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WP5 Measures

Interestuarine comparison:

Managed Realignment Measures

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Disclaimer

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Summary

In the frame of the TIDE project, estuarine management is an important topic. A wide range of measures planned or implemented in the four TIDE estuaries (Elbe, Scheldt, Weser, Humber) was collected and evaluated [1]. Based on the results, different inter-estuarine comparison studies are executed.

The topic of this report is an inter-estuarine comparison of estuarine habitat restoration measures [2-19]. These measures seem to be commonly implemented since nearly half of the estuarine measures studied in TIDE are related to estuarine habitat restoration. Two specific types of measures are analysed:

- Managed Realignment Measures (MRM) whereby restoration is operated by dike breaching or defence removal. Managed realignment (MR) - or 'dike-realignment', 'de-polderisation' – involves "setting back the line of actively maintained defences to a new line inland of the original and promoting the creation of intertidal habitat between the old and new defences" [20].
- Restricted Tidal Exchange (RTE) with a Controlled Reduced Tide (CRT) as a specific example.

In the first part, general aspects of the 17 MRMs (Table 0-1) are analysed and compared. The second part focusses on the sedimentation rate on these MR sites and determining site selection and site design aspects. Overall, the aim of this report is to conclude with recommendations for future nature restoration measures hence improve the success of estuarine management. For the Humber, only three of the selected MRM within TIDE are included in the main report, data for three other Humber measures are added in Appendix 2.

Table 0-1. List of the 17 TIDE managed realignment measures. Basic information and effectiveness analysis of the measures is available in the respective measure reports [2-19]

TIDE nr.	Estuary	Measure name	Code
1	Elbe	Spadenlander Busch/Kreetsand	E-Sp.B.
7	Elbe	Realignment Wrauster Bogen	E-Wr.B.
8	Elbe	Compensation measure Hahnöfer Sand	E-Hahn.S.
9	Elbe	Spadenlander Spitze	E-Sp.Sp.
13	Scheldt	Lippenbroek FCA-CRT	S-Lip.
15	Scheldt	Ketenisse wetland	S-Ket.
16	Scheldt	Paddebeek wetland	S-Pad.
17	Scheldt	Paardenschor wetland	S-Paard.
18	Scheldt	Heusden LO wetland	S-Heusd.
24	Weser	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.
25	Weser	Shallow water area Rönnebecker Sand	W-Ronn.S.
26	Weser	Tidal habitat Vorder- und Hinterwerder	W-VorHin
27	Weser	Shallow water zone Kleinensieler Plate	W-Kl.P.
28	Weser	Cappel-Süder-Neufeld	W-Cap.S.N.
30	Humber	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.
31	Humber	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS
33	Humber	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.

Part 1: General aspects of Managed Realignment Measures (MRMs)

The 17 TIDE MRMs are all implemented in the last 21 years. The **average size** of the TIDE MRM is 63 ha, ranging from 1.6 ha to 440 ha (Figure 0-1). However, only two cases are larger than 100 ha. Half of the TIDE MRMs are **located** in the freshwater zone and the other half is spread along the three other salinity zones according to the Venice System (mesohaline, oligohaline and polyhaline) [21].

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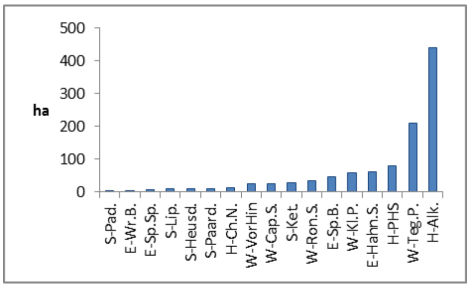

Figure 0-1. Restored surface

The MRM have been implemented **for different reasons**. The most common measure target is habitat conservation, restoration or creation. Only a few cases combine this conservation target with a safety target (flood storage capacity), research target, and/or recreation opportunities. Half of the cases are driven by a compensation reason. The **degree of target achievement** is overall high: almost half of the measures are considered to have a high degree of target achievement, the other part a medium degree meaning that not all targets are completely reached. However in some cases it was proved that the degree of target achievement could be improved by making some adaptations to the MR site.

An MRM could be executed **by different techniques**. Half of the TIDE cases are implemented by dike breach and half by defence removal (large dike breach), with a dike breach between 3m and 2650m (Figure 0-2). Another type of estuarine habitat restoration is by Reduced Tidal Exchange (RTE). Within TIDE we have only one RTE example (**S-Lip.**). In half of the measures, the dike breach or defence removal is combined with land lowering. In many cases it was proven that different design aspects such as initial site elevation, slope of the area and hydrodynamics do influence habitat development and the success of the measure. In some cases the initial design was not optimal, but adaptations to the site were possible to improve the success of the measure.

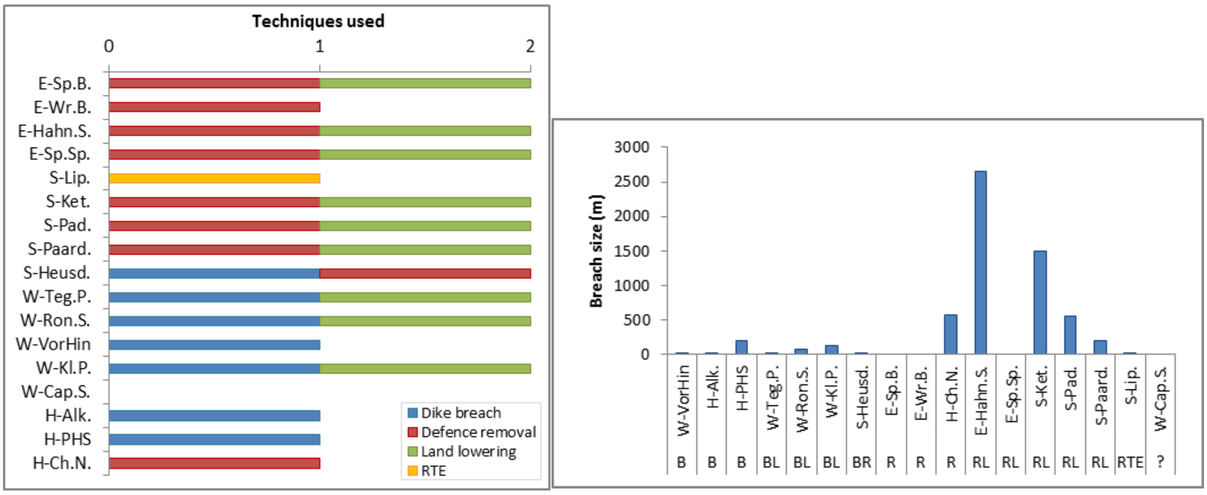

Figure 0-2. Overview implementation techniques used for the different TIDE examples (LEFT), and link between implementation technique and breach size (m) (RIGHT). Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), RTE.

The TIDE MRMs together transformed about 1000 hectares **adjacent land into estuarine habitat**, consisting mainly of marsh land and intertidal flat habitat (Figure 0-3). For the TIDE cases, about 90% of the created habitat surface (approx. 900 ha) was however implemented for compensation reasons meaning that it is not really new habitat because it was lost first somewhere else.

