IMMERSE WP3.1: Summary of status of current pressures and trends, and analysis of current measures effectiveness.

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Contents

1 Introduction

1.1 Context

The estuaries of the North Sea Region combine busy crossroads of transport routes with valuable ecological areas, as attested by the catchment areas and populations shown in Tab. 1.1. They offer opportunities to link important cities and ports (e.g. Hamburg, Tees, Antwerp, Hull-Immingham-Grimsby, Göteborg) within the European Megalopolis, while they also provide protected habitats for numerous species of fish, birds and sea mammals (e.g. porpoises, seals). As a result, the North Sea Region estuaries are of significant importance for both economic and ecologic reasons. However, these estuaries are under constant threat and subject to environmental pressures such as modified tidal range, larger and/or more frequent flooding, higher suspended sediment concentrations, loss of habitat[1] and diverse forms of pollution. These threats and pressures might impact the functioning and services of estuaries such that the implementation of management measures is required. The development of these measures is often challenging because they need to deliver multiple benefits. As a result, innovative solutions with large investments, long planning periods and stakeholder commitment are necessary.

Table 1.1: Catchment area and population as indicators for economic importance of the estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Catchment	21,863km^2 [2, 3]	1,092km^2 [4]	15,291km^2	767km^2	1,185km^2	50,229km^2 [5]	26,000km^2 [6]
Population	10 million [2, 3]	687,000 [4]	More than 2 million [7, 8]	400,000	400,000	1 million [5]	921,000 [9]

1.2 This report

The (IMMERSE) Implementing Measures for Sustainable Estuaries project focuses on international co-operation to address the challenges and threats faced by the estuaries. More specifically, a three step approach is used to address the challenges. First, the different pressures are investigated and potential solutions are explored. Subsequently, solutions are assessed, tested, and recommendations are provided. Finally, preparations for the implementation of the measures are undertaken, if possible. However, not all individual measures will go through all three development steps. First, because measure development and implementation is a long-term process, the project focuses more on improving the measures in the specific phase they are in and advancing them to the next phase. Therefore, measures with existing technical designs will be supported by pilot testing, while an already fully-assessed measure will be supported in its implementation phase. Second, some partners are not in the legal position to implement certain (larger management) measures.

The IMMERSE project consists of 7 work packages:

- WP1. Project management
- WP2. Communication activities
- WP3. Measures: Defining pressures and solutions
- WP4. Measures: Assessments, tests and pilots
- WP5. Measures: Preparing for implementation
- WP6. Horizontal: Stakeholder integration
- WP7. Horizontal: Transnationality

This report is part of the different actions foreseen in Work Package 3. 'Measures: Defining pressures and solutions' and presents the results of activity 3.1 - Summary of status of current pressures and trends, and analysis of current measure effectiveness. The aim of this work package is to analyse the estuary pressures to improve collective understanding of anticipated pressures and trends, as well as evaluate existing measure effectiveness. Specifically, measures will be evaluated for their delivery of expected benefits and transferability - including similarities among measures to address common problems. Based on the results from this activity, partners will work on designing solutions for their estuaries. Partners already have an indication of themes that require solutions, e.g. using dredged material for flood risk management. The goal of this activity is to form the foundation for others to tackle the issues in other projects or in their strategies or processes. However, it should be kept in mind that not all common trends and pressures identified can be addressed during the project. For activity 3.1, national and regional organizations relevant for estuary management are the key target group. Sometimes these are the partners themselves, sometimes project supporters. Surveys and interviews will primarily involve the target groups in these activities. This report presents the results of this task. It consists of 2 major topics:

- Overview of existing and anticipated/future pressures and trends, based on EU projects and current research.
- Analysis of existing measures' ability to deliver identified benefits

In order to limit the scope of the present work package, it was chosen to only consider a select number of pressures , and for which the following objectives are suggested:

- To achieve and conserve good water and sediment quality
- To develop strategies for the management of morphology, sediments and dredging works in relation to the good functioning of the ecosystem
- To create sufficient intertidal habitat and fresh water marshes
- To control risks of flooding and climate change

1.3 Note on the information obtained

The initial information given by the IMMERSE partners appeared to be very heterogeneous, possibly reflecting the research/management focus of the different partners, or reflecting specific characteristics of a single estuary. The available material or the available data was homogenized by requesting missing information from the partners.

In second instance, the authors held online meetings with most of the partners to obtain more information about the trends and pressures that are relevant for their system. Regarding the measures, an enquiry form was devised in collaboration with the project manager at s.Pro which was subsequently sent to all partners. Eventually, the enquiry forms for all measures were completed and returned.

Whilst this process yielded a lot of useful data, it is pointed out that part of the information provided in this report could be further specified through a deeper scientific analysis. Hence, conclusions derived herein are to be qualified as somewhat indicative since their substantiation would require a lengthier and more in-depth study.

Finally, for some estuaries, it was chosen to complete the received data with other information sources. It was therefore decided to use the Humber information from the TIDE project reports of the Humber cubage study[10] and the interestuarine comparison[11]. As a result, the discussion of the Humber is effectively limited to hydrology and morphology (Chapter 3). Likewise, missing data about the geometry and the tide in the Göta Älv has been partly resolved by resorting to scientific papers and by using water level data available from the Swedish Meteorological and Hydrological Institute (https://www.smhi.se). Also, discharge data for the Tees were obtained from the UK Department for Environment Food & Rural Affairs (https://environment.data.gov.uk/hydrology/explore) and consisted of daily averaged values at the Low Moor for the period 2001-2010. Finally, additional water level data for the Danish fjords were downloaded from the Danish Meteorological Institute (https://www.dmi.dk).

1.4 Outlook

The remainder of this report is organized as follows. First, the estuaries of the IMMERSE project will be briefly described in Chapter 2. Next, the trends and pressures related to hydrology, water quality and ecology will be discussed in Chapters 3, 4 and 5, respectively. Finally, Chapter 6 will be devoted to the measures that have been proposed to mitigate the pressures, with conclusions and an indication of transferability of measures to other estuaries.

2 The estuaries

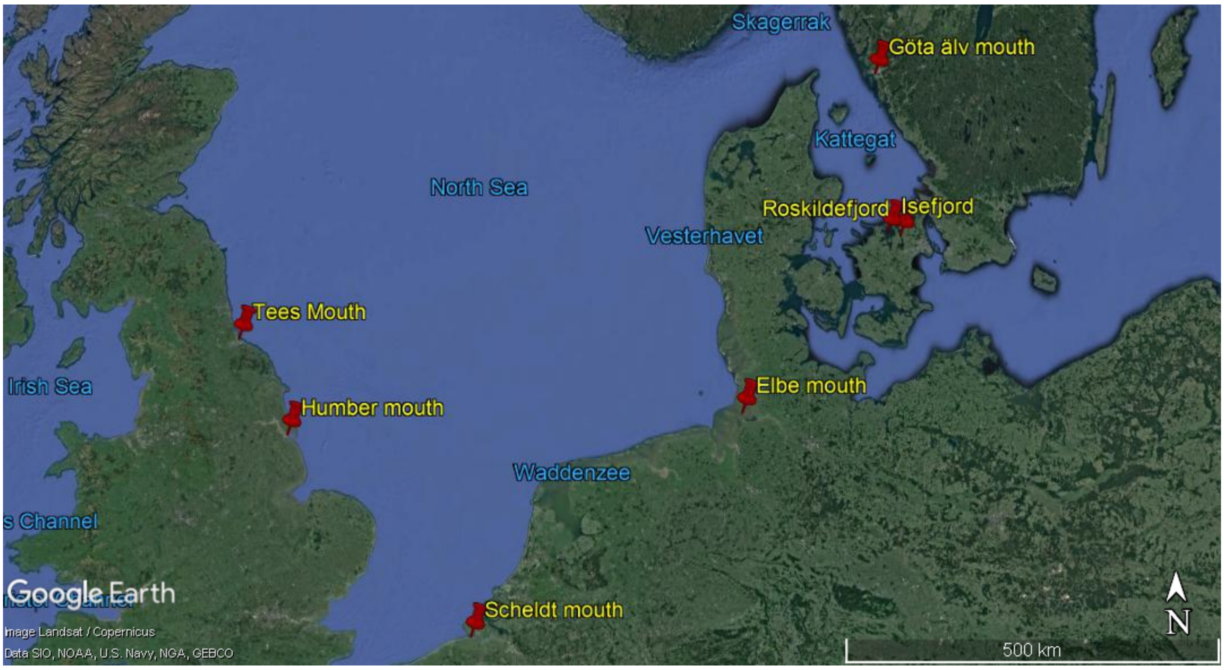

Figure 2.1: Satellite image of the North Sea showing the location of the 7 estuaries of the IMMERSE project

As mentioned previously, the IMMERSE project focuses on 7 estuaries, all discharging either in the North Sea or the Kattegat (see Fig. 2.1). This section briefly introduces each estuary, summarizing its geographic features and its importance for the economy. Each summary is entirely based on the information provided by the partners, unless specified otherwise by means of citations.

2.1 The Scheldt

The Scheldt (see Fig. 2.2) is a 355km long river originating in St. Quentin (France). Its catchment covers approximately 21,863km^2 distributed over the north of France (31%), the west of Belgium (61%) and the southwest of The Netherlands (8%). The river can be divided into the Upper Scheldt (in which there is no tidal influence) and the tidally influenced part. The latter part extends from the sluices at Gent (160km upstream) until the mouth at Vlissingen. The tidal part of the Scheldt can be further divided into the Upper Sea Scheldt and Lower Sea Scheldt, together forming the Sea Scheldt, and the Western

Figure 2.2: Satellite image of the Scheldt estuary and its surroundings

Scheldt. The Upper Sea Scheldt stretches from Gent to Antwerp, the Lower Sea Scheldt from Antwerp to the Belgian-Dutch border, and the Western Scheldt from the border to the mouth. The Sea Scheldt has three main tributaries: the Dender, the Durme and the Rupel. The canal Gent-Terneuze bypasses Antwerp and directly connects Gent with the saline part of the Western Scheldt. The river basin area is mainly urban with a total population of the catchment over 10 million people, which is an average population density of 477 inhabitants.km^{-2}.

2.2 The Elbe

The River Elbe (see Fig. 2.3) is a 1091km long river originating in the Karkonosze Mountains of the Czech Republic (1,386 m above sea level). Its catchment covers approximately 148,286km^2. The Czech part of the Elbe is 361km long, while the German part of the Elbe is 730km long and crosses the German Federal states of Saxony, Saxony-Anhalt, Lower-Saxony, Hamburg and Schleswig-Holstein where it reaches the North Sea. The river can be divided into the estuarine part, under tidal influence, from the Wadden Sea to the weir (149km upstream) and the non-estuarine part. The estuarine part of the Elbe can be divided into the lower Elbe, from Geesthacht to Cuxhaven, and the outer Elbe, from Cuxhaven to the Wadden

Figure 2.3: Satellite image of the Elbe estuary and its surroundings

Sea. The Elbe estuary has several main tributaries: the Ilmenau, Este, Lühe, Schwinge, Pinnau, Krückau, Stör and Oste. There is a canal, the Kiel Canal, connecting the Elbe with the Baltic Sea at Brunsbüttel. The Elbe is economically important for the region since it is the main shipping channel to the largest port of Germany, the port of Hamburg. Out of the 4.3 million inhabitants of Metropolitan Region Hamburg, 156,000 are directly or indirectly employed by the port. In total the port of Hamburg generates directly or indirectly 269,000 jobs. The shore area of the Elbe estuary is also densely populated (more than 2 million people) and is intensely used for smaller ports, industry, power stations, fishery as well as recreation and tourism. Additionally, the three neighbouring states of Schleswig-Holstein, Lower-Saxony and Hamburg are responsible for the nature conservation. Finally, the national Waterways Administration (WSV) and the Port Authority are responsible for the maintenance of the estuary and the port. Subsequently, the preservation of the valuable nature area and harmonization of ecological and economical demands of the estuary is a joint objective for the three federal states.

2.3 The Tees

Figure 2.4: Satellite image of the Tees estuary and its surroundings. The location of the Tees Barrage has been indicated.

The Tees (see Fig. 2.4) is a 137km long river originating at Cross Fell in the Pennines and emptying in the North Sea on the north-east coast of England. It drains an area of almost 2,000km^2, while its estuary covers an area of 69ha. The tidally influenced part of the Tees is limited by the Tees Barrage at Stockton on Tees. The Tees barrage was built to catalyse investment and improve the economy after the industrial decline. In total 672,000 people live in the Tees Valley, among which 369,600 live downstream of the Tees Barrage around Teesmouth.

2.4 The Fjords

The Roskilde Fjord and Isefjord are the estuaries of a 2,000km^2 river basin. The Isejord is 35km long and covers a total area of 305km^2. It is connected to the Kattegat Sea at its Northern border. The Roskilde Fjord has a total length of 38km and covers an area of 74km^2. It is not directly connected to the Kattegat Sea, but opens towards the Isefjord on its north-west border. The total population of the catchment area is 400,000, which is unequally distributed between denser urban areas south and east of Roskilde Fjord

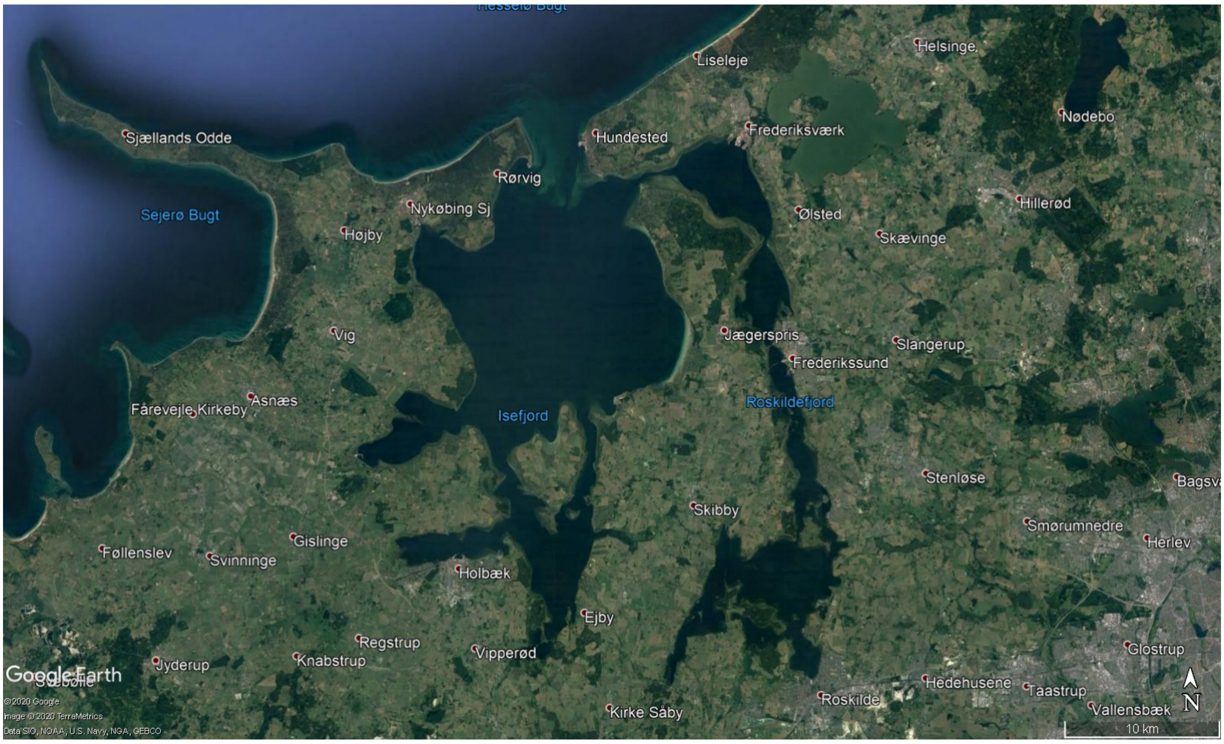

Figure 2.5: Satellite image of the Fjords and their surroundings

and lighter populated areas south and west of the Fjords. The three major cities are Roskilde, Holbaek and Frederiksværk. The region is economically important as tourist area since several stretches along the coastline are classified as bathing area. Simultaneously, several islands in the Fjords function as wild life habitats and breeding sites for the rich bird life that characterises the area. During the last decade, the Roskilde Fjord has experienced severe flooding. As a result, local solutions for flood protection have been initiated and in some places completed, but there is a large wish for a regional storm barrier solution.

2.5 Göta Älv

The Göta Älv is a 731km long river, and the longest river in Sweden. Here the lower part from Lake Vänern in the north to Göteborg in the south will be considered, which spans 93km[12] (see Fig. 2.6). Slightly upstream of the city of Kungälv, the river splits into the Nordre Älv, taking two thirds of the total river flow, and the Göta River estuary, taking one third of the total river flow. This report considers the latter branch which flows through the Port of Gothenburg, Scandinavia's largest and most important port. The city of Gothenborg and the surrounding Göta River valley are highly populated and have a

Figure 2.6: Satellite image of the Göta Älv passing through Göteborg.

long history of anthropogenic activities such as settlements, shipping, harbours, industry, ferries, tourism and other activities. As a result, the river is used by many different actors with various interests. For example, the region has infrastructure such as large roads and railroads but also faces contaminated soil.

2.6 The Humber

The Humber is a converging estuary that is formed by the confluence of the Ouse and Trent rivers at Trent Falls. The Humber proper has a length of approximately 60 km, while the tidal parts of the Ouse and Trent are 65 and 85 km long, respectively. Starting from the confluence, the inner part of the Humber extends over the first 25 km up to Humber Bridge, the middle part up to a distance of 50 km (Hawkins Point) while the more seaward region defines the lower estuary. In this report, the upper Humber is understood to coincide with the inner part while the lower Humber consists of the middle and more seaward part. The total surface area of the Humber is about 16,000 ha, of which 27% is intertidal and marsh area.

Figure 2.7: Satellite image of the Humber estuary. The Ouse and Trent river are approaching the confluence from the West and the South, respectively.

2.7 Categories

Since every estuary is unique, it is key to identify some common characteristics between them, such that shared potential threats can be addressed. However, this procedure is not trivial. In fact, estuaries all over the world are so diverse, that it is even challenging to come up with a single definition englobing them all, as proven by the numerous attempts that were made[13–24]. Nevertheless, for legal scrutiny (e.g. lawyers and planners) it is imperative to develop such definitions. As an illustration, the European Union (EU) Water Framework Directive requires that catchment management plans have components in which all surface waters are classified, monitored and compared against reference conditions. Following that, we will use the definition adopted by the European Union, designating estuaries as[25]: "Downstream part of a river valley, subject to the tide and extending from the limit of brackish waters. River estuaries are coastal inlets where, unlike 'large shallow inlets and bays', there is generally a substantial freshwater influence. The mixing of freshwater and sea water and the reduced current flows in the shelter of the estuary lead to deposition of fine sediments, often forming extensive intertidal sand and mud flats. [...]"

