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IMMERSE WP3.1

Summary of status of current pressures and trends, and analysis of current measures effectiveness

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Interreg
North Sea Region
IMMERSE
European Regional Development Fund

EUROPEAN UNION

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

S.J. Kaptein, G. Schramkowski, W. Vandenbruwaene and F. Mostaert

March 20, 2020

Contents

1 Introduction

1.1 Context

The estuaries in the North Sea Region combine busy crossroads of transport routes with valuable ecological areas. They offer opportunities to link important cities and ports (e.g. Hamburg, Tees, Antwerp, Hull, 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 be cost-effective and deliver multiple benefits. As a result, innovative solutions with large investments, long planning periods and stakeholder commitment are necessary.

1.2 This report

The (IMMERSE) Implementing Measures for Sustainable Estuaries project focuses on international cooperation 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, the solutions are assessed, tested, and recommandations are provided. Finally, the preparations for the implementation of the measures are undertaken , if possible. However, not all individual measures will go through all three development steps. First of all, because measure development and implementation is a long-term process, so 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. Secondly, some partners are not in the legal position to implement certain (larger management) measures.

The IMMERSE project consist out 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 the 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, cost-efficiency 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, related to the works of the TIDE project[2–7]:

- 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

The summary report was based on the information made available by the project partners, and divided into three categories, each of them comprising several subcategories.

- Biology/ecology
  - Development and/or protection of specific habitats
  - Development and/or protection of specific species
  - Development of natural gradients and processes, transition and connection
  - Prevention of introduction of or to fight invasive species
- Hydrology/morphology
  - Reduction of tidal energy, tidal range, tidal asymmetry and tidal pumping effects

  - Flood protection
  - Improvement of morphological conditions
  - Reduction need for dredging
- Physical/chemical quality
  - Reduction of pollutant loading
  - Reduction of nutrient loading
  - Improvement of oxygen conditions
  - Reduction of physical loading
  - Improvement of self-purifying power

This categorization is reflected in the structure of the present document. However, in order to avoid repetition, it was chosen to adjust the subdivision of each section according to (i) current status of the parameter, (ii) trends, (iii) planned and already conducted measures and (iv) (expected) effectiveness of measures. Moreover, in practice it appeared that not all the proposed sub-categorized goals were addressed by the partners in the provided information sheets. As a result, this also impacted the trends, measures and goals mentioned in this report.

Additionally, IMMERSE builds on the knowledge gained during previous projects (e.g. TIDE and SmartSediment). Nevertheless, it is important to mention that this report is not a result of direct scientific investigations carried out during this IMMERSE project. It should be considered as a first step towards a complete summary of the available information for the different estuaries provided at a particular moment about the current status, the pressures, the intended solutions and the benefits of these solutions as the information was gathered by the partners during a limited time.

1.3 Note on the available information

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 was homogenized by requesting missing information from the partners. These circumstances imply that part of the information provided in this report could be further specified through a deeper scientific analysis and some suggestions for such analyses are provided. Hence, conclusions derived herein are to be qualified as indicative since their substantiation would require a lengthier and more in-depth study.

Finally, it is noted that no data were obtained regarding the Humber Estuary. It was therefore decided to use information as adopted in the TIDE project reports of the Humber cubage study[2] and the inter-estuarine comparison[3]. As a result, the discussion of the Humber is effectively limited to hydrology and morphology (Chapter 3).

2 The estuaries

As mentioned previously, the IMMERSE project focuses on 7 estuaries, all discharging in the North Sea (see Fig. 2.1).

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

This section briefly introduces each estuary, summarizing its geographic features and its importance for the economy. Each summmary is entirely based on the information provided by the partners

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 (%). The river can be divided into the Upper Scheldt, in which there is no tidal influence, and the tidally influenced part. This 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, forming togehter the Sea Scheldt, and the Western 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 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

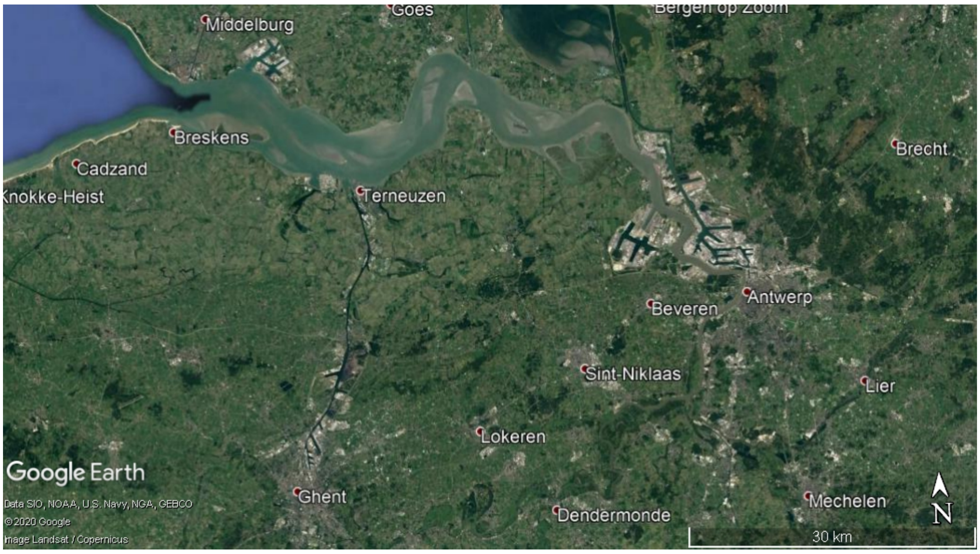

Figure 2.2: Satellite image of the Scheldt estuary and its surroundings

with a total population of the catchment over the 10 million people, which is an averaged 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 (1386 m above sea level). It catchment covers approximately 148,286km^2. The Czech part of the Elbe is 361km long, while the German part of the Elbe is 730 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 (140km 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 Sea. The River Elbe has several main tributaries: the Ilmenau, Este, Lühe, Schwinge, Pinnau, Krückau, Stör and Oste. There is a canel, the Kiel Canal, connecting the Elbe with the Baltic Sea at Brunsbüttel. The Elbe is an economically important for the region since it ia a 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 employements. The shore area of the Elbe estuary is also densely populated (more than 2 million people) and are intensely used for smaller ports, industry, power stations, fishery as well as recreation and tourism. The area fases storm floods coming from the North Sea. As a result, flood protection is an important issue. Additionallly, the three Neighbouring states of Schleswig-Holstein, Niedersachsen and

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

Hamburg are responsible for the nature conservation together with the national Waterways Administration (WSV) and the Port Authority. The latter two are also 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

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 2000km^2, while its estuary covers an area of 171 acres. 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. Intotal 672,000 people live in the Tees Valley, among which 369,600 living downstream of the Tees Barrage around Teesmouth.

2.4 The Fjords

The Roskilde Fjord and Isefjord are the estuaries of a 2000km^2 river basin. The Isejord is 35km and covers a total area of 305km^2. It is connected to the Kattegat Sea at its Northern border. The Roskilde Fjord

Figure 2.4: Satellite image of the Tees estuary and its surroundings

has a total length of 416km and covers an area of 74km^2. It is not directly connected to the Kattegat Sea, but opens towars the Isefjord on its north-west border. The total population of the catchment area is 400.000, which is inequally distributed between denser urban areas south and east of Roskilde Fjord and lighter popluated areas south and west of the Fjords. The three major cities are Roskilde, Holbaek and Hillerød. The region is economically important as holiday area since several strestches along the coastal lines 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 floodings. As a result, local solutions for flood protection has 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 (see Fig. 2.6) is a 731km long river, and the longest river in Sweden. It runs from Lake Vänern in the north to Göteborg in the south. 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. In the latter branch, it flows through the Port of Fothenburg, Scandinavia's largest and most important port. The city of Gothenborg and the surrrounding Göta River vally are highly populated and has a 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.

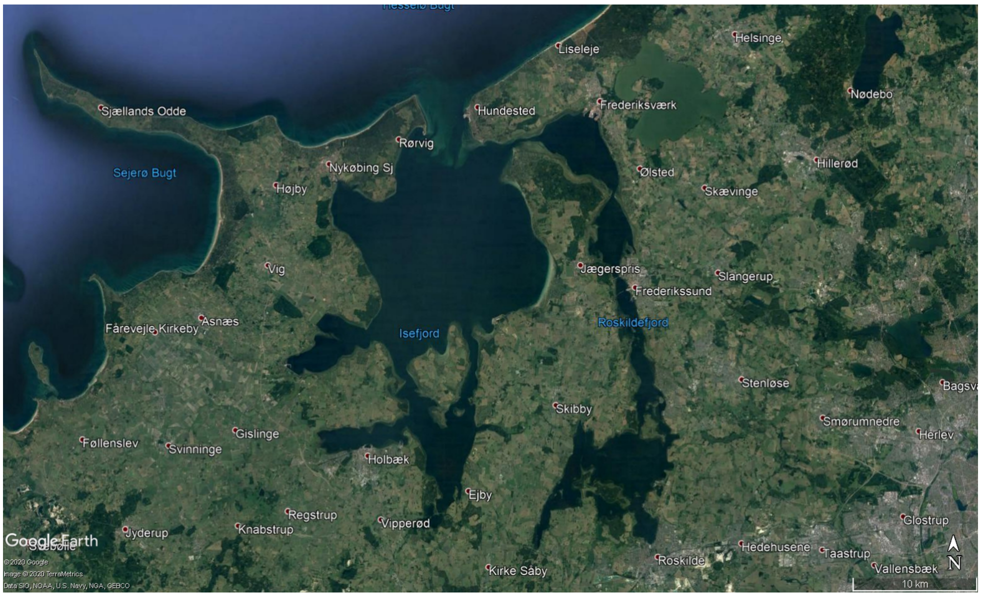

Figure 2.5: Satellite image of the Fjords and their surroundings

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 iand more seaward part. The total surface area of the Humber is about 16000 ha, of which 27% is intertidal and marsh area.

