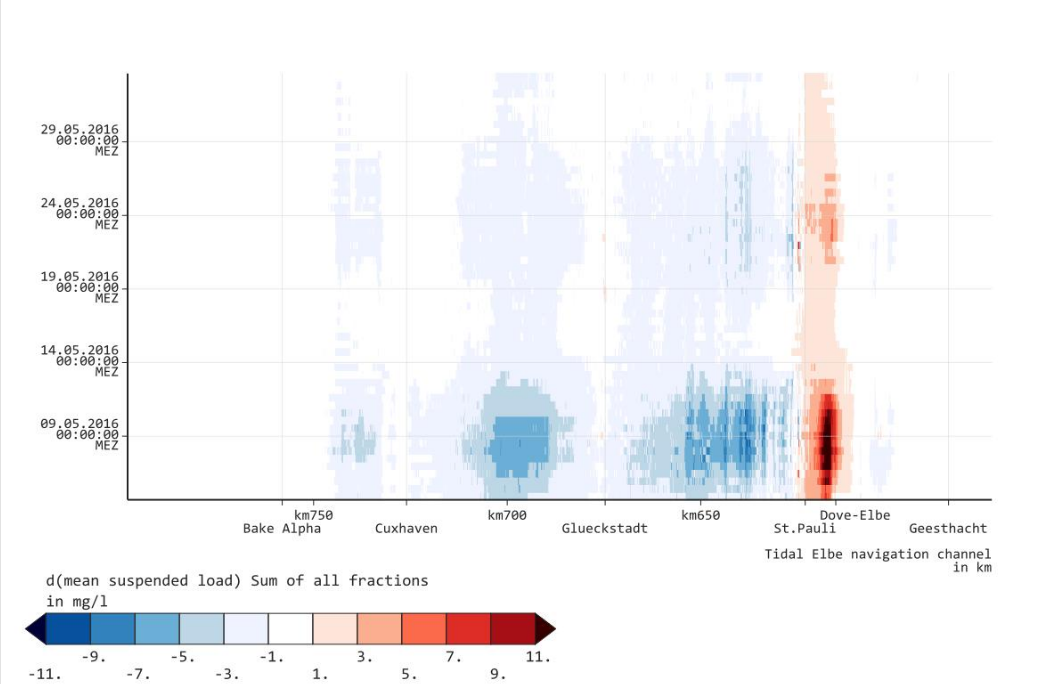

Figure 18. Difference of suspended particle mater between the reference and case study scenario along the tidal Elbe waterway (left seawards, right tidal limit) in time (vertical axis).

4 Discussion and conclusions

In this study, two aspects relevant for the sustainable sediment management in the Elbe estuary were addressed: adaptive sediment management and the assessment of largescale measures that positively influence the tidal dynamics and counteract the pressure tidal pumping.

The concept of adaptive management considers a flexible approach, different from the usual execution of a fixed management plan. This approach allows sediment management actions to be periodically adjusted to meet sustainable goals and to response to uncertain variables (e.g. sea level rise and its impact on tidal pumping) by intensifying monitoring and correcting based on the monitoring outcomes. Adaptive actions in response to pressures like tidal pumping, recirculation of dredged material or sediment pollution must build on a common understanding of the estuary system and clear collective objectives about the estuary development. Thus, adaptive management actions require a joint response among estuary managers and stakeholders that share responsibilities and competences within the estuary. That coordinated sediment management might be challenging, when the administration and management of the estuary is shared, like in the Elbe estuary, between three federal states and different governmental authorities.

Flexible practices in sediment relocation can for example improve the efficiency of maintenance works at the tidal Elbe, when the influence of environmental factors like the freshwater discharge is monitored and estimated as it controls the flushing capacity of the river flow and can boost sediment transport in both ways in the tidal stream. Similarly, integrated approaches that

consider the influence of biotic parameters on sediment transport processes can help to improve measure assessments that are based on (abiotic) hydrodynamic numerical models to adjust management actions with new knowledge.
Adaptive sediment management might also comprehend integrated approaches aimed to safeguard the 'natural benefits' of the estuary system used for human activities. Access to ports and navigation depends on natural benefits that are not changeless available, i.e. the proper functioning and supply of ecosystem services. Ecosystem services related to estuarine habitat services can be impacted for example by dredging works due to enhanced turbidity or direct impact on benthic communities (Sander et al. 2012), and regulating ecosystem services relevant for navigation, like riverbed friction, river discharge and tidal forcing, might be changed by sea level rise and climate change. Therefore, good practices in adaptive sediment management might emerge from integrative approaches that employ interdisciplinary knowledge and technologic tools like numerical models that estimate the effect of measures and management actions on the functioning and pressures of the estuary.