Additionally, it is beneficial from a scientific and management point of view to attempt to classify estuaries into several types, rather than to consider them on an individual level. Indeed, it can be expected that estuaries of the same type deal with similar pressures and, as a result, particular measures can be applied in several estuaries of the same type. On a first sight, it is already possible to differentiate the seven estuaries of the IMMERSE project based upon large scale characteristics. The UK estuaries and the Scheldt broaden toward the mouth. They are subject to a considerable tidal range morphology with moderate wave action[26]. The situation at the mouth of the Elbe estuary is further influenced by a complex morphology. According to Harten and Vollmers, the situation at the mouth of the Elbe estuary is characterized in the north by individual sand banks and shoals, and in the south by extensive tidal flats and tidal creeks as well as by the approximately 10 km long Kugelbake training wall[27]. The Fjords (Roskildefjord and Isefjord), are characterized by the presence of a sill at their mouth which constricts estuarine mixing. Finally, the Göta Älv can be categorized as an inundated coastal valley.

Classifications can be done along several parameters, which can range from water balance[28], water circulation[23,29,30], to salinity, tides[18,19,31], sedimentology[32], geomorphology[15,29,30,33] or a combination of these[18,20,34–36]. However, instead of defining global categories based on several different parameters (circulation, salinity distribution, sedimentation, tide), we define categories for each parameter and subsequently determine how an estuary fits in all these categories. This approach allows to immediately identify estuaries with similar potential pressures, and therefore, transferable measures. For the estuaries of the IMMERSE project, we decided to first differentiate along hydrodynamic and geomorphologic characteristics.

3 Hydrology/morphology per estuary

The hydrology and the morphology of an estuary are the key stones upon which many other parameters depend. Sedimentation processes, distribution and transport of tracers, and basic ecological processes are determined by estuary characteristics such as water-depth, flow velocities and turbidity. Accordingly, it was chosen to start the inter-estuary comparison with an inventory of some hydrological and morphological characteristics.

3.1 Description of the system

3.1.1 Geometry

Table 3.1: Length of each estuary.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Length (tidal) river	160km[2,3]	17km[4,37]	149km[11]	35km[38]	42km[38]	55km	60km (bifurcation), 145km (Trent), 125km (Ouse)

The most straightforward way of comparing estuaries is to analyse their geometrical properties: length, depth and width. The length of an estuary can be defined based on tidal properties, salinity properties or the presence of an upstream construction (also referred to as tidal limit) where the tidal propagation is terminated (e.g. weir). For the estuaries of the IMMERSE project, three estuaries are characterized by the presence of a weir: the Elbe, the Scheldt and the Tees. The tide in the Göta Älv is very weak (see Sec. 3.1.2) and its propagation is terminated at a dam with a lock complex and a hydropower station at Lilla Edet, some 55km from the river mouth. Therefore, Lilla Edet is set as the upstream boundary part of the estuary. The two Fjords are naturally semi-enclosed and therefore also have a specific length. Like the Göta Älv, however, the tides are weak and contribute only little to the water flow. Finally, the Humber does not have a tidal limit, but the river splits at 60km from the mouth into the Ouse and the Trent. The tidal influence is discernible up to 65km from the confluence on the Ouse and 85km from the confluence on the Trent. Due to these difference in tidal intrusion for the Ouse and the Trent, we maintain 60km as the river length. From Table 3.1, it is clear that the Tees and the Fjords are relatively short estuaries, while the Elbe, the Scheldt and the Humber are relatively long estuaries. The Göta Älv is somewhat distinct as it is not really short but lacks a significant tidal influence.

Alongside the length, two other important geometrical properties are the thalweg depth along the estuary and the low-water width along the estuary. The thalweg depth of each estuary is displayed in Fig. 3.1, and again, the differences in estuary lengths are evident. Through each longitudinal depth profile a fourth order polynomial was fitted using the least square method. This choice for a fourth order

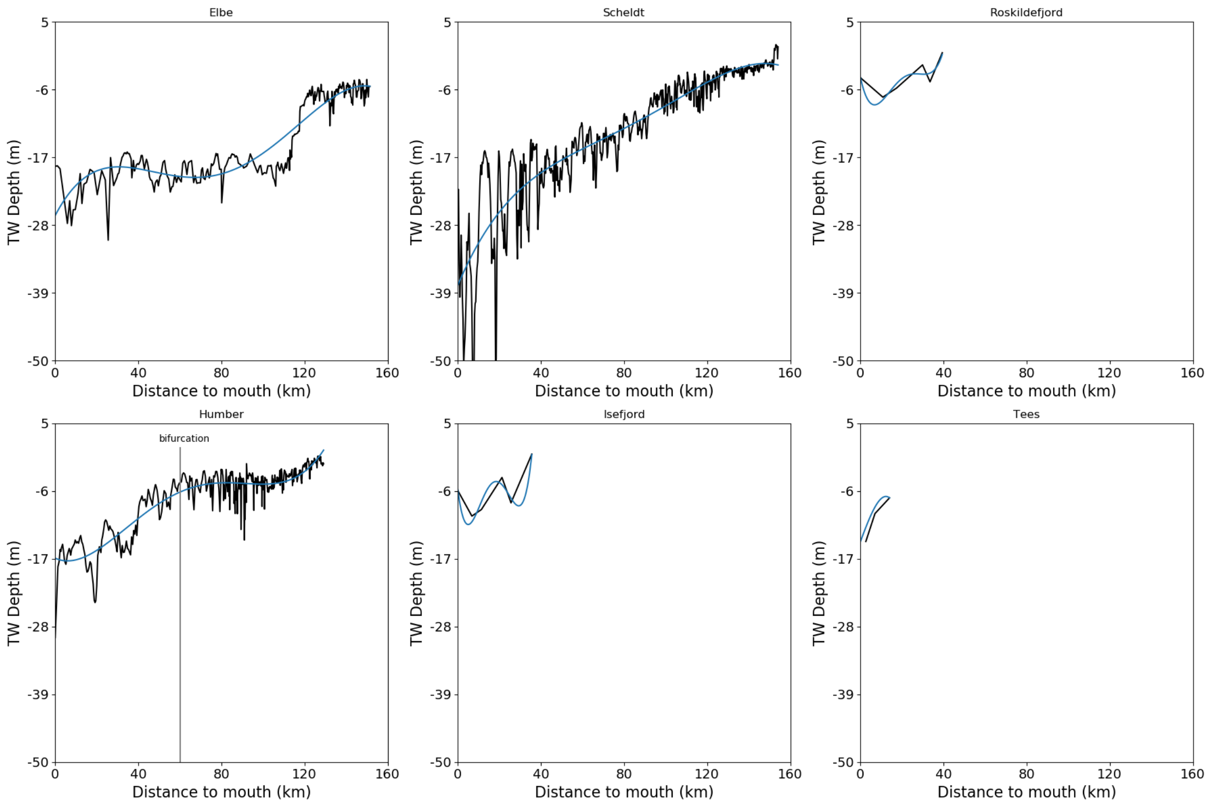

Figure 3.1: Thalweg depth of the different estuaries and polynomial fits. For the Elbe, the Scheldt and the Humber-Ouse [10], the low-water depth was considered. For the Fjords, tidal amplitude is minimal and mean-water depth was used. For the Tees, mean-water depth was also used. It was chosen to show the graphs using the same depth range in order to highlight the differences in mean depth.

polynomial was based on a trade-off between number of available data points, fit to the overall shape, and avoidance of over-fitting. The fitting polynomials of every estuary are displayed again, but now in the same panel, in Fig. 3.2. Here, the curves were scaled by the estuary length on the x-axis and by the thalweg depth at the mouth on the y-axis. No depth data were provided for the Göta Älv, but a typical thalweg depth is reported to be 7–10m[12].

The thalweg depth allows to identify any estuary specific trends, such as the remarkable fluctuations in the thalweg depth of the Scheldt (order of several tens of m over a few km). However, the global trend, emphasized by the fitted curves highlights some similarities between the Elbe, the Scheldt, the Humber, and even the Tees, in terms of depth evolution along the estuary. The depth is largest at (or very near) the mouth and then globally decreases towards the upper bound of the estuary. However, the rate of the depth decrease varies over the estuary and is sometime even locally negative (i.e. local increase of depth

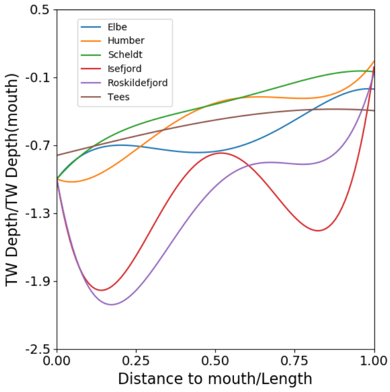

Figure 3.2: Scaled polynomial thalweg fits.

towards the upper estuary), for example for the Elbe and the Humber. The Fjords have a very different depth profile. The profile is marked by a sill at the mouth from which the depth first increases. No clear trend in the depth profile is discernible and the Fjords are marked by several deeper and shallower areas.

A similar exercise was carried out for the width of the estuary. The low water width is displayed in Fig. 3.3, along with the fits. In general it was chosen to fit the low water width with exponential functions, but this appeared inappropriate for the Fjords. The latter were fitted using a polynomial. The exponential fits are in turn scaled and displayed in the same panel in Fig. 3.4. It is clear that the estuaries of the Elbe, the Scheldt, the Humber and the Tees show a similar exponential decay of their width, which matches a funnel shape. However, it has to be pointed out that the Tees width is only based on three points. The estuaries also differ in the rate at which the width decays. The exponential decay of the Tees is the weakest followed by the one of the Elbe. The Scheldt and the Humber have similar exponential decays. Furthermore, it is important to re-emphasize that the Tees is much shorter than the other three funnel shaped estuaries. Finally, the Fjords do not have an exponentially decaying width, highlighting their different geometry. No width data were provided for the Göta Älv, but a typically width is reported to be 100–200m with a local widening to 300m just upstream of the Nordre Älv junction[12].

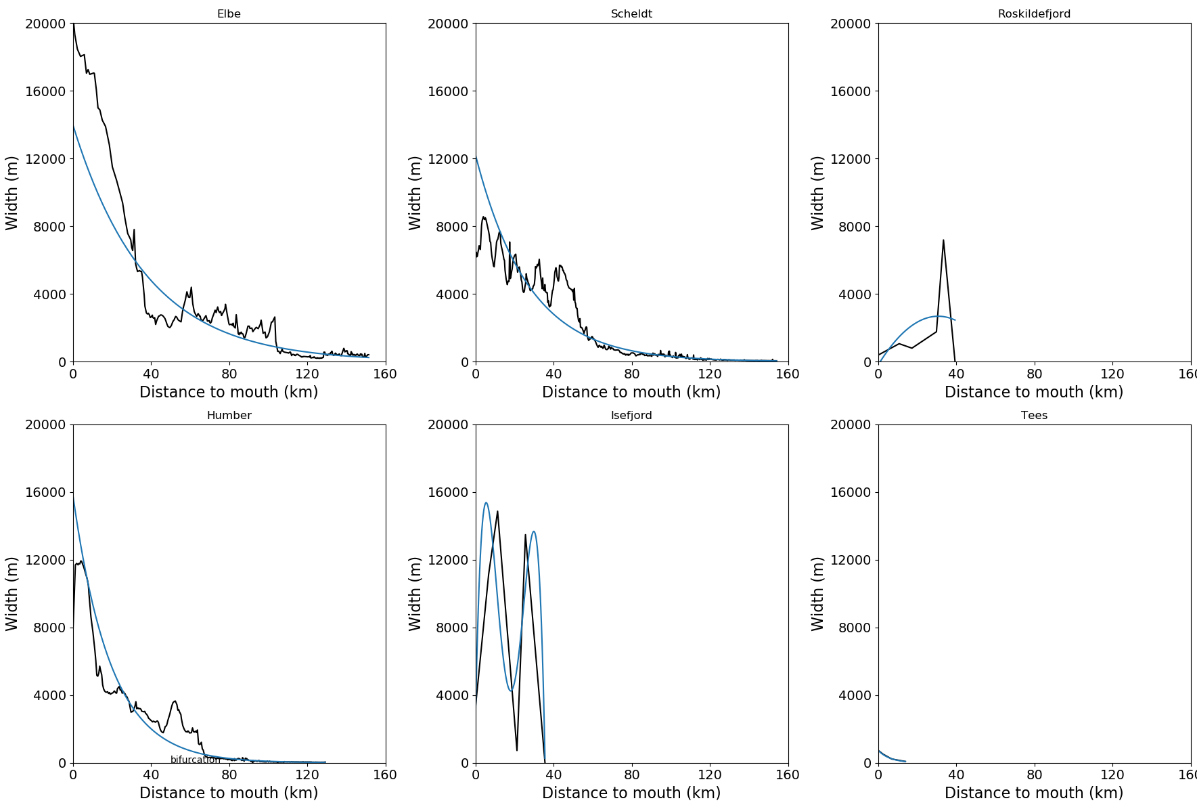

Figure 3.3: Low water width of the different estuaries and fits (exponential or polynomial).

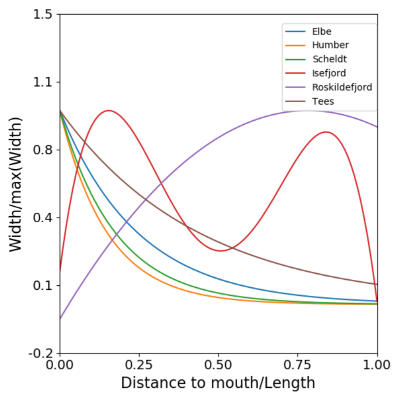

Figure 3.4: Scaled exponential and polynomial low water fits.

3.1.2 Tide

Besides the geometry, the tidal amplitude is another meaningful parameter to compare estuaries. It determines whether an estuary can be considered as microtidal (with a tidal range between 0m and 2m), mesotidal (between 2m and 4m) or macrotidal (with a tidal range over 4m)[31]. According to the tidal regime, estuaries are expected to be subject (or not) to certain specific pressures.

The tide within the estuary depends on several factors of which the two most important are (i) the tidal amplitude at the mouth and (ii) the geometrical shape (described in the previous section) of the estuary, including its depth and length. The tidal amplitude at the mouth determines the amount of tidal energy that enters the estuary, while the the geometrical shape of the estuary determines if this energy is dissipated, reflected or funneled (i.e. the energy concentrated over a smaller surface due to a decrease in width). Finally, when there is an up-estuary limit (i.e. weir, dyke or locks) the length controls the possibility of tidal resonance, which yields an increase of the tidal amplitude throughout the system. The latter has not been clearly observed in the IMMERSE estuaries. From the Table 3.2, two distinct categories emerge. The Scheldt, the Tees, the Elbe and the Humber have large tidal ranges (above 2.90m), while the Göta Älv and the Fjords have small tidal ranges (less than 0.5m).

Table 3.2: Tidal ranges at the mouth for each estuary.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Tidal range at the mouth	3.96m	4.60m	2.92m	0.16m	0.19m	0.22m	4.39m

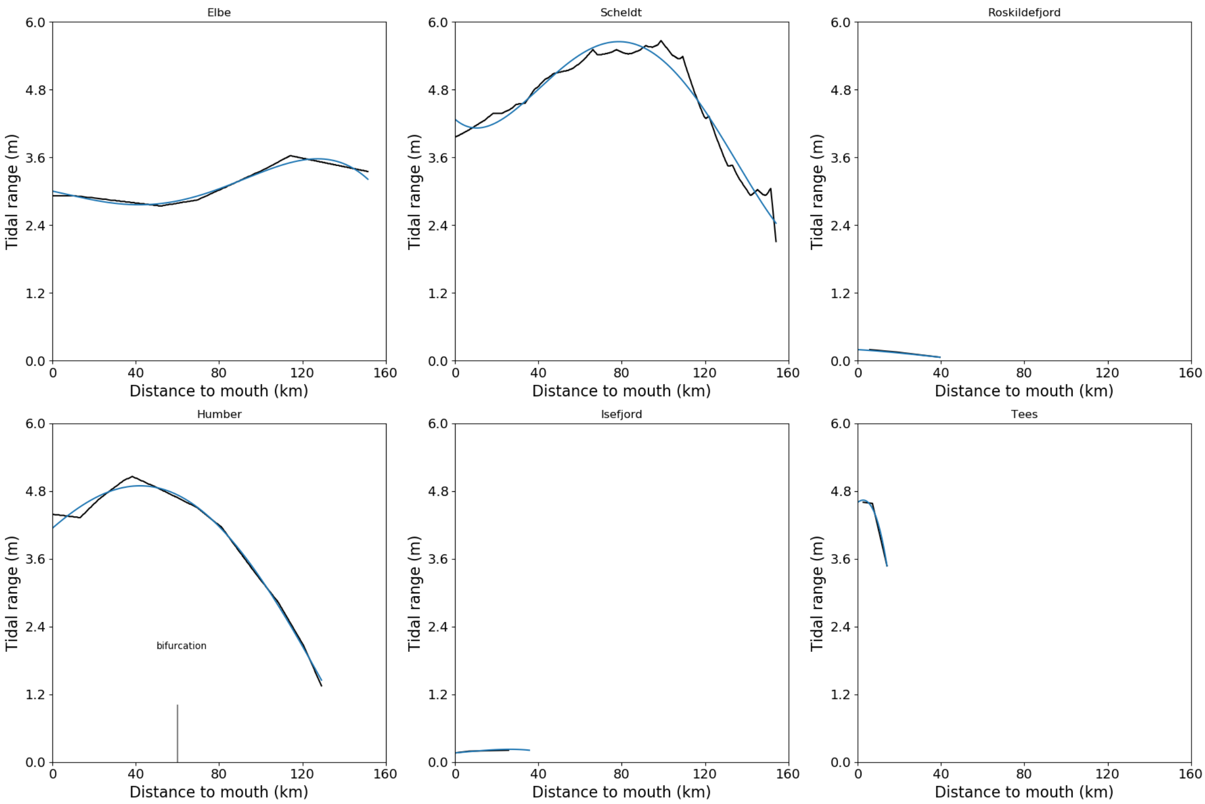

Figure 3.5: Tidal range at mean tide for the different estuaries and polynomial fits

As mentioned earlier, the width and depth of an estuary are of crucial importance for the tidal wave propagation[11]. In general, a funnel shaped width contributes to increase of the tidal range. However, as an estuary becomes more shallow in the upstream direction the relative importance of friction increases which lowers the tidal range. Furthermore, this interplay may be modified by reflections which occur at locations where the width or depth change abruptly and at the tidal limit. In the latter case the reflected wave may enhance or counteract the upstream propagating tidal wave, depending on the resonance properties of the basin. For the meso -and macrotidal funnel shaped estuaries this in general leads to both regions where the tide is enhanced and decreased relative to the value at the mouth.

The tidal ranges are displayed in Fig. 3.5 together with the polynomial fits. For the funnel shaped estuaries Elbe, Scheldt and Humber the enhancement of the tide is clearly visible, although the relative position where the maximum amplitude occurs differ. This is likely contributed to effects of width variation. The Scheldt and the Humber show a decrease in the tidal amplitude in the landward part, coinciding with the presence of shallow areas. For the Elbe, on the other hand, a slight decrease in amplitude is seen in first 80km, followed by a clear increase in the more upstream part. The Tees estuary does not

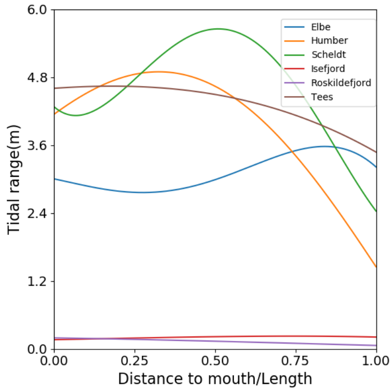

Figure 3.6: Scaled polynomial tidal range fits.

display tidal amplification despite its funnel shape. This characteristic is related to the short length of the estuary.