Figure 2.6: Satellite image of the Göta Älv estuary and its surroundings

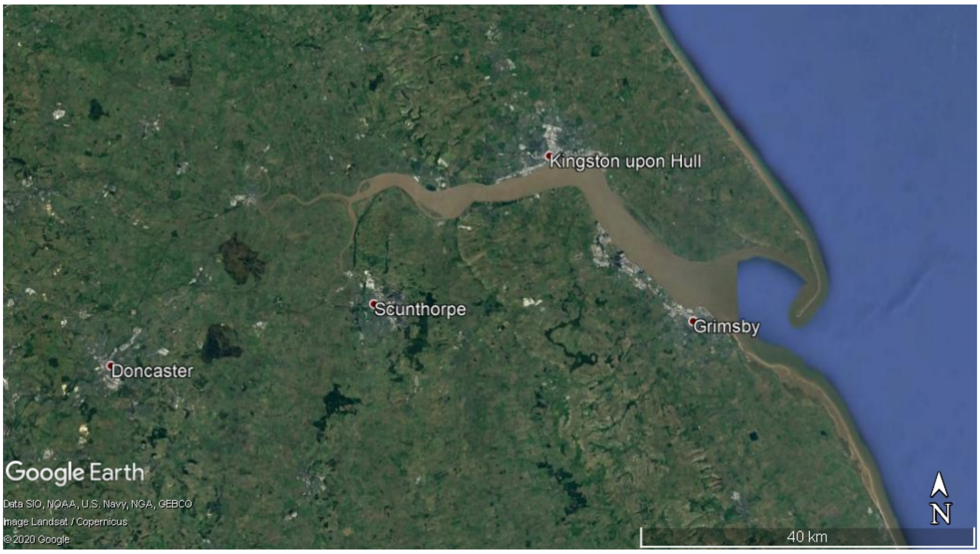

Figure 2.7: Satellite image of the Humber estuary. The Ouse and Trent river are approaching the confluence from the West and the South, respectively.

3 Hydrology/morphology per estuary

The hydrology and the morphology of an estuary are the key stones on 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

The examination of the hydrology of each estuary highlighted the key similarities and the key differences between the IMMERSE estuaries. According to Table 3.1, two major common points of the IMMERSE estuaries could be isolated. The first major common point is the economic importance of each estuary of the IMMERSE project. All the estuaries are located in densely populated areas and comprise large ports. This aspect makes them crucial for the persistence of the region in which they are located. A second common point is purely hydrological and reflects the relatively low fresh water discharge (with respect to for example Regions of freshwater influence) of each estuary, which causes very little to no stratification. This property is determinant both for the distribution and the transport of particles and substances (e.g. sediments and/or nutrients) as for the light availability for the primary production

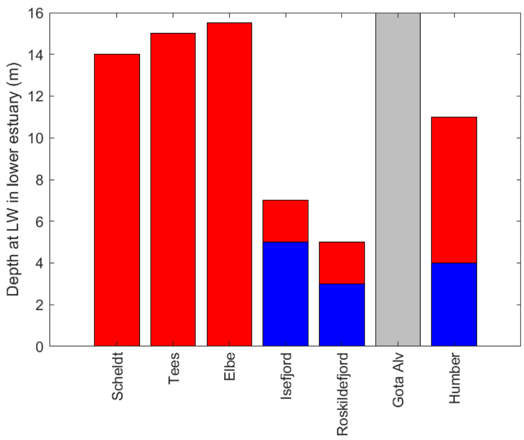

Figure 3.1: Typical water depth in the lower estuary. When a range applies, blue and red refer to minimum and maximum values, respectively. No data is available for the Göta Älv, which is indicated by the gray bar spanning over the entire panel.

As mentioned previously, the estuaries also present some key differences. These differences enabled to regroup them according to morphological arguments. A first distinction was made between the funnel shape estuaries (Scheldt, Tees, Elbe, Göta Älv, Humber) of the IMMERSE project and the Fjord estuaries (Isefjord and Roskildefjord). The first type is characterized by an overall decrease of the width and the depth of the estuary from the mouth towards the upper estuary. Fjords are often shallower at the mouth in comparison to further inland (as illustrated in Fig. 3.1), due to glacier depositions such as moraines. Moreover, the fjords of the IMMERSE project do not have a classical funnel shape. These characteristics have a crucial impact on the hydrology since Fjords are for example less subject to tidal amplification.

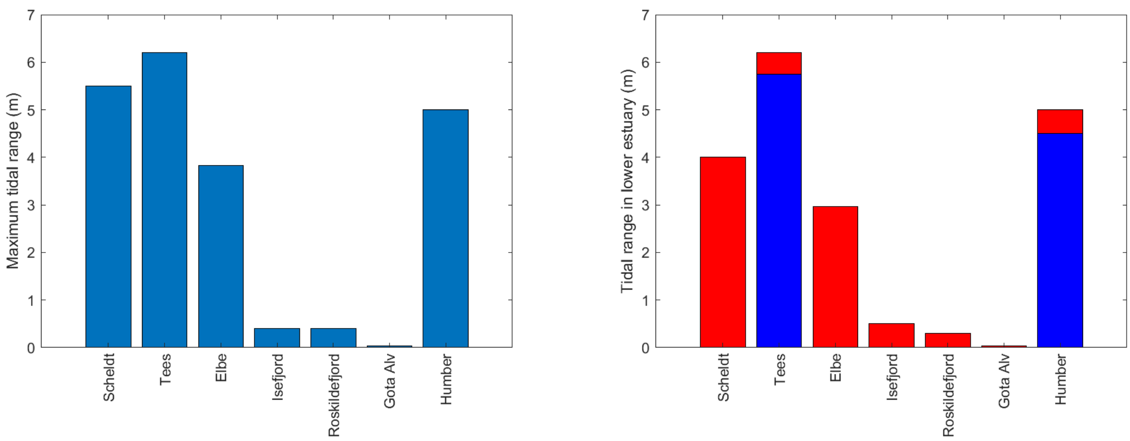

Figure 3.2: Maximum tidal amplitude over the estuary (left) and in the lower estuary (right). In some cases, a range of values is specified for the lower estuary. In that case, the minimum value is in blue and the maximum is in red.

As an illustration (see Fig. 3.2), the characteristic tidal amplitude within the Isefjord and Roskildefjord is more than 10 times lower (order of 10-50cm) than the characteristic tidal amplitude in the funnel shape estuaries (order of 1-5m), although this feature is also caused by the reduced tidal amplitude in the Kattegat. The differences in tidal ranges is also reflected in the tidal velocities, as can be seen in Fig.

In relation with the tidal amplitude, funnel shape estuaries, particularly the Scheldt, the Tees and the Elbe, have important intertidal zones (mudflats, sandflats) that are also susceptible to have a feedback influence on the tidal range, due to altered friction.

A second distinction can be made within the group of funnel shaped estuaries. The Scheldt and the Elbe have the peculiarity to be equipped with a deep inland port (respectively Antwerp and Hamburg). In contrast, in the Tees and the Göta Älv the main port (respectively Teesport and Göborg) is located close to the mouth. The location of the port can have important consequences for the dredging activities. If the estuary has a deep inland port, dredging is often necessary to maintain the depth of the fairway.

Additional further or different distinctions are also possible. Examples are (i) the length of estuary, which is often determined by weirs and barrages, and the presence and shapes (ii) of tidal channels. However, the limited number of estuaries do not allow for any categorization.

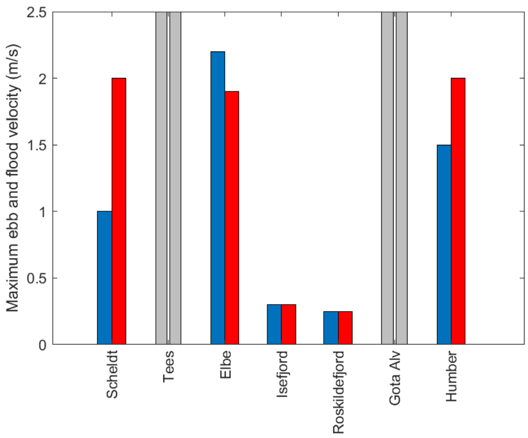

Figure 3.3: Typical ebb velocities (blue) and flood velocities (red). For the Tees and for the Göta Älv no data is available, which is indicated by the grey bars.

