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Management for estuarine ecosystem services: a review

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Abstract

The challenge of estuarine management is to maintain existing estuarine natural structure and functioning, to rectify historical damage and negative impacts of human actions which produced socio-economic problems, and at the same time to guarantee present and future economic development. Applying a multidisciplinary and functional, holistic approach is essential to maintain a healthy natural system. Scientists and managers are searching for measures to adapt the ecosystem in such a way that flood risk is decreased, harbour activities can further develop and nature is conserved. This literature review (including 286 publications) gives an overview of a broad range of management measures that are, or can be, applied for estuarine management, including measures to change hydrology, morphology, habitat, and water and sediment quality. Furthermore, the differences between the different management measures regarding its impact on ecosystem services and biodiversity are identified to detect which management measures can contribute to specific estuarine targets. By looking for trade-offs and synergies, opportunities to reduce management costs and increase benefits to society are revealed. This can help to develop an integrated management strategy among the many management departments and with respect to both ecological and socio-economic needs.

Keywords: hydrology, morphology, biodiversity, main target, additional benefits, trade-offs

Highlights

- Integrated management of ecosystems requires a thorough insight in the relevant ecosystem functions and services and the contribution of management measures
- A matrix links 39 estuarine management measures with 20 ecosystem functions and services
- The review of available knowledge reveals that still many effects are understudied.
- The information from this review can feed into further steps to develop integrated ecosystem management strategies.

Graphical abstract

<table>
<tr><td></td><td></td><td colspan="5">Ecosystem functions and services</td></tr>
<tr><td></td><td></td><td>ES1</td><td>ES2</td><td>ES3</td><td>ES4</td><td>...</td></tr>
<tr><td rowspan="4">Management measures</td><td>M1</td><td colspan="5" rowspan="4">Number of publications <u>describing</u> the effect
(Number of publications <u>quantifying</u> the effect)</td></tr>
<tr><td>M2</td></tr>
<tr><td>M3</td></tr>
<tr><td>...</td></tr>
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1. Introduction

Estuaries are a dynamic ecosystem with the tidal influence generating many gradients and a large variety of habitats (Meire et al. 2005). Estuaries have always been an attraction for humans. Large settlements have been grounded close to estuaries worldwide (Small and Nicholls 2003, Davis and Kidd 2012). The attractiveness of estuaries can be linked to the many ecosystem services (ES) that estuaries and its different sub-habitats (e.g. river and intertidal areas) provide such as the provisioning of water and fish, water for transportation, flood and storm protection, water purification, primary production, cultural services such as cultural heritage and opportunities for recreation (Edgar et al. 2000, Beaumont et al. 2007, Russi et al. 2013). For centuries, coastal systems and estuaries are managed in a way to enhance the economic use of the ecosystems. Common examples are deepening of channels to improve shipping possibilities, building dikes for flood prevention and embankments to create economic valuable land for agriculture or buildings (Turner et al. 2000, Atkins et al. 2011, Barbier et al. 2011). As a consequence, large parts of intertidal habitat are lost or degraded worldwide (Turner et al. 2000, Hood 2004). This has an impact on the general ecosystem functioning related to hydrodynamics, geomorphology, and ecological structure and functioning generating problems such as eutrophication, altered hydrologic regimes and marsh reclamation (Barbier et al. 2011). In addition, estuaries are also exposed to more global problems such as climate change and sea level rise. Consequently, the supply of many ES is affected leading to socio-economic losses (Worm et al. 2006, Barbier et al. 2011, Davis and Kidd 2012).

During history, estuarine policy was oriented towards the maximisation of specific uses. The development of ports was important for the regional economy and triggered the deepening and widening of many estuaries. Severe storms harmed large settlements along estuaries which resulted in the development of flood risk management plans (e.g. Delta works and Sigmaplan in the Schelde estuary; Broekx et al. 2011). International concerns on biodiversity resulted in conventions and directives such as the Ramsar Convention and European Habitat and Bird Directives (Turner et al. 2000). Finding a balance between the different, contrasting objectives complicate the management of estuaries and requires an integrated approach (Atkins et al. 2011, Lonsdale et al. 2015). Recently, there is a shift from a hard engineering approach to a broad multi-disciplinary and integrated approach with soft engineering measures (King and Lester 1995, Crooks et al. 2001, Meire et al. 2005). One good example of the development of an integrated management plan is the actualised Sigmaplan in the Schelde estuary. Tidal wetland restoration projects were included as more cost-effective alternative for hard defences as it combines flood risk management (water storage area and attenuation of storm surge propagation) and natural habitat conservation (Temmerman et al. 2013).

To be able to make use of the multifunctional character of management measures, and increase the options for integrated ecosystem management, we argue that it is important to have a detailed insight in the consequences of the planned management measures. This does not only relate to the intended targets, but also all other positive and negative effects on the ecosystem. This enables society to account for the full benefit of each management measure across management disciplines and also to mitigate or compensate negative effects. Furthermore, when designing an integrated management plan, it is important to know for each target which management measures can contribute and how much they can contribute. This review builds on three main questions: (1) Which management measures are available to manage an estuary? (2) What are the effects of management measures on the estuary and society (through changes in ES delivery) and can we quantify the effects? (3) Which management measures contribute to the different targets (i.e. ES) in the estuary, e.g. harbour sector, flood safety, biodiversity goals, water quality targets, etc.? With this review an overview of a broad variety of measures for estuarine management is given and the impact of the different management measures on ES is identified. This information can be used to look for opportunities for the development of future integrated management plan.

2. Materials and method

2.1. Which management measures are available to manage an estuary?

A list of 39 management measures is compiled based on the management measures studied in the European Interreg IVB TIDE project (Saathoff et al. 2013) and other management measures implemented in the Schelde estuary (e.g. Sigmaplan). This list is not exhaustive, but contains a diverse set of common management measures based on the aforementioned project and additional input from the well-studied Schelde estuary. All management measures are shortly explained in appendix A. The management measures are clustered in four broad categories based on the main targets (figure 1): (i) improve/change the hydrology of the estuary (mainly regarding flood protection), (ii) the morphology (mainly regarding the harbour sector), (iii) conserve/restore/develop specific habitats and habitats for specific species (fish, birds), and (iv) improve the water and sediment quality. A literature search in Science Direct for each of the 39 management measures was done to find papers that study the effects. In addition, a similar search was done in Google because monitoring results are often presented in reports and not in scientific papers. A total of 286 publications (reports and international publications) are collected dealing with the effects of one or more of the management measures.