The intensification of tidal pumping is a pressure of matter of concern in the Elbe estuary that according to the River Engineering and Sediment Management Concept for the Tidal River Elbe - *Strombau- und Sedimentmanagementkonzept Tideelbe* (2008) must be counteracted, for instances through largescale river engineering measures. Potential solutions to mitigate tidal pumping are measures that improve the morphological state of the estuary by re-creating former estuary volume, i.e. tidal prism. Within the IMMERSE-project, a measure layout to reconnect the cut-off anabranch Dove Elbe and re-create additional tidal volume in the estuary was developed integrating social and technical constrains, and the feasibility and hydraulic effects were published in BBS Greuner-Pönicke et al. (2020) and BAW (2021). In the present work, the case study of the Dove Elbe was similarly assessed, but using a new module of the modelling system UnTRIM-Sedimorph to simulate in more detail the weir control at the sluice Tatenberger Siel that should reconnect the anabranch into the tidal Elbe.

The effect of the anabranch reconnection on the tidal asymmetry, tidal range and suspended particle concentration was evaluated. In the Northern Elbe downstream the mouth of the Dove-Elbe, an initial morphological response to the locally changed flow behavior was evidenced in correspondence to a positive tendency of FVA (flow velocity asymmetry) which led to an increase in the suspended particle concentration that might subside in the medium term. A slight tendency to a negative asymmetry for the FVA and FDA (flow duration asymmetry) was caused by the measure in different sections at the branch Köhlbrand by Elbe-km 625. This negative asymmetry had a positive local impact on the sediment transport, in particular in the river sections with high suspended particle concentration around the branch Köhlbrand by Elbe-km 625. The positive local effect on the sediment transport showed in the study BAW (2021) was confirmed in this work.

The results showed that the measure effectiveness reducing the upstream sediment transport was local and considering the whole estuary low. It was constrained mainly by the limitation on the high water level within the Dove Elbe, as shown by BAW (2021), and to minor degree also by the narrowed cross-section in the weir and riverbed geometry downstream the weir. That evidenced that uses and potential measure impacts in the concerned area of implementation play a crucial role in the measure design and effectiveness; here, the high water limitation within the reconnected area was integrated in the measure layout to lower the measure impact for the local stakeholders. This constrained the additional tidal volume created through the reconnection. The additional tidal volume exchanged was reduced 54%, from approx. 5 million m^3 possible tidal prism to 2.7 million m^3 (BAW 2021), hence the measure effectiveness was reduced.

The case of study reflects that the effectiveness of a measure should be evaluated for every different measure layout or place of implementation because of differences on the morphology and hydrodynamic, and the non-linearity of the tidal dynamics. Consequently, a measure being successful at one estuary cannot directly be transferred as a solution for other estuaries, and a measure that is less effective or not feasible at one place of implementation might have high potential at another place. Site- specific characteristics must always be considered. Additionally, a long(er) lasting stakeholder process should be conducted in order to achieve a common understanding and potentially a compromise between the different interests.

The case of study evidenced also that one measure alone cannot bring the Elbe estuary back into balance as the current hydromorphological condition of the tidal Elbe is the result of 150 years of hydraulic engineering measures, port constructions, fairway adjustments and coastal protection. Further, pressures such as climate change will have also a negative impact on the salinity, sediment transport regime and particle-bound pollution. The combination of several measures that create additional flood space at different locations in the estuary could have in total a major effect reducing the tidal range and the net transport of sediments upstream. Also, a more adaptive management on the practices for maintenance dredging, and relocation is necessary to improve not only the dynamics and sedimentation patters in the estuary but also the sustainability of the use and management of the estuary services.

5 Publication bibliography

Allan, J. David (Ed.) (1995): Stream Ecology. Dordrecht: Springer Netherlands. Available online at https://link.springer.com/chapter/10.1007/978-94-011-0729-7_3.