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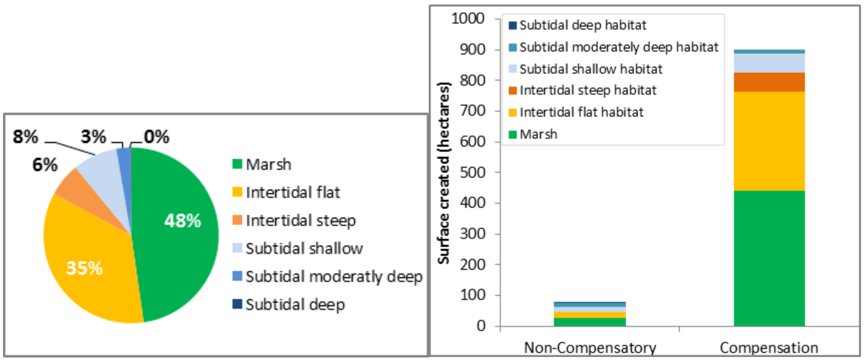

Figure 0-3. Distribution of different habitat types created by the TIDE cases (Left), and overview habitat creation per habitat type by the TIDE compensation measures and non-compensatory measures (Right).

All TIDE MRMs have a **monitoring program** with a duration between 3 to 15 years. The parameters mostly monitored (in at least half of the TIDE cases) are: vegetation, accretion and sedimentation on site, invertebrates, birds and fish.

MRMs generate many **synergies** between nature, flood protection, port development, recreation and natural resources, but also **conflicts** with agriculture and local inhabitants.

MRMs are **expensive** but could also generate **large benefits**. The **relative implementation cost** of the TIDE MRM cases amounts 280,000 €/ha with a large range between 16,000 and 1.4 Million €/ha. For some measures, only a rough estimation was available.

- Three TIDE MRMs are considered as outliers with a remarkable high relative implementation cost, because of a high amount of soil that had to be removed out of the area (**E-Hahn.S.**) and that had to be treated because of contamination (**E-Sp.B.**), or uncertainty about the total implementation cost (**S-Pad.**).
- Furthermore, different measure characteristics are studied to find reasons for the large variance in the relative implementation cost.
    - Size and age: No significant relationship is observed between the relative implementation cost and the size of the measures, nor could we observe a temporal evolution in the relative implementation cost.
    - Implementation techniques: A significant difference in the relative implementation cost is observed between the TIDE measures implemented by dike breach or by defence removal. The latter technique is, evidently, much more expensive. A positive relationship with the breach size was however not significant. Furthermore, measures with land lowering are expected to be more expensive but this difference was also not significant.
    - Creek system implemented: Measures with the implementation of a creek system are expected to be more expensive but this difference was not observed for the TIDE cases.
- Overall it is not possible to give a clear indication about what causes a higher or lower relative implementation cost. It depends too much on local conditions.
- **Critical note**: By comparing measure characteristics with the relative implementation cost nothing could be concluded about the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and to be sustainable is more important when considering the measure design than the implementation cost.

Besides the implementation cost of the measures, also the **benefits** are studied based on the Ecosystem Services (ES) concept. However, no scientific consensus exists yet on the monetary valuation of ES. Different approaches are explored with often also different outcomes.

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- A simple approach was applied to get a rough idea of the order of magnitude of the monetary benefits of the MRMs. A recent overall literature review with global monetary data for different biomes was used and multiplied with the habitat creation in the MRMs. Based on this approach, the TIDE examples generate an average benefit of 133,000 € per hectare and year, ranging from 70,000 to 155,000 € per hectare and year. The monetary benefit calculated here is however an overestimation because it is limited to the benefits generated within the estuary itself without counting for the lost adjacent land.
- A more detailed approach to calculate the local benefits of a measure is however recommended. Therefore, a guidance document is developed to support managers and decision makers in how to quantify and monetary value the changes in ecosystem services specifically for the study site [22].

By comparing the costs and benefits of the measures, the **cost-efficiency** of the TIDE cases is analysed.

- The first method is the earn-back time, i.e. the average time that the measure should be operational before the total implementation cost is earned back. For the TIDE MRMs this amounts on average 2.3 years, ranging from 0.1 year to 15 years.
- The second method is the benefit/cost ratio, i.e. the annual benefit (as calculated above) generated for every 1€ invested (as calculated above). For the TIDE cases the benefit/cost ratio is on average 2.82:1, meaning a benefit of 2.82 €/y for every 1€ invested. The benefit/cost ratio for the TIDE cases ranges from 0.07 to 13.35 €/y for every 1€ invested.
- The earn-back time and benefit/cost ratio both give an indication of the cost-efficiency of a measure, assuming that the measure targets are met completely. However, in reality the latter assumption is rarely the situation. It is therefore recommended to first check the success of measures to meet the development targets and additionally the cost-efficiency estimate could be used to make a selection between measures that are expected to be successful.

In the final section, the results of an **ES assessment** for the MRMs are analysed (based on the TIDE ES study [23]).

- In a first part, the target ES are indicated per measure based on the development targets (Table 0-2). Most TIDE MRMs target the supporting and habitat services. In a few cases, this target is combined with a regulating service (flood water storage, dissipation of tidal and river energy), and/or a cultural services (opportunities for recreation and tourism, and information for cognitive development).
- The TIDE MRMs have a positive expected impact (from slightly positive to very positive) on at least 12 of the 20 considered ecosystem services.
- The expected impact on the targeted ES is in most cases very positive. On average, only 10% of the ES with a positive expected impact (slightly positive to very positive) are also targeted. This means that the MRMs are expected to generate many co-benefits!
- Regarding the beneficiaries, the TIDE MRMs are mainly beneficial in an indirect way, at a longer term (for future use), and at a local and regional scale.

Table 0-2. Translation of measure targets in terms of ES

Target	Corresponding Ecosystem Service
Safety	R1 - Erosion and sedimentation regulation by water bodies R9 - Water quantity regulation: dissipation of tidal and river energy R12 - Reg. of extreme events: flood water storage
Habitat conservation/restoration	S - Supporting and habitat services (biodiversity)
Compensation	S - Supporting and habitat services (biodiversity)
Access opp. and education	C4 - Cult. Opportunities for recreation and tourism
Research	C3 - Cult. Information for cognitive development

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Part 2: Optimisation of MRMs with a focus on the sedimentation rate

The second part of the MRM report focusses on issues related to the sedimentation rate at MR sites. Sedimentation and erosion processes have an important role in the development of MR sites and hence in the success of the MRMs. It is however a complex issue and difficult to predict and anticipate on in practice. Although for many measures some modelling work on this topic was done in the planning stage, the reality after measure implementation turned out to be different and does not always suit the development goals. In some TIDE cases the sedimentation rate was therefore considered as a problem, e.g. because tidal water areas silted up quickly due to unexpectedly high sedimentation rates or because habitat development was curtailed due to unexpectedly strong erosion. However, if the situation arises where we require a system which is not in equilibrium this might be more a problem of setting the goal than of the sedimentation rate that is “too high”. Meaning: the project might be in the wrong place, the objectives might be unrealistic or the design of the project might be suboptimal.