2.2. What are the effects of management measures and can we quantify the effects?

A list of 17 (sub-) ecosystem services (ES) is used as a tool to summarise the effects of the management measures (explained in appendix B). The list of ES is based on the most important ES for estuaries (Jacobs et al. 2013) and three other effects are added besides the ES: 'habitat' and 'biodiversity' are added to take into account the contribution of management measures to the European Habitat and Bird Directive targets; and 'surface for infrastructure' to take into account the requirements of space as this is often a limiting factor. For the reason of textual simplification, ES and biodiversity, habitat and place for infrastructure is referred to as ES. For each of the 39 management measures it is recorded how many publications study the effect on one or more ES. A distinction is made between the number of publications that describe the effects (qualitative) and the number of publications that quantify the effect. The latter gives information on the effects that are studied in detail and quantified and not only described and expected. Furthermore a distinction is made between four types of effects: effects that are described as being the main target of the management measure, or described as an additional (unintended) positive or negative effect, or as effect that is not clearly positive or negative or both positive and negative depending on the local situation (noted as other effects). The latter category is often linked to changes in ecosystem functions and processes underlying the delivery of ES, but on its own not positive or negative (e.g. changes in the sedimentation process). This information, including a short description of the effects, is presented for each of the 39 management measures in appendix C and summarised in two matrices for all management measures and 20 ES. The first matrix shows the qualitative result (all effects that are described) (table 2) and the second matrix the quantitative result (only effects that are quantified) (table 3).

The description of the results is subdivided in two sections: qualitative results based on what is described in the literature and quantitative results based on what is quantified in the literature. The first section describes the impact of the 39 management measures on the 20 ES. First, the effects of the four management categories are compared by comparing the number of ES they affect and the proportion of main targets, positive, negative and other effects. Secondly, the effects of some of the management measures are compared in detail. A qualitative description is given on how the different management measures are alike or different in how they affect several ES (depending on the ES that are described in literature for these management measures).

The first example compares three management measures from the category of hydrology measures, all with the same main target of improving flood protection. To illustrate the differences between the sub group 'flood protection' and 'flood protection + habitat development', the effects that are described for dikes are compared with these for ecological friendly dikes and flood control areas with controlled reduced tide. The second example compares six management measures from the category of morphology measures, all with the same main target of improving the opportunities for the shipping and harbour sector. The management measure dredging is compared with management measures to reduce the need for dredging (sediment trap, current deflecting wall, nautical depth concept) and management measures to dispose dredged material (land disposal or beneficial use: habitat development with dredged material). The third and last example compares three management measures from the category of habitat measures, all with the same main target of improving habitat either by habitat protection (with hard structures: groynes), habitat restoration (natural friendly shore) and habitat development (wetland creation).

The second section indicates which effects are not only described but also quantified in literature. An overall comparison is made between the main targets, positive, negative and other effects for all 39 management measures and the different ES. First, the number of occurrences of the different types of effects are compared, which is the difference in the number of coloured cells between table 2 and 3. Secondly, the number of publications describing and quantifying effects are compared, which is the difference in the value in each coloured cell between table 2 and 3. This is corrected for publications that study more than one ES or more than one management measure.

2.3. Which management measures contribute to specific ES?

The collected information can also be used in the opposite direction: identification of management measures that can contribute, or might have a negative effect, for a specific ES. Results are described for five important goals in estuaries (flood prevention, water quantity regulation for transportation, habitat, biodiversity and water quality regulation). For each of the five goals, the four categories of management measures are compared based on the proportion of management measures in each category that have an effect on this goal (either as main target, additional positive or negative effect, or other effect).

3. Results

3.1. Which management measures are available to manage an estuary?

Effects of management measures are most frequently studied in the category of hydrology measures (134 publications, 47% out of all reviewed publications), followed by habitat measures (87 publications, 30%), morphology measures (84 publications, 29%) and water and sediment quality measures (30 publications, 10%). The top six management measures for which effects are mostly studied are: managed realignment measures, dredging, tidal wetland creation, hard defences: dikes, flood control area with controlled reduced tide and agro-measures for water quality improvement (e.g. buffer strips).

3.2. What are the effects of management measures and can we quantify the effects?

3.2.1 Qualitative results

We found a high diversity in the number of ES affected between measure categories and specific management measures. When comparing the four measure categories, the number of ES that are described ranges between 13 and 20 with the lowest number for measures in the water and sediment quality category and the highest for measures in the hydrology category. The five most studied main targets correspond to the four measure categories: flood protection for the hydrology related measures, water quantity regulation for transportation and for the morphology related measures, habitat and biodiversity for the habitat measures, and water quality regulation for the water and sediment quality measures. Furthermore, for some measures other ES are also described as main target, for example habitat development for hydrology measures in the sub-category 'flood protection + habitat development' or erosion and sedimentation regulation for habitat related measures aiming to stop habitat erosion.

Besides the main targets, most measures generate many additional effects, both positive and negative (60%-80%, figure 1). Additional positive effects (not categorised as main target of the measure) are recorded for 10 to 15 ES. The most studied additional positive effects relate to biodiversity, erosion and sedimentation regulation, flood protection and water quality regulation. Negative effects are described for 2 to 9 ES. The most common negative effects relate to biodiversity, habitat, erosion and sedimentation regulation, food provision and water quality regulation. Other effects, not clearly positive or negative, are described for 2 to 8 ES. The most common 'other effect' is for erosion and sedimentation regulation.

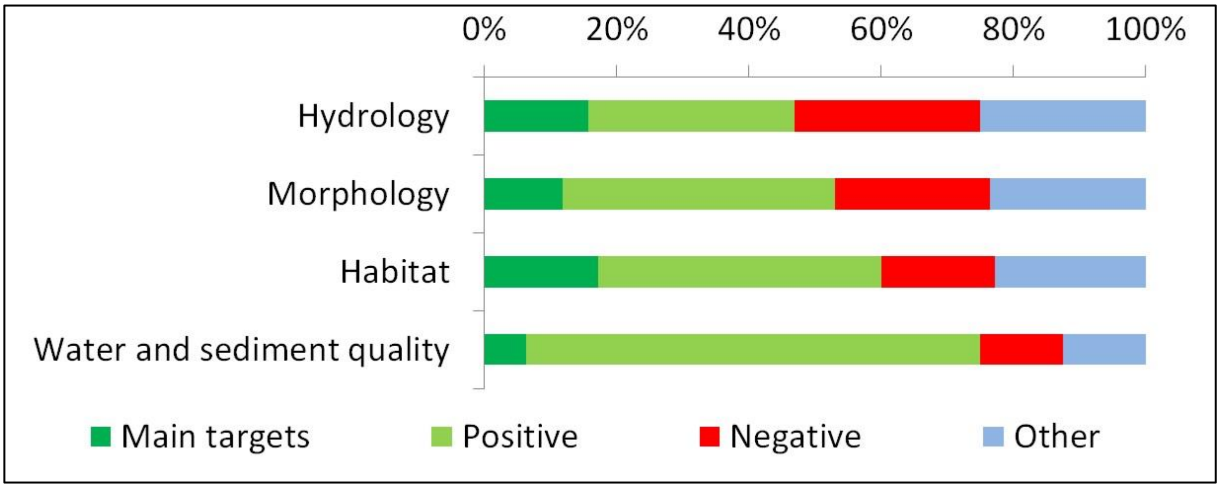

Figure 1: Proportion of effects on ES per measure category that are described as the main target, additional positive, negative or other effects (other effect: not clearly positive or negative, or both depending on the situation).