BAW (2011): KFKI – Projekt OPTEL: Windstaustudien und Entwicklung eines operationellen Tideelbemodells. OPTEL – C Entwicklung eines operationellen Tidemodells sowie einer Modellkopplung mit dem BSH-Vorhersagemodell der Nordsee. Fördernummer BMBF 03KIS071. Bundesanstalt für Wasserbau. Available online at https://izw.baw.de/publikationen/kfki-projekte-berichte/0/101_2_3_e35944.pdf.

BAW (2014): Untersuchung des Strombaus und des Sedimentmanagements im Rahmen des "Tideelbekonzeptes". Bundesanstalt für Wasserbau. Hamburg (BAW-Gutachten, A39550310172-6).

BAW (2016): FuE-Abschlussbericht Modulares System für Schelf und Küste Synthese (MOSSCO Synthese). Bundesanstalt für Wasserbau. Hamburg (BAW-Gutachten, B3955.02.04.70224). Available online at https://www.baw.de/content/files/forschung_entwicklung/documents/B3955.02.04.70224.pdf.

BBS Greuner-Pönicke; Planung & Moderation; Ingenieursbüro Dr. Lehners + Wittorf (2020): Auswirkungen der Anbindung der Dove Elbe an die Tideelbe und Auswirkungen für die Stakeholder. Machbarkeitsstudie. Im Auftrag von Hamburg Port Authority/IMMERSE. Available online at https://www.forum-tideelbe.de/files/download/20200930-machbarkeitsstudie-doveelbe-end.pdf, checked on 6/2/2022.

Boehlich, Marcus J.; Strotmann, Thomas (2008): The Elbe Estuary. In *Die Küste* 74, pp. 288–306. Available online at https://hdl.handle.net/20.500.11970/101612, checked on 5/17/2021.

Boerema, A.; Van der Biest K.; Meire, Patrick; Swerdt, Sofie de; Taal, Marcel; Vrebos, Dirk et al. (2020): The Smartsediment tool: a QGIS plug-in for evaluating ecosystems services. Available online at https://www.iadc-dredging.com/article/smartsediment-tool-ecosystems-services/, checked on 2/21/2022.

Boerema, A.; Van Duyse, E.; Maris, T. (2013): WP5 Measures. Basic analysis reports. Measure nr° 13. Lippenbroek: Flood Control Area with Controlled Reduced Tide (FCA-CRT). TIDE Project. Available online at https://www.tide-toolbox.eu/pdf/measures/Lippenbroek.pdf.

Bundesanstalt für Wasserbau (BAW) (2006a): Fahrrinnenanpassung der Unter-und Außenelbe. Gutachten zu Ausbaubedingten Änderungen von Hydrodynamik und Salztransport. Gutachten BAW-Nr. A39550310062-H.1a. Hamburg.

Bundesanstalt für Wasserbau (BAW) (2006b): Fahrrinnenanpassung der Unter-und Außenelbe. Fahrrinnenanpassung der Unter-und Außenelbe. Gutachten zu Ausbaubedingten Änderungen der morphodynamischen Prozesse. Gutachten BAW-Nr. A39550310062-H.1c.

Bundesanstalt für Wasserbau (BAW) (Ed.) (2020a): Validierungsdokument EasyGSH-DB Nordseemodell. Teil UnTRIM2 - SediMorph - UnK. Hamburg. Available online at https://doi.org/10.18451/k2_easygsh_1.

Bundesanstalt für Wasserbau (BAW) (Ed.) (2020b): Verbesserung der Validität und der Prognosefähigkeit des morphodynamischen Verfahrens SediMorph. FuE-Abschlussbericht B3955.03.04.70178. Hamburg. Available online at https://hdl.handle.net/20.500.11970/107457.

Bundesanstalt für Wasserbau (BAW) (Ed.) (2021): Auswirkung der Schaffung von Flutraum im Bereich der Tideelbe -Wiederanschluss Dove Elbe. Ergebnisse der Wasserbauliche Systemstudie zur Maßnahme Dove Elbe. Hamburg. Available online at https://northsearegion.eu/media/16076/20210121_44_hydrologischeauswirkung_doveelbe_baw.pdf.

Casulli, V.; Zanolli, Paola (2002): Semi-Implicit Numerical Modeling of Nonhydrostatic Free-Surface Flows for Environmental Problems. In *Mathematical and Computer Modelling* 36, pp. 1131–1149.