Managers have to deal with the unpredictability of the dynamic estuarine system but this does however not mean that managers do not have the possibility to improve the success of the measure and for example reduce the need to dredge the sites. Different aspects of the MRsites are studied to analyse their relationship with the sedimentation rate on the site. It is the aim of this study to better understand the link between the MRsites (both the location within the estuary and the design of the site) and the sedimentation rate and to formulate recommendations to enable managers to improve the selection and design of the site and hence the success of the measure.

a. Sedimentation rate TIDE cases

In general, the sedimentation rate is highest immediately after implementation and then levels off after some years. The overall average sedimentation rate on the TIDE MR sites is 9 cm/yr (Figure 0-4), with the highest sedimentation rate measured at parts of the Kleinensieler Plate (75 cm/yr, **W-Kl.P.**) and the strongest erosion in some parts of Ketenisseschor (-30 cm/yr, **S-Ket.**). The average accretion at Kleinensieler Plate (**W-Kl.P.**) is very high compared to all other TIDE cases, and without **W-Kl.P.** the overall average sedimentation rate is only 5 cm/yr.

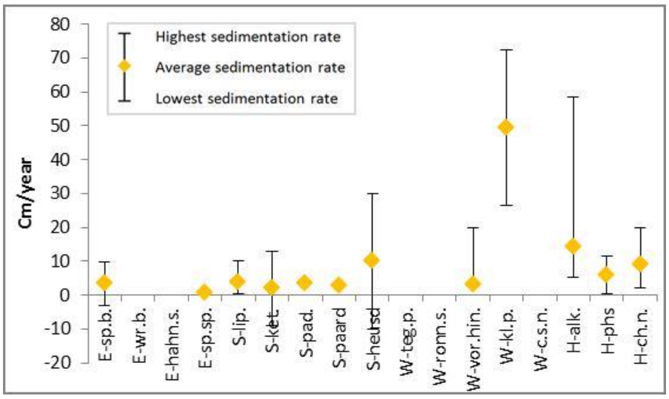

Figure 0-4. Average sedimentation rate per TIDE MRM, with indication of the highest and lowest measured (or monitored) sedimentation rate as error bars.

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b. Impact of site selection and site design aspects on the sedimentation rate

1. Outer-dike vs inner-dike measures

A first difference is made between outer-dike and inner-dike areas. In this study, outer-dike sites are defined as the areas that are under direct influence of the river and hence under influence of the full tidal range. Most TIDE cases are outer-dike sites. The inner-dike sites are defined as areas with a hydraulic constriction by a (narrow) construction (eg. sluice, sill or overflow barrier) in between the site and the estuary, resulting in a dampened tidal range on the site. A special case of inner-dike measures is a Controlled Reduced Tide (CRT), of which one example is analysed within TIDE (**S-Lip.**). It is expected that the sedimentation and erosion processes will differ between outer- and inner-dike sites due to the different site conditions, depending on water depth, residence time, concentration of suspended matter in the water column, erosion forces etc.. The Kleinensieler Plate is an example for a measure with more or less outer-dike character at the beginning which later on has been converted into an inner-dike site. By this water exchange, sediment entry and sedimentation rate has decreased significantly.
Indeed, based on the TIDE measures no significant relationship was found between the average sedimentation rate at the MR site and whether the site is located outer- or inner-dike.

2. Factors related to the location of the MR site in the estuary

Overall, the following location characteristics are considered as determining both global and local sedimentation and erosion processes: salinity gradient (TIDE-km and estuarine zone), Suspended Particulate Matter (SPM) and turbidity maximum, location at inner or outer side of a river bend, and hydrodynamics in the area.

i. Salinity gradient (TIDE-km and estuarine zone)
The first factor is the location of the MR site along the **salinity gradient**: at a certain TIDE-km or certain estuarine zone (freshwater, oligohaline, mesohaline and polyhaline). No relation with the average sedimentation rate at the MR site was found.

ii. Suspended Particulate Matter (SPM) and turbidity maximum
The second factor is the **SPM** near the MR site and the location of the site at a **turbidity maximum**. For the TIDE cases, the average SPM amounts 200 mg/l, ranging from 38 mg/l to 700 mg/l. As expected, the sedimentation rate is higher at sites with a high SPM supply (Figure 0-5).

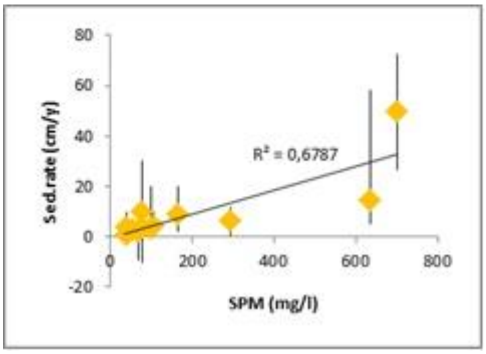

Figure 0-5. Correlation between SPM and the average sedimentation rate on the site (R^2=0,6787; T=4,6; p<0,001).

iii. Location at inner or outer side of a river bend
The third factor is the location of the MR site at the **inner or outer side of a river bend**. It is expected that the sedimentation rate will be higher at sites located at the inner side of a river bend, because here current

velocity is lower. This is however mainly expected for outer-dike sites because only these sites are under full influence of the river. Based on the TIDE data we are not able to verify this assumption (small dataset).

iv. Hydrodynamics in the area

Sedimentation and erosion processes are also influenced by the **exposure of the area** to the turbulence of the estuary: tidal wave action (large in case of a wide connection to the estuary; essentially a very wide breach); wave action from wind (large in case of exposure to significant fetch from the predominant wind direction); and wave action from ships (large in case of relatively high waves from ships). Firstly, it is possible to select a location along the estuary that is more exposed or sheltered to the hydrodynamic turbulences (e.g. close to the navigation channel will give more ship waves). Secondly, it is also possible to influence the hydrodynamics in the measure site by adapting the site design, e.g. by the size of the opening to the river.

Highly exposed zones with high tidal dynamisms could be characterised by inadequate sedimentation or even erosion which could lead to only bare mudflats without marsh development (e.g. S-Paard Figure 0-6 black circled zone). In contrast, sheltered zones, depressions and completely embanked inner-dike areas (such as a CRT) could be characterised by higher sedimentation rates by which mudflats could disappear and only marshes remain (e.g. S-Paard Figure 0-6 red circled zones).

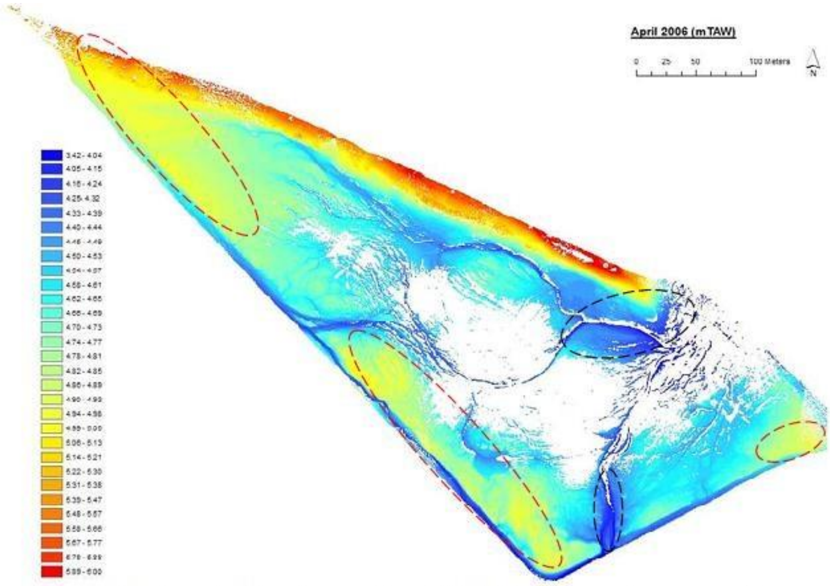

Figure 0-6. 3D-picture of the Paardenschor in April 2006 (m TAW). The red circled zones are low hydrodynamic zones, the black circled zones high hydrodynamic zones. [24]