The Fjords have a very small tidal amplitude. However, this is clearly related to the reduced amplitude at the mouth and not to their geometry. In fact, water levels in the Fjords and in the Göta Älv are dominated by wind effects as can be seen in Fig. 3.7. Here, the total water level and the tidal contribution are shown for the Isefjord (left panel), based on predictions. For the Göta Älv (right panel) the observed water level for the year 2019 has been shown, along with the tidal signal that was reproduced a posteriori by using the UTide Matlab program[39].

Since the tidal range is around 4m or larger for the Elbe, the Scheldt, the Humber and the Tees, these four estuaries can be categorized as macrotidal, while the Fjords and the Göta Älv can be characterized as microtidal. This categorization has significant impact on the pressures to which the estuaries are subject. For example, estuaries with a large tidal range could face navigability issues at low water, but need high and sturdy dikes to protect against flooding at high water. Additionally, estuaries with large tidal ranges are more susceptible to be subject to tidal pumping (see Sect. 3.2.5) which is the case for the Elbe and - to a lesser extend - the Scheldt and the Humber. Tidal pumping is a phenomenon where the tidal water motion yields a flood directed (i.e. up-estuary) net sediment transport. Tidal pumping may arise from a variety of mechanisms[40], and a brief theoretical framework is given in Section 3.2.5. On the other hand, microtidal estuaries can be more subject to weather related flooding events, such as storms and this is also the case for the Fjords and the Göta Älv, see Sect. 3.2.6. The flooding risk associated with storm events is certainly not negligible in macrotidal estuaries. However, storms need to coincide with high water and/or spring tides to pose a significant threat.

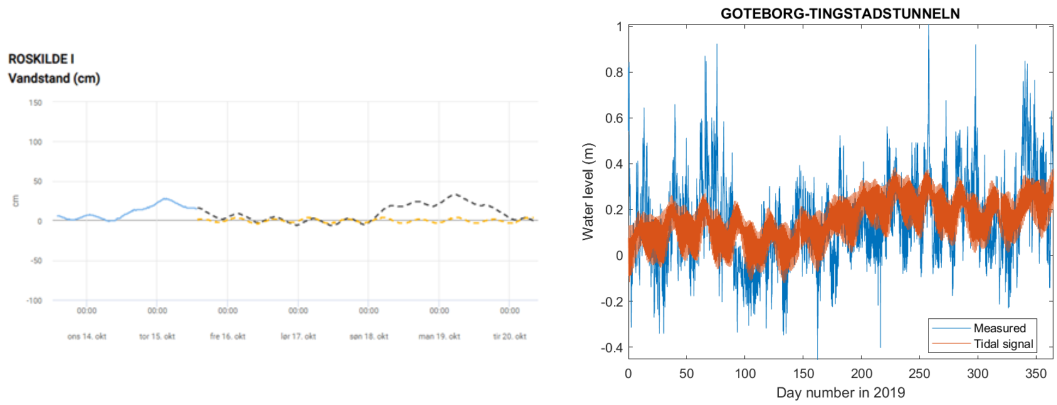

Figure 3.7: Temporal behaviour of total water level and tidal contribution at a specific location for the Roskildefjord (left) and the Göta Älv (right).

3.1.3 Discharge

Besides the tide, the second important hydrological factor of an estuary is its discharge. The level of discharge has several major implications. From a purely hydrological point of view, the discharge partly determines the navigability of the estuary. Additionally, periods of low discharge lead to intrusion of saline seawater up the estuary and can disrupt drinking water intake, the intake of water for agricultural purposes and alter the ecological conditions upstream of the river. High discharge episodes, on the other hand, generate flooding risks, such that estuaries with a large variability in the discharge have to focus both on navigability and flood protection. Nevertheless, high discharge can also be beneficial for flushing out sediment that is accumulating in the estuary due to the tidal pumping mechanism mentioned in Sect. 3.1.2.

On much larger timescales, the discharge regulates the global salinity dispersion in the estuary. Therefore, it influences the distribution of habitats (polyhaline, mesohaline, oligohaline). However, this aspect is more relevant for ecological purposes and is addressed in Chapter 5 on ecology.

Table 3.3: Discharges.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Summer discharge (m^3 s^{-1})	30[2,3]	13	815 (medium)	Not applicable	Not applicable	575 (maximum)[5]	38

Table 3.3: Discharges.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Winter discharge (m^3 s^{-1})	300[2,3]	37	866 (medium)	Not applicable[38]	Not applicable[38]	1,000 (maximum)[5]	320
Average discharge (m^3 s^{-1})	107[11]	22	722[11]	11	11	No information	209[11]
Dry events, 5%percentile (m^3 s^{-1})	34[11]	3.5	247[11]	No information	No information	No information	34[11]
Flushing events, 95%percentile (m^3 s^{-1})	253[11]	73	1709[11]	No information	No information	No information	615[11]

3.2 Pressures and trends related to hydrology

The estuaries of the IMMERSE project were subjected to human interventions for centuries. In particular land reclamation, construction of dikes and barriers for flood protection, as well as deepening of the fairway, altered the estuary. Consequently, the natural estuarine system is out of balance and subject to pressures. However, the exact nature of the dominant pressure differs from estuary to estuary.

The examination of some hydrological and morphological characteristics of each estuary in the previous paragraph highlights the key similarities and the key differences between the IMMERSE estuaries. These similarities and differences directly impact the hydrological pressures observed in the estuary. It is also beneficial to remark that some pressures are interconnected. For example, sand extraction causes deepening, which in turn leads to an increase in tidal amplitude due to reduced friction. The increase in tidal amplitude itself can lead to higher velocities with an increase in sediment concentration or the loss of ecologically valuable low dynamic shallow water and intertidal areas. We refer to these 'secondary' pressures as 'connected pressures'.

Additionally, the economical benefits of an estuary also contribute to the pressures. For example, the Elbe, the Göta Älv and Scheldt have inland ports, resulting in a need for regular dredging or even permanent deepening of the fairway. On the other side, the Fjords have a different economic focus. They have no major ports, but function more as a recreational area with a lot of housing. As a result, they do not face the need for dredging but are more vulnerable for weather caused floods.

These factors lead to a regrouping of the estuarine pressures of hydrologic/morphologic origin in different categories. Additionally, it was chosen to only consider pressures for which a measure is developed by one of the partners within the IMMERSE project. Finally, only hydrology related pressures are considered in this section: permanent removal of sediment, river straightening and land reclamation, increase in tidal amplitude, reduced discharge, tidal pumping and weather induced flooding.

3.2.1 Permanent removal of sediment from the estuary

Sediment removal from an estuary can lead to changes in the geometry and bathymetry of the estuary and, accordingly, to changes in tidal propagation. Sediment removal can occur in three different ways. First, there is capital dredging, the action of permanently widening and/or deepening the fairway to facilitate port access of ships. Second, there is the extraction of sand for commercial purposes. Finally, there is the need for maintenance dredging. All these three factors can potentially contribute to a (local) enlargement of the cross-section which (in turn) influences the tidal propagation. However, a distinction has to be made between the different types of sediment removal. For instance sand extraction, whether commercial or not, can be considered as a direct pressure, and the IMMERSE project provides a measure for it. On the contrary, dredging is not a direct pressure itself, but is the main cause for several pressures, such as sand extraction and increase in tidal range. The relation between maintenance dredging and sand extraction is explained later in this paragraph, while the relation between capital dredging and increase in tidal range is elaborated in Sect. 3.2.3.

Sand extraction in the Scheldt occurs on a large scale since the 1960's by governmental entities, and since 1981 by commercial entities. From 1956 to 2012, 2Mm^3 of sand was yearly extracted on average from the Western Scheldt[41]. From 1981 to 2012, 1.5Mm^3 of sand was yearly extracted on average from the Sea Scheldt, with strong variation from year to year[41]. The sand extractions before 1980 were generally related to infrastructural works for the Port of Antwerp, while more recently sand extractions were used for the building of dykes.

Additionally, maintenance dredging can also potentially lead to indirect sediment extraction. It usually occurs in estuaries with inland ports (i.e. the Elbe, the Scheldt and the Humber). The conditions under which maintenance dredging leads to sediment extraction are very specific. They depend on the general sediment transport patterns within the estuary, the type of sediment (silty, clayey, sandy) as well as on the dumping strategy used for the dredged sediment. To illustrate these differences, we take two case examples: the Elbe and the Scheldt.

In the Elbe, dredged material involves in general both sandy and silty species. The sandy species are typically original marine sediments which are transported upstream due to tidal pumping (see Section 3.2.5). The silt comes mainly from riverine sediments. Dredged sandy material is mainly relocated within the estuary in areas with sufficient depths to support the natural sediment transport regime within the estuary and where it does not cause any disturbance. Riverine fine sediments enter into the estuary with certain levels of contamination, for instance of heavy metals. Thus, dredged fine material with non-acceptable levels of contamination must be treated on land at the METHA plant. This sediment is permanently removed from the estuary. The majority of the fine sediments is relocated in western Hamburg (within the estuary close to Neßsand) or in the North Sea (buoy E3). Since the transport pattern in the estuary is mostly flood dominant, the import of sediments into the upper estuary prevails. Thus, measures that relieve the sediment budget in the estuary and remove the oversupply of fine sediments out of the system are considered to be beneficial for the system and part of the sediment management strategy: like for example the disposal site in the North Sea, which since 2005 has reduced the silty sediment budget in particular in the Hamburg area by means of sediment relocation seawards of the estuary mouth.

In the Scheldt, the situation is different. It is not clear yet whether the system is globally exporting, but several studies (e.g. [42]) suggest so. If an estuary is not importing sediment, storing dredged sandy sediment on land could potentially lead to permanent sediment extraction. To prevent this extraction, new dumping protocols are set in place in the Scheldt, taking advantage of the natural sediment transport patterns. Maintenance dredging in the Scheldt is often limited to sills, which are locations of strong deposition. Meanwhile, other locations in the estuary are more subject to erosion. By redepositing dredged sediment within the estuary, preferably at sites where erosion takes place, it remains available for sediment transport. Nevertheless, not all sites with significant erosion are suitable for deposition, so that sediment is sometimes deposited at a location where erosion is not strong enough and where it therefore accumulates. Accordingly, sand extraction is still needed to maintain the capacity of these low dynamic sites. This extraction then indirectly leads to dredged material being removed from the estuary. The current relocation sites in the Sea Scheldt are Schaar van Ouden Doel and (more recently) Parelputten,while the dredged material for the Western Scheldt is relocated to several sites within the Western Scheldt itself (i.e. in Dutch territory). Schaar van Ouden Doel is a site where the currents are too weak to erode all the deposited sediment. Therefore Parelputten was put in use in 2017, but this site could not take over the entire capacity of Schaar van Ouden Doel, such that sand extraction is still necessary.

3.2.2 Capital dredging, river straightening and land reclamation.

As briefly mentioned in Section 3.2.1, capital dredging consists of permanently widening and/or deepening the fairway of an estuary to facilitate ship navigation. Overall, capital dredging works are expected to have taken place in all estuaries having an inland port: the Scheldt, the Elbe and the Göta Älv. For the

Scheldt and the Elbe, information on the increase in depth due to capital dredging was available.

Works aimed at facilitating larger ships to reach the inland port happened in the Scheldt at three specific moments. Between 1970 and 1976, capital dredging works took place and the fairway depth was increased a first time from 10.6 m to 11.9 m, extracting approximately 14 Mm^3 of dredged sediment in the Lower Sea-Scheldt and 57.5 Mm^3 of dredged sediment in the Western Scheldt[41]. Between 1997 and 1998, the fairway depth was increased a second time to 13.3 m, dredging another 17.5 Mm^3 in the Western Scheldt[41]. Between 2008 and 2011, the fairway depth was increased a third and last time to 14.7 m, dredging a final 6.35 Mm^3 in the Western Scheldt and a final 7.7 Mm^3 in the upper Sea-Scheldt[41]. During the capital dredging works, the dredged material from the Upper Sea Scheldt was permanently removed from the system, while the dredged material from the Western Scheldt was partly deposited back in the estuary[41]. For the two following capital dredging works, the sediment dredged from the Western Scheldt was entirely relocated in the estuary, whereas the dredged sediment from the Lower Sea-Scheldt was partly deposited in the estuary and partly stored on land[41]. In the Elbe, the first capital dredging works took place in 1868 with a deepening to 5.3m in area of Hamburg[3]. Since then, six more capital dredging works took place, such that vessels with a draught of 14.5 m are able to reach the port of Hamburg.

In contrast to river deepening, which is a relatively new pressure that only started in the 20th century, other infrastructural works that permanently altered the estuary are much older. These works include river straightening and land reclamation. Such works are believed to have had a profound impact on the hydrodynamics (which are dealt with in this section), but also on the ecotopes (which are dealt with in Chap. 5, the ecology chapter).

River straightening is an operation in which the estuary is shortened by bypassing the most pronounced meanders. These shortenings cause a reduction in the distance between the most upstream part of the estuary and the mouth. As a result, the tidal penetration is effectively facilitated since it encounters less obstacles and since the length over which it experiences friction is reduced. The increase of tidal penetration therefore generates a rise in the high water levels and a drop in the low-water levels, particularly upstream of the river straightening, effectively increasing the tidal range[41].

In the Scheldt, several bends and curves have been cut and bypassed between the late 19th century and the early 21st century, mainly to facilitate water evacuation during flushing events, as well as to enhance navigability[41,43]. The bypassing of several meanders lead to a shortening of the estuary by 10.3km. Additionally, between 1878 and 1903, a 5.5km long quay wall is built in Antwerp to facilitate ship docking. These works also aimed at shifting the irregular thalweg around Antwerp close to the docks[43].

Land reclamation in tidal rivers and estuaries often focuses on intertidal zones. These areas are already dry at low tide and the construction of dykes prevents flooding during high tide. The destruction of intertidal area reduces the storage volume available for the estuary during high tide events. As a result, land reclamation in tidal areas are mainly expected to lead to an increase in high-water levels and do not affect low water levels that much.

Along the Sea-Scheldt and its tributaries, both tidal flat and tidal marsh area were reduced by respectively 66% and 82% between 1850 and 2003[41]. Although not all loss is directly related to it (see Fig. 5.1 Chap 5.2), land-reclamation is a crucial factor. In the microtidal Fjords, the reclaimed areas are not former intertidal zones, but lie below sea-level. The largest reclaimed area project is Lammefjorden, which constitutes an enclosed area of approx. 6000 ha. The reclaimed area is situated 7.5 meters under MSL, which is Northern Europe's largest reclaimed area. Land reclamation took also place in the Elbe, the Humber and the Tees. More specifically in the Tees, maps reveal a 93% loss of intertidal habitat between 1861 and 1993 from 2425 acres to 171. Areas of the estuary were reclaimed up to the 1970's, creating new areas for industry.

3.2.3 Increase in tidal amplitude

The removal of sediment, river straightening and land reclamation can also generate additional pressures. For example, deepening the estuary modifies the propagation of the tidal wave, while removing intertidal area removes storage capacity from the estuary. Data analysis[41,44] show that the first widening of the Scheldt in the 1970's lead to a significant decrease in low water levels. The influence on high water levels is insignificant, such that the tidal amplitude increases. During this widening, the majority of the dredged sediment was removed from the system, in contrast with the later widening works of 1997-1998 and 2008-2011. During the latter two widenings, the same effect (decrease in low water levels but no effect on high water levels) are observed, but with a much weaker trend[41]. The modelling results of Maximova et al.[45] estimated that the changes in high water and low water values were mostly negligible except at some locations where the variation was a few cm at most, becoming even smaller when the dredged sediment is redeposited in the estuary. It is important to emphasize that for long term predictions, it is very difficult to differentiate the effect of sand extraction due to widening operations from the effect due to commercial activities. These difficulties are exacerbated due to the temporal extent of sand extraction in combination with a lack of documentation of sand extraction in the Sea Scheldt, mainly in the freshwater and oligohaline zone[41].

The effect of land reclamation on the tidal amplitude was investigated in several studies. In the study of Meyvis[46], no direct consequences of the land reclamation were observed, although calculations showed that an increase of the high water level was expected. A study by Witteveen en Bos[47] confirmed that effects of land reclamation on water levels were difficult to detect, even if they mention that this would not mean this effect is absent. Small changes in the water levels also appear to be difficult to observe in measurements, even after filtering for the fluctuations of which the cause is known. Later numerical studies by Maximova and co-authors[45] indicated that land reclamation in the Braakman polder en the Nieuw- Westlandpolder lead to an increase of the high-water levels of 3 to 4cm along the Western Scheldt, the lower Sea-Scheldt and the Rupel (a tributary river). From a more general perspective, the extent of the area upon which the effect of land reclamation is expected depends on location and the size of the polder in the estuary[41,45].

The tidal range of the Elbe has also increased significantly over the last century. The mean high water level at St Pauli increased from slightly more than 150cm above mean sea level (MSL) in 1870 to about 200cm above MSL around 2005. At the same time, the mean low water level decreased from approximately 35cm below MSL in 1870 to approximately 150cm below MSL around 2005[48]. These changes in tidal amplitude coincide with operations of channel deepening, the closure of tributaries and land reclamation in the tidal freshwater zone[48].

An increased tidal amplitude creates less favorable hydrodynamic conditions such as lower water levels at low water (undesirable for navigation) and higher water levels at high water (undesirable for flood protection). Additionally, higher current velocity are expected, which could lead to a higher turbidity (see next paragraph).

3.2.4 Reduced discharge

The upstream discharge is a crucial factor for the management of an estuary. A sufficiently high discharge hampers salt intrusions, facilitates the flushing of sediment and other suspended matter, and ensures the navigability of a river. The latter is particularly true in the upstream sections, where the tidal penetration is reduced. As a result, weirs are often constructed in these upstream sections to have a better control over the water depth. A reduced discharge is a concern in many rivers, and has two main origins. First, the upstream drainage of river water is done for other purposes such as the filling of canals or industrial and agricultural use. Second, fluctuations occur in the natural water inflow.

For example, the upstream drainage in the Scheldt and its tributaries has lead to a significant reduction of the flow rate in comparison to its original value[43]. In particular, water is deviated to feed the Schipdonk Canal, and the channels Gent-Terneuzen and Gent-Brugge[43]. The channel Gent-Terneuzen is partly fed by water from the Durme (a tributary of the Scheldt), and the resulting reduced discharge in the Durme has lead to important siltation problems since the beginning of the 20$^{\text{th}}$ century.