Casulli, Vincenzo (1999): A Semi-Implicit Finite Difference Method for Non-Hydrostatistic, Free-Surface Flows. In *International journal for numerical methods in fluids* 30, 425-440.

Casulli, Vincenzo (2009): A high-resolution wetting and drying algorithm for free-surface hydrodynamics. In *Int. J. Numer. Meth. Fluids* 60 (4), pp. 391–408. DOI: 10.1002/fld.1896.

Casulli, Vincenzo; Lang, Günther (2004): Technical Report. Mathematical Model UnTRIM. Validation Document. 1.0th ed. Edited by Bundesanstalt für Wasserbau. Trento, Hamburg. Available online at http://wiki.baw.de/downloads/wasserbau/mathematische_verfahren/pdf/Simulationsverfahren_Kueste_validation_document-untrim-2004.pdf.

Casulli, Vincenzo; Walters, Roy A. (2000): An unstructured grid, three-dimensional model based on the shallow water equations. In *International journal for numerical methods in fluids* 32, pp. 331–348.

Casulli, Vincenzo; Zanolli, Paola (1998): A Three-Dimensional Semi-Implicit Algorithm for Environmental Flows on Unstructured Grids.

Casulli, Vincenzo; Zanolli, Paola (2005): High Resolution Methods for Multidimensional Advection-Diffusion Problems in Free-Surface Hydrodynamics. In *Ocean Modelling* 10, pp. 137–151.

Central Dredging Association (CEDA) (2015): Integrating Adaptive Environmental Management into Dredging Projects. Position paper. Available online at http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2015-01-ceda_positionpaper-integrating_adaptive_environmental_management_into_dredging_projects.pdf.

Dialog Strombau- und Sedimentmanagement Tideelbe (2015): Ergebnisbericht. Available online at https://www.dialogforum-tideelbe.de/wp-content/uploads/2015/07/FOSUST-Ergebnisbericht.pdf, checked on 5/12/2022.

Elbe estuary working group (2012): Integrated management plan for the Elbe estuary. Available online at http://www.natura2000-unterelbe.de/links-Gesamtplan.php, checked on 6/17/2021.

EMOVE (2015): A governance vision on adaptive estuarine management. Interreg IVB project EMOVE. Available online at http://www.emove-project.eu/publications/emove-results.

Entelmann, Ingo; Röper, Henrich; Netzband, Axel (2013): Überlegungen für ein zukünftiges Sedimentmanagement Tideelbe. Abschlussworkshop Elsa-Elbe. Wasserstraßen- und

Schifffahrtsverwaltung (WSV); Hamburg Port Authority (HPA), 2013. Available online at http://elsa-elbe.de/assets/download/abschlussworkshop_12_2013/8_Entelmann-Roeper-Netzband_Ueberlegungen-Sedimentmanagement.pdf.

Forum Tideelbe (2020): Die Zukunft der Tideelbe gemeinsam gestalten. Ergebnisbericht des Forum Tideelbe. Hamburg. Available online at https://www.forum-tideelbe.de/files/download/200928-fte-ergebnisbericht-s-61-korrigiert.pdf.

Freitag, C.; Ohle, N.; Strotmann, T.; Glindemann, H. (2008): Concept of a sustainable development of the Elbe estuary. In : River, coastal and estuarine morphodynamics. RCEM 2007; proceedings of the 5th IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Enschede, the Netherlands, 17 - 21 September 2007. London: Taylor & Francis (Balkema-proceedings and monographs in engineering, water and earth sciences, 2), pp. 1085–1092.

Friedrichs, Carl T. (2010): Barotropic tides in channelized estuaries. In Arnoldo Valle-Levinson (Ed.): Contemporary Issues in Estuarine Physics. Cambridge: Cambridge University Press, pp. 27–61.

Frielingsdorf, Barbara; Klein, Bastian; Meißner, Dennis (2018): Langfristige Abflussvorhersage für die Binnenelbe mit FEWS. vom Input zum Report. Delft-FEWS – Regionales Anwendertreffen. BfG. Hamburg. Available online at https://www.hydrotec.de/wp-content/uploads/2019/07/2019-06-26-Vortrag-Frielingsdorf_etal.pdf, checked on 1/27/2022.