Table 3.1: Hydrological characteristics of the different estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Entire estuary							
Catchment	21,863km^2[7,8]	1,092km^2[9]	148,000km^2[10] among which 13,255km^2 for the estuary	767km^2	1,185km^2	50,229km^2[11]	No information
Population	10 million[7,8]	687,000[9]	more than 2 million[10,12]	400,000	400,000	1 million[11]	No information
Total length	355km[7,8]	137km[9,13,14]	1,094km[10]	35km	42km	731km[11]	60km
Length tidal river	160km[7,8]	17km[9,14]	141.8km[10]	Not applicable[15]	Not applicable[15]	Not applicable	60km
Main tributaries	3[7,8] (See App. A)	7[9,14] (See App. A)	15[10]	6 (See App. A)	7 (See App. A)		2
Summer discharge	30m^3 s^{-1}[7,8]	No information	815 m^3 s^{-1} (medium) (1926-2014)	350 mio.m3	350 mio.m3	575m^3 s^{-1} (maximum)[11]	38 m^3 s^{-1} (Ouse and Trent, excluding tributaries thereoff)
Winter discharge	300m^3 s^{-1}[7,8]	No information	866m^3 s^{-1} (medium)	Not applicable[15]	Not applicable[15]	1,000m^3 s^{-1} (maximum)[11]	320 m^3 s^{-1} (Ouse and Trent, excluding tributaries thereoff)
Shape	funnel	Highly modified channel[9]	funnel	fjord	fjord		funnel

Table 3.1: Hydrological characteristics of the different estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Maximum tidal range	5.5m (100km from the mouth)	5.9m[9] -6.2m[14]	3.83 in Hamburg (St. Pauli)	0.4m	0.2m	Little tidal impact (a few cm)[11]	5m (25 km from confluence)
Maximum ebb currents	1m s^{-1}[7,8]	No information	Up to 2.2m s^{-1} (mouth)	0.3 m s^{-1}	0.25 m s^{-1}	Not relevant[11]	1.5m s^{-1}
Maximum flood currents	2m s^{-1}[7,8]	No information	Up to 1.9m s^{-1} (mouth)	0.3	0.25	Not relevant[11]	2m s^{-1}
Velocity asymmetry	flood dominant[7,8]	No information	flood dominant[10]	Symmetrical[15]	Symmetrical[15]	flood dominant[11]	flood dominant (based on maximum ebb and flood velocities)
Depth averaged SSC	30-300mg L^{-1}[7,8]	No information	0-0.7 kg/m3	Not applicable[15]	Not applicable[15]		20-720mg l^{-1} (surface SSC)
Dependence of the turbidity maximum location on the time of the year	yes[7,8]	No[9]	yes	No information	No information	yes[11]	yes
Upper estuary							
Width	100m[7,8]	66.78m[9], 85 m[14]	300-500 m	Not applicable[15]	Not applicable[15]	Approx. 400 (Kungälv)[11]	1.5-4km
Low water depth	3m (Gent)[7,8]	No information	around 3.5 m	Not applicable[15]	Not applicable[15]	Not relevant[11]	1.5-4m

Table 3.1: Hydrological characteristics of the different estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Tidal range	3m[7,8]	5.75m[9]	2.53 m weir Geesthacht	Not applicable[15]	Not applicable[15]	Little tidal impact (a few cm)[11]	4.5-5m
Tidal channels	narrow, single channel[7,8]	single channel[9]	Mostly one single channel. Two channels in the city/port area of Hamburg	Not applicable[15]	Not applicable[15]	Not applicable[11]	multi-channel
Intertidal zones	No information	steep slag banks; concrete walls; mudflat[9,14]	sandflats, mudflats, wetlands	Not applicable[15]	Not applicable[15]	Not applicable[11]	No information
Stratification	small during high discharges[7,8]	No information	well-mixed estuary	Not applicable[15]	Not applicable[15]	Salt water wedge with limited mixing of salt and freshwater[11]	well-mixed estuary
Sediment accumulation	yes[7,8]	No[13]	No upstream of Hamburg	Not applicable[15]	Not applicable[15]	Yes[11]	yes
Lower estuary							
Width	5km[7,8]	1.25 - 1.58km at mouth[9,14]	2.5 km (downstream of the port of Hamburg), 17.5 km (mouth)	3km	3km	Approx. 400m (Älvs-borgsbron)[11]	4-12km

Table 3.1: Hydrological characteristics of the different estuaries.

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Low water depth	14m[7,8]	Approx. 15m	15.5 m (mouth)	5-7m	3-5m	Not applicable[11]	4-11m
Tidal range	4m[7,8]	5.75m[9] 6.2m[14]	2.97 m (Cuxhaven)	0.5m	0.3m	Not applicable[11]	4.5-5m
Tidal channels	several, flood-ebb[7,8]	straightened[9]	Multi-channel system.	Not applicable[15]	Not applicable[15]	Not applicable[11]	one
Intertidal zones	large mud and sand flats[7,8]	steep slag banks; concrete walls; sheet piling; mudflat areas; sandflat; saltmarsh[9,14]	mud- flats, sand flats[10]	Sand/muddy sand/till[15]	Sandy mud/till[15]	rare	No information
Stratification	well-mixed[7,8]	No information	well-mixed estuary	Periodical	Exceptional	Mostly mixed[16]	well-mixed
Sediment accumulation	No[7,8]	No information	yes[10]	Yes[15]	No[15]		Yes

According to the available information (see Table 3.2), the geomorphology also depicts some fundamental differences between the previously categorized funnel shape estuaries and the Fjord type estuaries. In funnel shape estuaries there seems to be more deposition of silt and sand while in the Fjords, the morphology seems to be very much determined by glacial deposits, such as moraines, dead ice, till and eskers. The estuarine depositions in Fjords also consists of mussels, which are not reported for the other estuaries.

In general, North Sea estuaries have a different ecosystem in comparison to fjords in the Baltic region because of hydraulogical and water quality conditions [17]. The hydraulogical conditions include high tide, windwaves, strong tide and wave currents, tidal amplification due to funnel-shape in the inner estuary while the water quality conditions include available sediments, available organic matter, barocline efffects due to salinity gradients and salinity variabions, mixing of salt and fresh water, turbidity and oxygen conditions[17].

The high dynamic conditions in estuaries do nat allow for mussels to settle. It would be interesting to investigate the effect and the cause/consequence link between the tidal amplitude and the type of bed structures and material.

Table 3.2: Geomorphological characteristics of the different estuaries.

	Scheldt	Tees	Elbe	Isefjord	Roskildefjord	Göta Älv	Humber
Bed rock	No information	Mercia Mudstone[9]	no	Limestone	Limestone	Gneiss with granit[16]	No information
Thickness clay layers	No information	Up to 9m[9]	0-10 m marine Clay	No information	No information	100m[16]	No information
Thickness of silt and sand layers	No information	No information	1-20 m (at highest at the mouth)	No information	No information	yes[16]	No information
Glacier deposits	No information	late-glacial laminated clay associated with the marginal shore line[9]	Glacial till	Till, dead ice, eskers, moraines	Till, dead ice, eskers, moraines	Clays[16]	No information
Marine/Fluvial Deposits	No information	Silt and sand[9]	medium-size sand, fine sand, silty sand, sandy Silt, Silt	Sands, mud, lacustrine, 5 m of shell banks	Sands, mud, lacustrine, 5 m of shell banks	silt and sand[16]	No information

3.2 Observed trends

The observed trends are investigated for the categories mentioned in the introduction. These categories are based upon the pressures for which measures are undertaken or considered. All the estuaries of the IMMERSE project are facing increasing flooding threats mainly due to sea level rise. However, there are crucial difference between the estuaries subject to a large tidal amplitude (the funnel shape estuaries), and the estuaries subject to a small tidal amplitude (the Fjords). For the funnel shape estuaries, the tide can be amplified depending on the convergence and the depth of the estuary. It is imaginable that reducing this amplification could (partly) compensate flooding risks caused by mean sea level rise. However, trends suggest that tidal amplication has a tendency to increase due to human interventions as has been shown, for example, for the Scheldt[18]. Flood risks caused by an increasing tidal amplitude are much less likely for the Fjord type estuaries. Another risk, shared by several estuaries is increase in extreme weather conditions. These weather conditions can lead to low river discharge (droughts), or floods. An overview of recent the trends for the hydrology is given by Table 3.3.

Table 3.3: Observed or expected trends for the hydrology in the different estuaries.