More recently, natural fluctuations in the upstream discharge have occurred due to unusual weather conditions. Recurring droughts can diminish the discharge to such a point that sustaining navigability requires higher maintenance efforts. These dry events especially occurred during the last years in the upper catchment of the Elbe[7]. The low discharge in turn makes it more difficult to flush out sediment which leads to sedimentation and ultimately increases the required dredging volume in the port of Hamburg[7]. Additionally, the increased turbidity has also lead to a declination of environmental conditions for protected natural habitats such as shallow water areas. Finally, a lowering discharge also negatively impacts the salinity intrusion of seawater, which can penetrate much deeper inland. In the Scheldt, a minimum flow rate at the weir was imposed by the the Vlaamse Waterweg. The concern mainly addresses the lack of flushing capacity during low discharge periods, causing an accumulation of sediment in the upstream part of the estuary. Subsequently, low primary production periods also occurs.

3.2.5 Tidal pumping

Tidal pumping is the net transport due to a temporal correlation between tidal velocity and tidally induced concentration. The correlation may mean, for instance, that higher (lower) concentrations occur during the flood (ebb) flow so that net (i.e. tidally averaged) sediment transport is directed up-estuary. The reverse (down-estuary transport) may also occur while also parts of an estuary may be exhibit up-estuary transport whereas other regions are characterized by down-estuary transport.
To conceptualize tidal pumping, we consider a one-dimensional flow u and sediment concentration c[40]. These quantities can be assumed to be cross-sectionally averaged values. Furthermore, we split the flow in a tidally averaged part $< u >$ and a tidally varying part u', where $<>$ denotes time averaging over a tidal period. The tidally averaged flow includes effects like river flow and wind forcing. Likewise we consider the concentration c to consist of a tidally averaged part $< c >$ and a tidally varying part c'. Hence we have

$$\begin{aligned} u &= < u > + u' \ , \\ c &= < c > + c' \ . \end{aligned} \tag{3.1}$$

The tidally averaged sediment flux (i.e. sediment transport per cross-sectional unit area) is then given by $< uc >$ which reads

$$< uc > = < u > < c > + < u'c' > \quad .$$

The first term $< u > < c >$ is the mean sediment flux due to river flow. The second contribution $< u'c' >$ is the mean sediment flux due to the tidal flow, and this is what is actually referred to as tidal pumping. This term is non-zero when there is a temporal correlation between time varying flow and and time varying concentration, as stated at the beginning of this paragraph.
A temporal correlation exists when there is some kind of tidal asymmetry (different velocities and/or concentrations during ebb and flood). There are various causes of tidal asymmetry[40]. For example, there may be a velocity amplitude asymmetry which is more relevant to relatively coarse sediment. In this case the flood flow, for instance, may be higher then the ebb flow, yielding more erosion (hence suspended sediment) during flood and thus a net up-estuary transport. For finer sediment, other mechanisms are more dominant. One of them is temporal settling lag, which is related to the rate of velocity change around velocity slack being different going from flood to ebb and visa versa. Another important mechanism for fine sediment transport is spatial settling lag, where spatial (rather than temporal) velocity variation causes net transport of fine sediment to regions of relatively low tidal velocity.
Within the context of IMMERSE, tidal pumping is mostly understood to refer to up-estuary directed net transport (e.g. Elbe). Since the mean river flow transports sediment seaward, a net total up-estuary transport implies up-estuary tidal pumping. Furthermore, an increase in tidal range may enhance the tidal asymmetry mechanisms stated above and thus lead to stronger tidal pumping. In the Elbe for example, natural morphological changes in the mouth of the estuary are believed to have increased the hydraulic capacity of the estuary mouth[49,50]. This increase in hydraulic capacity, together historical waterway adaptations and maintenance for shipping, has affected the tidal asymmetry and most probably exacerbated tidal pumping.

Finally, very low discharge during the last years has also severely enhanced the upstream sediment transport and deposition by tidal pumping. In the Upper Sea Scheldt also increasing sediment concentrations have been observed during dry periods, although this situation usually disappears when the discharge increases again[51].
As an alternative to computing the advective transport as stated above, one can also use the historic change of bed level throughout an estuary to obtain the net sediment transport by using mass conservation for sediment. Note that this also includes the transport due to river flow. This approach has been adopted to the Scheldt estuary by Cleveringa[52] and Vandenbruwaene et al.[42], but has some complications. First, since sediment consists of inhomogeneous material with different grain sizes, one has to differentiate between sand and silt fractions. Additionally, sand and silt do not necessarily obey the same large scale transport patterns so that an estuary can be globally importing for sand but exporting for silt. In this regard, the results of the studies by Cleveringa[52] and Vandenbruwaene et al.[42] cannot definitively settle the tidal pumping question in the Scheldt. Both studies indicate an upstream sand transport in the Scheldt. However, Cleveringa[52] suggests a net upstream silt transport in the Western Scheldt over the period 1996-2000, while the study by Vandenbruwaene et al.[42] suggests a net downstream transport of silt in the Sea-Scheldt over the period 2001-2011. Here, it has to be mentioned that the study of Vandenbruwaene et al. is based on measurements to estimate upstream sediment transport, while the study of Cleveringa assumes that the sediment consists of equal fractions of silt and sand. Therefore, the study by Vandenbruwaene contains less uncertainties than the study of Cleveringa.

3.2.6 Weather induced flooding

Weather induced flooding is a pressure that has always been threatening estuaries. It can be divided into two subcategories. First, the flooding caused by excessive rainfall. Second, flooding may be caused by storms in the North-Sea and Kattegat. Excessive rainfall can cause the discharge to increase significantly whereas storms can blow water into the estuaries, where it is trapped and piles up. Since more extreme weather conditions are likely to happen in the future, these phenomena will potentially become more frequent. If the extreme weather conditions are combined with a mean sea-level rise they can pose a serious threat.

This threat is clearly reported for the microtidal estuaries. For the Fjords a 52 to 96 cm sea level rise [53] is expected due to climate change combined with more frequent and heavier storms[54]. The Göta Älv expects a 1m sea level rise by 2100 equally combined with more frequent and heavier storms[55,56].

For macrotidal estuaries, the threat is also a reality (in particular for the Humber). The Humber has a significant history of being impacted by storm surges. For example 17 December, 1921 31 January, 1953 14 October, 1954 12 November, 1954 30 December, 1959 20 March, 1961 29 September, 1969 3 January, 1976 13 November, 1977 11 January, 1978 5 December, 2013. However, hazardous situations could be slightly less recurrent than in microtidal estuaries. Indeed, for a threatening situation in macrotidal estuaries, unfavourable weather conditions need to be combined with high water and/or spring tide.

3.2.7 Summary of the pressures

The above described pressures experienced by the different estuaries are summarized in Table 3.4. Note that maintenance dredging and capital dredging are not considered direct pressures and are, therefore, not mentioned in this table. Nevertheless, they play a crucial role in being the direct or partial cause of some pressure (tidal amplification, sand extraction), see Sects. 3.2.1 and 3.2.2 for more details.

Table 3.4: Pressures faced by the estuaries of the IMMERSE project.

Pressure	Affected estuaries	Potentially affected estuaries
Sand extraction	Scheldt	
River straightening/land reclamation	Scheldt, Elbe, Isefjord, Tees, Humber	
Tidal amplification	Scheldt, Elbe, Humber	
Reduced discharge	Scheldt, Elbe	
Tidal pumping	Elbe	Humber
Weather induced floods	Scheldt, Tees, Elbe, Isefjord, Roskildefjord, Göta Älv, Humber	
Sea level rise	Scheldt, Tees, Elbe, Isefjord, Roskildefjord, Göta Älv, Humber	

4 Physical and chemical quality

When talking about concentrations and trends of nutrients and pollutants in the partner estuaries, one has to distinguish between dissolved or particle bound substances, as well as substances incorporated in biota. In this document, only dissolved substances are considered. Additionally, common pollution threats shared by the estuaries of the IMMERSE project, should be further differentiated in threats for the water-quality and threats for the suspended matter or sediment quality. Indeed, the water quality reacts much faster to changes in chemical or biological composition as a result of actions/restrictions within the estuary (e.g. water-treatments or fertilizer restrictions). In contrast, sediment quality varies on a much longer time-scale since it is usually a development of a process of accumulation of pollutants in the past. Accordingly, the quality does not depend only on regulations but also on the residence time of sediment within the estuary. To illustrate this difference we use the Elbe as an example case. After clarifying the impact of regulations on the water quality, we give a concise overview of the types of pollutants that are found in the different IMMERSE estuaries. This overview is relevant since the contaminants found in sediments determine whether dredged sediments can be redeposited into the estuary, or have to be repurposed.

4.1 The Elbe: an example case of pollution related to the current and past management of the estuary

Overall, the quality of both water and sediments is partly determined by local policies of each estuary, such as treatment of waste waters or the activities in the surrounding area (e.g. agriculture, industry). Nevertheless, nutrients and pollutants also originate from the broader (upper, riverine) catchment or the North Sea. For example approximately 50% of metallic contaminants are transported back from the marine area into the Elbe estuary[57].

In the Elbe estuary, the water and sediment have improved since the reunification of Germany in 1989. The plants in the industrial areas of the former GDR that had discharged heavily polluted water into the Elbe were shut down. Within the last years there is no overall trend for the different pollutants either in the water phase or in sediments. Hence, one has to distinguish between many different pollutants, not only between different chemical groups, such as organic contaminants (DDT, PCBs,..) and metallic contaminants (copper, cadmium, etc.) TBT and others, but also between the different substances of the chemical classes[57]. Typically, Nitrate and Phosphorus are a threat for the water column, since they can lead to eutrophication (excessive algae blooms). In turn, after a bloom, the organic matter is consumed by bacteria which could lead to oxygen depletion.

Despite the improvements in the Elbe, the water quality and the sediment quality are still not good. In fact, there are still many point and diffusive sources that release pollutants. These sources origin from losses of pollution legacies, old (and closed) mines, remobilization from riverine shore areas and flooding areas, sewage water systems, etc. of the former GDR and the Czech Republic. Metallic contaminants, Tributyltinhydride (TBT) and pesticides are more a concern for the quality of the sediment. Many of them were prohibited and are no longer present in the water column, while they still exist in the sediment[1].

In the Tees, the situation is comparable. Many of the industries around the estuary dumped effluent directly into the Tees releasing metallic contaminants and reactive compounds into the water effecting wildlife and habitats. This has left a legacy of poor water quality, from which the Tees is still recovering despite huge improvements in recent decades.

4.2 Overview of the sediment pollutants found in the different estuaries of the IMMERSE project.

To have knowledge of the type of pollutants present in the water column or sediments of an estuary is essential for the management of the estuary. First, it provides indications on future measures to reduce these types of pollutants. Second, the type of pollutants contained in sediment indicates whether the sediment meets criteria for being repurposed (stored on land, redeposited in the sea, or repurposed). The presence of different types of pollutants in the IMMERSE estuaries is displayed in Tab. 4.1. Overall, all the estuaries seem to deal with metallic contaminants, and TBT pollution. These are pollutant that may remain -and therefore also- come from the sediments. As a result, sharing knowledge concerning the use and treatment of polluted sediment could be an opportunity for the IMMERSE partners. The levels of oxygen seem to be highest in the Fjords, followed by the Göta Älv. However, there is a lack of information to determine if these lower levels of oxygen in the funnel shaped estuaries are related to higher sediment concentrations, higher nutrient flux or a different parameter.

Table 4.1: Indication of the physical and chemical water quality.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskilde-fjord**	**Göta Älv**	**Humber**
Pollutants (sediment)							
Metallic contaminants	Yes[2,3]	No information	Cu, Zn, As, Hg	Pb, Ni, Hg, Cd, Ba, Cu, Cr, Zi	Pb, Ni, Hg, Cd, Ba, Cu, Cr, Zi	Cu, Zn[56], Hg, Cr[58], Pb, V, Cd, Ni, As, Sn, Co[59]	Al, Co, Cr, Fe, Ni, Pb, Mn, Ba [60]
Organic pollutans/micro-pollutants	Yes[2,3]	Yes[4]	Yes [61]	No information	No information	Yes[58]	Yes
Organotin compounds	TBT[62]	TBT[4]	TBT	TBT	TBT	TBT[56]	TBT
Micro-plastics	Yes	No information	Yes	No information	No information	Yes[56]	Yes [63]

5 Biology and ecology for each estuary

In general, North Sea estuaries have a different ecosystem in comparison to fjords in the Baltic region because of the flow conditions and water quality conditions[57]. The flow conditions are influenced by wind waves, strong tides and wave induced currents, as well as tidal amplification due to the funnel shape in the inner estuary. The water quality conditions include available sediments, available organic matter, barocline efffects due to salinity gradients and salinity variations, mixing of salt and fresh water, turbidity and oxygen conditions[57].

Additionally, biodiversity in estuaries should not be considered as just the number of species, because estuaries are less diverse taxonomically but more diverse in other ways like functionality. For example only a small number of fish species are able to reside permanently in estuaries, due to the challenges that these highly variable environments pose to the physiology of aquatic organisms. A good ecological status and well-functioning of the estuary is a first prerequisite for sustainable estuarine management – the topic of IMMERSE.

Finally, a comparison of nutrient contents is not as useful as it seems. Indeed, although nutrient content reflects the estuary state, estuaries are naturally eutrophic and productive systems as they concentrate water from large drainage areas in relatively small water bodies, and they are quite turbid. Due to the latter, very often nutrients are not being taken up by the existing flora, nor by algae as they are often light limited by the turbidity or due to the low amount of macrophytes, but transported to the sea. However, excess in nutrients and organic matter input, following from increased human activity (industry, agriculture, sewage disposal), on top of the naturally eutrophic conditions, can lead to severe oxygen deficiencies.

As a result of these three factors, it is very difficult to come to a meaningful comparison between the estuaries, based on ecotopes, habitats or species. For example, management directives in macro-tidal estuaries can focus on the preservation or creation of intertidal zones. These zones offer a variety of different ecotopes (marshes, tidal mudflats) that are important from a biodiversity point of view. However, these ecotopes are almost completely absent in microtidal estuaries. As a result, the remainder of this chapter is divided in two section. First, an overview is given of the status of the estuaries in the Water Framework Directive (WFD) and Natura 2000 related directives (Birds as well as Habitats & Species Directives). This review allows to relate the estuaries from a directive point of view. Following, we describe the role of river widening and land reclamation on the ecotopes. Although this topic is specific to macro-tidal estuaries, different measures during the IMMERSE project refer to this pressure.

5.1 Directives for environmental protection

Different European frameworks are implemented in national law to evaluate the state of the natural system, such as the WFD and the Birds- and Habitats Directive as well as Ramsar for birds. In this regard, it is interesting to note that all the funnel shaped estuaries (Scheldt, Tees, Elbe, Göta Älv) are marked as heavily modified water bodies, whereas the Fjords (which are part of the marine strategy[64,65]) are not (see Table 5.1). This designation is important since it determines if a water body should achieve good ecological potential (heavily modified water bodies) or good ecological status (Fjords). As a result, the ecological objectives of the funnel shape estuaries and the Fjords are different[64,66].

The different status and labels of the estuaries is summarized in Table 5.1. All the estuaries of the IMMERSE project are (at least partly) marked as Natura 2000 areas. All those estuaries are marked as Special Protection Areas (SPAs), whereas the Scheldt, the Elbe and the Göta Älv are also marked as Special Areas of Conservation (SACs). Additionally, parts of the funnel shaped estuaries are all designated RAMSAR sites in contrast to the Fjords. Nevertheless, the estuaries differ in the types of habitat they offer (see Tab. 5.2. There is a net difference between the macrotidal estuaries (Scheldt, Tees, Elbe, Humber), which have tidal marshes, and the Baltic Sea/Kattegat estuaries (the Fjords and the Göta Älv).

Table 5.1: Implemented legislation and administrative protection of nature areas.

	Scheldt	Tees	Elbe	Isefjord	Roskildefjord	Göta Älv	Humber
Heavily modified water body	Yes[2,3]	Yes[4,37]	Yes[7,67]	No	No	Yes[56]	No
EU Special areas of conservation (SAC)	Yes[2,3]	No[4,37]	Yes (40,802 ha)[7,67]	No	No	Yes[56]	Yes[3]
EU Special protection areas (SPA)	Yes[2,3]	Yes (1,247.31 ha) (Teesmouth and Cleveland Coast Extension pSPA)[4,37,68]	Yes (25,122ha)[67]	Yes	Yes	Yes[56]	Yes
Natura 2000 (includes both SAC and SPA[64])	Yes, (4,684 ha[2,3,64,69,70])	Yes, (Teesmouth and Cleveland Coast Extension pSPA[4,37,64])	Yes, (46.770ha[7,64,67,71])	Yes, (5.000 ha (approx.))[64]	Yes, (14.810 ha)[64]	Yes[56]	Yes-37630.24ha
UNESCO World Heritage	Applying[64,72]	No[4,37]	Yes (Elbe mouth as part of the Wadden-sea)[7,67]	No	No	Yes[56]	No

Table 5.1: Implemented legislation and administrative protection of nature areas.

	Scheldt	Tees	Elbe	Isefjord	Roskildefjord	Göta Älv	Humber
Ramsar sites included (Wetland convention)[2,3,64]	Yes	Yes[4,37]	Yes[7,67]	No	No	Yes[56]	Yes
National or state controlled habitat protection	Yes, some marshes[64]	Yes[4,37,68]	Yes	No	Yes	Yes[5]	Yes

5.2 River straightening and land reclamation.

In the previous section, it appeared that all the funnel shaped estuaries are designated as heavily modified water bodies. The causes of this designation (land reclamation, river straightening and widening) also have impacts on the estuary's ecotopes and their surface area. In macro-tidal estuaries, the presence and evolution of typical estuarine habitats such as marshes and tidal mud-flats mainly depends on two parameters: the tidal range and the slope of the river bed. This dependency is illustrated in Fig. 5.1: a larger tidal range or a gentler slope of the river bed will both lead to a larger area of a certain ecotope. The effect of land reclamation is therefore straightforward: land reclamation in intertidal zones reduces the area of tidal marshes and/or tidal mudflats. The effect of river widening is less obvious. If river widening causes an increase in the tidal amplitude, the tidal mudflat area or tidal marsh area can also be increased. However, this increase can be cancelled if the slopes of the river bed are significantly steepened. Additionally, an increase in tidal amplitude also implies changes in flow conditions. If the flow velocities become too high, it is increasingly difficult for species to settle.

The effect of river bed modifications in the ecotope areas are very clear in the Tees. Maps of the Tees Estuary reveal a 93% loss of intertidal habitat between 1861 and 1993 from 2,425 acres to 171. Areas of the estuary were reclaimed up to the 1970's, creating new areas for industry. The Scheldt also suffers from significant habitat loss. Along the Sea Scheldt tidal flats were reduced by 66% between 1850 and 2003, whereas tidal marsh area was reduced by 82% over the same period[41]. Additionally, 30% of the shallow subtidal area was lost since 1930, due to destruction, but also to changes in hydrodynamic and morphological conditions[41].

Some of the remaining ecotopes and habitat types are summarized in Tab. 5.2. Once more, there is a clear difference in between the macrotidal estuaries and the microtidal estuaries: there are no tidal marshes in the latter ones. Additionally, it is remarkable that the Tees is the only estuary without meadows. This absence might be related to a high level of solid surface and canalization. In other words, there is no place available for meadows. Both habitat examples, show that the transferability of measures for increasing the ecological potential is highly dependent on the habitat type they focus on.