i. Effects of different measures to manage hydrology

To illustrate the differences and similarities between the hydrology sub-categories 'flood protection' and 'flood protection + habitat development', the effects that are described for dikes (hard defences), ecological friendly dikes and flood control areas with controlled reduced tide (FCA-CRT) are compared (see table 1 and appendix C for more details and references). All three measure types contribute to the ES flood protection, by its barrier function between the river and the land (dike, ecological friendly dike) (Hartig et al. 2011, Pelling and Mattias Green 2014) or by additional water storage capacity and reduce the high water level in the river (FCA-CRT) (Cox et al. 2006, Meire et al. 2014). Furthermore, the ecological friendly dike and FCA-CRT also add important benefits for habitat development (Hughes et al. 2009, Borsje et al. 2011). Dikes on the other hand, usually have negative effects on habitat caused by habitat loss and fragmentation. Nevertheless, dikes can also provide valuable habitat (Chapman and Underwood 2011, Dugan et al. 2011). However, it is proven not to be a good surrogate for natural habitats and furthermore can serve as stepping stone for invasive species (Moschella et al. 2005, Wehkamp and Fischer 2013). On the other hand, the habitat function of dikes can be improved with specific dike cover, more structures, micro habitats, etc. (ecological friendly dike) (Borsje et al. 2011). Furthermore, regarding biodiversity, habitat development measures such as the FCA can cause changes in species composition (e.g. when converting a terrestrial system into an tidal wetland habitat). Besides these main targets, the three measures show similarities and differences for several other ES such as food production, climate regulation, water quality regulation, recreation, aesthetics and platform for infrastructure.

The impact of the three management measures for food production varies with food type (crops, livestock, fish and shellfish). Dikes enable agriculture along the river in otherwise wet areas (arable land and pastures) which is also linked to the benefit of platform for infrastructure (embankment generates more usable land with often high economic importance). The flood control area with controlled reduced tide (FCA-CRT) measure causes the opposite: usable land is converted to estuarine nature which can be considered as negative from the food production perspective in case this land was used for agriculture. However, in an FCA-CRT there are also opportunities for food production: certain crops can cope with some degree of flooding and some degree of saline water, livestock grazing is possible on higher areas and on the dikes surrounding the FCA-CRT, and lower areas can contribute to the nursery function in the area for fish production (Edwards and Winn 2006, Luisetti et al. 2011). Dikes along the river disturb the water quality regulation capacity of estuaries (Hood 2004, Bilkovic and Mitchell 2013), although, on the other hand, it can prevent contaminated runoff from the land to the river (Dugan et al. 2011). The ecological friendly dike and FCA-CRT measures, with vegetation in and at the shore of the river, contribute to the improvement of the water quality (e.g. nutrient and particle filtering capacity and aeration of the water) (Blackwell et al. 2010). All these measures create opportunities for recreation such as walking and cycling on dikes. Dikes are in general aesthetically displeasing, and also the inland dikes surrounding an FCA-CRT can cause visual intrusion for local residents living close to the FCA-CRT (Broekx et al. 2011). Ecological friendly dikes can potentially contribute to landscape attractiveness (Airoldi et al. 2005). Finally, an FCA-CRT can contribute to climate change regulation by carbon sequestration through litter accumulation (seagrass, vegetated marshes) and burial through sedimentation (subtidal habitat, seagrass, tidal flats, marshes) (Burden et al. 2013). Furthermore, its ability to keep up with sea level rise by vertical accretion is an important contribution to climate change adaptation (French 2008).

Table 1: This matrix shows the ES that are described as main target (++), additional positive (+), negative effects(-), and other effects (not clearly positive or negative or both depending on the situation) (?) for 1) three examples of hydrology measures, 2) six examples of morphology measures, and 3) three examples of habitat measures. The entire matrix for the 39 management measures is given in table 2.

Legend:
Effects on ES described as:
Main target (++)
Positive effect (+)
Negative effect (-)
Other effect (?)

		Food: crops (e.g. freshwater supply)	Food: animals (cattle, sheep)	Food: animals (fish)	Water for industrial use	Materials (e.g. sand)	Climate regulation	Erosion and sedimentation regulation	Flood protection	Water current reduction	Wave reduction	Water quality regulation	Drainage of river water	Water quantity regulation for transportation	Aesthetic information	Information for cognitive development	Inspiration for culture, art and design	Opportunities for recreation and tourism	Biodiversity (vegetation, birds, fish...)	Habitat	Infrastructure (houses, roads...)
		P	P	P	P	P	R	R	R	R	R	R	R	R	C	C	C	C			
1) Hydrology measures: three examples:																					
Flood protection	Hard defences: Dikes	+	+				-	?	++	?		?		+	-			+	-	-	+
Flood protection +Habitat	Flood control area with Controlled Reduced Tide (FCA-CRT)	+	+	+		+	+	?	++	?		+	?	-	-		+	+	+	++	
	Ecological-friendly dikes							++	++		?	?			+			+	+	++	
2) Morphology measures: six examples:																					
Shipping	Dredging	+		-		+	-	?		?		?	+	++					-	-	+
Shipping: Reduce need for dredging	Current deflecting wall							++						?							
	Nautical depth concept							?				+		++					?		
	Sediment trap						+	++				+	+	+					+	+	
Shipping: dispose dredged material	Habitat creation						-	+					+	++				+	+	++	
	Land disposal					+	-	?				-		++	-						-
3) Habitat measures: three examples:																					
Habitat protection	Groynes	+						++	+	++	++	+		?	-			?	+	++	
Habitat restoration	Ecological-friendly shoreline	+						++	+		+	+	+		+			+	+	++	