Reduction of tidal energy, tidal range, tidal asymmetry and tidal pumping	
Scheldt	Worsening for the mean low-water and the duration of high water and low water. Improving for the mean high-water[7,8]
Elbe	Increase of tidal energy. Increase of tidal range[10]
Flood protection	
Scheldt	Neutral changes with respect to 2009, trends are worsening for the yearly mean low water, the duration during high water and the duration during low water[7,8].
Elbe	Increasing floods[10]
Isefjord	30 - 100 cm sea level rise expected due to climate changes[19]
Roskildefjord	30 - 100 cm sea level rise expected due to climate changes[19]
Göta Älv	Increased risk due to sea level rise and extreme weather conditions ; the sea level might increase by one meter until year 2100[16,20]
Improvement of morphological conditions	
Elbe	Partial widening of the estuary mouth. Smoothing of bed-structures[10]
Need for dredging	

Elbe	Increase of the dredging volume in the Port especially during the last 6 years due to low river discharge[10]
Göta Älv	Constant need for dredging but volume remains constant[16]
Low discharge	
Scheldt	Increasing droughts cause a lowering of the discharge. This in turn favorizes the deeper penetration of sea-water inland. [21]
Elbe	This pressure especially occurred during the last years is related to low precipitation of the upper catchment for the riverine part[10]

3.3 Taken measures

In the table below, the various pressures that the IMMERSE estuaries have to face, as well as taken and anticipated measures, are listed. Sediment related problems (e.g. tidal pumping, morphological conditions, needs for dredging) seem to be tackled in similar ways in the two funnel shape estuaries with a deep inland port, the Scheldt and the Elbe. In both estuaries the focus appears to be on defining a sediment strategy consisting of several aspects, for example finding optimized ways of dredging, and optimized locations for dumping. The detailed description of the strategies will be beyond the scope of this document, but a brief overview of the challenges and needed requirements for the strategy is given for several estuaries.

For the Elbe, the transport of sediments from the North Sea into the upper Elbe estuary ('tidal pumping') does not only lead to unfavorable environmental conditions for protected nature areas but also to high maintenance dredging efforts and costs for both responsible authorities 'Hamburg Port Authority' (HPA) and the federal 'Waterways and Shipping Administration' (WSV). As a result, a flexible and adaptive sediment management strategy is considered to be essential to reduce this upstream sediment transport. It is necessary to use different dredging techniques (i.e. trailing suction hopper dredging or water injection) and relocation sites in the estuary. These techniques and sites can depend on the legal, technical and natural boundary conditions such as hydrological parameters, as well as sediment quality, ecological factors, biological processes and nautical demands. However, the sediment management strategy at the Elbe estuary has not only to consider environmental boundary conditions. In fact, it should also aim at improving scientific knowledge on the functioning of the system, finding innovative technical solutions or working on the improvement of the sediment quality. Indeed, the estuary receives polluted sediments from the upper catchment. Furthermore, societal aspects, that means manifold administrative responsibilities as well as the interests of various stakeholder groups have to be considered when it comes to choose for suited relocations sites. It must also include a communication strategy with stakeholders and involved administrations that are responsible to provide relocation permissions to find the best possible solution. As HPA has only access to one relocation site for dredged harbour sediment within the property of the City of Hamburg, it has been searching for additional sites within the estuary and in the adjacent North Sea. Therefore, a 'communication forum' has been set up with all relevant stakeholders along the estuary. Additionally, it became clear that common understanding and a stable basis for the future sediment management should be established, and river engineering and remediation measures for the estuary should be discussed, respectively. In 2016, a follow-up process was therefore established - the estuary partnership, the so-called ‘Forum Tideelbe’. This estuary partnership should identify and assess potential river engineering measures that support a sustainable development of the Elbe estuary, i.e. that does not only address hydromophological, but also ecological and societal aspects. The partnership chose six measures that should be assessed more in detail, one of them is the reconnection of the ‘Dove-Elbe’ to the tidal part of the Elbe.

The Göta Älv estuary seems to be the only is a partner taking measures to export sediment out of the estuary via a new application of used and polluted sediment (stabilization and solidification method, see Table 3.4) The underlined measures will be further detailed in Section 3.4.

Table 3.4: Measures against the trends in the hydrology and morphology of the estuaries

	Tidal energy, tidal range, tidal asymmetry and tidal pumping
Scheldt	Stopping or reduction sand extraction, sediment strategy, sediment pilot, Sigmaplan[7,8,22,23]; dispose more sediment in the deeper part of the estuary (dampening effect), cross-border solutions for maintenance dredging[7,8]. Building a side channel[7,8,24,25]
Tees	Removal of hard engineering structures that modify the natural flow and sediment regime, including weirs, locks, floodgates, sluices, and erosion control structures, removal/softening of hard engineering structures that modify natural bank profile[13].
Elbe	Adaptive and flexible sediment strategy [5, 26, 27], filling the mouth area with dredged material[10] e.g. underwater relocation area,[10]; potential locations for long term river engineering measures[28], extension and creation of tidally influenced areas such as the realignement measure ‘Kreestand/Spedenlander Busch’[6,29], new locations for dredged harbor sediment to reduce the amount of upstream transported sediments, reconnection of anabranches such as the Dove-Elbe[10,28];
	Flood protection
Scheldt	Deltaprogram, Sigmaplan, integral plan Boven Zeeschelde[7,8,23]; sturdier and higher levees, flood control areas[7,8,23]. Efficient and cross-border use of dredging material[7,8] Sand nourishment (active part and coastal foundation), research and monitoring program[7,8]
Tees	Managed realignment[9]
Elbe	set-up of projectProject RISA Rain infrastructure adaptation, adaption of dykes[10];

Isefjord	Municipal climate adaptation plans, local stakeholder groups[30]. yes - 189 MASL in 2013. Intended Solutions: Municipal climate adaptation plans. Wish for a regional storm barrier, Presentation of a flood protection catalogue, Evaluation of the impact of flood protection on the estuary[30]. Modeling and assessment of the best solution.
Roskildefjord	Municipal climate adaptation plans, local stakeholder groups, Presentation of a flood protection catalogue[30] yes - 138 cm MASL (meters above sea level) in 2013 Intended Solutions: Municipal climate adaptation plans
Göta Älv	Building barriers (proposition), several studies initiated among which financing models for climate change measures[16] .
Improvement of morphological conditions	
Scheldt	Morphological management, sediment strategy, pilot project[7,8,22,31]
Elbe	Finding of potential locations for long term river engineering measures, extension and creation of tidally influenced areas[10]
Göta Älv	A financing model for climate change measures, project for sustainable coastal development[16]
Reduction need of the dredging	
Scheldt	Sediment strategy, pilot projects, new disposal strategy[7,8,22]
Tees	Avoid the need for dredging activities, implement an active and operational dredging disposal strategy, reduction of re-suspension of sediments, implement an active sediment management regime[13]
Elbe	Optimized dredging and disposal strategies, sediment trap[10]
Göta Älv	Safe handling of contaminated sediment, stabilization and solidification method, Large scale dredging every 3-5 years[16,32,33]
Low discharge	
Adaptive and flexible sediment management strategy	

3.4 Evaluation of the measures and their usability

Not all the measures given in Section 3.3 have been evaluated in detail in the information provided by the IMMERSE partners. As a result, only the measures for which a detailed evaluation is available are displayed in Table 3.5. It is important to mention that the majority of the benefits are expected benefits since the evaluation of the measures has not yet taken place or is currently undertaken.

Table 3.5: Evaluation of the measures and their usability

Measure	(Possible) benefits and employability
Presentation of a flood protection catalogue *(Fjords)*	Better evaluation of expected flooding risk at every location in the estuary, stakeholder involvement for better understanding of the pressures and measures[30].
Evaluation of the impact of flood protection on the estuary *(Fjords)*	Increased knowledge of the impact of different flood protection solutions on the estuary[30].
Adaptive and flexible sediment strategy *(Scheldt, Elbe)*	Scheldt: Extra storage volume for dredged sediment 14.4Mm^3 (i.e. 30%) of dredged material disposed near sandbars[7,8,22], More efficient reuse of dredged material for coastal defense, positive influence on tidal characteristics (expected benefit but feasibility still investigated)[8]. Elbe: relocation of dredged sediments to the area of the turbidity zone's maximum to decrease the recirculation of sediments in Hamburg and costs for maintenance works for the responsible authorities, set up of estuary partnership for understanding of mutual interests and acceptance of the strategy[10]
Creation of new tidally influenced areas *(Elbe)*	Reduction of tidal energy. Positive influence on sediment transport. Improvement of natural habitats. Establishment of a recreational area.[10]
Filling mouth or other areas with dredged material *(Elbe)*	More efficient reuse of dredged material, create positive influence on tidal characteristics[7,8]. Dissipation of tidal energy[10] .
Rain infrastructure adaptation *(Elbe)*	Flood protection. Inland flood control. Water body conservation. Near natural water balance[10]
Cross-border solutions for maintenance dredging *(Scheldt)*	More efficient reuse of dredged material for coastal defense, positive influence on tidal characteristics[7,8].
Building a side channel *(Scheldt)*	Reduces pressures caused by tidal intrusion in upper estuary[7,8,24,25] more accommodation space, safety benefit, reduce dynamics, space for the river[34]