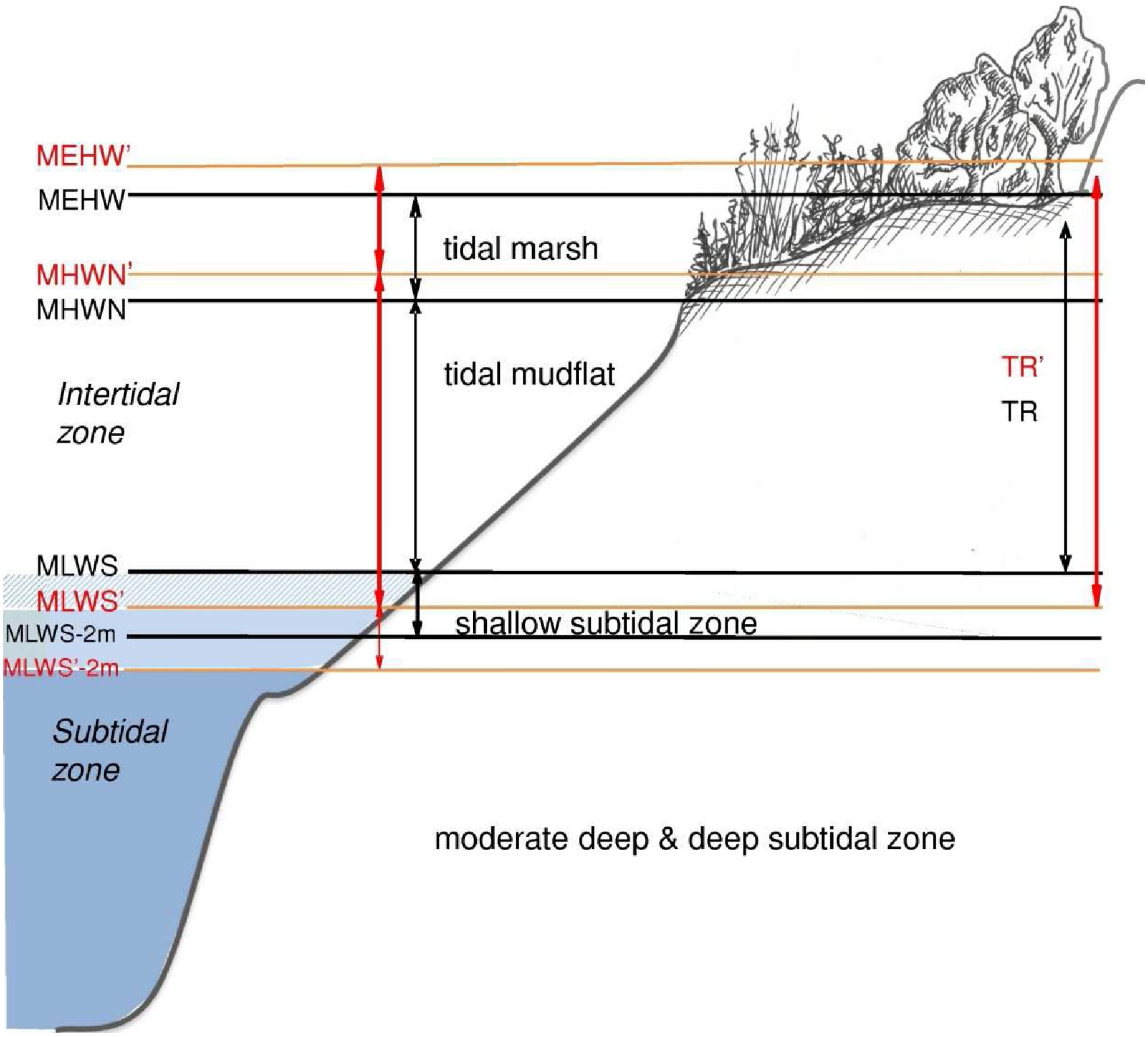

Figure 5.1: Ecotopes along a cross-section of an estuary under tidal influence (MLWS: mean high water spring tide; MHWN: mean high water at neap tide; MEHW: mean exceptional high water). This image was taken from [41].

Table 5.2: General overview of the existance and size of specific habitats and selected fauna classes of the different estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Tidal marshes	3000 ha[2,3,73]	Yes[4,37]	8,882 ha[67]	No	No	No[5]	Yes-630 ha [74]
Meadows	Grazed marshes in Saeftinge, Galgenschoor[64]	No[4]	No information	Yes	Yes	Yes[5]	Yes
Freshwater marshes	Yes[64]	Grazing marshes[4,37]	Yes (1,116 ha)[67]	Yes	Yes	Yes[5]	No information
Saltwater marshes[4]	Yes[64]	Greatham Creak, Seal sands[37]	Yes	Yes	Yes	No[5]	No information

6 Measures

In this Chapter, the twelve measures that have been specified within the IMMERSE project (see Table 6.1) will be discussed. These measures have been grouped according to the types of pressure they mitigate. In Section 6.1 measures related to reduction of the tidal amplitude will be described. Note that some of the measures described here indirectly tackle other pressures, such as tidal pumping or creation of habitats and improvement of ecological conditions, but for simplicity they are gathered in Sect. 6.1. Measures regarding protection against sea level rise are dealt within Sect. 6.2. In Sect. 6.3 the testlab measure approach for the Humber will be outlined. Section 6.4 is devoted to measures related to water quality and ecology. Finally, Sect. 6.5 addresses, amongst others, the transferability of each measure.

Table 6.1: Recapitulation of the measures and the pressure they deal with.

Name	Estuary	Description	Related pressure
M1	Scheldt	Develop a morphological management strategy	Tidal amplification
M2	Göta Älv	Design solutions managing contaminated sediments, including assessing existing pilot on stabilization/solidification of dredged masses and develop method for recovery of metals and polluted sediments	Contaminated sediments
M3	Tees	Improve the water quality and economic stimulus through co-location of mariculture within inshore wind farm	Water Quality, ecological conditions
M4	Humber	Design measures for flood risk management while maintaining/enhancing environmental protection measures	Weather induced floods
M5	Scheldt	Explore solutions as part of a sediment strategy to adapt to the effects of climate change and sea level rise in the Scheldt estuary	Weather induced floods, ecological conditions

Table 6.1: Recapitulation of the measures and the pressure they deal with.

Name	Estuary	Description	Related pressure
M6	Fjords	Improve understanding of contributing role of local waterways to flooding Holbæck Fjord; development of risk and value maps	Weather induced floods
M7	Fjords	Analysis, design and environmental assessment of a dynamic flood protection measure	Weather induced floods
M8	Tees	Pilot on intertidal habitat creation	Ecological conditions
M9	Elbe	Feasibility study on the reconnection of the Dove-Elbe, including assessment of adapted sediment management through the use of numerical modelling	Tidal pumping, ecological conditions
M10	Humber	Testlab - proof of concept test for measures (virtual lab testing)	Weather induced floods
M11	Scheldt	Pilot on cross-border solutions for maintenance dredging	Sand extraction
M12	Scheldt	Measure to reduce tidal intrusion and increase nature value (widening flood channel Upper Sea Scheldt	Tidal amplification

6.1 Taken measures - Reduction of the tidal amplitude

The increase in amplitude of the tidal wave is assessed as negative for the Scheldt[75] and the Elbe. As a result, several different measures were developed in different estuaries to limit or even counteract trends of increasing tidal amplitude. These measures mainly deal with the tidal amplitude but can have secondary benefits due to the interdependence of some pressures.

6.1.1 M11 (Scheldt): Pilot on cross-border solutions for maintenance dredging

As discussed in Sect. 3.2.3, changes in the geometry of the Scheldt are mainly responsible for the increase in tidal amplitude[76]. The changes in geometry are in turn primarily achieved via dredging, and in particular sand extraction. Sandy material is dredged from the sills in the fairway of the Lower Sea Scheldt to ensure maritime access for the harbor of Antwerp. This material is relocated to the relocation site Schaar van Ouden Doel of which the capacity is maintained by allowing commercial sand extraction in a similar volume as the annual volume sand that is brought in from dredging activities. Therefore, material from maintenance dredging is indirectly extracted from the estuary, and contributes to the net reduction of sediment volume within the estuary. It is important to emphasize that this indirect sediment extraction is directly related to the sheltered flow conditions at Schaar van Ouden Doel.

A secondary challenge is that local extraction of sand can also lead to a reduction of sediment volume at other locations[77]: the main current patterns can transport sediment from these other locations to resupply the zone were sand has been extracted. Motivated by its negative impact, it was decided that new net sand extraction was undesired and that the material dredged within the Scheldt should be redeposited within the Scheldt: the sediment volume in the Scheldt should remain constant.

Accordingly, new sites for relocating dredged sand were investigated. One new relocation was found in the Lower Sea Scheldt (Parelputten, Flanders) and introduced in 2017. Although this site does not require sand extraction, it was not able to completely take over the capacity of Schaar van Ouden Doel' and other sites were not found in the Sea Scheldt (Flanders)[78]. As a result, cross-border solutions were investigated. Cross-border solutions imply that sediment dredged in the Flemish part of the Scheldt can be deposited in the Dutch part of the Scheldt. This type of relocation was not used so far. Nevertheless, it has the potential to be efficient since it seems to take advantage of the natural sediment transport patterns within the Scheldt. Indeed, sediment is naturally transported within the Scheldt and is not bound by borders. Sand is on average displaced from the Western Scheldt (in the Netherlands) to the Sea Scheldt (in Belgium)[77]. This phenomenon has two implications. First, it means that sand extraction at a certain location can lead to a reduction of the sediment volume over the entire estuary (as already stated previously). Second, it means that sand redeposited at a certain location can be spread again over the estuary due to favourable currents. However, it is important to state that the projected benefits for cross-border relocation are at the moment only academic, since no cross-border relocation has been undertaken so far[78].

Based on the current patterns, new relocation sites were identified, based on several criteria.

1. Safety against flood risks must be guaranteed;
2. the accessibility of the harbors needs to be ensured;
3. the natural condition of the estuary needs to be maintained or improved;
4. the dredged material must meet the standards set by the Dutch and Flemish government;
5. the field pilot is a 'no-regret'-solution, it will not have irreversible effects.

Additionally, the new sites must comply with the Dutch legislation. This legislation includes (i) prevention and where needed restriction of flooding, water risks and water scarcity, (ii) the protection and improvement of the chemical and ecological quality of the water systems, and (iii) the fulfilment of societal functions of water systems. Originally, five relocation sites were studied, among which three were selected to be part of a field pilot. The selection criteria included

- possibility of knowledge development,
- safety on the long-term (risk of high waters),
- accessibility (effects on the fairway),
- nature effects (short and long-term) and
- the practicality (influence on other projects, cost effectiveness, available volume) of the project.

Eventually, it was decided to leave out one of the sites because of the concern of a stakeholder on the possible negative effect that the project might have on the 'Verdronken Land van Saeftinghe', which is a Natura 2000 area. This concern could not be eliminated by showing results of numerical models indicating no negative influence[79]. It was decided to take into account this concern and leave out the site to preserve a good relationship with the stakeholder.

The two remaining sites are already used as relocation sites for dredged materials from the Western Scheldt. A field pilot is being organised in which sandy sediment from the fairway in the Lower Scheldt (Flanders) is relocated to two sites in the upstream part the Westerschelde (NL). The dredged material will originate from maintenance dredging works and will be relocated just across the border in the two selected sites. The process needs to ensure that only sandy material is transported into the cross-border locations. This requirement is guaranteed by several steps in the process. First, the sediment is dredged from locations where sandy material is largely available[78]. Second, the supervisor of the dredging works determines if the dredged volume contains mostly sand or mostly silt[78]. Third, while the hold of the hopper dredger is filled with sand during the dredging procedure, a part of the silt fraction is allowed to flow back to the Scheldt[78]. An extensive monitoring program is set-up to see influences on the morphology and ecosystems in the neighborhood of the relocation sites. The pilot aims to study the effects on the environment (morphology and ecosystems) of the relocation of dredged sandy material from the Lower Sea Scheldt towards the Western Sea Scheldt.

The objective of the measure is to limit or completely eliminate the sand extraction from the Scheldt. As a result, the morphology of the estuary is expected to move to a natural balance which will halt the amplification of the tidal wave and potentially limit turbidity. Indirectly this will also positively influence the chemical quality (e.g. improved oxygen conditions) and the biology/ecology (e.g. more capacity for photosynthesis). In terms of applicability in other estuaries, these objectives should be carefully remembered. Indeed, a cross-border solution has no meaning for the other estuaries since they are located in one single country. However, the aim of limiting the net sand extraction by making a smart use of the average natural sand transport patterns can be a focus in other estuaries.

6.1.2 M12 (Scheldt): Measure to reduce tidal intrusion and increase nature value (widening flood channel Upper Sea Scheldt)

Another IMMERSE measure is to widen the Scheldt locally. A side channel can reduce the incoming tidal wave energy by spreading it over a larger cross-section with a higher resistance. Based on the hydraulic and ecological characteristics of existing managed realignment sites, the site of Wijmeers was chosen as an appropriate location.

Prior to the implementation of the side channel, technical drawings were developed in close collaboration with nature and hydraulic research institutions. Other active participants included the nature administration and local authorities. Different channels were designed and simulated, in order to have an idea of the sustainability by self dredging of these channels. The models and assessments included

- a three dimensional hydraulic model of the Sea Scheldt, with a local refinement of the mesh by Flanders Hydraulics,
- terrain assessment on present vegetation and bird life by the Nature Research Institute (INBO),
- drone based topographic measurements to monitor elevation in the first channel and the surrounding managed realignment site by the Flemish Government Technical Support,
- field study on the presence and distribution of the Cullicoides by the Royal Belgian Institute of Natural Sciences.

In the meantime, an important extra motive arose. Wijmeers was experiencing a sudden infestation of Cullicoides causing severe health problems for the nearby community. Therefore, a smaller side channel was first quickly excavated to resolve the local needs for this health issue (Cullicoides cannot thrive in running water).

During the initial simulations, four different channel configurations were tested using a one-dimensional model (MIKE11)[80]. Each of the scenarios resulted in (i) a lower maximum high water, (ii) 12% diversion of the discharge and (iii) a lower velocity (0.5 m/s) in the flood channel[80]. Subsequently, two of the original configurations were further investigated, with slight adaptations, in a three dimensional Telemac model. The results suggest that the discharge in the secondary channel is about 5% to 10% of the total discharge[81]. This range is sufficient to reduce the sediment flux in the channel[82]. Additionally, the results show there is some variability among the scenarios regarding their ability to reduce the tidal range. Typically the reduction in tidal range is between 1cm and 3.5cm[81].

The appropriate design was finally tendered and is currently being implemented in the area. After the implementation, the field pilot in Wijmeers will be monitored to evaluate the four following aspects :

- Accuracy of the 3D hydraulic model used to simulate the effect of the flood channel on local water levels
- Sustainability of the measure in terms of its self-dredging capacity
- Effects of side currents and navigability on the inland shipping vessels in the main channel
- Effects on the main channel in terms of sedimentation/erosion

If the pilot is positively evaluated, a wide implementation of this type of measure will be prepared on a broader range of areas in the upper Sea Scheldt.

The implementation of a side channel to reduce tidal penetration could be interesting in some of the other IMMERSE estuaries. Potential candidates are the Elbe and the Humber since they are relatively long rivers with a macrotidal regime. The Tees is too short while the Fjords are too wide to make the construction of a side channel beneficial. Additionally, the Fjords are microtidal estuaries, similar to the Göta Älv. Nevertheless, a side channel could be considered in the Göta Älv, but for other purposes, such as dealing with peak discharge events.

6.1.3 M1 (Scheldt): Develop a morphological management strategy

While in the past large volumes of sand were extracted from the Scheldt to build dikes or to develop harbour facilities, nowadays there is an excess of available sand for large infrastructure work. This relative good quality sand could possibly be brought back to the Scheldt estuary according to a specific morphological management strategy. This strategy should aim at reducing the tidal penetration, while maintaining the port accessibility.

Within IMMERSE, a feasibility study is executed to investigate the effect of sand deposits on the tidal range. With the help of hydromorphological and ecological models, locations are explored for their suitability, the stability of the sand depositions, the required sand volumes, as well as the effects on hydrodynamics, suspended sediment concentrations and ecology. Four different scenarios were defined for which the hydro-morphological conditions are simulated.

- Scenario 1: Filling deeper parts of the navigation channel between Kallo and Rupelmonde
- Scenario 2: Rising of the bed level of the river between Kallo and Rupelmonde
- Scenario 3: Filling deeper parts of the navigation channel between Bath and Kallo
- Scenario 4: Rising of the bed level of the river banks between Burcht and Rupelmonde

The different scenarios for the deposition of sand were set up in cooperation with the other managers of the Scheldt estuary. The scenarios are computed with a reduced Scaldis model (Telemac) for the hydrodynamics, including both mud and sand modules. A primary production model developed by the University of Antwerp is used for the ecology. Expert judgement is also consulted for sand transport, and habitat related questions. It was decided to estimate the ecological effects for only one scenario because of the minimal impact of the other scenarios on the tidal range.

Currently the project is in the phase of exploring other possible scenarios. By researching the feasibility to deposit sand in the estuary, a first estimation of the effects are obtained. Based upon this outcome, a decision can be made to develop this measure further for example with an in situ pilot. The continuation of the explored measure into a feasibility phase depends on the sand stability, the effects on the tidal range and ultimately on the benefits for ecology. Other important factors not considered within IMMERSE are, for example, the efficiency of sand excess reduction and the total cost of the entire process.

Similar pilots could be undertaken in other estuaries facing similar challenges of tidal amplification (e.g the Humber and the Elbe). In fact, in the Elbe estuary a similar pilot was already researched, and is currently executed. If sand transport patterns due to the mean flow are included, this measure might even be applicable to microtidal estuaries such as the Göta Älv. By exchanging experiences, double work is avoided and the lessons learned can be integrated into new research.

6.1.4 M9 (Elbe): Feasibility study on the reconnection of the Dove-Elbe, including assessment of adapted sediment management through the use of numerical modelling[83]

As many other estuaries, the Elbe has to cope with the preservation of the valuable nature area and harmonization of ecological and economical demands. However, these demands sometimes conflict. The reduction of intertidal area for flood protection, or the deepening of the estuary to facilitate ship navigation have negative impacts on the ecology through the loss of habitat or an increase in sediment concentrations. The latter is also undesirable from an economic point of view, since it might increase the required dredging efforts.

As a result, a collaboration was initiated to develop solutions that counteract the flood dominated sediment transport (tidal pumping) and also favours the improvement of the ecological conditions in the estuary. The collaboration includes the three federal states of Lower Saxony, Schleswig-Holstein and Hamburg, as well as the administrations that are responsible for the maintenance of the waterways in the estuary and the port, the national Waterways Administration (WSV) and the Hamburg Port Authority (HPA). A proposed solution is the creation of additional flood space/ways in the estuary.

In estuaries, flood space consists of intertidal areas, but also lateral branches such as tributaries or harbor basins. In this flood space, part of the tidal energy is reflected and part of it is dissipated when basins and flood ways in the branches are filled and emptied by the tide. This dissipation yields a decrease in tidal range. A reduced tidal range is expected to weaken the advective transport processes and counteract the tidal pumping force. Finally the reduction of the tidal range is anticipated to have a positive effect on the intertidal habitat creation (i.e. ecological conditions) by reducing the current velocities.