3. Factors related to the design of the MR site

Overall, the following site characteristics are considered as determining both global and local sedimentation and erosion processes: initial elevation (lower vs higher zones), inundation (flood frequency and duration high vs low), slope (weak vs steep), opening to the river, vegetation at the site, drainage and creek system development.

i. Site topography: elevation and inundation

Spatial **differences in elevation** in the area will have an influence on spatial patterns of accretion and saltmarsh vegetation, with implications for the habitat development on the site such as benthic invertebrate diversity and bird usage of the site. It has previously been shown that an inverse relationship exists between elevation and accretion rates inside the realignment site. This is a consequence of the tidal regime in the area, i.e. lower parts

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will be flooded more frequent and for a longer time and hence more sediment could be deposited. It is proved that there is a positive relationship between inundation (frequency and duration) and the accretion rate and hence with elevation. This is also observed at the TIDE cases: sedimentation rates are higher at the lower areas (e.g. **S-Lip**. Figure 0-7 and **W.Kl.P.**Figure 0-8).

Inappropriate elevation could result in specific site objectives (e.g. marsh development) not being met. Areas that are located much lower than mean high water level (MHWL) for example are quasi constantly flooded and hence vegetation development is difficult. Old polders, frequently used as project sites, are however often located much lower than MHWL as a consequence of increasing water levels and alignment of the areas. In general, an **elevation of the site at MHWL** is considered as an optimal condition for realignments. The elevation of most TIDE cases is indeed situated around MHWL.

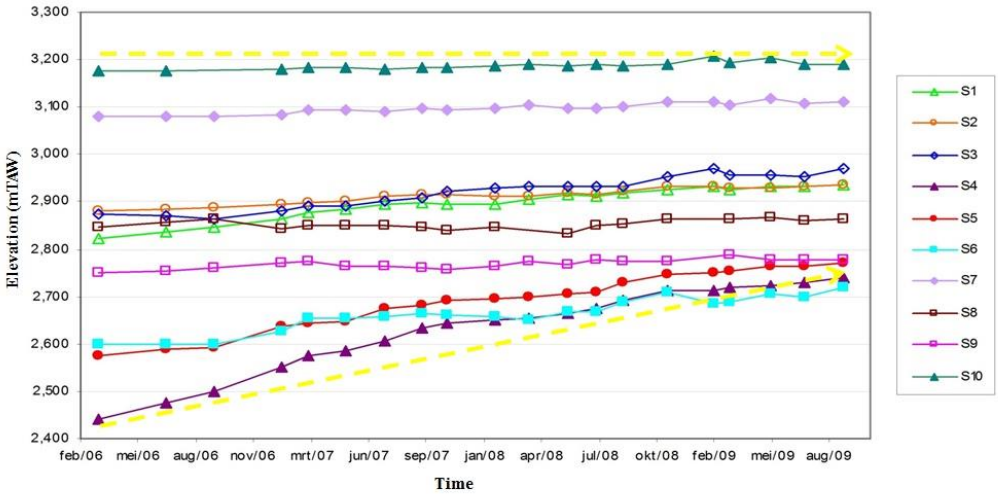

Figure 0-7. Comparison of sedimentation in the time at the 10 sites of Lippenbroek, February 2006-August 2009: elevation changes (m TAW) [25, 26]. Lower sites (eg. 4 and 5) are characterised by higher sedimentation rates and hence elevate much more over time than higher sites (eg. 7 and 10), indicated by the yellow arrows.

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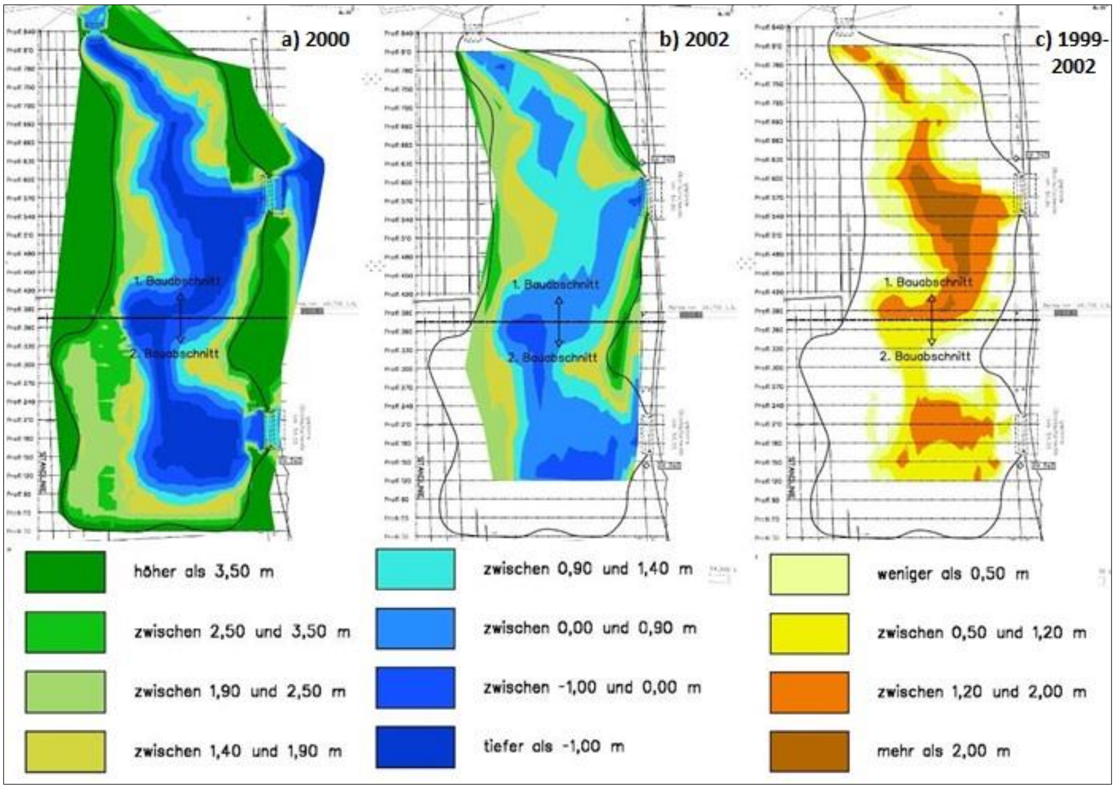

Figure 0-8. Topography and bathymetry (elevation in m NN) at Kleinensieler Plate: (a) in 2000; (b) in 2002; (c) difference between 1999 and 2002: largest difference in the deepest zones.