Habitat development	Tidal wetland	?	+	+			+	?	+	?		+		+	+	+	+	+	+	++	

ii. Effects of different measures to manage morphology

The similarities and differences between the morphology sub-categories are illustrated with the following management measures: dredging for the sub-category 'shipping', sediment trap, current deflecting wall (CDW) and nautical depth concept for the sub-category 'reduce the need for dredging', and land disposal and habitat development with dredged material for the sub-category 'dispose and use dredged material' (see table 1 and appendix C for more details and references). Measures from the sub-category 'shipping' and 'reduce the need for dredging' have a direct positive effect on the ES water quantity regulation for transportation, either by increasing the water depth needed for (tide independent) shipping or for example by decreasing the required water depth (nautical depth concept or 'fluid mud') (Kirby 2013). Related effects to reduce the need for dredging are linked to the ES sedimentation and erosion regulation: avoid sedimentation at places where it is unwanted by changing the sedimentation process (e.g. CDW at harbour docks) (van Maren et al. 2011), or stimulate sedimentation at certain places where it is more efficient and less harmful to dredge (e.g. sediment trap) (Knüppel 2012). Measures from the sub-group 'dispose and use dredged material' have a more indirect effect for this ES, namely to mitigate for fairway deepening, capital and maintenance dredging and comply with the regulations to be allowed to dredge. Dredging can have many different negative effects relating to habitat and biodiversity, some examples: erosion of intertidal areas (steeper river walls) (Spearman et al. 2014), impact multi-channel system by changing the primary and secondary flow (Jeuken and Wang 2010), and increased turbidity can cause a decrease in primary production (Hossain et al. 2004, van Maren et al. 2015). Management measures to reduce the need for dredging hence prevent these negative effects to happen (e.g. nautical depth concept and sediment trap). The sediment trap furthermore also has the advantage that in the case of contaminated sediment, this is trapped and removed at a location where vulnerable nature areas are not harmed and this technique can also help to avoid dredging for example in the spawning season (Knüppel 2012). When dredging is unavoidable and habitat is at risk, habitat can be restored or developed with dredged material as compensation (Yozzo et al. 2004).

For several other ES, dredging can have both additional positive and negative effects. With dredging, turbidity can be increased and contaminants can be remobilized which is harmful for the environment (Wasserman et al. 2013). Measures to reduce the need for dredging have a positive effect by avoiding the disturbance of contaminated sediment (nautical depth) (Wurpts 2005) or by collecting contaminated sediment at one location where it can be removed in a more controlled way (sediment trap) (Knüppel 2012). On the other hand, dredging can be used as a technique to remove contaminated sediments. When this is disposed on land, this can cause a risk for leaching of contaminants. Related to the ES food production, dredged material can be used as fertile sediment to put on agricultural land, but dredging can harm fish and shellfish (Cooper et al. 2013). Lastly, the sand fraction (dredging, land disposal) can be used as construction material (Barbosa and de Souza Soares de Almeida 2001).

Iii. Effects of different measures to manage habitat and biodiversity

From the habitat measures the following management measures are compared to illustrate some differences and similarities: groynes as a measure for habitat protection (prevent shore erosion), natural friendly shore as a habitat restoration measure and tidal wetland creation as a habitat development measure (see table 1 and appendix C for more details and references). All these measures have a positive impact on habitats, the main target. However, hard structures such as groynes can cause fragmentation or loss of habitat and are artificial hard substrata changing the original habitat complexity (Pinn et al. 2005). Protection and restoration of habitats relates to water and sediment processes in the area. A positive effect of groynes is to prevent shoreline erosion by absorbing and dissipating wave energy and modify nearshore currents to deflect the flowing water away from critical zones (Schoonees et al. 2006). However, it can also generate possible unwanted effects away from the project area by changing the sediment balance (Walker et al. 2008). At a large scale, preventing shoreline erosion can also contribute to flood protection. Reducing shore erosion with groynes and natural friendly shores is also important for shipping (to avoid more sediment entering the navigation channel) (Dehghani et al. 2013) and food production (in case of agricultural land). Food production can be negatively affected with tidal wetland creation when agricultural land is converted. However, tidal wetlands provide other opportunities for food production such as edible saline crops (e.g. Salicornia), grazing livestock and fish productivity with increased nursery habitat (Vieira da Silva et al. 2014).

All three measures are positive for biodiversity by providing habitat for vegetation, birds, benthos, invertebrates, shellfish and fish. Artificial structures such as groynes and sometimes in the case of natural friendly shore, measures can however function as stepping stone for invasive species and do not function as surrogates for natural habitat (Wetzel et al. 2014). The presence of fauna and flora, such as vegetation and mussels, in the different measures can contribute to the improvement of the water quality, by influencing the nutrient cycling and the water filtration capacity (Wetzel et al. 2014). Tidal wetland creation can also contribute to climate regulation with carbon sequestration although the effect is reduced by greenhouse gas emissions (e.g. methane from mudflats, with a much stronger global warming potential compared to carbon dioxide) (Duarte et al. 2013). For cultural services, these measures positively affect recreation opportunities by the prevention of shoreline erosion and for bird watching.

3.2.2 Quantitative results

Three quarter of the publications quantify the effect on at least one ES for the management measure(s) that they study (212 out of 286). The number of ES that are not only described but also quantified is rather low (50%), except for hydrology measures (85%). Furthermore there is a clear difference in the quantification of effects between the main targets and additional positive, negative and other effects. The majority of the effects (70%) described as the main target are also quantified but only by half of the publications that describe these effects (figure 2).