Gong, Wenping; Schuttelaars, Henk; Zhang, Heng (2016): Tidal asymmetry in a funnel-shaped estuary with mixed semidiurnal tides. In *Ocean Dynamics* 66 (5), pp. 637–658. DOI: 10.1007/s10236-016-0943-1.

Graf, Gerhard; Rosenberg, Rutger (1997): Bioresuspension and biodeposition: a review. In *Journal of Marine Systems* 11, pp. 269–278.

Hamburg Port Authority (HPA); Wasserstraßen- und Schifffahrtsverwaltung (WSV) (2008): Strombau- und Sedimentmanagementkonzept für die Tideelbe.

Heyer, Harro; Schrottke, Kertin (2013): AufMod (03KIS082-03KIS088). Gemeinsamer Abschlussbericht für das Gesamtprojekt mit Beiträgen aus allen 7 Teilprojekten. Bundesamt für Seeschifffahrt und Hydrographie (BSH). Available online at https://doi.org/10.2314/GBV:780783271.

Holzwarth, Ingrid (2018): Implications of direct anthropogenic pressures on dissolved oxygen dynamics in a well-mixed estuary, Kiel. Available online at https://hdl.handle.net/20.500.11970/105564.

HPA (2022): Gewässerkundliche Information - Pegel Hamburg-St.Pauli. Gewässerkundliches Jahr 2021 (01.11.2020 - 31.10.2021). Hamburg Port Authority.

Internationale Kommission zum Schutz der Elbe (IKSE) (Ed.) (2005): Die Elbe und ihr Einzugsgebiet. Ein geographisch-hydrologischer und wasserwirtschaftlicher Überblick, checked on 5/20/2019.

Knüppel, J. (2012): 'Spadenlander Busch' (Elbeestuary). Measure analysis in the framework of the Interreg IVB project TIDE. Measure 01. Hamburg. Available online at https://www.tide-toolbox.eu/pdf/measures/Measure_Spadenlander_Busch.pdf.

Lang, Günther (2017): PROGHOME – Software für Anwendungen im Küstenwasserbau. PROGHOME – Software for Coastal Engineering Applications. In : Kompetenz für die Wasserstraßen – Heute und in Zukunft. Forschungs- und Entwicklungsprojekte der BAW. Karlsruhe (BAWMitteilungen, 100), pp. 127–146.

Le Hir, P.; Monbet, Y.; Orvain, F. (2007): Sediment erodability in sediment transport modelling. Can we account for biota effects? In *Continental Shelf Research* 27 (8), pp. 1116–1142. DOI: 10.1016/j.csr.2005.11.016.

Liekens, Inge; Broekx, Steven; Nocker, Leo de (2013): Manual for the valuation of ecosystem services in estuaries. TIDE. Tidal River Development. Vlaams Instituut voor Technologische Ontwikkeling (VITO); Antwerp Port Authority. Available online at https://www.tide-toolbox.eu/pdf/reports/TIDE_ManualValuationEcosystemServicesEstuaries.pdf, checked on 2/11/2022.

Malcherek, Andreas; Piechotta, Friederike; Knoch, Denise (2005): Mathematical Module Sedimorph. Validation Document Version 1.1. 03.2005th ed. Edited by BAW. Bundesanstalt für Wasserbau. Hamburg. Available online at http://wiki.baw.de/downloads/wasserbau/mathematische_verfahren/pdf/vd-sedimorph.pdf.

Nasermoaddeli, Mohammad Hassan; Lemmen, Carsten; Hofmeister, Richard; Kösters, Frank (2014): The Benthic Geoecology Model within the Modular System for Shelves and Coasts (MOSSCO). In : 11th International Conference on Hydroinformatics (HIC 2014), (Special Issue - Journal of HydroInformatics). Available online at https://hdl.handle.net/20.500.11970/104579, checked on 1/28/2022.

OP_WEIR.DAT (2021) (BAWiki). Available online at https://wiki.baw.de/en/index.php/OP_WEIR.DAT, checked on 9/3/2021.

Reinert, D.; Prill, F.; Frank, H.; Denhard, M.; Baldauf, M.; Schraff, C. et al. (Eds.) (2021): DWD Database Reference for the Global and Regional ICON and ICON-EPS Forecasting System. Version 2.1.4. Deutscher Wetterdienst. Available online at https://www.dwd.de/DWD/forschung/nwv/fepub/icon_database_main.pdf.