ii. Slope

A causal relationship exists between the percentage of slope grade of the mudflat and the intensity of sedimentation and erosion: flat areas are characterised by more sedimentation and steep areas by less sedimentation or even erosion. In the TIDE example **S-Ket.,** a sedimentation shift to erosion from a **critical slope grade of 2.5%** or more was determined. This also corresponds to the difference between the TIDE habitat types intertidal flat habitat (slope rate <2.5%) and intertidal steep habitat (slope rate >2.5%).

iii. Opening to the river

The connection of the site with the river proved to influence the sedimentation and erosion processes in the site. The **dimensions of the opening (width and elevation)** will (partially) determine to which extent the site is under influence of the tidal prism. In addition, this will influence currents and water levels in the site and hence also the inundation and correspondingly the sediment inflow and the accretion rates. A larger opening (wider and/or low in elevation) can correspond with a larger water volume flowing in the area potentially bringing in also more suspended material. In addition, it is expected that a more or less proportion of suspended material that enters the area will also be deposited there and not return to the river. Hence, to control the sedimentation in the area, it might be crucial to control the inflow of suspended material. From the TIDE cases no clear relationship was observed between the average sedimentation rate and the breach size (both absolute and relative to site surface), nor with the elevation of the opening. However, in the TIDE case **W-Kl.P.** the overflow barriers were heightened to reduce tidal range and by this the amount of suspended matter entering the project area and indeed siltation tendencies were slowed down (see above). In another TIDE case (**S-Heusd**) it occurred however that the elevation of the opening was too high to properly drain the area, but this was solved by making an extra breach at MLWL.

As the dimensions of the breach are important for the development of the area, much attention is addressed during the planning phase to create optimal dimensions. For specific measures it might be necessary that at a

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long term perspective **dimensions remain stable**. For instance, sedimentation and erosion processes could, depending on the dynamics, enlarge or diminish the opening and change the hydromorphological characteristics in the area. To improve the stability, breaches are frequently enforced by a sill. Also a sluice system (such as in case of the FCA-CRT **S-Lip.**) could offer a solution, because the dimensions are constructed in detail and fine-tuning is possible.

Another aspect of the opening to the river is the **number of breaches**. If only one breach connects the site to the river, the site will function as a reservoir which will cause a different hydrodynamic situation compared to a site with at least two openings by which the site will function as a flow through (e.g. **S-Lip.** with high inlet and low outlet to improve the flow through characteristic). In a flow through case, hydrodynamics will be higher causing less sedimentation. However, flow current could also be too strong causing strong erosion obstructing habitat development. This was the case in the TIDE example **E-Wr.B.** where one site of the creek had to be closed to stop erosion and make habitat development possible.

In principle, wherever practicable a measure should aim at a dynamic estuary-specific development of a site. Within such a site one might have both, sedimentation and erosion processes. For example, by forming the opening to the river and by designing the morphology within the measure site (meandering creeks, tidal pools etc.) the coexistence of sedimentation and erosion zones/processes can be furthered.

Recommendations part 2:

Overall, managers have several possibilities to control, at least to a certain extent, the sedimentation in the MR site and hence improve the success of the MRM. In the **site selection** phase, it is advised to take into account the location of the turbidity maximum in the estuary, the SPM concentrations along the estuary and the location of river bends. In the **designing** phase, many factors could be controlled: outer- or inner dike area with full or dampened tidal influence; initial elevation of the area relative to the tidal prism; elevation differences within the MR site to improve habitat diversity; the slope of the area (a slope of 2.5% and more has to be avoided to make habitat development possible); sheltered sites have higher sedimentation rates compared to exposed sites; and with a larger opening more suspended matter could enter the area and could hence be deposited.

Part 3: General recommendations for successful MRMs

The overall success of a MRM depends on the possibility to meet the different development targets. Hence the targets have to be specific, measurable and achievable within the context of the project [27]. MRMs executed in an estuary have to deal with the dynamic and complex context of the estuary. Biotic and abiotic factors of the estuary interact constantly, ultimately resulting in a dynamic equilibrium situation. When intervening in the estuary, e.g. by implementing a MRM, the system is disturbed will evolve towards a new dynamic equilibrium. For a successful MRM, the development targets have to be in accordance with what can be expected to become the new situation in the long term. The manager has however also the opportunity to guide the development of the MR site towards a targeted equilibrium situation by a well-considered design and location. When understanding the impacts of a MRM it will become easier to manipulate the ecological and hydromorphological processes in such a way that the MRM will evolve to the targeted equilibrium situation. In practice it is however difficult to predict the resulting equilibrium situation when implementing a certain measure and hence if this will be in accordance with the development targets.

Realistic goals: dynamic and with time trajectory

To limit the unpredictability of the success of MRMs it is recommended to formulate **dynamic goals with a time trajectory** that corresponds to the perceived and predicted changes in the project area and in the estuary, rather than a fixed target without temporal consideration. That implies that the goals do not only contain a qualitative description of the desired situation (eg. which habitat types and which species communities), but also a time frame to reach the target (eg. at year t, t+10 and t+20) [27]. Since the development of the

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restoration project does not end after the completion of the engineering phase, it is recommended to incorporate realistic predictions of the time frame of evolution in tidal wetland restoration planning [28]. Existing and on-going projects in similar conditions could be used as reference to estimate the evolution of habitat development and to determine feasible performance criteria for different habitats.

Formulating dynamic goals (eg. marshland with mudflats and creek development) has to follow from the understanding of both the ecological and the hydromorphological changes [27]. As sedimentation, erosion and the development of the vegetation are natural processes of the restored estuarine habitats, changes will occur (eg. mudflat will evolve to marsh). The character of the estuarine habitat will therefore inevitably change. The goals of restoration projects should hence be formulated with the ecological and the hydromorphological (desired and undesired) changes in mind because they are intrinsic aspects of the estuarine habitats. This means that it is advised to target certain habitat types and species communities, but not in quantitative terms (exact number of hectares of each habitat type or exact number of species).

Nevertheless, it is obvious that many natural processes within the big North Sea estuaries are considerably disturbed. Therefore one probably has to accept that the safeguarding of specific habitat functions (also at MR sites) will require here and there some maintenance.

Optimisation of measure success

Overall success

To optimise the success of the MRMs it is recommended to start in the planning phase with incorporating lessons learned from previous and on-going projects. Indeed, the general knowledge on how to develop realignment sites has already been greatly advanced through practical experiences in many case studies. **Knowledge sharing** could be improved by an iterative approach, i.e. follow and further develop best practices established in the past. The evaluation of previous and on-going projects will provide valuable information on the short- and long-term development of restoration projects. This could help to understand the impact of management interventions on overall developments and this can also indicate which other tools are required to guide restoration projects towards their goals [27]. A deeper going analysis of comparable successful measures realized under similar conditions could also minimize the risk of associated problems (eg. additional maintenance effort after measure implementation; reconstruction of overflow barriers; etc.). Exchange of experiences, also across estuaries, is hence necessary to improve the overall success of MRMs and this TIDE report aims to be a first step in that direction.

The success of MRMs also depends on the pre- and post-project **monitoring**.