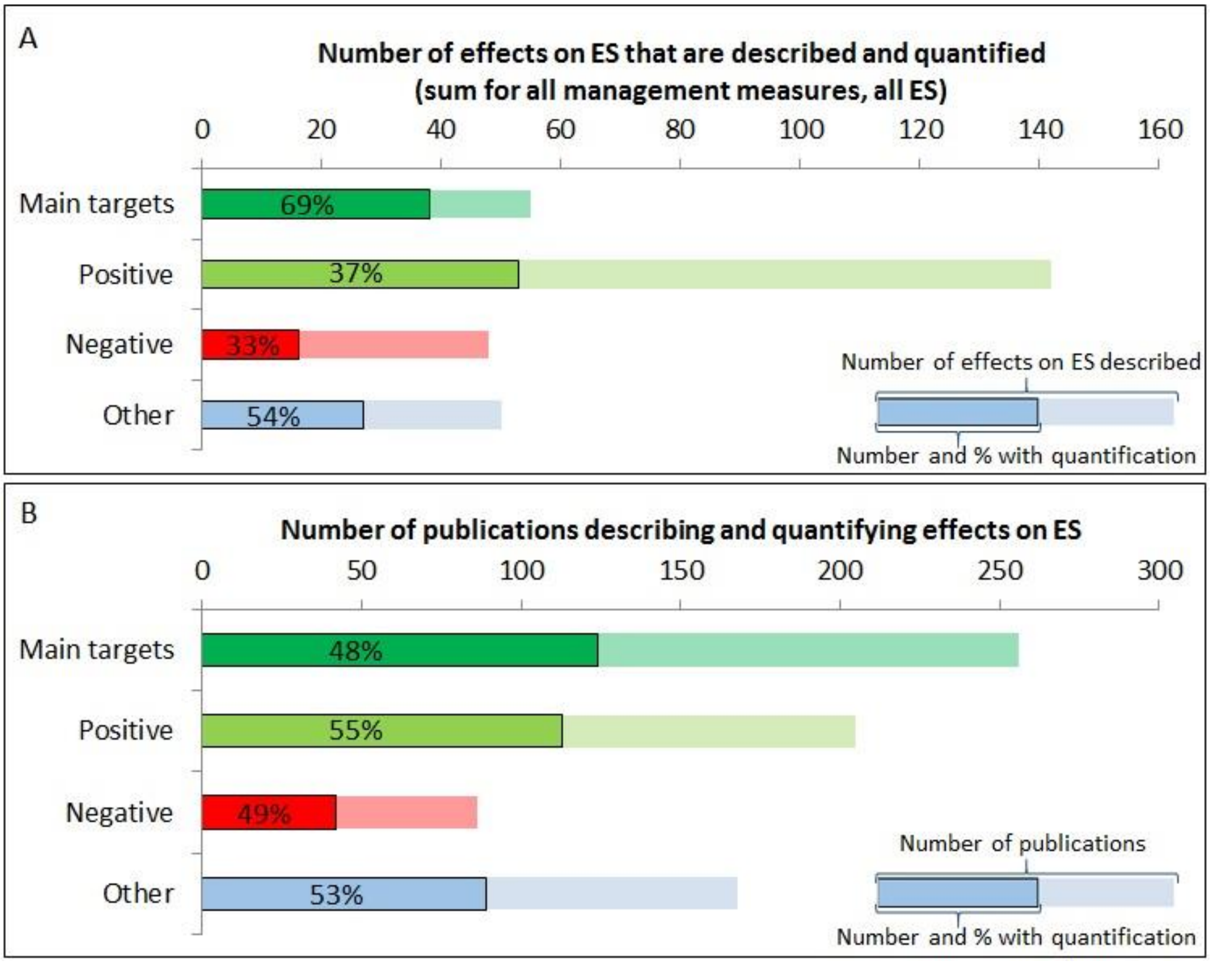

Figure 2: Total number of effects on ES that are described and quantified (A) and total number of publications (B) that describe (light long bar) and quantify (dark short bar with percentage) effects for all 39 management measures for the 20 estuarine functions and ecosystem services with a distinction between main targets, positive, negative and other effects.

The following main targets are quantified the most: habitat provision, erosion and sedimentation regulation, and water quality regulation. For the positive, negative and other effects, only a small fraction is quantified. In absolute numbers, the positive effects are described and quantified most frequently, but only 37% of all positive effects that are described are also quantified and about half of the publications that describe positive effects also quantify them. The most quantified positive effects are biodiversity and water quality regulation. Negative effects are the least studied and quantified; only 33% of the negative effects that are described are also quantified and half of the publications that describe negative effects also quantify them. The most quantified negative effect is food production. This links to the many cases where agricultural land is sacrificed for managed realignment projects. The group of other effects are overall the most quantified; 54% of all other effects are quantified and 53% of the publications that describe other effects also quantify them. The most quantified other effect is erosion and sedimentation regulation.

3.3. Which management measures contribute to specific ES?

When looking to table 2 and 3 in the opposite direction, starting from one specific ES and looking down, it is possible to indicate which management measures can contribute and which management measures might give conflicts (negative effect). We discuss here the management measures that affect some of the main goals in estuaries, linked to the estuarine functions and ES flood protection, water quantity regulation for transportation, habitat, biodiversity, and water quality regulation (figure 3). All reviewed information is summarised in appendix C.