Ridderinkhof, Herman (1997): The Effect of Tidal Asymmetries on the Net Transport of Sediments in the Ems Dollard Estuary. In *Journal of Coastal Research*, pp. 41–48. Available online at http://www.jstor.org/stable/25736104, checked on 4/13/2022.

Sander, Jacobs; Wouter, Vandenbruwaene; Dirk, Vrebos; Olivier, Beauchard; Annelies, Boerema; Kirsten, Wolfstein et al. (2012): Ecosystem Service Assessment of TIDE Estuaries. TIDE Project. Available online at https://www.tide-toolbox.eu/reports/ecosystem_service_assessment_of_tide_estuaries/.

Scully, Malcolm E.; Friedrichs, Carl T. (2003): The influence of asymmetries in overlying stratification on near-bed turbulence and sediment suspension in a partially mixed estuary. In *Ocean Dynamics* 53 (3), pp. 208–219. DOI: 10.1007/s10236-003-0034-y.

Song, Dehai; Wang, Xiao Hua; Kiss, Andrew E.; Bao, Xianwen (2011): The contribution to tidal asymmetry by different combinations of tidal constituents. In *J. Geophys. Res.* 116 (C12). DOI: 10.1029/2011JC007270.

TEEB (2010): The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Edited by Pushpam Kumar. The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Earthscan: London and Washington. Available online at http://teebweb.org/publications/teeb-for/research-and-academia/.

TIDE (2012): Management of Estuaries. The need to understand nature & society. Summary report, Interreg IVB project TIDE. Available online at https://www.tide-toolbox.eu/pdf/reports/TIDE_Summary_Report.pdf.

van de Kreeke, J.; Robaczewska, K. (1993): Tide-induced residual transport of coarse sediment; Application to the EMS estuary. In *Netherlands Journal of Sea Research* 31 (3), pp. 209–220. DOI: 10.1016/0077-7579(93)90022-K.

Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV) (2016): Digitales Geländemodell des Wasserlaufes. DGM-W 2016 der Unter- und Außenelbe. Available online at www.kuestendaten.de.

Wasserstraßen- und Schifffahrtsverwaltung (WSV); Hamburg Port Authority (HPA) (2008): Strombau- und Sedimentmanagementkonzept Tideelbe. Available online at https://www.kuestendaten.de/media/zdm/portaltideelbe/Allgemeine_Informationen/Publikationen/Datencontainer/H/SuSmanagementkTideelbe.pdf.

Weilbeer, Holger (2015): Sediment Transport and Sediment Management in the Elbe Estuary, Germany. In *Terra et Aqua* (139), pp. 11–23. Available online at https://www.iadc-dredging.com/article/sediment-management-elbe-estuary-germany/, checked on 6/1/2021.

Weilbeer, Holger; Winterscheid, Axel; Strotmann, Thomas; Entelmann, Ingo; Shaikh, Suleman; Vaessen, Bernd (2021): Analyse der hydrologischen und morphologischen Entwicklung in der Tideelbe für den Zeitraum von 2013 bis 2018. In : Die Küste, vol. 89. Available online at https://hdl.handle.net/20.500.11970/107518.

Winkel, Norbert (2020): Ästuarmanagement Tideelbe. Flexibel und adaptiv. BAW / BfG Kolloquium. Bundesanstalt für Wasserbau. Hamburg, 2020. Available online at https://izw.baw.de/publikationen/kolloquien/0/07_Winkel_%C3%84stuarmanagement%20Tideelbe.pdf, checked on 3/10/2022.

Winterwerp, Johan C. (2011): Fine sediment transport by tidal asymmetry in the high-concentrated Ems River: indications for a regime shift in response to channel deepening. In *Ocean Dynamics* 61 (2-3), pp. 203–215. DOI: 10.1007/s10236-010-0332-0.

WSA Elbe-Nordsee (2021): Bekanntmachung für Seefahrer 253/21. Allgemeinverfügung zur Verkehrsregelung auf der Seeschifffahrtsstraße Elbe. Wasserstraßen- und Schifffahrtsamt Elbe-Nordsee. Available online at https://www.elwis.de/DE/dynamisch/BfS/index.php?target=3&source=2&db_id=272396, checked on 4/19/2022.

Federal Waterways Engineering and Research Institute

Hamburg, June 2022

Signed,

Rahlf	Ortiz
H. Rahlf	V. Ortiz