As a part of a stakeholder consultation process "Strombau und Sedimentmanagement Tideelbe (FOSUST)" was initiated by the WSV and HPA, and supported by the Federal Waterways Engineering and Research institute (BAW). Twenty-three potential locations were identified for various engineering measures that could positively influence the tidal pumping and ecological conditions in the Elbe estuary. The estuary partnership '*Forum Tideelbe*' discussed the most suitable locations for measure implementation with representatives of all relevant stakeholders of the Elbe estuary. The partnership identified the reconnection of the Dove Elbe, an anabranch located in the east of the city of Hamburg that has been separated from the estuary in 1952, as one of the most suitable locations to address tidal pumping but also to provide benefits for nature and society. During the feasibility phase, HPA and BWA investigated the impact of the Dove-Elbe reconnection by

- developing a measure layout to reconnect the Dove Elbe with the participation of stakeholders within the estuary partnership "Forum Tideelbe",
- assessing the hydromorphological effects of the developed measure layout through numerical modelling[84], and
- tendering a feasibility study that should investigate the ecological effects of the measure as well as the possible support of the measure by the local groups of interest.

The involvement of stakeholders was a major issue during the whole project, as it became clear that the plans severely affected most of the human activities in the area. Although some stakeholders were in favor of conducting the measure, especially environmental NGO´s, there was strong resistance from the locals against the reconnection of the Dove-Elbe. In the beginning, there was particular concern about the induced increase of the water level in the anabranch during flood tide, but also that shipping will be hindered by ebb tide. As a result, the working group developed an optimized scenario with a tidal weir that should regulate the flow at the reconnection and limit the water level between +0.9 m and -1.2 m NHN at the landward side of the weir. Nevertheless, the local acceptance of the measure still remained low and likely, the local disapproval could not be changed during the IMMERSE project. Overall, the relevance of stakeholder participation and relevance of adequate communication to achieve acceptance of a measure appears crucial. Time and resources are required for conflict resolution, a process that starts by communicating the pressures and functions of the estuary effectively. It also requires raising the awareness of stakeholders and estuary managers in developing alternatives, identifying solutions and taking responsibilities, to be able to engage the general public. Within the IMMERSE project, this took place with stakeholder interviews, workshops and by including them in the design of the potential measure and increase the measure acceptance. Nevertheless, it is a long-lasting process that at the Elbe Estuary has just started and has to be further developed.

Regarding the measure effectiveness, the objective of the developed measure layout remained to simultaneously achieve the maximal possible hydrological effect and an ecological improvement. However, given the adaptions to limit the maximum water level in the anabranch, the potential hydrological benefits were constrained.

The results of the hydromorphological calculations (hn-model) depicted that the adapted reconnection lowers the tidal range 2 to 3 cm on average within Hamburg[83]. Locally, a reduction of approximately 10 cm is expected in the mouth of the Dove Elbe. Along the estuary, the net sediment transport upstream decreased on average by 1 to 2%. Also, a total of 120 ha of newly created tidal habitats were estimated. The results showed that the investigated measure at the Dove Elbe can help counteract the historically unfavorable developments of the tidal Elbe and improve the ecological potential of the tidal Elbe. However, this measure alone cannot bring the tidal Elbe back into balance, and more similar measures will be required to have a major positive effect on the dynamics of the estuary.

The applicability of this measure in other estuaries first depends on the availability of such anabranches in the estuary. If such an anabranch exists, studies are required to estimate if a reconnection is beneficial or even possible. This measure does not seem applicable to the Fjords and the Göta Älv, due to their microtidal regime, while the Tees is, again, very short for this application.

6.2 Taken measures - Sea level rise

The effects of sea-level rise (SLR) and more frequent and extreme weather conditions are primarily hydrogical and are known to cause increased flood risk. Additionally, SLR can cause ecological issues such as the disappearance of shallow habitats. The measures described in the following paragraphs deal with the risks and issues related to sea level rise in the Scheldt, the Danish Fjords and the Humber, respectively.

6.2.1 M5 (Scheldt): Explore solutions as part of a sediment strategy to adapt to the effects of climate change and sea level rise in the Scheldt estuary

The issues related to relative SLR in the Western Scheldt are attributed to both absolute SLR, and land subsidence. The current strategy in the Netherlands to deal with SLR is to nourish the active part of the coast (approximately from the 10 meter depth contour up to and including the beach) and the coastal foundation (approximately between the 10 meter and 20 meter depth contour) with sand at strategic locations. Nourishing annually ensures that the coastal growth will keep up with the SLR in the long-term.

No nourishment is actually executed in the estuary since it is believed that the required sand will autonomously be imported from the adjacent coastal foundation. However, the actual available sand supply in this part of the coastal foundation and the estuary, as well as the magnitude and direction of the sediment transport between them is not very well known. To bridge this knowledge gap, a pilot nourishment of 1.5 Mm3 in the mouth of the Western Scheldt will be executed in 2023 and subsequently studied. The initial idea of the pilot nourishment was further developed with both modelling and desktop studies, including the use of geographic information system (GIS). These desktop studies include a set of suitable locations for the pilot nourishment and an inventory of all relevant parameters. The evaluation framework for the locations included three criteria:

- the contribution of the nourishment to the morphological and ecological knowledge objectives,
- the impact on the main functions of the estuary (safety, nature and navigation),
- the construction and monitoring of the nourishment itself.

The set of parameters contained among others a list of existing infrastructure, restricted areas and available monitoring data.

The choice between different alternative nourishment locations was based more specifically on data analysis, model simulations of sediment transport paths and expert judgment. The latter was gathered during several sessions in which experts on hydraulics, morphology and ecology were represented. The study results in a design for the pilot nourishment. The nourishment is followed by a large monitoring program, combined with hydraulic and morphological modelling and desktop studies. In particular, hydraulic and morphologic modelling with Delft3D is used in the coming years to further design the nourishment itself. Innovative monitoring methods, i.e. for tracing sediment after it has been nourished is also planned to be used. Accordingly, the pilot is not meant to solve a problem directly, but rather to gain data and knowledge to contribute to the design of a future long term sediment management strategy.

The ambition to collect data about large scale sediment transport can potentially be useful for every estuary. However, in the current pilot project, this data collection is combined with nourishment operations that are already occurring on a regular basis, albeit in a different form and at different locations. For the other estuaries it has to be investigated whether large scale nourishments already take place, and whether the current patterns are significant enough to generate specific sediment transport. The Scheldt is a macrotidal estuary such that sand transport is largely influenced by tidal currents. This influence is absent from the Fjords and the Göta Älv, but again, similar pilots can be undertaken to map the mean sediment transport patterns.

6.2.2 M7 (Danish fjords): Analysis, design and environmental assessment of a dynamic flood protection measure

The Danish fjords are surrounded by low-lying areas with respect to the sea-level. For example, the reclaimed area Lammefjorden lies 7.5m below mean sea-level (MSL) and there are cottage areas around the Fjords where the land level lies lower than 2m above MSL. An increasing pressure from sea-level rise and storm-surges is already occurring and is expected to increase in the future. As a result, flood protection is on the agenda on a local, regional and national level. Nevertheless, an improved knowledge of the flood protection possibilities is required since the area is particularly sensitive from an ecological point of view.

Different solutions for flood protection measures were identified based upon criteria such as economy, physical conditions, biology/ecology etc. The solutions were tested using a regional model upon sea level rise, relative effect of sediment dynamics and future weather conditions. This model covers the North Sea, the Baltic Sea and the inner Danish waters taking into account tides, river runoffs, winds and precipitation and covering a time period from 1979 to present date. Additionally, a local model covering the estuary of Isefjorden and Roskilde Fjord was set up with a finer mesh resolution. The local model was calibrated against the measured water level time series from Holbaek and Roskilde. Special emphasis was given to the storm event "Bodil" (6th of December 2013) where peak water levels at Roskilde and at the city of Holbaek were 2.06m and 1.94m, respectively (Danish Coastal Authority, 2017).

The solutions under investigation include two estuary barriers, a submerged dike, permanent solutions with open/closed gates and flood storage channel. Furthermore morphodynamics and sea level rise are investigated using two sedimentation rates, two SLR scenarios as well as +/- storm delay and constant high wind velocity scenarios. The estuary barriers would have a height of 6m and a width of 3.8km (scenario 1), or 6.2km (scenario 2). The submerged dike would extend over a length of 2.0km at a depth of 1m below MSL (scenario 3). The flood storage channel would have a width of 25m and a depth of 0m below MSL (scenario 4). The two elevated sedimentation rates would lead to a bed elevation of 0.25m (scenario 5) or 0.50m (scenario 6), respectively. The SLR scenarios are 0.52 m and 0.96 m. The simulated storm delays are +/- 3 and 6 hours and the constant high velocity wind is 25 m/sec from true north. The options are summarized in Tab. 6.2. It appeared that it was important to include time for stakeholder involvement and for handling and balancing diverging political opinions on local and regional level. As a result, Sweco facilitated a public consultation process including meetings with stakeholders, organizations, citizens, discussion groups, dialogue with municipalities and participation in conferences.

The construction of a dynamic flood protection measure is potentially relevant for any estuary. However, since these protection measures are very costly an estuary specific, thorough investigations are required. In particular, it should be questioned in any estuary whether such investments are really necessary, or whether other measures are also adequate.

6.2.3 M6 (Danish fjords): Improve understanding of contributing role of local waterways to flooding Holbaek Fjord; development of risk and value maps

In Denmark, the municipalities took over from the State the responsibilities for decisions regarding coastal protection, in September 2018. This change was motivated by a supposed increase in speed and simplicity in making large joint coastal protection projects. However, this change also implied that the municipalities needed to undergo a competence building process since this field of expertise is completely new to them. The takeover process, and more specifically the competence building process, is initiated with the preparation of risk maps and value maps in order to upgrade the staff.

The developments of these maps are a fundamental basis for rational planning of climate adaptation. As mentioned earlier, the Holbaek municipality desires a value map in addition of developing risk maps for floods. These value maps are meant to give an overview where the values, in terms of a more fiscal

Table 6.2: List of studied flood protection measures.

Scenario	**Flood protection measure**	**Location**	**Dimensions**
	Flood protection measures		
Scenario 1	Estuary barrier	Hundesteld - Korshage	Height: 6m Length: 3.8m
Scenario 2	Estuary barrier	Lynæs - Rørvig	Height: 6m Length: 6.2km
Scenario 3	Submerged dike	Korshage - Tærsklen	Height: 0m Length: 2.0km
Scenario 4a and 4b	Permanent solution with open (a)/closed gates (b)	Frederikssund	Adjusted to channel
Scenario 5a and 5b	Permanent solution with open (a) /closed gates (b)	Kulhuse	Adjusted to channel
Scenario 6	Flood storage channel	Across Hornsherred	Width: 25m Depth: -2m
	SLR and morphodynamics		
Scenario 7	Sedimentation in nav. channels at estuary mouth	Lynæs - Rørvig	Elevated tidal channel bottom level
Scenario 8	Sedimentation rate 0.25 m	Storesand and Korevle	Elevated bed level 0.25m
Scenario 9	Sedimentation rate 0.50 m	Storesand and Korevle	Elevated bed level 0.50m
Scenario 10	Sea level rise 0.52 m (2071-2100)	Isefjord and Roskilde Fjord	Applied to BC in regional model
Scenario 11	Sea level rise 0.96 m (2071-2100)	Isefjord and Roskilde Fjord	Applied to BC in regional model
Scenario 12	±3 and 6 hrs storm delay	Isefjord and Roskilde Fjord	Applied to BC in regional model
Scenario 13	Constant 25 m/sec wind from true north	Isefjord and Roskilde Fjord	Regional model

approach, are found within the municipal boundary. More specifically, value maps are geographical maps that show the total economic values per unit area in a given area. In principle, they can include all kinds of tangible and intangible values, such as essential societal infrastructures, sites worthy for preservation and protection. For example, a multi-store house is included in a value card with the full property value, while in the context of a risk card, only the value of the potential damage is included. This value normally corresponds to the value of the damage in the basement and ground floor. Other values such as historical values, cultural values, architectural values are also included in the value map. As a result, value maps recognize the full economic value, whereas risk maps only assess property and land values based on the costs that result from the damage caused by a flood.

Besides the maps, the municipality also aims at a holistic approach concerning the role of the different water sources in the flooding events. Seawater, rainwater, rivers, stream and groundwater all need to be incorporated in a climate adaptation plan. So far, seawater and rainwater are prioritized while rivers and streams are included indirectly via flood maps.

A difficulty encountered during the process was the involvement of stakeholders. Dialogues were initiated and information was exchanged with the stakeholders in the threatened areas. However, several different obstacles showed up. For example, there is still a reluctance to collaborate with the public institutions. As a result, the establishment of measures preventing serious flooding damages is difficult to initiate.

The present measure is strongly motivated by the change in administration responsible for coastal protection. Nevertheless, risk and value maps are beneficial for every estuary. The estuaries should therefore check if such maps are available and whether they are needed.

6.2.4 M4 (Humber): Design measures for flood risk management while maintaining/enhancing environmental protection measures

The Humber is surrounded by low-lying floodplains which are at severe risk of flooding during storm surges. This risk is expected to intensify due to the sea level rise, which is forecasted between 0.26m and 1.45m by 2100. As in any populated estuary, the estuary managers face the conflicting interests of economic activity (such as port expansion), the environment (such as the protection of habitats) and flooding risk. An additional challenge is that flood risk and habitat protection fall under the remit of two different actors, respectively the Environment Agency and Natural England. As a result, developing a management solution that accounts for flood risk under climate change, maintains good ecosystem function and preserves or enhances intertidal and saltmarsh habitat requires co-development by two independent Agencies, informed by a range of estuary stakeholders with often competing interests.

It is clear that a satisfactory solution requires co-development with the estuary stakeholders. Subsequently, the Humber 2100+ flood risk strategy was developed by the University of Hull, the Environment Agency and partners- 12 local authorities, the Humber Local Enterprise Partnership (LEP), Natural England and Internal Drainage Boards. This risk strategy aims at simultaneously reinforcing the long-term ambition for a safe and prosperous Humber while maintaining safety and sustainability. The risk strategy can be subdivided into three categories: managing the tide, adapting the tide and keeping out the tide. Managing the tide and adapting the tide would involve an improvement of the flood defences, in combination with additional flood storage and a change in the land use. Keeping out the tide involves the construction of a tidal surge barrier.

Potential collections of measures were initially identified through collaboration and engagement with the Environment Agency. The identified measures were subsequently evaluated according to their level of intervention. These levels ranged from 'do nothing measures', for which the flood risk management in the Humber would be abandoned, to 'do something measures', which would include for example flood walls, habitat creation, flood space or a tidal flood risk management barrier.

The flood risk benefit of the 'do something' measures was assessed using 2D hydrodynamic modelling and comparing estimates of flood volumes against baseline values for three sea level rise forecasts (present day, +1.0m, +2.0m) and storm surges of three different annual exceedance probabilities (100%, 0.5% and 0.1%). In particular, numerical modelling has identified optimal and suboptimal locations and geometries of flood defence and storage measures. Results show that completed managed realignment schemes in the outer estuary, primarily to provide compensatory habitat, such as those at Paull Holme Strays and Welwick, are likely to have increased flood risk within the estuary. This is also the case for proposed managed realignment schemes at Donna Nook, Goxhill, Saltfleet and Sunk Island. In contrast, managed realignment schemes in the mid- to inner estuary, at Alkborough and Chowder Ness, have reduced flood risk. Modelling results were used to highlight opportunities and constraints in a series of stakeholder engagement workshops that were held in March 2020 and involved the University of Hull and the 14 Humber 2100+ partners. One of the aims was to engage stakeholders to collaborate with partners.

Similar to the previous flood protection measures, this measure is potentially applicable to other estuaries. Naturally, different models would have to be built for each estuary. Nevertheless, the lessons learned during the above mentioned studies could serve on targeting more specific scenarios.

6.3 M10 (Humber): Testlab - proof of concept test for measures (virtual lab testing)

Potential measures for flood risk management in the Humber estuary were first investigated individually using 2D-numerical simulations. The outcome of this assessment was used to construct hybrid "scenarios" (i.e. measure combinations), made up of a range of different measures, through the identification of key opportunities and constraints. The effectiveness of each collection of measures was scored on a three-point scale (i.e. positive, negative, and neutral) against twelve development principles:

1. Flood risk and resilience
2. Climate adaptation and mitigation
3. Technical feasibility
4. Economics and funding
5. Place and community
6. Connectivity
7. Water environment
8. Economic development
9. Sustainable agriculture

10. Cultural heritage
11. Habitat and biodiversity
12. Key infrastructure

The development and assessment of the measures was facilitated through the development of a virtual test lab in which the efficiency of different measure combinations were evaluated. In particular, care was taken at identifying collections of measures that could yield flood risk benefits that are greater than those provided by merely summing individual measures (synergy). During workshops with the Humber 2100+ partners (the Environment Agency, the Local Enterprise Partnership and the 12 local authorities), screenable scenarios for long term tidal flood risk management were developed. The resulting 33 hybrid “scenario” maps included a suite of measures such as ideas for potential flood storage, areas where hard defences could be raised, and locations where wider resilience measures help reduce the consequences of flooding. In addition, workshop attendees identified what they considered to be the most important development principles, which have since been used to score the “scenario” maps.

Finally, modelling work has been extended through the use of a generic funnel-shaped estuary geometry to assess the reliability of initial modelling and to explore the transferability of results from the Humber to other large funnel-shaped estuaries. Initial results of this work indicate that the findings are indeed directly transferable to funnel shape estuaries, while the principle of a testlab is applicable to all estuaries.

6.4 Taken measures - Water quality and ecology

6.4.1 M3 (Tees): Improve water quality and economic stimulus through co-location of mariculture within inshore wind farm

In the Tees, the interests of environmental protection agencies and economical actors often clash. The main economical activities in the Tees are industrial and related to the port. This factor implies that port expansions may lead to the destruction of habitat while the creation of habitat within the estuary will restrict port developments and therefore hamper the economy. As a result, industrial development has sometimes been favoured over ecology, leading to a poor water quality status. As an example, we can mention the findings of the Environment Agency’s Reasons for Not Achieving Good status (RNAGs) within the Water Framework Directive, which is currently the main driver of water quality improvements. This agency faces the challenge that no measures to deliver improvements have been put in place so far, since any compensating measures within the estuary would lead to an impediment of the heavy ship traffic (delivering and collecting of cargo activities from industrial companies). Accordingly, there is an awareness within the environmental agencies that it is key to work alongside the industrial partners rather than in opposition to them.

A possible alternative to the current economical model is to develop economic drivers that are not in direct conflict with environmental protection, such as tourism or mariculture. However, tourism development is hampered by major challenges such as (i) too little space available in the estuary and (ii) little infrastructure in the wider Tees Bay. As a result, mariculture is the only viable economic alternative, and the species that grow in mariculture habitats can provide a source of income for fishing communities as well as providing further ecosystem services themselves. Additionally, the coastal habitats associated with mariculture can provide multiple ecosystem services and can be combined with a habitat bank outside the estuary, such that the development of mariculture does not interfere with industrial or port activities.