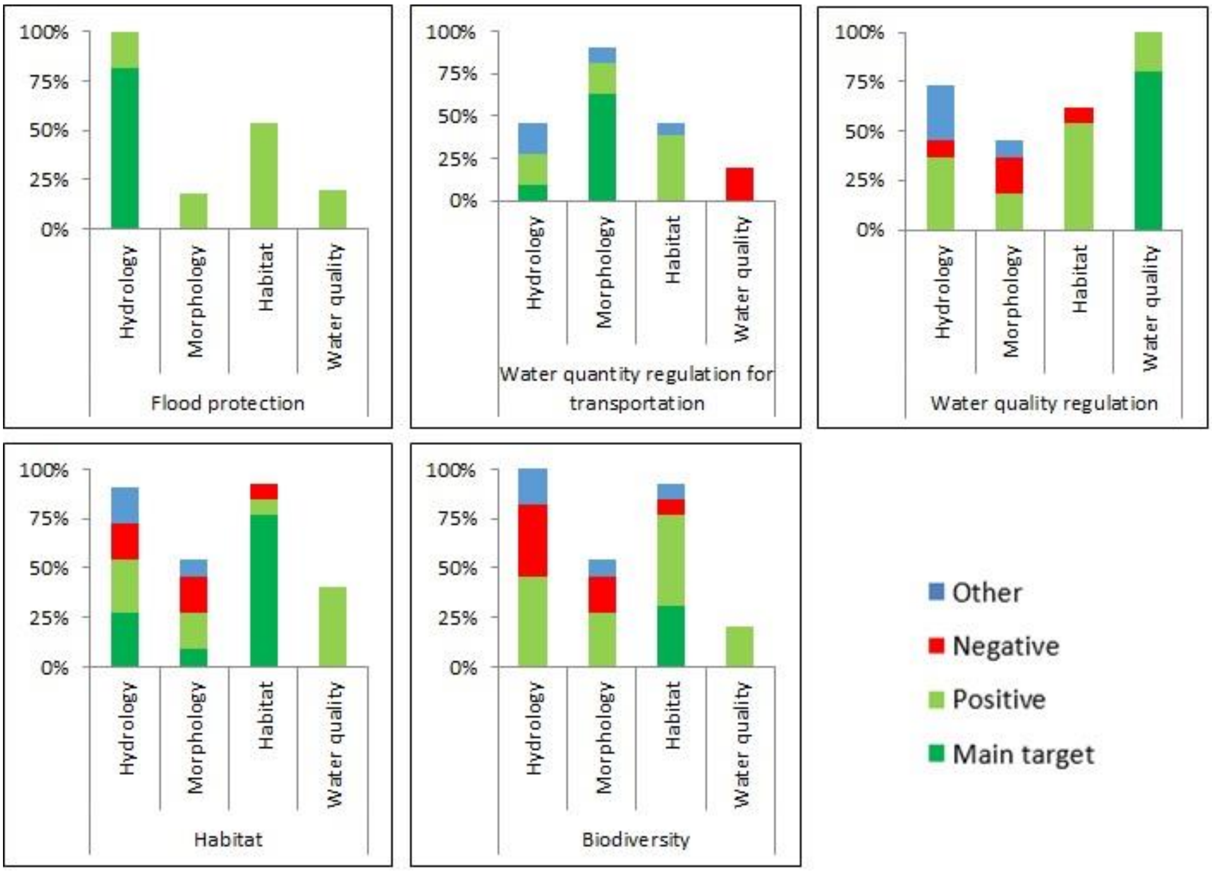

Figure 3: Proportion of management measures in each category (hydrology, morphology, habitat and water and sediment quality) for which effects related to the ecosystem service are described as main target, additional positive or negative effect, or other effect (not clearly positive or negative, or both depending on the situation).

Related to the ES flood protection, about half of all management measures have a positive effect and none of the management measures have negative effects for this ES. Positive effects are expected from all management measures from the group hydrology but also from several other management measures from other groups (e.g. tidal wetland creation). However, when also related effects on 'Drainage of river water', 'Wave reduction' and 'Water current reduction' are considered, several management measures show effects that are negative or potentially negative depending on the situation ('other effect'). For example for dredging, several studies investigated the changes in the tidal characteristics (amplitude, range) which could be linked to flood risk.

For the ES water quantity regulation for transportation, about half of the management measures are expected to have an effect which is mostly positive. The main targets are to increase the navigation depth, straighten the river, build facilities for shipping (quay wall, dock) and provide useful applications for dredged material (underwater disposal, habitat creation and land disposal). Many other management measures also have a positive impact on this ES (2 hydrology, 2 morphology and 5 habitat measures) by reducing the need for dredging (sediment trap, stop shore erosion), improving sediment storage outside the navigation channel (tidal flats, marshes) and creating useful applications for dredged material (restore intertidal marshes). For one management measure of the water and sediment quality category (sluice management for oxygen improvement), a negative effect for shipping is described: trade-off between longer sluice opening and shipping possibilities.

A majority of the management measures have an impact on habitat (30 out of the 39 measures). Many of these management measures, from the habitat category and also from the hydrology and morphology category, have habitat creation, restoration or conservation as the main target. Several other management measures from all four measure categories have a positive effect by the creation/restoration/conservation of a certain area of specific habitat types (marsh, mudflat, reed, grass, shallow water, beach, shoreline, marine/brackish/fresh water). However, other management measures have negative effects: removing vegetation from rivers, fragmentation and habitat loss due to hard structures (although they can, to some degree, function as surrogates), and increased habitat erosion due to dredging (although dredged material could be used for habitat restoration and creation).

About the same amount of management measures that have an impact on habitat, also affect biodiversity (30 out of 39) however much less as the main target but more as positive effect. Only 4 management measures, all from the habitat category, aim at improving biodiversity (vegetation plantation, habitat for fish or birds). Furthermore, 15 management measures from all four categories, are expected to generate positive effects for biodiversity. Most of these management measures include habitat development (or restoration, conservation) for which certain species are expected (vegetation, fish, birds, invertebrates, insects, etc.) to benefit. Water quality related measures (e.g. agro-measures) are expected to reduce eutrophication which is positive for biodiversity. Building of hard structures (e.g. quay wall, groynes and riprap) can function as habitat for species (e.g. algae, mussels, oysters, birds) but also invasive species and overall they are not considered to function as surrogates for natural habitat. Negative effects for biodiversity are diverse and associated with specific management measures. Hard structures such as dikes, barriers and dams have a negative impact due to their impact on habitat (habitat fragmentation and loss) and they cannot function as natural surrogate. Aquatic vegetation removal is detrimental to the ecosystem, for vegetation species but also for all other organisms living on and between the vegetation. Dredging and underwater disposal of dredged material generate increased turbidity and changes in benthic assemblages.

More than half of the management measures also have an effect on the ES water quality regulation (26 out of 39 different management measures). Only management measures in the category water and sediment quality have water quality improvement as the main target. Several other management measures, from all four measure categories, have a positive effect including water filtration capacity, nitrogen removal by burial, denitrification or runoff reduction, and the improvement of oxygen, turbidity and organic matter content and other parameters such as pH. Furthermore changes in sediment quality are linked to water quality: removal or burial of heavy metals and nutrients to prevent them dissolving in surface and groundwater. Some other management measures have negative effects or other effects that are not clearly positive or negative: hard structures can disturb water quality regulation and cause algae blooms if stagnant systems occur but on the other hand also reduce contaminant runoff. Dredging can increase turbidity and mobilize contaminants but on the other hand also remove contaminated sediment. Disposal of dredged material can also cause increased turbidity and resuspension of contaminants. Lastly, with aquatic vegetation removal nutrients are also removed but with less vegetation in the river the denitrification capacity will be decreased.

4. Discussion

A wide variety of management measures are in use to manage estuaries. These management measures aim to improve several goals in the estuary (flood protection, harbour sector, habitat and bird directive and water framework directive), but generate many more effects by changing the ecosystem which we linked to different ES and also habitat, biodiversity and space for infrastructure. The qualitative result demonstrates that many effects are recognised. However, there are also many white cells in the management measures – ES matrix. This can simply mean that these effects do not exist, or if they do exist that they have not been described or studied. This review aims to give an overview of the available information and does not elaborate on the missing information. Nevertheless, by comparing the qualitative and quantitative results it can be concluded that in general only a small amount of publications that describe certain effects also quantify them (number of publications in table 3 is overall much lower than in table 2). In addition, for most management measures a diverse set of effects is described but only a few quantified (number of cells with at least one publications is much lower in table 3 compared to table 2). However, there is a clear difference between the effects that relate to the main target of the management measure and additional effects. Effects on the main target are in general well quantified, but additional effects are not. Overall, the effects that are well studied, both as main effect or additional effect, relate to habitat, biodiversity and erosion and sedimentation processes. For other effects, that relate to for example climate regulation or water quality regulation, quantification is mostly lacking.