Table 3.5: Evaluation of the measures and their usability

Measure	(Possible) benefits and employability
Pilot/research and monitoring plan for sediment nourishment project *(Scheldt)*	Enlarge knowledge about how to nourish the coastal foundation, investigate the possibilities of the Western Scheldt to rise at the same speed as the sea, protection against flooding level rise[7,8].
Sigmaplan *(Scheldt)*	Improve protection against flooding, flood control areas buffer water during storms (e.g. during the storm on December 6th 2013, twelve flood control areas became operational). Flood control areas buffer water during storms[7,8,23].
Stabilization and solidification method *(Göta Älv)*	Reuse of contaminated dredged sediments, hard to give a straight answer about the sustainability of the method but long term prognosis appears reasonable, well functioning and sustainable compared to alternatives[16,32,33] Disposal capacity maintenance dredging works. Better understanding of using remediated sediments in constructions.
Morphological management *(Scheldt)*	Feasibility of the project is being investigated, no evaluation possible; the expected benefits are a disposal capacity for maintenance dredging works[8,31]
Realignment measure “Kreetsand/Spadenlander Busch” *(Elbe)*	Reduction of tidal energy, positive influence on sediment transport, establishment of a recreational area (expected benefits, still to be monitored)[10]
Reconnection of anabranches, e.g. the ’Dove-Elbe’ *(Elbe)*	Dissipation of tidal energy (expected benefit, no evaluation possible for the moment)[10,28]
RISA-Project *(Elbe)*	Flood protection, water-body conservation, near natural water balance[10,35]

4 Physical and chemical quality

In this chapter the data on water quality as obtained from the partners will be discussed. 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 substance incorporated in biota. However, in this document only dissolved substances are considered.

4.1 Description of the system

Common pollution threats shared by all the estuaries should be distinguished in threats for the water-quality and threats for the suspended matter or sediment quality. The quality of both compartments is in each esetuary partly determined by local policies such as treatment of waste waters or the activities in the surrounding area (e.g. agriculture, industry but also by nutrients and pollutants originating of the broader (upper, riverine) catchment or the North Sea. For example approximately 50% of heavy metals are transported back from the marine area into the Elbe estuary [17]. In this estuary .- although the quality of the water and the sediments has improved since the reunification in 1989, because most of the plants in the industrial areas of the former GDR that had discharged heavily polluted water into the Elbe were shut down - the water and sediment quality still is not good, as there are still many point and diffusive sources that release pollutants. They 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. Within the last years there is no overall trend for the different pollutants neither in the water phase nor in sediments. That means, it also has to be distinguished between many different pollutants, not only between different chemical groups, such as organic contaminants (DDT, PCBs,..) and heavy metals (copper, cadmium, etc.) TBT and others, but also between the different substances of the chemical classes [17].

The water quality of each estuary is largely determined by local policies such as treatment of waste waters or the activities in the surrounding area (e.g. agriculture, industry). Common pollution threats shared by all the estuaries should be distinguished in threats for the water-quality and threats for the sediment quality or the soil quality. The water quality reacts much faster to changes in chemical or biological composition due to 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 the result of a process of accumulation of pollutants in the past. As a result, the quality does not depend only on regulations but also on the residence time of sediment within the estuary. 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. Heavy metals, Tributyltinhydride (TBT) and pesticides are more a concern for the quality of the sediment. Many of them have been prohibited and are not longer present in the water column, while they are still existing in the sediment[1]. Information about the occurence pollutants, pollution threats and water quality parameters are summarized in Table 4.1. However, one has the keep in mind, that the values provided are not representative for the whole estuary. They only reflect a certain moment or season and are measured at a certain location. A lot of spatial and seasonal or yearly fluctuation exists .

Additionally, they might differ from the current situation in some cases.

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

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Pollutants (water column)							
Annual Nitrate discharge	14,300 t (2009)[1]	7434.8 tons (2005-2007)[14]	70,000 tons	767 tons(2012)	983.6 tons (2012)	15,747 tons[11]	No information
Nitrate from agriculture		Unknown[14]	up to 20 kgs $year^{-1}$ ha^{-1}	590t (77%) [19]	757t (77%) [19]	6,190(40%)[11]	
Annual Phosphorus discharge	15t (only dissolved fraction)[1]	579.12 tons (2005-2007)[14]	approx. 3,500 tons (2005-2007)	55t[19]	55t[19]	327 tons[11]	No information
Phophorus from agriculture		Unknown[14]	up to approx. 40kg $year^{-1}$ km^{-2}	24.2t (44%)[19]	24.2t (44%)[19]	196.2(60%)[11]	
Pollutants (sediment)							
heavy metals	yes[7,8]	[36]	Cu, Zn, As, Hg	Pb, Ni, Hg, Cd, Ba, Cu, Cr, Zi	Pb, Ni, Hg, Cd, Ba, Cu, Cr, Zi	Cu, Zn[16]	No information
organic micro-pollutants	yes[7,8] (see App. A)	yes[9] (see App. A)	yes (see App. A)	yes (see App. A)	yes (see App. A)	yes[11]	No information
organotin compounds		Tributyltin[9]	Tributyltin compounds	TBT	TBT	Paint of ships in sediments[16]	

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

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Micro-plastics			Yes, but not sufficiently investigated. They are subject of ongoing research.			yes[16]	
Pollution sources							
Diluted domestic wastewater	yes[7,8]	No[9]	Minor diffusive sources.	yes	yes	yes[11]	No information
Untreated domestic wastewater	yes[7,8]	yes[9]	Minor diffusive sources.	yes	yes	Contamination by faeces[16]	No information
Treated domestic wastewater	yes[1]	No[9]	Minor diffusive sources.	yes	yes	Difficulties under flood events[16]	No information
Infrastructural activities	Dredging, weir[1]	N/A[9]	no	Ship traffic[19]	Ship traffic, bridge construction[19]	yes[16]	No information
Industrial outlets		Food, steel, chemical[9,14]	There are different types of industries	Food, steel, concrete, airport, chemical, asphalt production	Food, steel, concrete, airport, chemical, asphalt production	Pulp and paper, petrochemi al, CHP, steel[11]	
Water quality parameters							

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

	Scheldt	**Tees**	**Elbe**	**Isefjord**	**Roskildefjord**	**Göta Älv**	**Humber**
Current status Chlorofyl	High (upper Sea Scheldt[1]) Low (in the remainder part)[37]			moderate (inner fjord); good (outer)	moderate (inner fjord); good (outer)	No data[11]	
Primary production	peak in summer and autumn , light limited[1,7,8]	Unknown[9,14]	Peak in May (223 mmol C/m2 d) calculated by L. Geerdts /TIDE project	Spring, late summer	Spring, late summer	No data[11]	No information
Minimum oxygen levels	above 2.5mg L^{-1}[1]	Unknown[9,14]	Low; < 3 mg/l*	2019: 7,3 mg/l, 2018: 6,5 mg/l	6,8 mg/l - 7,8 mg/l	4.20 mg.L^{-1} (Alelyckan 2016-2018)[11]	No information

4.2 Observed trends

The trends in pollution are very estuary specific, and are detailed in Table 4.2.

Table 4.2: Observed trends in water and sediment quality.

Pollutants (water column) - Reduction nutrient loading	
Scheldt	Phophorus and Nitrogen[1] load are decreasing, but the rate of decrease weakened the last years. Recovering from hypereutrophication. Increasingly autotrophic[1,7,8,38].
Elbe	Nitrogen: positive evolution; Phosphorus: improvements occurred but both concentrations are still too high[10]
Isefjord	Overall nutrient load declining. Ev. Water-bottom: neutral; Ev. BOD: positive; Ev. Orthophosphate: positivel; Ev. Nitrate: positive; Ev. Ammonia: positive
Pollutants (water column and sediments) - Reduction pollutant loading	
Scheldt	For some pollutants the load clearly decreases, others don't[1]
Elbe	No general, overall trend, for some pollutants the load clearly decreases, for others it don't. Pollutant specific analysis required. The overall state remains bad according WFD reporting[10]
Göta Älv	Increase capacity stormwater system and water treatment plant. Bacterial contamination remains constant[16]
Water quality parameters - Improvement self purifying power	
Scheldt	Significant improvement over the last 20 years, although the rate of improvement slows down probably due to worsening light conditions[1,7,8]
Elbe	No clear trend but seasonal variation[10]
Water quality parameters - Improvement oxygen conditions	
Scheldt	Oxygen conditions are improving, but the rate is slowing down. Oxygen levels not below 5mg/L for the first time in 2009.[7,8]
Elbe	No clear trend but seasonal variation[10]
Isefjord	Improving
Roskildefjord	Improving
Water quality parameters - Salt intrusion	

Scheldt	Since 2009 an increase of chloride ion in the oligohaline zone and freshwater zone[1]. Oligohaline persistently deficient[7,8]
Elbe	Increasing (Expected due to climate change and also to the planned deepening of the fairway)[10]
Isefjord	The catchment area is in over all good condition with respect to salinity intrusion
Roskildefjord	The catchment area is in over all good condition with respect to salinity intrusion

4.3 Taken measures

As the pollutants are process-, origin- or pollutant- specific, i.e. they originate from different sources and sub-catchments, differentiated measures are necessary. The major measures concerning the reduction of pollutants are related to the treatment of waste-water, agriculture policy (fertilizers, bufferzones) and legislation (prohibition of certain chemicals[1]. The measures proposed by the IMMERSE partners for water quality challenges can be categorized as prevention and remediation. Concerning the improvement of the sediment quality, the Elbe partner focuses on improving the quality of the sediment flowing into the system from upstream (see below), while the Göta Älv targets the removal of the polluted sediment of the estuary via a new purpose such as export or use as a raw material.