Before further discussing the measures applied in the Tees, a brief introduction on habitat banks is necessary. A habitat bank is a streamlined, cost-effective compensation activity[85], which offers a solution to implement European laws for environmental protection, which encourage, or require, reparations for significant impacts on biodiversity. Habitat banks ensure that compensatory measures occur on a less individual basis, but are more collective, with greater efficiency and consistency[86]. With habitat banks, developers leave the creation, restauration or preservation of ecologically valuable habitats to specialized institutions and pay them with so called mitigation credits[86]. The mitigation credits represent the value of lost habitat elsewhere. Despite the fact that habitat banks require initial funding, they offer planners and developers a swift, reliable and economical solution for compensating lost habitat[85]. The funds generated by the purchase of habitat subsidize in turn the long-term conservation management of the habitat bank[85]. As a result, habitat banks offer a win-win-win situation for developers (instant, predictable, and cost-effective supply of conservation credits), landowners (additional income stream) and wildlife (larger and better connected sites)[85]. Therefore, habitat banks can offer a welcome remedy for the earlier mentioned conflict of interest of the different stakeholders.

Currently, investigations are ongoing about a suitable location for developing mariculture and a habitat bank. The Tees Bay wind farm is an area free from shipping traffic and has subsequently been identified as a promising area for reef habitat where potentially fishery could be developed. A feasibility study and case study are being populated with information and further information is being gathered, including input from stakeholders and experts. Multiple stakeholders have been engaged through this process including the wind farm owners (EDF). This study has driven a successful partnership with the port authority in the Tees, in order to deliver part of the Tees Rivers Trusts intertidal habitat creation works within the Tees. Once completed the documents will give a better idea of whether or not a mariculture venture could be located within the wind farm, which species might do best there, and what changes to water quality could mean to the survival of other key species. The comparative benefits and drawbacks of the Habitat Banking Scheme will be identified compared to traditional grant funding, giving a framework for what could be further delivered under this scheme.

There are two specific aims of the current measures. The first objective is to able to use the habitat banking scheme as an alternative funding stream for further habitat creation works within the estuary. It would allow to store sufficient compensating measures, without interfering with ship trafficking by developing the measures outside the estuary. The second objective is that the mariculture feasibility study will act as a starting point to attract further funding in order to deliver this investigation as a field pilot within the Teesside wind farm. Works completed following the IMMERSE project will hopefully be used as an example for further work in the Tees Estuary as well as other estuaries around the wider North Sea region.

So far, the project has already lead to several interesting insights concerning the implementation of mariculture, habitat banks and the collaboration with industrial partners. For example, seabed within wind farms turned out to be an untapped resource if implemented correctly since it is not used by the wind farm for maintenance. Large areas of seabed have no cables or other assets that could be affected by developing habitat there. Additionally, it appeared that industrial partners require a long lead in time, such that a joint effort demands significant planning ahead. Furthermore, it became clear that the process of gaining permission to have a commercial enterprise within the footprint of the wind farm may be complicated, such that projects with indirect economical stimulus (e.g. create habitat for vulnerable native species potentially leading to more robust fishery) are preferred.

Potentially, habitat banks can be implemented in any estuary. However, when designing a habitat bank, special care should be taken when designing these banks, since the type of nature that is created is estuary specific. As a result, it is likely that the creation of habitat banks requires an in-depth preliminary study.

6.4.2 M8 (Tees): Pilot on intertidal habitat creation

Land reclamation and habitat loss has led to coastal squeeze within the Tees Estuary, putting pressure on the various species that rely on the intertidal zone. Current measures to address habitat loss focus on expensive hard engineering options, which include concrete walls as retaining structures or the use of gabion baskets. These options limit the area of habitat that can be created and therefore reduce the impact that projects can have on intertidal populations.

To explore less expensive options, the idea is to create steps within the intertidal zone, increasing the area available to each level of habitat, using softer and more natural designs. Several such designs were examined with the input from stakeholders. The materials used are familiar in other settings and have been used by the Tees Rivers Trust before in, for example, bank erosion works in freshwater systems. An overview of the different designs is given in Fig. 6.1

So far, one of the sections of the intertidal habitat creation site has been realized. It was completed under budget and under timing by utilizing natural materials and the river works expertise within the Tees Rivers Trust. The remaining sections of the site will be completed, including a gravel berm that will enclose the site and create a large area of low level mudflat.

Monitoring of several species took place prior to and after the works, with the aim to assess whether the project has been successful. The focus was on fish, seal, bird, plant and lichen, and benthic invertebrate. It appeared that most birds recorded during surveys were utilising intertidal habitat on the opposite bank to the IMMERSE site. Due to the geographic proximity, it is safe to assume that if suitable habitat was provided, it would be utilised by these birds and potentially draw further individuals in, due to increased food supply. Saltmarsh plant species have already been recorded in small numbers within the IMMERSE site. Given expanded habitat at a suitable level above low water, it is expected to detect increased abundance of saltmarsh, and other intertidal, species, and increased percentage cover in these suitable levels. Seals have been recorded around the site, usually travelling past, however, it would appear that some sort of usage of the site currently exists, if only to provide an area to rest. As thriving habitats draw in other organisms from different levels of the food chain, it is expected that other species, such as seals, will be seen more frequently using this site, as it is developed further.

Creating steps in the intertidal zones is a measure that is only meaningful for macro-tidal estuaries. Particularly in estuaries with very steep intertidal zones, this measure could be applicable: the Humber, the Scheldt and the Elbe. For the Göta Älv and the Fjords, this measure is not applicable.

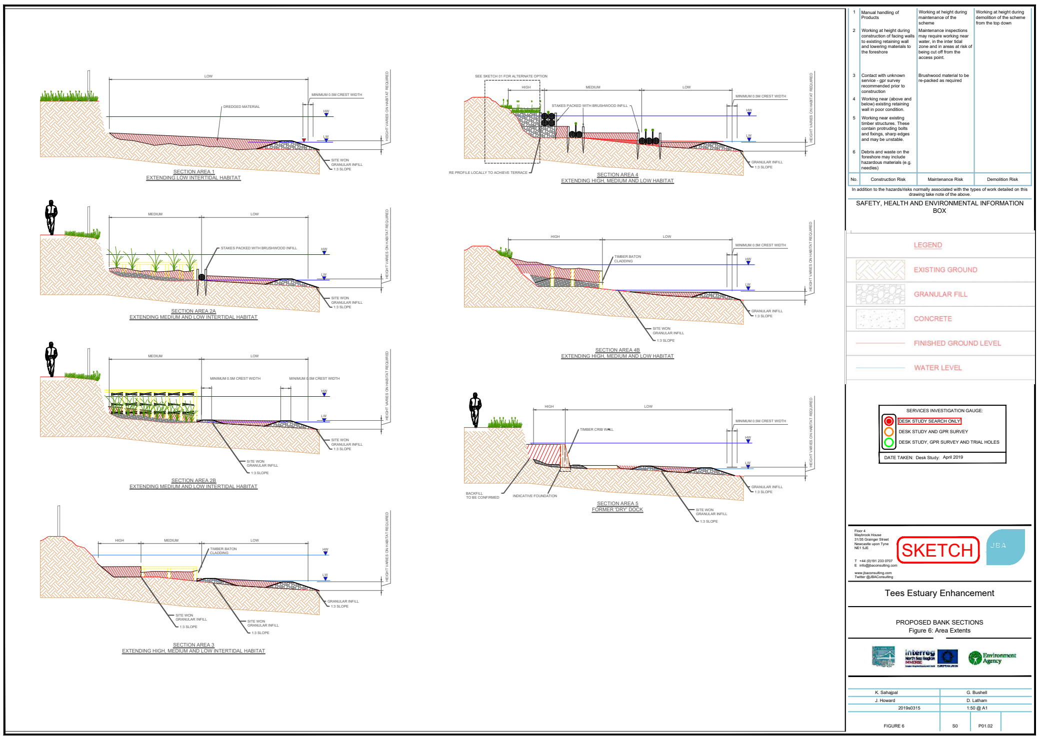

Figure 6.1: Overview of the different designs for intertidal zones

6.4.3 M2 (Göta Älv): Design solutions for managing contaminated sediments, including assessing existing pilot on stabilization/solidification of dredged masses and develop method for recovery of metals and polluted sediments

Although Tributyltin (TBT)-containing paints are banned on all Swedish ships beside ocean-going vessels since 1993, large amounts of Organotin compounds (OT) remain in the environment, especially in harbor sediments. These remains pose serious pollution problems since they act as point diffusers and TBT concentrations of 0.01-10 µg/g have been reported on the Swedish West Coast, with the highest concentrations at Gothenburg harbor.

The sediments themselves need to be dredged regularly to maintain sufficient depth for ships to access harbors. The contaminated sediments cannot be relocated in the estuary and need to be landfilled, shifting the pollution problem from water to land. Accordingly, more sustainable solutions for polluted sediment are required. A first measure is to develop a new purpose for sediments, such as for example treating them and using them as a construction material. A second measure is to put in place a specific protocol for handling polluted sediments. This protocol is necessary since different sediments may have different levels of pollution and can be used for different purposes. Not all sediments will be transformed into construction material.

New solution for contaminated sediments and Life Cycle Assessment

The possibility to use the sediments as a construction material is a sustainable solution that is already well in progress. In the Port of Gothenburg, an entirely new terminal is constructed using contaminated sediments. However, the sediments need to be treated before they can be used as a construction material. Indeed, it is desired that the construction material permanently traps polluted sediment and that there is no further leaching of TBT and other organic pollutants into the surrounding waters. Additionally, valuable metals could be recovered from the sediments. Finally, it is expected that the treatment of the sediment will change the structure of the material and will potentially give a construction material of other quality than the stabilized sediment without any treatment. More precisely, there are specific conditions regarding TBT leaching from the construction, and sediments need to be stabilized. The stabilization of the sediment is performed by adding binders, consisting of cement and granulated blast furnace slag. Determining the optimal binder requires considerable research and is divided in several steps.

1. laboratory tests and evaluation of geotechnical properties and leaching of contaminants

2. monitoring environmental and geotechnical properties in a field pilot test according to a specific program

So far, the pilot structure was found to leach TBT in too high concentrations during and after the construction, although there is hope that the leaching of TBT will decline with time. Currently, more advanced methods are being investigated at Chalmers University, again in a multiple step approach. The first step is to develop new methods for removal of polluting agents. Examples are

1. washing with alternative leaching agents[87];

2. degradation of TBT with Fenton's reagent and the recovery of tin and other valuable metals via electrolysis[87] ;

3. phytoremediation (i.e. the use of living plants for cleaning substances with plants) of organotin polluted sediments, although this method gave mixed results (some degradation occurred but the plants died due to salt);

4. stabilisation of sediment treated with electrolysis, and durability and leaching tests of the constructions.

The analysis for the organotin compounds (OTs) are expensive and, accordingly experimental series need to be planned with few analyses. Additionally, degradation of OTs is challenging and thus hard to reach with low-impact reagents that do not affect the sediment residues much. Finally, sediments contaminated with both OTs and metals are even more challenging to treat but occur more often in real-life cases.

A comparative Life Cycle Assessment (LCA) was carry out. The LCA aimed at studying the environmental impact of the deep-sea landfill, landfill on land, stabilisation in concrete construction without any pretreatment of the sediment, and electrolysis with and without subsequent stabilisation of the sediments has been initiated. The LCA will be done using the software SimaPro® EPD and the database Ecoinvent, applied on and complemented with real site data. The real site data will be acquired from previously dredged sediment in the port of Gothenburg and data achieved from the pilot construction in the port that used the dredged sediment. The study also applies data from the laboratory investigations described above on the potential sediment remediation techniques applying electrolysis.

- All dredged sediment masses are disposed of in landfills for non-hazardous waste. According to the results of the measurements, this is a possible scenario in Gothenburg.
- Part of the sediments is disposed of in a landfill for hazardous waste and the rest in a landfill for non-hazardous waste. This is an alternative action that needs to be taken if part of the sediments is heavily polluted. (The fraction of hazardous waste is taken from real site measurements in another more polluted Swedish port than the port of Gothenburg that has recently been remediated, i.e. the port of Oskarshamn). (Landfill NHW+HW)
- Deep-sea disposal and landfill for non-hazardous waste. Everything that is not allowed to be dumped in the sea is deposited at a landfill. The fractions are based on measurements of sediments in the Port of Gothenburg. (Sea + landfill)
- Deep-sea disposal and landfill for non-hazardous and hazardous waste. The fractions are based on measurements in Oskarshamn. (Sea + landfill NHW+HW)
- Use of all the dredged sediments as filling material for the construction of port areas (Construction)
- Electrolysis of sediments to extract valuable metals. Use of the rest of the sediments as filling material for the construction of port areas. Metal content from measurements of sediments in the port of Gothenburg (Construction + electrolysis GBG)
- Electrolysis of sediments. Use of the rest of the sediments as filling material for the construction of port areas. Metal content from previous measurements in Oskarshamn (Construction + electrolysis OSK)
- Electrolysis of sediments. The rest is deposited in deep-sea landfills and landfills for non-hazardous waste. The fractions are based on Gothenburg. (Electrolysis + sea + landfill GBG)
- Electrolysis of sediments. The rest is deposited in deep-sea landfills and landfills for non-hazardous waste. The fractions are based on Oskarshamn (Electrolysis + sea + landfill OSK)

Sediment management protocol and Integrated Assessment

A specific protocol for polluted sediment management requires the development and the evaluation of new systematic stepwise **integrated assessment (IA)** method. This IA assesses the impacts of different management approaches for dredged contaminated sediments and focused on three objectives: (1) development of a six step IA framework (see Fig. 6.2); (2) selection of five relevant management alternatives for dredged sediments (see Table 6.3); (3) application of the developed IA frame-work to six case study areas in Sweden, including the collection of relevant data (sediment characteristics, management costs, and potential revenues) and the use of the IA framework to compare management alternatives for dredged sediments.

Table 6.3: Relevant management alternatives for dredged sediments.

Alternative 1	Materials that meet the criteria for the SSV Vinga (Vinga) are deep-sea disposed, while materials that do not meet the Vinga disposal criteria but are less contaminated than soils suitable for LSLU are landfilled, and the remaining materials are used for metal extraction
Alternative 2	Materials that meet the criteria for Vinga are deep-sea disposed, materials that do not meet the Vinga disposal criteria, but are less contaminated than soils suitable for LSLU are landfilled, and the remaining materials are used for metal extraction;
Alternative 3	Materials that meet the criteria for Vinga are deep-sea disposed, while all other materials are used for metal extraction;
Alternative 4	All materials not classified as hazardous waste (HW) are landfilled, remaining materials are used for metal extraction;
Alternative 5	Only materials with low-moderate contamination levels (bLSLU) are landfilled, remaining materials are used for metal extraction.

Overall, the treatment of sediment is interesting in each estuary suffering from historical pollution. Metals can be extracted from the sediments and treated sediment can eventually be used as construction material. Particularly this possible use can be kept in mind for infrastructural works within an estuary.

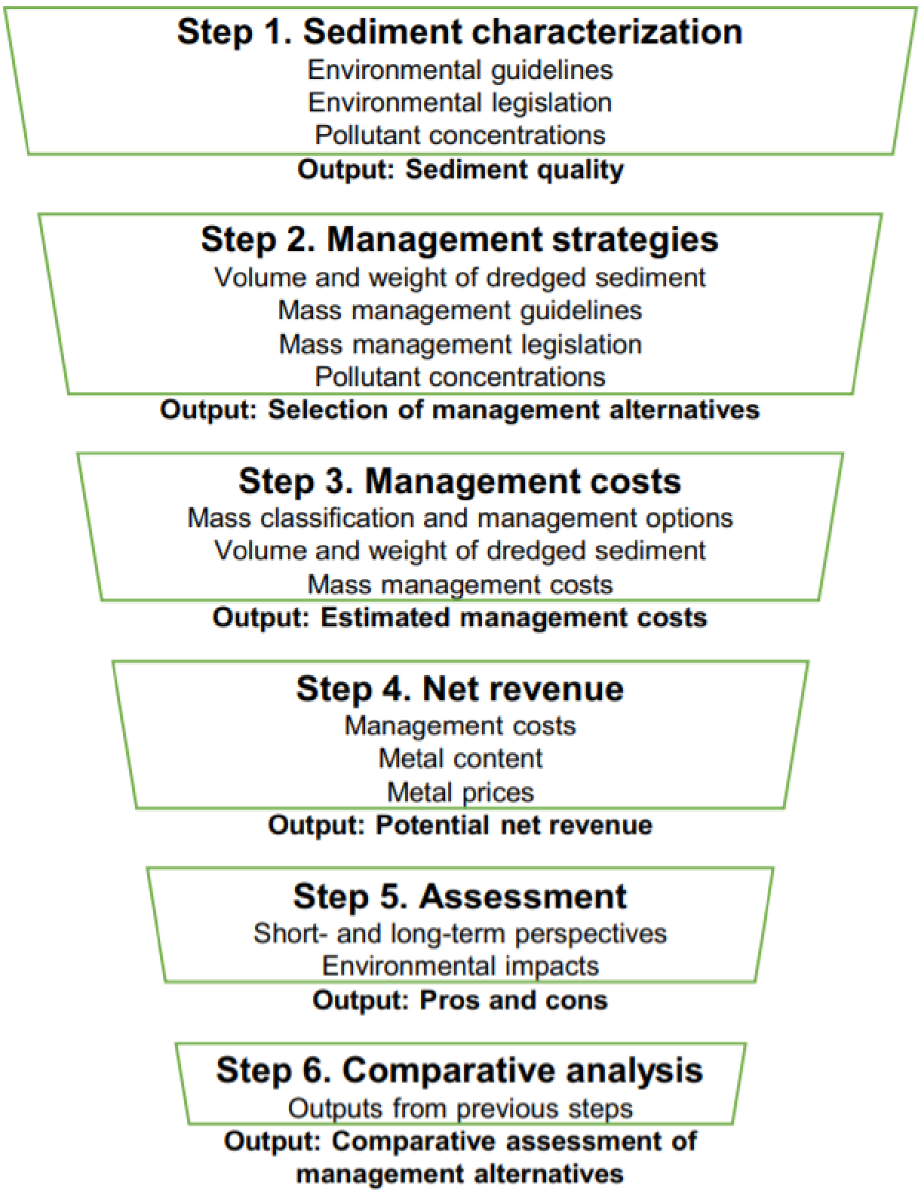

Figure 6.2: Assessment framework for the developed integrated assessment method comparing different management approaches for dredged contaminated sediments from [88]

6.5 Conclusions

In the present report, several measures to tackle common threats of European estuaries are described. The measures focus on general topics such as flooding, tidal pumping and water quality. One of the objectives of the IMMERSE project is to investigate the transferability of the measures from an estuary to another. Despite common threats between estuaries, not all measures are potentially transferable to each estuary. This non-transferability mainly has to do with the estuary characteristics highlighted in Sec. 3.1. For example, measures against tidal amplification make no sense in estuaries with negligible tidal amplitude such as the Fjords or the Göta Älv. Table 6.4 summarises the different measures and marks for each measure

- the estuary in which the measure takes place by ✓,
- the estuaries in which the measure is potentially transferable, because similar issues occur, by a 'o',
- the estuaries for which the transferability could be possible but for which additional research/information is needed by a '?'.
- the estuaries for which a measure is not potentially transferable because a particular issue does not occur by a 'x'

Some measures are not directly applicable to specific estuaries but can be interesting if slightly adjusted. For example, measure M5 deals with sand nourishment at strategic locations. The idea is to investigate the actual available sand supply in this part of the coastal foundation and the estuary, as well as the magnitude and direction of the sediment transport such that nourishment can be undertaken more efficiently. The measure specifically focusses on preventing further amplification of the tidal wave. Nevertheless, it could also be applied to systems which are not dominated by tidal currents, such as the Fjords and the Göta Älv. Similarly, measure M1, which takes advantage of the mean tidal sand transport direction, could be adjusted to fit the Göta Älv, for example by taking into account the sand transport due to mean flow. Finally, measure M12 which focusses on reducing the tidal range with a side-channel, could be adapted for storing excess rain water.