The review of available knowledge reveals that still many effects are understudied. Not knowing the impact of a management measure is a problem since then these effects could not be taken into consideration. When these effects are not considered in decision-making, negative effects that deteriorate the estuary system are not compensated for and positive effects for other targets and ES might be overseen. The latter makes it impossible to use all opportunities for integrated management and take full advantage of management measures that contribute to several targets, possibly from different departments.

The matrix used in this review links management measures with estuarine functions and ecosystem services. It reveals how the management of one function can influence other functions. This approach can facilitate the collaboration between different management departments because it makes the overlap in the management strategies of different departments explicit. This framework makes the comparison between management measures easier (e.g. more or less negative effects). However, this review does not have the aim to conclude that one measure is better than another. That is not possible based on the reviewed information alone. For example, some negative effects are easier to compensate and others are impossible to compensate.

Management of an ecosystem will inevitably generate trade-offs between different goals. Furthermore, single management measures generate trade-offs between different ES. Revealing these trade-offs is already a first step towards the development of an integrated management strategy. One common trade-off is between private and public interest. A typical example is the expropriation of agricultural land for a coastal managed realignment project with the purpose of increasing flood protection. Building a (higher) dike could be an alternative to increase flood protection and to safeguard the agricultural land, but this causes negative effects on other ES (e.g. increasing flood risk and disturbance of estuarine functions) while a coastal managed realignment project generates positive effects besides flood protection (e.g. water quality regulation, carbon sequestration and fish nursery function) (Boerema et al. 2016). However, different benefits of a coastal managed realignment project are also conflicting: habitat development in the area requires sedimentation but this is in conflict with the flood protection function for which the water storage capacity should remain maximal (and hence sedimentation limited). Furthermore, the conversion between land use types and habitat types, and any intervention in general, also influences biodiversity and species composition. Beach nourishment for example could be used as a technique to restore the beach, but this changes the soil composition which might affect local species composition. Another example of trade-offs relates to food production in the estuary which can consist of crops, livestock grazing, saline agriculture, fish and shellfish. Management measures could be beneficial for one food type but negative for another since the variety of food types require different land uses and habitat types.

This review gives an overview of the current understanding and research about the impact of estuarine management. Nevertheless, many aspects that complicate future improvements towards integrated management are not included in this review. First, when comparing management measures and their effects, it is important to incorporate the time scale of both: the lifetime of management measures and the time horizon of its effects. Seasonal aspects for example could restrict ES benefits to certain periods of the year. Vegetated foreshore could contribute to flood protection by attenuating waves, but not during winter when the vegetation died off. In such a case, a combined solution is necessary to guarantee full flood protection throughout the year. Second, involvement of different management levels (municipality, province, catchment, river, etc.) and governance departments (spatial planning, economy, finance, agriculture, environment, etc.) complicate the development of an integrated management plan. Third, goals might be specific for certain zones of the ecosystem which causes restrictions to the spatial implementation of management measures. Fourth, the effect of management measures on certain ES could be influenced by local factors such as tidal characteristics and salinity which might cause another spatial restriction. Fifth, the success of management measures to improve certain ES depends on many factors. For example, the success of dynamic marsh development depends on sedimentation and erosion processes. When a specific habitat type is aimed at (e.g. tidal flat), unexpectedly high sedimentation could result in the development of a marsh area which then is sometimes considered as a fail. In that case a management intervention could be required to lower the area (dredging) which disturbs the environment and might be unsustainable. This raises the question of how goals should be defined: too vague versus too specific.

The main aim of this review was to investigate the diversity of effects of management measures on the functioning of the estuary. The information from this review can feed into further steps to develop integrated ecosystem management strategies. It provides a qualitative assessment of the effects of different management measures and the availability of a quantitative assessment. This can be used to further investigate which management measure is, for example, more beneficial or more cost-effective for one or more targets in the estuary.

5. Conclusions and recommendations for further research

The management measures – ES matrix presented in this review could be used as a first step to develop an integrated management plan. First, it shows which management measures could contribute to each of the ES, habitat, biodiversity and space for infrastructure. Secondly, for each of the management measures of interest it shows the additional benefits besides the main targets and potential negative effects to take into consideration. However, for a full understanding of the impact of estuarine management and trade-offs more research is needed to quantify all effects. This is a prerequisite for the development of an integrated management plan that is effective, cost-efficient and minimises negative effects.

Table 2: Overview of 39 management measures for estuarine management organised in 4 categories and 15 sub-categories. Number of publications that describe the effect of each of the 39 management measures on up to 17 (sub-)ecosystem services (P: provisioning, R: regulation, C: cultural), and biodiversity, habitat and space for infrastructure. A distinction is made between effects that are described as a main targets (numbers in bold), additional positive effects, negative effects and other effects that are not clearly positive or negative.

Legend:
Number of publications describing effects on ES:
Main target
Positive effect
Negative effect
Other effect