These measures are preventive. The stabilization and solidification method[16,32,33] is a concrete proposition to remove polluted sediment from the estuaries, depending on the specific location, the amount of polluted sediments and maybe also the kind of pollutant. More details on the different measures can be found in Table 4.3.

However, sometimes measures have to be specifically related to the area or source they originate from. For example at the Elbe, most important sites for restoration concerning sediment bound pollutants are side structures of the Elbe located in the Czech Republic and the Bilina, a tributary of the Elbe (CZ), side structures (groynes) of the middle Elbe, the barrages of the Saale, a tributary of the middle river Elbe, and point sources (mines), adaptation of the management strategy of the Czech part of the Elbe. As these sediment-bound pollutants finally all reach the area or the port of Hamburg, respectively, and led to high cost for maintenance, the Hamburg Port Authority and the Ministry of Environment & Energy of the City state Hamburg established in 2010 the project “ELSA” (Schadstoffsanierung Elbsedimente). It aims at financially supporting measures that improve the situation concerning polluted sediments already at their source – e.g. located in the riverine part of the Elbe, within other federal states or the Czech Republic[17].

The underlined measures will be further detailed in Section 4.4.

Table 4.3: Taken measures to improve the water quality.

Pollutants (water column) - Reduction pollutant loading

Scheldt	Improving treatments of households effluents (1996). Stricter norms also contributed to a reduction of the pollutant load, although many toxic chemicals (pesticides are not sufficiently removed by the treatment plants[1]. Treatment of waste-water of Brussels (2007). Improvement of treatment facilities (2015).[7,8,39,40]
Elbe	Reduce point and diffusive sources of pollutants, project ELSA[10,41]; Closing plants in industrial areas in the early 90's[10]
Isefjord	Improved treatment at waste water treatment plants[10] - including conversion to biological treatment and elimination of smaller treatment plants. Elimination of CSO's. Improving initiatives ongoing but reduction objectives not met.
Roskildefjord	Improved treatment at waste water treatment plants - including conversion to biological treatment and elimination of smaller treatment plants. Elimination of CSO's. Improving initiatives ongoing but reduction objectives not met.
Göta Älv	Ongoing project to reduce contaminants in waste water and release of storm water. New surveillance system with self cleaning probes. Automatic sampling of E. coli.[16]
Pollutants (water column) - Reduction nutrient loading	
Scheldt	Improving treatments of households effluents (1996).Measures in the agriculture, Sigmaplan[1,23]. Treatment of waste-water of Brussels[7,8,42]
Elbe	European nitrate framework in the German Fertilizer Regulation. Improve nutrient retention. Improve sewage plants.[10]
Isefjord	Closure of combined sewer overflows, increased requirements for private waste water treatment in rural areas, increased outlet restrictions for municipal waste water treatment plants, establishment of wetlands for removal of nutrients (nitrate, ammonia)[30]
Pollutants (sediment) - Reduction pollutant loading	
Elbe	Improve the polluted sediment at the source, ELSA project.
Göta Älv	Reuse. Deposit on land/remediation, sea bottom deposit, export of sediment, stabilization and solidification method[16,32,33].
Water quality parameters - Improvement self-purifying power	
Scheldt, UAComments	Sigmaplan[1,23]
Elbe	European nitrate framework, optimizing sediment management strategy[10]
Water quality parameters - Improvement oxygen conditions	

Scheldt	Sediment strategy, Sigmaplan, integral plan Brussels (2007), improvement of treatment facilities (2015)[7,8,22,23]
Tees	Discharge of water over Barrage[9]
Elbe	European nitrate framework in the German Fertilizer Regulation, restrictions for the maintenance of the fairways, optimizing sediment management[10]
Isefjord	Increased knowledge of the effects of regional and local storm surge barriers

4.4 Evaluation of the measures and their employability

Not all the measures given in Section 4.3 have been evaluated in detail in the information provided by the IMMERSE partners. As a result, only the measures for which a detailed evaluation is available are displayed in Table 4.4.

Table 4.4: Evaluation of the measures taken for the estuaries to improve the water quality.

Measure	(Possible) benefits and employability
Export of sediments *(Göta Älv)*	Business deal, large scale landfill[16,32,33].
Sea bottom deposit *(Göta Älv)*	If sediment is free from pollution it is a cheap solution but need a legal authorization, dumping of contaminated sediments are in most cases not allowed[16,32,33].
Deposit on land *(Göta Älv)*	Costly, high land area demand, less accepted and questioned from an environmental point of view[16,32,33].
Stabilization and solidification method *(Göta Älv)*	Transformation into a material useful for building foundations, reducing the exposure to the environment, minimizing spreading of contaminants from sediments, development of a sustainable, innovative, and effective treatment method for polluted sediment, increased knowledge about the mechanisms that control leaching of metals from the sediment matrix[16,32,33]
Improve the polluted sediments at the source, Project ELSA *(Elbe)*	Improving the quality of sediments that are transported from the catchment of the upper and middle river Elbe into the estuarine part, cost reduction for maintenance works for the responsible authorities, understanding of processes related to polluted sediments and their potential restoration (expected benefits, no evaluation possible)[10,41]

Table 4.4: Evaluation of the measures taken for the estuaries to improve the water quality.

Measure	(Possible) benefits and employability

5 Biology and ecology for each estuary

In this chapter the data on biology and ecology as obtained from the partners will be discussed. This information has been extended on some points by external reviewers of INBO.

5.1 Description of the system

It was chosen to analyze the current ecological and biological status of the estuaries along two criteria: (i) the legislation and administrative protection (see Table 5.1) and (ii) a brief overview of the types of habitat and species present in the estuary (see Table 5.2).

First of all, it is important to state there are different european frameworks, that are implemented in national law to evaluate the state of the natural system. Examples of these frameworks are the WFD and the Birds- and Habitats Directive as well as Ramsar for birds. In this regard, it is interesting to remark that all the funnel shape estuaries (Scheldt, Tees, Elbe, Göta Älv) are marked as heavily modified water bodies, whereas the Fjords(, which are part of the marine strategy[34,43]) are not. 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[34,44]. 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, whereas the Scheldt, the Elbe and the Göta Älv are also marked as special areas of conservation. Additionally, parts of the funnel shape estuaries are all designated RAMSAR sites in contrast to the Fjords.

A more detailed inventory of the habitats and species shows that the estuaries are all important wetland areas, with important sites for migrating birds, breeding birds, fish and mammals. The distribution of the different type of wetland differs from estuary to estuary, as was already highlighted in a previous study[45]. A brief list the most important in terms of being important for the system as well as being rare and therefore protected of fish and bird species is given in Table 5.2. A much more detailed investigation on the different species will lead to a more meaningful comparison of the diversity between the estuaries. This could be performed on the basis of earlier work[34,46,47] describing a set of variables to be measured for a basic evaluation of the ecological status or functioning. Furthermore, each of the Natura 2000 habitattypes had to make a EU Habitat Report in 2018. In those reports one can find the status (and trend) of different habitats and also the important pressures which are prevalent on the habitat types[48]. Besides, there was an evaluation of the Water Framework Directive in 2019[49]. It is suggested that the systems could be compared by highlighting the percentage of protected area with respect to the total estuary area. Additionally, the presented numbers of species could be differentiated in periods of the year[49].

Table 5.1: Implemented l egislation and administrative protection of nature areas.

	Scheldt	Tees	Elbe	Isefjord	Roskildefjord	Göta Älv	Humber
Heavily modified water body	yes[7,8]	yes[9,14]	yes[10,50]	no	no	yes[16]	No information
EU Special areas of conservation (SAC)	yes[7,8]	No[9,14]	yes (40,802 ha)[10,50]	no	no	yes[16]	No information
EU Special protection areas (SPA)	yes[7,8]	yes (1247.31 ha) (Teesmouth and Cleveland Coast Extension pSPA)[9,13,14]	yes (25.122ha)[50]	yes	yes	yes[16]	No information
Natura 2000 (includes both SAC and SPA[34])	yes, (4684 ha[7,8,34,51,52])	yes, (Teesmouth and Cleveland Coast Extension pSPA[9,14,34])	yes, (46.770ha[10,34,50,53])	yes, (5.000 ha (approx.))[34]	yes, (14.810 ha)[34]	yes[16]	No information
UNESCO World Heritage	Applying[34,54]	No[9,14]	yes (Elbe mouth as part of the Wadden-sea)[10,50]	No	No	yes[16]	No information

Table 5.1: Implemented l egislation and administrative protection of nature areas.