- This is indeed necessary in order to check whether the targeted results finally have been achieved. And more important to identify unwanted changes or a lack of change in certain aspects for which interventions may be required to steer the development in the aimed direction [27].
- Adaptive management, both during and after implementation, forms an important part of the management strategy to improve the overall success of the restoration project.
- Previous and on-going projects could also help to identify which factors are important to monitor, as well as identifying which monitoring techniques should be used.
- Regarding the success of MRMs, it is recommended to consider (at least) tidal prism, breach design (and breach flow speeds), the role of site morphology in delivering particular habitats, and how future accretion may influence site development [29].
- The time-scale of the monitoring program has to follow the time-frame of project and hence of the development goals. Because long-term monitoring is in practice often difficult to establish within the project, it is recommended to incorporate the monitoring and possibly the evaluation in a regular long-term monitoring program [27].

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MRMs generate many ecosystem services and many synergies, but also conflicts between different stakeholders could occur. An effective, clear, honest and early **communication strategy** with the public, stakeholders and regulators is hence also a key aspect in the overall success of MRMs. It is indeed important to optimise the social support for the measure: by securing landowner involvement and allow sufficient time for landowner negotiations [29], by emphasizing the multiple socio-economic benefits of the measure, and if necessary by explaining that the design has changed as far as possible to minimise negative effects on public.

Success related to sedimentation issues

The success of MRMs depends, among many others, on the **induced sedimentation and erosion processes** [30] because these processes are key factors in realising most development goals, i.e. to ensure a site is at the right elevation and receives sufficient tidal inundation for habitat development and for flood storage capacity. However, the real sedimentation and erosion processes on the site are not always in favour of the development goals. When sedimentation rates are higher or lower than expected this could be a disadvantage for certain goals. Reduction of the sedimentation rate in the realignment site could be beneficial to meet for instance the goal flood water storage and additionally this could also reduce the need for maintenance efforts in the future which is then beneficial for vegetation, fauna and water structures.

The presented study (part 2) illustrates that by considering certain aspects of the **site selection and design**, the expected sedimentation and erosion processes could be manipulated to a certain extent in favour of specific development goals. A first recommendation is to evaluate existing and on-going projects to use one or several reference states from a comparable setting (in terms of geomorphology, tidal range and elevation) as basis to establish the design on a target state for the restoration site [27]. Furthermore, the conclusions from the presented study (part 2) could be used as guideline for optimal site selection and design. Depending on the development goals (habitat development and/or safety), the sedimentation and erosion processes could be guided in a favourable way by designing certain site aspects in a specific way. For many realignment sites the development goals are however a combination of the development of different habitat types. It is therefore recommended to adapt the design of different zones of the site in favour of the different goals. This means a large spatial variation in elevation, slope, etc.

An overall rule for designing realignment sites should be to **minimise land manipulation** and work with the existing topography as far as possible. It is hence recommended to maximise the advantage from natural physical and vegetative processes and natural sources from the site (e.g. materials for dike enforcement). Furthermore, the extent of any landform manipulation must be justified due to the consideration of project objectives, the potential gains and the likely cost [29].

Overall, it is important to keep always in mind that the estuary is a highly dynamic ecosystem and the most important rule for successful management is to **work with the system, not against it**!

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The Interreg IVB North Sea Region Programme

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Tidal River Development

List of abbreviations

CRT	Controlled Reduced Tide
ES	Ecosystem services
EU	Europe
FCA	Flood Control Area
m NN	Indication of the sea level in Germany
m OD	Indication of the sea level in the United Kingdom
m TAW	Indication of the sea level in Belgium
MHHW	Mean Higher High Water
MHWL	Mean High Water Level
Mio	Million
MLLW	Mean Lower Low Water
MLWL	Mean Low Water Level
MR	Managed Realignment
MRM	Managed Realignment Measure
MRMs	Managed Realignment Measures
MTL	Mean Tide Level
NGVD	National Geodetic Vertical Datum
RTE	Reduced Tidal Exchange
SPM	Suspended Particulate Matter (in mg/l)
TIDE	EU project Tidal River Development
UK	United Kingdom
WFD	Water Framework Directive

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1. Introduction

1.1. Aim of the report

The topic of this report is an inter-estuarine comparison of estuarine habitat restoration measures. These measures seem to be commonly implemented since nearly half of the estuarine measures studied in TIDE are related to estuarine habitat restoration. Two specific measures are analysed:

- Managed Realignment Measures (MRM) whereby restoration is operated by dike breaching or defence removal. Managed realignment (MR) - or 'dike-realignment', 'de-polderisation' – involves "setting back the line of actively maintained defences to a new line inland of the original and promoting the creation of intertidal habitat between the old and new defences" [20].
- Restricted Tidal Exchange (RTE) with a Controlled Reduced Tide (CRT) as a specific example.

The first part of this study consists of a general description of MRM. Some general aspects such as implementation techniques, measure targets, monitoring program and costs and benefits will be compared for the TIDE examples.

The second part will focus on the sedimentation rate on MR sites. High sedimentation rates, by which habitat types evolve to higher elevated types (eg. shallow water habitat to flat habitat or flat habitat to marsh), is often considered as a problem by managers because this obstructs the success of reaching the development targets. The link between site selection and site design aspects and the sedimentation rate is analysed to define recommendations to improve the success of MRMs regarding the sedimentation rate.

1.2. Introduction of the TIDE Managed Realignment Measures (MRM)

Almost half of all TIDE measures are Managed Realignment Measures (MRM), spread over the four TIDE estuaries: four examples in the Elbe, five in the Scheldt, seven in the Weser and three in the Humber (Table 1-1). For the Humber, only three of the selected MRM within TIDE are included in the main report, data for three other Humber measures are added in Appendix 2.

For the purpose of this study, the TIDE cases are presented shortly by comparing chosen basic aspects such as years implemented and size. In addition, a picture of each measure is added. For a more detailed description of these measures, see the overall measure report [1] and the individual measures reports [2-19].

Table 1-1. List of the 17 TIDE managed realignment measures with chosen basic information.

TIDE nr.	Estuary	Measure name	Code	Year of impl.	Size (ha)	Cat. [1]	Zonation [2] (in TIDE-km) F	O	M	P
1	Elbe	Spadenlander Busch/Kreetsand	E-Sp.B.	2012	47	BH	30			
7	Elbe	Realignment Wrauster Bogen	E-Wr.B.	1991	2,2	B	18			
8	Elbe	Compensation measure Hahnöfer Sand	E-Hahn.S.	2002	63	B	57			
9	Elbe	Spadenlander Spitze	E-Sp.Sp.	2002	8	B	32			
13	Scheldt	Lippenbroek FCA-CRT	S-Lip.	2006	10	BH	38			
15	Scheldt	Ketenisse wetland	S-Ket.	2003	30	B			92	
16	Scheldt	Paddebeek wetland	S-Pad.	2003	1,6	B	18			
17	Scheldt	Paardenschor wetland	S-Paard.	2004	12	B			100	
18	Scheldt	Heusden LO wetland	S-Heusd.	2006	10	B	0			
24	Weser	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.	1997	210	B		58		
25	Weser	Shallow water area Rönnebecker Sand	W-Ronn.S.	2002	34	B	32			
26	Weser	Tidal habitat Vorder- und Hinterwerder	W-VorHin	1997	27	B	12			
27	Weser	Shallow water zone Kleinensieler Plate	W-Kl.P.	2000	60	B		57		
28	Weser	Cappel-Süder-Neufeld	W-Cap.S.N.	2002	27	B				90
30	Humber	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.	2006	440	BH			60	
31	Humber	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS	2003	80	B				95
33	Humber	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.	2006	15	B			73	

1) **Category**: Biology/ecology (B), hydrology/morphology (H), combination of biology/ecology with hydrology/morphology (HB)

2) **Zonation**: freshwater zone (F), Oligohaline zone (O), mesohaline zone (M), and polyhaline zone (P) [21]

<u>Pictures</u> of the 17 TIDE Managed Realignment Measures planned or implemented at Elbe (E), Scheldt (S), Weser (W) and Humber (H):

E-Sp.-B.