4 categories: 39 management measures:			# publications	P	P	P	P	P	R	R	R	R	R	R	R	R	C	C	C	C			
				Food: crops (e.g. freshwater supply)	Food: animals (cattle, sheep)	Food: animals (fish)	Water for industrial use	Materials (e.g. sand)	Climate regulation	Erosion and sedimentation regulation	Flood protection	Water current reduction	Wave reduction	Water quality regulation	Drainage of river water	Water quantity regulation for transportation	Aesthetic information	Information for cognitive development	Heritage, inspiration for culture, art and design	Opportunities for recreation and tourism	Biodiversity (vegetation, birds, fish...)	Habitat	Infrastructure (houses, roads...)
Hydrology	Flood protection	Hard defences: Dikes	24	**2**	**2**				1	11	**21**	3		3		**1**	1			**6**	13	14	**1**
		Hard defences: Quay walls	7	1						**1**	**3**					**3**				**2**	**1**		1
		Storm surge barrier	7				**1**			1	**6**	1				2				1	1	3	**2**
		Dam	5	**1**						3	**2**			1	1	**1**				**1**	4	2	**1**
	Flood protection +Habitat development	Flood control area	5	**3**					**1**	2	**5**			**2**			2		1	**1**	3	**4**	
		Managed realignment	70	24	**2**	**2**		**3**	**14**	47	**48**			**21**	8	2	**1**	**1**	**1**	**12**	**45**	**63**	1
		Flood Control Area with Controlled Reduced Tide	20	4	1	**1**		**2**	**1**	9	**15**	6		**8**	1	1	1		**1**	**9**	**9**	**18**	
		Ecological-friendly dikes	12							**7**	**4**		1	2			**1**			**4**	**10**	**12**	
		Beach nourishment	12						**1**	**9**	**6**									**2**	2	**6**	1
		Foreshore defence	5	1		**1**		1	**2**	**2**	**5**		**3**	**2**			**2**			**3**	**4**	**4**	
	River hydrology	Vegetation removal for river drainage	3	1			1			2	**3**			3	**3**						3	2	
Morphology	Shipping	Dredging	42	**1**		1		**8**	1	19		7		13	**7**	**35**					9	12	**2**
		Training wall	7							6		2				**4**						**2**	
		Harbour docks and sluices	5				**1**			3						**4**				**1**	**1**		
	Shipping: Reduce need for dredging	Current deflecting wall (CDW)	15							**15**						3							
		Fluid mud (nautical depth concept)	5							5				**2**		**4**					1		
		Sediment trap	3						**1**	**3**				**1**	**1**	**2**					**2**	**1**	
		Current direction control	1							1													
	Shipping: dispose dredged material	Underwater disposal	12						1	9		**2**		6		**4**	1				3	4	
		Habitat creation	11						1	**8**					**1**	**4**				**1**	**6**	**9**	
		Land disposal	4					**2**	1	1				2		**1**	1						1
	Sand excavation		7					**7**		1					1	**2**						1	
Habitat	Habitat protection	Groynes	18	**2**						**15**	**6**	**3**	**2**	**2**		3	1			4	**6**	**14**	
		Riprap	11	**1**						**8**	**3**		**2**	2		**1**	1			**2**	7	**8**	
		Bioengineering	5							**5**	**1**			**4**		**1**	**1**			**2**	**5**	**4**	
	Habitat restoration	Ecological-friendly shoreline	13	**1**						**10**	**3**		**1**	**5**	**2**		**4**			**5**	**9**	**12**	
		Restore intertidal areas	5	**1**	**1**	**2**	1	**1**	**3**	**5**	**4**		**2**	**3**		**1**	**2**	**2**	**1**	**2**	**4**	**5**	1
	Habitat development	Tidal wetland creation	35	7	**3**	**4**			**6**	24	**16**	5		**12**		**1**	**2**	**2**	**2**	**5**	**24**	**20**	
		Constructed shallow water	1							1				**1**							**1**	**1**	
		Transplantation measures	9						**1**												**8**	**3**	
	Habitat for fish	Fish habitat	2																		**2**	**2**	
		Removal fish bottlenecks	3																		**3**		
	Habitat for birds		7			1				1	**1**			**1**		**1**					**7**	**7**	
	Habitat development +recreation		2							1										**2**	1	1	2
Quality	Water quality	Agro-measures	20	9			**1**		**2**	**11**	**4**			**14**						**1**	**3**	**4**	**1**
		Water treatment plant	10											**10**									
		Oxygen improvement	2			**1**				1				**2**		1							
	Sediment quality	Land treatment plant dredged material	3					**3**						**2**									1
		Treatment, remediate river sediment	2											**2**								**1**	

Table 3: Overview of 39 management measures for estuarine management organised in 4 categories and 15 sub-categories. Number of publications that quantify the effect of 39 management measures on 17 (sub-)ecosystem services (P: provisioning, R: regulation, C: cultural), and biodiversity, habitat and space for infrastructure. A distinction is made between effects that are described as a main targets (numbers in bold), additional positive effects, negative effects and other effects that are not clearly positive or negative.

Legend:
Number of publications quantifying effects on ES:
Main target
Positive effect
Negative effect
Other effect

4 categories: 39 management measures:			# publications with quantification / # publications	P: Food: crops (e.g. freshwater supply)	P: Food: animals (cattle, sheep)	P: Food: animals (fish)	P: Water for industrial use	P: Materials (e.g. sand)	R: Climate regulation	R: Erosion and sedimentation regulation	R: Flood protection	R: Water current reduction	R: Wave reduction	R: Water quality regulation	R: Drainage of river water	R: Water quantity regulation for transportation	C: Aesthetic information	C: Information for cognitive development	C: Heritage, Inspiration for culture, art and design	C: Opportunities for recreation and tourism	Biodiversity (vegetation, birds, fish...)	Habitat	Infrastructure (houses, roads...)
Hydrology	Flood protection	Hard defences: Dikes	7/24								3	1									3		
		Hard defences: Quay walls	2/7								1										1		
		Storm surge barrier	3/7								2					1							
		Dam	2/5							1											1		
	Flood protection +Habitat development	Flood control area	4/5						1		3			1			1			1		2	
		Managed realignment	51/70	12		1			7	26	7			13	3					1	32	25	
		Flood Control Area with Controlled Reduced Tide	17/20	1				1	1	9	2	6		5	1	1	1			2	8	11	
		Ecological-friendly dikes	4/12							1			1							1	4	2	
		Beach nourishment	2/12							1											1		
		Foreshore defence	3/5			1				1			1				1			1	1	1	
	River hydrology	Vegetation removal for river drainage	3/3	1			1				2			1	2						3		
Morphology	Shipping	Dredging	17/42	1						5		4		3		8					3	2	
		Training wall	2/7							2													
		Harbour docks and sluices	1/5							1													
	Shipping: Reduce need for dredging	Current deflecting wall (CDW)	14/15							14						1							
		Fluid mud (nautical depth concept)	4/5							3				1		2							
		Sediment trap	2/3							2													
		Current direction control	1/1							1													
	Shipping: Dispose dredged material	Underwater disposal	8/12						1	6		1									2		
		Habitat creation	8/11						1	4											5	4	
		Land disposal	2/4						1	1													
	Sand excavation		2/7					2															
Habitat	Habitat protection	Groynes	12/18							5		1	1	1		1					6	3	
		Riprap	6/11							1											5	1	
		Bioengineering	2/5							1				1							1	2	
	Habitat restoration	Ecological-friendly shoreline	9/13							6			1	1							5	4	
		Restore intertidal areas	3/5			1			1	2	1						1						
	Habitat development	Tidal wetland creation	30/35			1			1	11	6	4		5			1				13	12	
		Constructed shallow water	1/1							1												1	
		Transplantation measures	5/8						1												5	1	
	Habitat for fish	Fish habitat	2/2																		2		
		Removal fish bottlenecks	0/3																				
	Habitat for birds		4/7																		2	4	
	Habitat development +recreation		0/2																				
Quality	Water quality	agro-measures	12/20	5						4	1			9									
		Water treatment plant	5/10											5									
		Oxygen improvement	2/2											2									
	Sediment quality	Land treatment plant dredged material	2/3					1															1
		Treatment, remediate river sediment	0/2																				

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