	Scheldt	Tees	Elbe	Isefjord	Roskildefjord	Göta Älv	Humber
Ramsar sites included (Wetland convention)[7,8,34]	yes	yes[9,14]	yes[10,50]	no	no	yes[16]	No information
National or state controlled habitat protection	yes, some marshes[34]	yes[9,13,14]	no	no	yes	yes[11]	No information

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[7,8,48]	yes[9,14]	8882 ha[50]	no	no	No[11]	No information
Meadows	grazed marshes in Saeftinge, Galgen-schoor[34]	No[9]		yes	yes	Yes[11]	No information
Freshwater marshes	yes[34]	Grazing marshes[9,14]	yes (1116 ha)[50]	yes	yes	yes[11]	No information
Saltwater marshes[9]	yes[34]	Greatham Creak, Seal sands[14]		yes	yes	No[11]	No information
Current status Eelgrass	absent[34]	absent[9,14]	not known[50]	Good to moderate	Good to moderate	Good to moderate (Nordre älv)[11]	No information
Current status Bottom fauna	Depends on the water body[34]	Moderate[9,14]	moderate (WFD)[50]	moderate	good		No information
Number of migrating fish species	Important (7 species[7,8,34,55]	5-7 (see App. A)[9,14]	11[50] (see App. A)	Not applicable[15]	Not applicable[15]	Reproduction area for Salmo salar[16]	No information
Total number of fish species (fish diversity)	61[34,56]	35[14]-41[9]	76 species docu-mented[50] [57].	35 recorded species	35 recorded species	15 (2014)[11]	No information

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
Birds species	Wintering, migrating, breeding[34] Important waterbird area[7,8,58,59]	Wintering and non wintering[9,14]	38 (migrating) - 31 (breeding)[50] (see App. A)	Migratory birds, eider	24	60[11]	No information
Ramsar species	79[7,8]	6[9]	69[50] (see App. A) 30 (breading)	30 (breading)		No information	
Mammals	Common seal, gray seal, harbor Porpoises[7,8,34]	Harbour porpoise, Harbour Seal, European Otter, Gray Seal[13,14]	Harbor porpoise, common seal, gray seal[50]	Harbor porpoise	Harbor porpoise[15]	Seals[16]	No information

5.2 Observed trends

Significant information about the trends in ecological and biological categories were only available for the Scheldt estuary and the Elbe estuary (see Table 5.3). However, within the Elbe estuary no specific monitoring on the overall development of the different habitat types, that means an analysis on the increase or decrease of the areaof the whole esturay, has recently been carried out. Therefore, no trend analysis can be carried out. Furthermore, in contrast to the Western Scheldt which consists of just one Natura 2000 site (Westerschelde and Saeftinghe), in the Elbe estuary there are 13 different protected areas for birds and habitats located on the property of three federal states of Hamburg, Schleswig-Holstein and Lower Saxony (see also introduction text). No coordinated monitoring program exists[10].That means, that for example monitoring data for bird species are collected by the three federal states for each of their single protection areas and aggregated by the national environmental ministry in order to report to the EU. Therefore no overall dataset for the estuary is available – there might be differences in species-specific trends between the protected sites of the three federal states. Additionally, in some cases there are differing monitoring cycles within the three federal states. The estimation for the trends for mammals – if provided here - e.g. on the occurrence of harbour porpoises is based on recent observations (2012 – 2019) of animals that were more or less absent in the estuary before this time.

Table 5.3: Observed trends of specific habitats and flora/fauna classes in the different estuaries

Development and/or protection of specific habitats	
Scheldt	The global trend in the Western Scheldt is improving, with a general exception for salt marshes. In the sea Scheldt the trend is opposite. It is worsening with a general exception for salt marshes[7,8]
Tees	Reduction of intertidal habitat by 93% between 1861 and 1993[13]
Elbe	No specific monitoring[10]
Development and/or protection of specific species	
Scheldt	The abundance of specific vegetation types, ph ytoplankton and waterbirds is worsening, while the abundance of benthos, fish and mammals is improving. The development and/or protection of key species is worsening for fish and birds but improving for plankton[7,8][34,60]
Elbe	Improving for: vegetation, ph ytoplankton, mammals, benthos, fish (both abundance and diversity)[10]
Trends in numbers/biomass of exotic species[34]	
Scheldt	Trend in the number of species found is positive; Trend in the abundance is negative[34] for the vegetation and Zooplankton, but worsening for benthos, fish and birds[7,8]

Elbe	No recent data available. Since 2012 increase of the invasive species *Neogobius melanostromus*[10]

5.3 Taken measures

Table 5.4: Taken measures for the improvement of biology and ecology in the different estuaries

	Development and/or protection of specific habitats
Scheldt	Sediment strategy, Sigmaplan, integral plan Boven Zeeschelde, cross-border solutions for maintenance dredging, Pilot/research and monitoring plan for sediment nourishment project[8]
Tees	Activity to create new habitat where it did not exist before, preserve and/or restore existing in stream and riparian/shoreline habitats, leaving habitat or parts of natural habitat while undertaking operations or maintenance in a water body[13]
Elbe	Implementation of the IMP (2012) [61], Create different habitat types and flooding space, within r ealignment measure e.g. 'Kreetsand/Spadenlander Busch', or reconnecting anabranches lie the 'Dove-Elbe',[10,62,63],
Isefjord	Denmark's Ocean Strategy, Natura 2000 action plan[30]
	Development and/or protection of specific species
Scheldt	Sediment strategy, Sigmaplan, integral plan Boven Zeeschelde[8]
Tees	Installation of structures designed to facilitate and improve the passage of migratory (e.g. salmon and sea trout) and non-migratory fish where structures cannot be removed, Retro-fitting existing structures to accommodate niche habitats, as opposed to more substantial structural modifications that would be likely to deliver greater hydromorphological change but may not be possible given the use, structure modification to reduce or increase flow, e.g. culvert flow velocities may be too fast for fish migration; baffles can be constructed to slow water velocities, amending the timing of dredging and disposal operations so that they have a reduced impact on the ecology e.g. retiming to avoid breeding times of fish/birds etc.[13]

Elbe	Implementation of the IMP (2012) [61]. Construction of fish passages, restrictions for the maintenance of the fairway in spring, planting program for protected plant species, seasonal fishing ban, improve breeding condition for certain species[10]; establishment of the foundation "Lebensraum-Elbe"[64];
Isefjord	Natura 2000 action plan
Gota Alv	Salmon and trout are protected; eelgrass or seawrack are protected and replanted or reintroduced[16]
	Prevention of introduction of or to fight invasive species
Tees	Action(s) to reduce the extent and spread of invasive non-native species, including actions on our own assets[13]
Elbe	Regulation on release of ballast water within specific reservoirs within the port of Hamburg[10]
Göta Älv	Funding of projects for prevention and management of invasive alien species[16]
	Strategy to make sediment depositions more environmental friendly
Tees	Selection of dredge disposal sites to cause minimum ecological impact
Scheldt	New disposal strategy near the 4 sandbars[7,8]
Elbe	Additional relocation site for dredged sediment, communication forum[10,26,28]
	Holes left by Shell harvesting
Isefjord	Dumping with unpolluted soil; filled with clean sand
	Unfavourable environmental conditions
Elbe	Implementation of the IMP (2012) [61] Creation of new tidally influenced areas, reconnection of anabranches[28]. Filling mouth area with dredged material, compensation measures[10,62,63]

5.4 Evaluation of the measures and their employability

Table 5.5: Benefits of the measures and intended solutions for ecological issues in the different estuaries.

Measure	(Possible) benefits and employability
Communication forum *(Elbe)*	Trust; building mutual understanding[10,28]

Table 5.5: Benefits of the measures and intended solutions for ecological issues in the different estuaries.