E-Wr.B.

E-Hahn.S.

E-Sp.Sp.

S-Lip.

S-Ket.

S-Pad.

S-Paard.

S-Heusd.

W-Tegl.P.

W-Ronn.S.

W-VorHin

W-Kl.P.

W-Cap.S.N.

H-Alk.

H-PHS

H-Ch.N.

1) Zonation

Half of the TIDE MRMs are located in the freshwater zone (53%), followed by the mesohaline zone (23%), and only few TIDE examples are located in the oligohaline (12%) and polyhaline (12%) zones. The spatial distribution of the measures along the four estuaries is visualised in Figure 1-1. The TIDE MRM are however only a sample and hence not to be seen as a representation of all MRMs along the four estuaries.

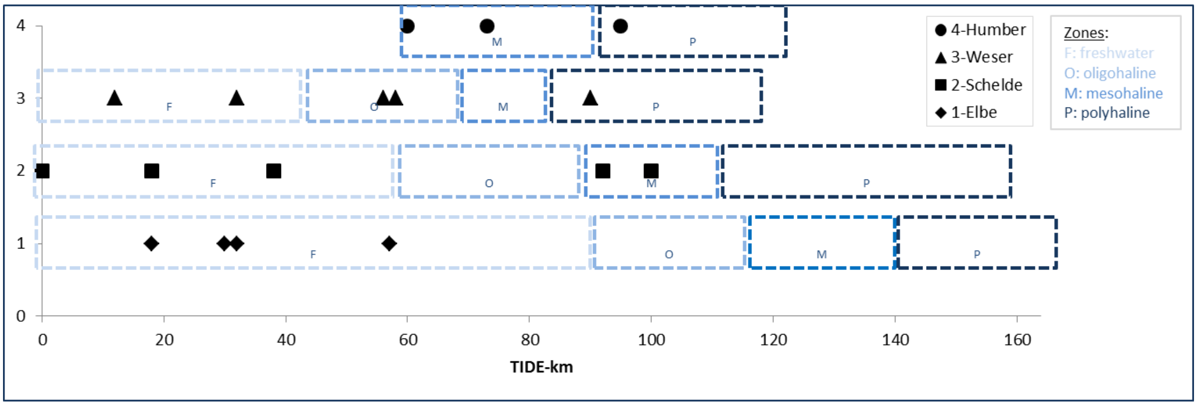

Figure 1-1. Distribution of the TIDE MRMs along the four estuaries (in TIDE-km, based on the salinity gradient [21]).

2) Age (Years implemented in 2012)

The TIDE MRMs are all implemented in the last 21 years (Figure 1-2). The oldest TIDE example was implemented in 1991 (**E-Wr.B.**) and the most recent TIDE example is planned for autumn 2012 (**E-Sp.B.**).

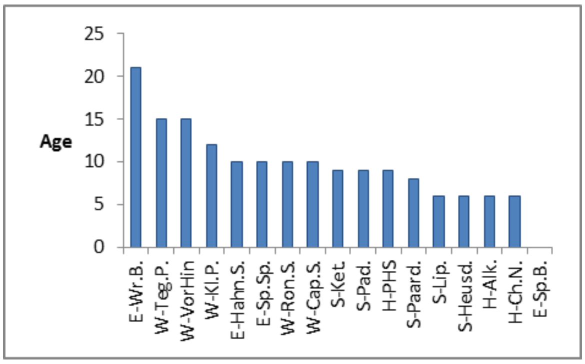

Figure 1-2. Number of years that each TIDE case is implemented in 2012.

3) Size (ha)

The average size of the TIDE MRM is 63 ha (Figure 1-3), ranging from 1.6 ha (**S-Pad.**) to 440 ha (**H-Alk.**) and only two cases are larger than 100 ha (**W-Tegl.P.** and **H-Alk.**). No temporal trend was observed in the size of the MRM.

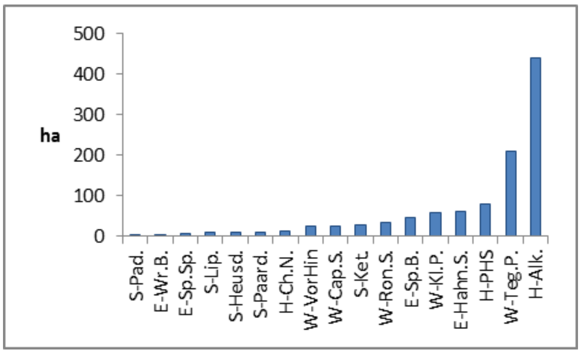

Figure 1-3. Restored surface

2. Part 1: General aspects of MRM

A general definition of a managed realignment measure is made in this part of the study by comparing different topics of the 17 TIDE MRM examples. The topics that are described here are: (1) measure targets, (2) implementation techniques, (3) habitat creation, (4) monitoring program, (5) synergies and conflicts, (6) impact on ecosystem services and (7) costs and benefits.

2.1. Measure targets and degree of target achievement

Main question: Why are MRMs executed? And, are MRMs successful in achieving these targets?

During history, many dikes were breached accidently by the tide. In some cases it was decided not to repair the dike but let the tide enter the adjacent land. This is called an **accidental realignment**. This happened when the benefits of the lost land were valued less than the costs to repair the dike. The land under tidal influence develops to wetlands and could also supply additional benefits. During last decades, accidental realignments are rare because adjacent lands have a high value and dikes are therefore mostly repaired.

Also managed realignment (MR) is a frequently used measure in estuarine management. The oldest form of managed realignment is probably as part of the **military strategy**. A realignment area was used as a permanent buffer against the enemy.

More recent MR measures have other targets: safety, nature compensation or nature restoration [31-33].

- **Safety**: MR measures proved to be useful as cost effective coastal defence and for flood protection. The safety aspect of MRMs consists of different aspects:
    - Marshes form a natural protection for adjacent land and dikes. Marshes act as a barrier against waves and erosion. This barrier could also be climate change proof if the marshes grow equally with increasing sea water levels [30, 34].
    - The MR area offers flood water storage capacity by allowing water to reclaim the land at high tide and in times of flooding (new tidal volume).
    - The MR area also reduces the energy of the incoming tidal wave because the water is spread over a larger area (energy dissipation).
- **Habitat compensation**: MRMs are often used to compensate for protected habitats that were lost elsewhere (hence no extra habitat is created). Wetlands have an important ecological value and are often protected by international, European and local legislation (Water Framework Directive, Habitat and Bird Directive, Ramsar, Natura 2000, red list for species).
- **Habitat conservation/restoration/ creation**: MRMs improve the natural scenery by upgrading the ecological characteristic landscape of the estuary region. This means the development and re-establishing of functioning intertidal and ecological valuable habitat, as resting, feeding and breeding area for aquatic flora and fauna. This involves the improvement of specific estuarine gradients (from aquatic to terrestrial) and functions such as the chemical condition (oxygen, nutrients, self-purifying power) and morphological condition (sedimentation-erosion processes and creek formation). Important biotopes for aquatic flora and fauna to develop and restore are shallow water areas, marsh habitat (eg. saltmarsh), intertidal mudflat structures, natural floodplain habitats (floodplain forest), tidal reeds, creek systems, sandy shores, bushes, and wide grasslands.
- Most MR measures are executed for a combination of targets and combined with secondary targets such as **recreation and tourism**.