Besides the measures themselves, the involvement of, and relationships with, stakeholders is mentioned by almost all IMMERSE partners. This involvement varied from an informative relationship (Scheldt, Göta Älv), a more collaborative (Humber, Tees) to even a strained relationship (Fjords, Scheldt, Elbe). Involving stakeholders in the development of measures is one of the focus points within the IMMERSE project. Stakeholder engagement is discussed in more detail in other IMMERSE reports.

Table 6.4: Indication of transferability of the IMMERSE specific measures amongst the IMMERSE estuaries. For further explanation, see the main text.

	Description	Scheldt	Tees	Elbe	Fjords	Göta Älv	Humber
M1	Develop a morphological management strategy	✓	x	o	x	?	o
M2	Design solutions for managing contaminated sediments, including assessing existing pilot on stabilisation/solidification of dredged masses and develop method for recovery of metals and polluted sediments	o	o	o	o	✓	o
M3	Improve water quality and economic stimulus through co-location of mariculture with inshore windfarm	o	✓	?	o	o	o
M4	Design measures for flood risk management while maintaining/enhancing environmental protection measures	o	o	o	o	o	✓
M5	Design solutions to prevent further amplification of the tidal range	✓	?	o	?	?	o
M6	Improve understanding of contributing role of local waterways to flooding; development of risk and value maps	o	o	o	✓	o	o
M7	Analysis, design and environmental assessment of a dynamic flood protection measure	o	o	o	✓	o	o
M8	Pilot on intertidal habitat creation	o	✓	o	x	x	o
M9	Feasibility study on the reconnection of the Dove-Elbe incl. Assess adapted sediment management through use of numerical modelling	o	x	✓	x	x	o
M10	Testlab: proof of concept test for measures (lab testing)	o	o	o	o	o	✓
M11	Pilot on cross-border solutions for maintenance dredging	✓	x	o	x	?	o
M12	Execute measure to reduce tidal intrusion and increase nature value	✓	x	o	x	?	o

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Bibliography

(1) Maris, T. Microsoft Word Document-Revision.docx, unpublished, (personal communication via e-mail), 2019.

(2) Pauwels, C. Microsoft Word Document-201909_IMMERSE_WP3_1_ScheldtEstuary.docx, unpublished, (personal communication via e-mail), 2019.

(3) Ahlhorn, F. et al. *Management of Estuaries-The need to understand nature society-TIDE summary report*; tech. rep.; The Scheldt, Elbe, Humber and Weser. Study in the framework of the Interreg IVB project TIDE, 2013.

(4) Fraser, Z. (Tees Rivers Trust) Microsoft Excel Document-WP3.1 Further Information.xlsx, unpublished, (personal communication via e-mail), 2019.

(5) Norberg, P. Microsoft Word Document-WL2019R19_005_1_IMMERSE_WP31_V1.docx, unpublished, (personal communication via e-mail), 2020.

(6) Boyes, S.; Elliott, M. *Marine Pollution Bulletin* **2006**, *53*, 136–143.

(7) -unknown- Microsoft Word Document-191011_WP3.1_Elbe_partners.docx, unpublished, (personal communication via e-mail), 2019.

(8) Statistisches Bundesamt, 2010.

(9) Humber Local Enterprise Partnership *Strategic Economic Plan 2014-2020.* Tech. rep.; 2014.

(10) Plancke, Y.; Vandenbruwaene, W.; Schramkowski, G.; Mostaert, F. *TIDE - WP3 task 4: Inter-estuarine comparison: "Cubage" calculation for the Humber.* WL Reports 770_62b, version 6.0; Antwerp: Flanders Hydraulics Research, 2012.

(11) Vandenbruwaene, W.; Plancke, Y.; Verwaest, T.; Mostaert, F. *Interestuarine comparison: Hydro-geomorphology: Hydro -and geomorphodynamics of the TIDE estuaries Scheldt, Elbe, Weser and Humber.* WL Reports 770_62b, version 4.0; Antwerp: Flanders Hydraulics Research, 2013.

(12) Göransson, G.; Larson, M.; Bendz1, B. *Hydrology and Earth System Sciences* **2013**, *17*, 2529–2542.

(13) Conley, D. J.; Kaas, H.; Møhlenberg, F.; Rasmussen, B.; Windolf, J. *Estuaries* **2000**, *2*, 820–837.

(14) Dalrymple, R. W.; Zaitlin, B. A.; Boyd, R. *Journal of Sedimentary Research* **1992**, *62*, 1130–1146.

(15) Day, J.; Hall, C.; Kemp, W.; Yañez–Arancibia, A. Estuarine Ecology, 1989.

(16) Day, J. *South African Journal of Science* **1980**, *76*, 198–198.

(17) Dionne, J. *Zeitschrift fur Geomorphologie* **1963**, *7*, 36–44.

(18) Elliott, M.; McLusky, D. S. *Estuarine, coastal and shelf science* **2002**, *55*, 815–827.

(19) Fairbridge, R. *New York, Wiley* **1980**, *1*, 35.

(20) Ketchum, B. *Estuaries and enclosed seas* **1983**.

(21) Kjerfve, B. *Estuarine ecology* **1989**, 47–78.

(22) Perillo, G. M. In *Developments in Sedimentology*; Elsevier: 1995; Vol. 53, pp 17–47.

(23) Pritchard, D. W. *Estuaries* **1967**.

(24) Wolanski, E. Estuarine ecohydrology. 2007.

(25) Romao, C. **1996**.

(26) Whitfield, A.; Elliot, M. Ecosystem and biotic classifications of estuaries and coasts. Treatise on Estuarine and Coastal Science, 2011.

(27) Harten, H.; Vollmers, H. *Die Küste, 32 Die Geschichte des deutschen Küstengebietes-The History of the German Coastal Area* **1978**, 50–65.

(28) Pritchard, D. W. In *Advances in geophysics*; Elsevier: 1952; Vol. 1, pp 243–280.

(29) Dyer, K. R. **1997**.

(30) DYER, K. **1972**.

(31) Hayes, M. *New York, Academic Press* **1975**, *2*, 3–22.

(32) Rusnak, G. A. **1967**.

(33) Davidson, N.; Laffoley, D. d.; Doody, J.; Way, L.; Gordon, J.; Key, R. e.; Drake, C.; Pienkowski, M.; Mitchell, R.; Duff, K. *Nature Conservancy Council, Peterborough* **1991**, 1–76.

(34) Bulger, A. J.; Hayden, B. P.; Monaco, M. E.; Nelson, D. M.; McCormick-Ray, M. G. *Estuaries* **1993**, *16*, 311–322.

(35) Jay, D. A.; Geyer, W. R.; Montgomery, D. *Estuarine science: a synthetic approach to research and practice. Island Press, Washington DC* **2000**, 149–176.

(36) Gray, J. S.; Elliott, M., *Ecology of marine sediments: from science to management*; Oxford University Press: 2009.

(37) Fraser, Z. (Tees Rivers Trust) Microsoft Excel Document-Copy of Information Still Needed Tees Estuary.xlsx, unpublished, (personal communication via e-mail), 2019.

(38) Pedersen, L. M.; Garborg, K. Microsoft Word Document-20200117_Lotte_Denmark.docx, unpublished, (personal communication via e-mail), 2020.

(39) Codiga, D. L. *Unified Tidal Analysis and Prediction Using the UTide Matlab Functions*; Technical Report 2011-01; Narragansett: Graduate School of Oceanography, University of Rhode Island, 2011.

(40) De Swart, H.; Zimmerman, J. *Annual Review of Fluid Mechanics* **2009**, *41*, 203–229.

(41) Van Braeckel, A.; Coen, L.; Peeters, P.; Plancke, Y.; Mikkelsen, J.; Van den Bergh, E. *Historische evolutie van Zeescheldehabitats Kwantitatieve en kwalitatieve analyse van invloedsfactoren*; Report; Antwerpen: Instituut voor Natuur- en Bosonderzoek, Brussel i.s.m. het Waterbouwkundig Laboratorium, 2012.

(42) Vandenbruwaene, W.; Levy, Y.; Plancke, Y.; Vanlede, J.; Verwaest, T.; Mostaert, F. *Integraal plan Boven Zeeschelde: deelrapport 8. Sedimentbalans Zeeschelde, Rupel en Durme*; tech. rep.; Antwerpen, 2017.

(43) Meyvis, L. *Werken uitgevoerd in de Scheldebedding en haar bijrivieren sinds 1850, tussen Gent en de Belgisch-Nederlandse grens: deel 1*; tech. rep.; Antwerpen, 1977.

(44) Vandenbruwaene, W.; Beullens, J.; Meire, D.; Plancke, Y.; Mostaert, F. *Agenda voor de Toekomst–Schelde estuarium, historische evolutie getij en morfologie: deelrapport 2. Data-analyse morfologie en getij*; 2020.

(45) Maximova, T.; Ides, S.; Plancke, Y.; De Mulder, T.; Mostaert, F. *Vervolgstudie inventarisatie en historische analyse van slikken en schorren langs de Zeeschelde: deelrapport 3. Scenario analyse 2D model*; WL rapporten 713_21; Antwerpen: Waterbouwkundig Laboratorium, 2010.

(46) Meyvis, L. *Indijkingen en waterbouwkundige werken langs de Westerschelde en de Zeeschelde, 2*; tech. rep. 77; Antwerpen, 1977.

(47) Zitman, T. J. *Getijanalyse Westerschelde*; tech. rep.; Deventer, 1999.

(48) Barendregt, A.; Gloer, P.; Saris, F. *Tidal freshwater wetlands* **2009**, 185–196.

(49) Ohle, N.; Schuster, D.; Kappenberg, J.; Sothmann, J.; Rudolph, E. In *ICHE 2014. Proceedings of the 11th International Conference on Hydroscience & Engineering*, 2014, pp 461–468.

(50) Weilbeer, H. *Terra et Aqua* **2015**, *139*, 11–23.

(51) Vandenbruwaene; Vanlede, J.; Plancke, Y.; Verwaest, T.; Mostaert, F. *Slibbalans Zeeschelde: deelrapport 4. Historische evolutie SPM*; tech. rep.; Antwerpen, 2016.

(52) Cleveringa, J. *Project LTV Veiligheid en Toegankelijkheid. LTV V&T-Rapport K-17, Arcadis (Emmeloord)* **2013**.

(53) Danish Meteorological Institute Climate Atlas, 2021.

(54) Karsten Garborg Microsoft Excel Document-InformationSheet_AMAS.xlsx, unpublished, (personal communication via e-mail), 2019.

(55) Bergström, S.; Jóhannesson, T.; Aðalgeirsdóttir, G.; Ahlstrøm, A.; Andreassen, L.; Andréasson, J.; Beldring, S.; Björnsson, H.; Carlsson, B.; Crochet, P., et al. *Joint final report from the CE Hydrological Models and Snow and Ice Groups* **2007**.

(56) Stromvall, A.-M.; Andersson-Skold, Y.; Rauch, S. Microsoft Word Document-COWI 2019-09-30_IMMERSE_WP3_1, unpublished, (personal communication via e-mail), 2019.

(57) Wolfstein, K.; Rahlf, H.; Ortiz, V. Microsoft Word Document-WL2019R19_005_1_IMMERSE_WP31_KW_VO_HR unpublished, (personal communication via e-mail), 2020.

(58) Göta Älvs vattenvÅrdsförbund *Fakta om Göta älv - En beskrivning av Göta Älv och dess avrinningsomrÅde nedströms Vänern 2015*; tech. rep.; 2015.

(59) Johansson, K.; Skrapste, A.; Oscarsson, H. *Miljögifter i och kring Göta Älv – sammanställning av undersökningar av vatten, sediment, biota och utsläpp*; tech. rep.; 2003.

(60) Neal, C.; Jarvie, H. P.; Oguchi, T. *Hydrological Processes* **1999**, *13*, 1117–1136.

(61) FGG Elbe *Hintergrundpapier zur Ableitung der überregionalen Bewirtschaftungsziele für die Oberflächengewässer im deutschen Teil der Flussgebietseinheit Elbe für den Belastungsschwerpunkt Schadstoffe*; tech. rep.; 2009.

(62) Parmentier, K. F.; Verhaegen, Y.; De Witte, B. P.; Hoffman, S.; Delbare, D. H.; Roose, P. M.; Hylland, K. D.; Burgeot, T.; Smagghe, G. J.; Cooreman, K. *Frontiers in Marine Science* **2019**, *6*, 633.

(63) Green, B. C.; Johnson, C. L. *Marine pollution bulletin* **2020**, *151*, 110788.

(64) Ryckegem, G. V. Microsoft Word Document-Review_EVINBO_12122019.docx, unpublished, (personal communication via e-mail), 2019.

(65) Jensen, H. M.; Panagiotidis, P.; Reker, J. *Delineation of the MSFD Article 4 marine regions and subregions*; tech. rep.; 2015.

(66) Guidance, Identification and Designation of Heavily Modified and Artificial Water Bodies Common implementation strategy for the Water Framework Directive (2000/60/EC), 2003.

(67) Wolfstein, K. Microsoft Excel Document-191111InformationSheet_Elbe_BAW_HPA.xlsx, unpublished, (personal communication via e-mail), 2019.

(68) -unknown- Microsoft Word Document-2019_10-IMMERSE-WP3.1-Tees.docx, unpublished, (personal communication via e-mail), 2019.

(69) Natura 2000 Vlaanderen Specifieke natuurdoelen, https://www.natura2000.vlaanderen.be/gebied/zeeschelde-sigma/specifieke-natuurdoelen, -.

(70) Ministerie van Landbouw Natuur en voedselkwaliteit Westerschelde & Saeftinghe, https://www.synbiosys.alterra.nl/natura2000/gebiedendatabase.aspx?subj=n2k&groep=10&id=n2k122, -.

(71) Natura 2000 Elbe Integrated management plan Elbe estuary, https://www.natura2000-unterelbe.de/media/downloads/IBP_engl_mit_Titel_72dpi_RGB.pdf, -.

(72) Vlaams-Nederlanse Schelde commissie Op weg naar het Geopark Schelde Delta, https://magazines.vnsc.eu/scheldemagazine2019/geopark-schelde-delta/.

(73) Paelinckx, D.; De Saeger, S.; Oosterlynck, P.; Vanden Borre, J.; Westra, T.; Denys, L.; Leyssen, A.; Provoost, S.; Thomaes, A.; Vandevoorde, B.; Spanhove, T. Regionale staat van instandhouding voor de habitattypen van de Habitatrichtlijn. Rapportageperiode 2013 - 2018, rapporten van het Instituut voor Natuur- en Bosonderzoek 2019 (13). https://pureportal.inbo.be/portal/files/16266937/Paelinckx_etal_2019_RegionaleStaatVanInstandhoudingVoorDeHabitattypenVanDeHabitatrichtlij
pdf, 2019.

(74) Humber Nature SALTMARSH, accessed May 21, 2020.

(75) Cleveringa, J. *Onderbouwing nuttige toepassing voor grensoverschrijdende proefstortingen Zeeschelde-Westerschelde*; Arcadis rapporten; Zwolle: Arcadis Nederland B.V., 2018.

(76) Vandenbruwaene, W.; J., S.; Plancke, Y.; Mostaert, F. *Agenda voor de Toekomst – Historische evolutie getij en morfologie Schelde estuarium: Deelrapport 5 – Synthese.* WL rapporten 14_147_5; Antwerpen: Waterbouwkundig Laboratorium, 2020.

(77) Vandenbruwaene, W.; Levy, Y.; Plancke, Y.; Vanlede, J.; Verwaest, T.; Mostaert, F. *Integraal plan Boven-Zeeschelde: deelrapport 8. Sedimentbalans Zeeschelde, Rupel en Durme*; WL Rapporten 13_131_8, version 4.0; Antwerpen: Waterbouwkundig Laboratorium, 2017, 42 + 22 p. bijlagen pp.

(78) De Boer, M. *Passende beoordeling en toets beschermde soorten - concept. Grensoverschrijdende proefstortingen Westerschelde*; Arcadis rapporten 083788143 C; Zwolle: Arcadis Nederland B.V., 2020.

(79) *Morfologisch modelleren grensoverschrijdende proefstortingen; Ontwikkelingen bij het Land van Saeftinghe ten gevolge van de proefstortinge*; 083684058-A; Zwolle: Arcadis, 2018.

(80) *Ebb-flood channel system at the Upper Sea Scheldt (Wijmeers)*; I/NO/11448/18.231/EKR/GVH; Antwerp: IMDC, 2019.

(81) Bi, Q.; Smolders, S.; Vanlede, J.; Mostaert, F. *A new ebb-flood channel system in the Upper Sea Scheldt (Wijmeers). A model study with Telemac-3D*; WL rapporten 18_138_1; Antwerpen: Waterbouwkundig Laboratorium, 2019.

(82) Barneveld, H. J.; Nieuwkamer, R. L. J.; Klaassen, G. J. *Water science and technology* **1994**, *29*, 335–345.

(83) Bundesanstalt für Wasserbau and Hamburg Port Authority *Effects of the reconnection of the Dove Elbe to the tidal Elbe and local stakeholders - Executive summary and lessons learned from a feasibility study*; tech. rep.; 2021.

(84) Bundesanstalt für Wasserbau *Auswirkung der Schaffung von Flutraum im Bereich der Tideelbe, Wiederanschluss Dove Elbe. Ergebnisse der Wasserbauliche Systemstudie zur Ma ß nahme Dove Elbe.* Tech. rep.; 2021.

(85) Environment Bank Habitat Banking, `https://www.environmentbank.com/habitat-banking/`, 2021.

(86) Dupont, V. Habitat banking in the quest for effective biodiversity offsets : comparative legal analysis of the schemes in place in the United States and Australia in view of their potential establishment in the European Union, Ph.D. Thesis.

(87) Norén, A.; Karlfeldt Fedje, K.; Strömvall, A.-M.; Rauch, S.; Andersson-Sköld, Y. *Journal of Environmental Management* **2021**, *282*, 111906.

(88) Norén, A.; Fedje, K. K.; Strömvall, A.-M.; Rauch, S.; Andersson-Sköld, Y. *Science of The Total Environment* **2020**, *716*, 135510.