Measure	(Possible) benefits and employability
Filling mouth area with dredged material *(Elbe)*	Improve tidal dynamics and therefore positively affect natural environment[10]
Adaptive and flexible sediment strategy *(Scheldt)*	Improvement in ecological habitat quality, creation of ecological valuable habitat, increase of 145ha in ecological valuable habitat[7,8,22]
Cross-border solutions for maintenance dredging *(Scheldt)*	Habitat creation (feasibility still being investigated)[7,8]
Building a side channel *(Scheldt)*	Increase nature value, improve gradients, habitat area[34][7,8]
Pilot/research and monitoring plan for sediment nourishment project *(Scheldt)*	Preservation of the ecological and economical functions[7,8]
Sigmaplan-habitat creation[34] *(Scheldt)*	Increase nature value, new ecological valuable habitats[7,8,23]
Stabilization and solidification method* *(Göta Älv)*	Improvement in ecological habitats[16]
Protection, replantation or reintroduction of eelgrass or seawrack *(Göta Älv)*	protect the habitat from disappearing, plays a crucial role for many species[16]
E stablishment of the foundation "Lebensraum-Elbe" *(Elbe)*	Higher abundances of the endangered 'Elbe Water Dropwort due to p' lanting programs , Improvement of natural habitats by restoration of natural shore structures , higher abundances of the endangered species by establishment of opportunities for fish passages[10,64]
Realignement measure 'Kreetsand/Spadenlander Busch' *(Elbe)*	Improvement of natural habitats by creating additional mudflats, shallow water area, reed and floodplain forests, and provision of habitat for the endemic plant 'Elbe-Water Dropwort' which is protected by EU legislation[6,10,29]
Reconnection of anabranches e.g. the 'Dove-Elbe'	Establishment of new valuable estuarine habitats

6 Conclusions

6.1 Conclusions regarding hydrology and morphology

- All estuaries are located in densely populated areas and have economical importance due to port activities
- All estuaries have relatively low discharges resulting in an absence of stratification
- It is possible to make a distinction between funnel shape estuaries (Schelde, Tees, Elbe, Göta Älv, Humber) and Fjords (Isefjord and Roskildefjord)
- The location of the main port (i.e. close to the mouth or deep inland) is closely related to the depth of the estuary and has significant consequences (e.g. dredging needs, tidal amplitude).
- It would be interesting to investigate the cause and consequent relationship between the bed structures and materials in Fjords (particularly mussel beds) and the reduced tidal amplitude in these water-bodies
- All estuaries face climate change related issues: increased flooding risk (due to sea-level rise and/or extreme weather conditions) and/or low discharges (due to droughts)
- Increase in tidal energy/tidal range is an issue
- The Elbe and the Scheldt have reported a sediment strategy for deposition and dredging; sharing the results of this strategy to evaluate the effectiveness could be very beneficial
- The Göta Älv partner found a new application for used and/or polluted sediments (stabilization and solidification method)[16,32,33]

6.2 Conclusions regarding water quality

- All the estuaries seem to face pollution from agriculture (Nitrate en Phosphorus), heavy metals, and Tributyltin compounds (from ship paint)
- Many partners report on improvements in the treatment of waste-waters
- The Göta Älv partner found a new application for used and/or polluted sediments (stabilization and solidification method)[16,32,33]
- Both prevention and remediation is proposed for limiting the presence of polluted sediment in the estuary

6.3 Conclusions regarding biology and ecology

- All estuaries are partly designated Natura 2000 areas with special protection areas.
- The funnel shape estuaries in the IMMERSE project are designated as heavily modified water bodies while the Fjords within this project are not.
- The scattering of the protected areas and the administrative regions make it difficult to generate a consistent monitoring method or a consistent data set within a single estuary. While this is a specific feedback from the Elbe, it appeared during the redaction of this report that consistency in data inter-estuary is a similar challenge.

6.4 Conclusions regarding the measures

Based upon the available information, it is very challenging to evaluate the efficiency of the measures and their susceptibility to be applied in other estuaries. This is mainly related to two factors. The first factor is that for the majority of the measures, their effectiveness is not well known yet. The measures have been applied too recently, and most of the benefits are rather expected than observed. The second factor is that it is difficult to find measures that are applicable to every estuary of the IMMERSE project. The Scandinavian estuaries (i.e. the fjords and the Göta Älv) are too different from the other estuaries. This difference is particularly related to their negligible tidal amplitude whereas most of the measures in the Elbe and in the Scheldt deal with challenges related to a high tidal amplitude. Accordingly, the application of some of the measures of the Scheldt and the Elbe could be relevant for the Humber and the Tees.

6.5 General remarks

As indicated in the introduction, it is quite challenging to compare the IMMERSE estuaries based on the information provided by the partners. As a result some suggestion have been given in order to improve the homogeneity of the data and criteria. Based on the presented data overall conclusions are premature, partly because a significant amount of measures are still ongoing or under the form of a feasibility study.

7 Acknowledgements

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Appendices

A Further details

Some additional information provided by the partners is given in Table A.1

	Main tributaries
Scheldt	Dender, Ruppel, Durme[7,8]
Tees	Greatham Creek, Dabholm Gut, Normanby Beck, Ormesby Beck, Lustrum Beck, Billingham Beck, Old River Tees channel[9,14]
Elbe	Ilmenau, Seeve, Bille, Norderelbe, Alster, Norderelbe, Este, Lühe, Schwinge, Pinnau, Krückau, Stör, Nord-Ostsee-Kanal, Oste, Medem und Hadelner Kanal[10]
Isefjord	Sidinge Fjord, Lammefjord, Tuse Å / Kalve Å, Elverdamså, Hobæk Fjord, Catchment area Hornsherred
Roskildefjord	Kornerup Å, Catchment area Arresø, Græse Å, Værebro Å, Hove Å/Maglemose Å, Havelse Å/Gørløse Å, Catchment area Hornsherred
	Organic micropollutants
Tees	BDPE and Cyanide
Elbe	PAKs and PCBs, PFOS (e.g.Benzo(a)pyren, Fluoranthen, Hexachlorbenzen, Hexachlorcyclohexan)
Isefjord	PAH, PCB, Pesticides, Detergents, Phenols, chlorinated hydrocarbons, aromatic hydrocarbons, oil components, Arsenic, dioxin
Roskildefjord	PAH, PCB, Pesticides, Detergents, Phenols, chlorinated hydrocarbons, aromatic hydrocarbons, oil components, Arsenic, dioxin
	Migrating fish species
Tees	Atlantic Salmon, European Eel, Sea Trout, River Lamprey, sea lamprey (possible shad, smelt not confirmed)[9,14]
Elbe	Petromyzon marinus, Lampetra fluviatilis, Alosa fallax, Salmo salar, Salmo trutta trutta, Osmerus eperlanus, Anguilla anguilla, Coregonus maraena, Gasterosteus aculeatus, Lota lota, Platichthys flesus
	Important fish species
Elbe	Petromyzon marinus, Lampetra fluviatilis, Alosa fallax, Salmo salar, Coregonus maraena, Aspius aspius, Misgurnus fossilis,Cobitis taenia
	Bird species

Tees	Knot, Little Tern, Redshank, Sandwich Tern, waterbird assemblage[14]/Wintering waterbirds, Common Tern, Avocet, Sandwich Tern[9]
Elbe	Migrating: Dunlin, White-fronted goose, Shelduck, Spotted Redshank, Common tern, Eurasian gold plover, Grey goose, Eurasian curlew, Greenshank, White swan, Ruff, Lapwing, Gray ploever, Common teal, Black-headed gull, Nothern shoveller, Eurasian widgeon, Bar-talled godit, Whimbrel, Bent Goose, Redshank, Pied avocet, Sanderling, Comon ringed plover, Curlow sandpiper, Whooper swan, Pintail, Mallard, Common gull, Broad-billed sandpiper, Temminck's stint, Black tern, Barnacle goose, Little gull, Smew, Tundra swan, Little stint, gadwall, white-tailled eagle, short-eared owl, spotted crake, Black-tailed godwit, Corncrake, Pergrine, Water rail, White stork, yellowwagtail, Montag's harrier[50] Breeding: Common snipe, Penduline tit, white-spotted bluethroat, whinchat, Kingfisher, Skylark, Common tern, Ruff, Lapwing, Garganey. Teal, Gull-billed tern, Shoveller, Red-backed shrike, Bittern, Marsh harrier, Red kite, Redshank, Pied avocet, Sedge warbler [50]
Roskildefjord	Dunlin, ruff, herring gull, gull, eider, mute swan, shelduck, black-headed gull, oyster catcher, arctic tern, avocet, mallard, greylag, black-headed gull, tern, tufted duck, coot, whooper, eagle, goldeneye, pintail, widgeon, garganey, shoveler, migratory birds

Table A.1: Additional information about tributaries, chemicals and animal species present in the estuaries

B Definitions

In this list, an attempt is made to define the words appearing in the different tables.

Main tributaries	
Summer fresh water discharge	Typical (e.g. mean/median order of magnitude) value that of fresh water discharge during summer.
Winter fresh water discharge	Typical (e.g. mean/median order of magnitude) value that of fresh water discharge during summer.
Depth averaged SSC	From the Scheldt report "Suspended sediment concentrations (depth-averaged) vary between 30 and 300 mg/L" from the context it seems that it is about the SSC within the ETM.
Upper Estuary	Unless specified otherwise, the most landward half of the estuary
Lower Estuary	Unless specified otherwise, the most seaward half of the estuary
Width	Typical value or range of values.
Low water depth	Typical water-depth or range of water-depth at low water.
Tidal range	Difference between high water and low water, depends on the phase in the spring-neap cycle
Intertidal zones	Characteristics and type of intertidal zones (bed and/or vegetation)
Sediment accumulation	Accumulation of sediment in the water-column at a specific location (ETM)
Thickness of silt and sand layers	Thickness of the marine/fluvial deposits
Infrastructural activities	Activities related to infrastructer and potentially polluting and/or modifying the estuary
Industrial outlets	Type of industries located in the estuary area and potentially polluting the estuary
Tidal pumping	Flood directed (i.e. up-estuary) net sediment transport due to the tidal water motion

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