The number of targets per MRM varies between 1 and 4. All TIDE examples have habitat conservation as one of the main development target (Figure 2-1). Half of the TIDE examples are driven by a compensation reason, mostly linked with port development. Three of the more recent examples have the aim to combine habitat conservation with safety (extra tidal volume). Three examples are implemented as pilot project and therefore have a research aim. Only two of the most recent examples explicitly mentioned the improvement of access opportunities and recreation as a target.

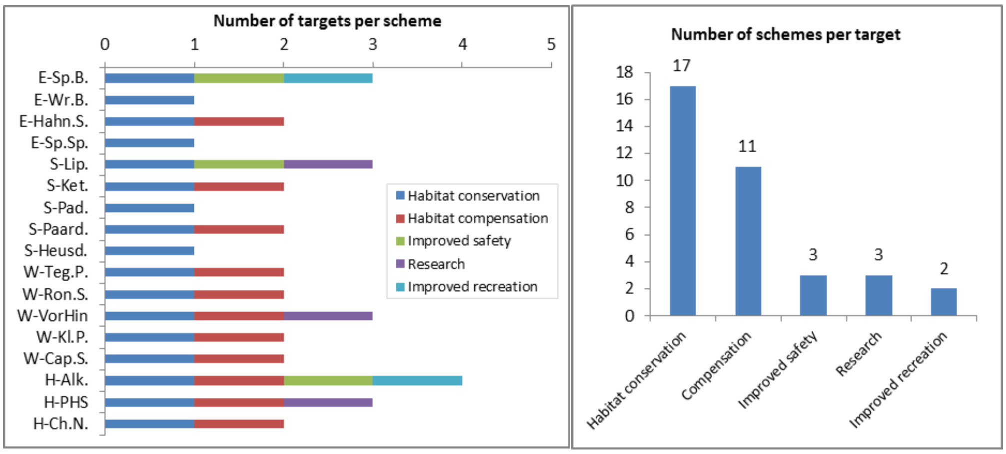

Figure 2-1. Overview of the measure targets per TIDE MRM (LEFT) and number of schemes with each target (RIGHT)

The measure targets could be linked with the TIDE measure categories. All TIDE MRMs belong to the "biology/ecology" category, and a few explicitly combine the category "biology/ecology" with "hydrology/morphology" (see also §4.1 in [1]). This corresponds with the fact that all cases have habitat conservation as a main target, and only a few examples aim to combine this with a safety target.

In the following part, the different measure targets will be explained in more details for the TIDE cases as well as the degree of target achievement for all the measures (Table 2-1).

Table 2-1. Overview measure targets and degree of target achievement per measure. Degree of target achievement: low (0), medium (+), high (+++).

TIDE nr.	Measure	Number of years implemented	Habitat conservation, creation, restoration				Safety	Research	Recreation
			1. Processes	2. Habitat	3. Specie	4. Compensation			
1	E-Sp.B.	0	+++	+++	+++		+++		+++
7	E-Wr.B.	21		+	+				
8	E-Hahn.S.	10		+	+	0			
9	E-Sp.Sp.	10	+	+	+				
13	S-Lip.	6		+++			+++	+++	
15	S-Ket.	9	+			+			
16	S-Pad.	9	+	+					
17	S-Paard.	8	+	+		+			
18	S-Heusd.	6	+	+					
24	W-Tegl.P.	15	+++	+++		+++			
25	W-Ronn.S.	10	+++	+++		+++			
26	W-VorHin	15	+++	+++		+++		+	
27	W-Kl.P.	12	+			+			
28	W-Cap.S.N.	10			+++	+++			
31	H-Alk.	6		+		+	+++		+++
32	H-PHS	9		+	+	+		+++	
34	H-Ch.N.	6	+++	+++	+++	+++			

1) Habitat conservation/restoration/creation

All TIDE examples aim to conserve, restore or create estuarine habitat. The concretisation of this target is diverse and four main types could be distinguished (Table 2-1):

1. Target to improve estuarine processes such as sedimentation processes, creek formation, and soil development.
2. Target to create a specific habitat (freshwater or brackish) such as valuable habitats like mudflats, marsh habitat, shallow water habitat, reed, meadows and floodplain forest.
3. Target to support specific species by creating habitat for certain fauna and flora, e.g. the 'Elbe Water Dropwort' (*Oenanthe conioides*) (**E-Sp.B.**, **E-Hahn.S.**, **E-Sp.Sp.**) and the 'Northern Shoveler' (*Anas clypeata*) (**E-Hahn.S.**).

4. Compensation targets: Many of the TIDE MRMs are driven by compensation targets (Table 2-1), mainly related to lost habitats due to port development. All TIDE MRMs from the Weser are compensation measures, i.e. habitat compensation is the driver for measure implementation. But also in the other estuaries, different MRMs are driven by compensation targets e.g. to compensate for port facilities and industry development (**E-Hahn.S.**, **S-Ket.**, **S-Paard.**, **H-Ch.N.**).

Degree of target achievement?

Almost half of the measures are considered to have a high degree of target achievement regarding habitat conservation, the other part of the measures are considered to have a medium degree of target achievement meaning that not all targets are completely reached (Table 2-1). Only one measure (**E-Hahn.S.**) was not able to realise all compensation targets.

Successful measures with a high degree of target achievement:

Measure	Description degree of target achievement
E-Sp.B.	The measure is not implemented and monitored yet. Though the achievement of the different development targets are considered to be as high as estimated as described in the planning approval documents.
S-Lip.	Lippenbroek started functioning as freshwater intertidal habitat since the introduction in March 2006 and hence was successful. Tidal marsh restoration with a FCA-CRT construction can happen very fast and spontaneously. The inundation curve is different than in natural intertidal areas (duration is longer, and has three phases: ebb, stagnant and flood) but this does not obstruct the colonization by fauna and flora.
W-Tegl.P.	The available monitoring results show that the development targets defined for the compensation measure are fully reachable until the end of the 15 year runtime of the monitoring program. In summary, the measures realized on the Tegeler Plate represent a sustainable habitat development which contributes to restore the lower part of the river Weser which is strongly affected by human activities. W-Tegl.P. also showed that it is principally possible to create self-preserving tidal creek systems within highly dynamical estuaries.
W-Ronn.S.	The available monitoring results show that the development targets defined for the compensation measure are fully reachable until the end of the 10 year runtime of the monitoring program.
W-VorHin	The compensation measure 'Tidal habitat Vorder- und Hinterwerder' is a flagship measure, because several experienced partners worked together during the planning and implementation stages, the social status of nature conservation was very strong at that time and there were no conflicting plans to be considered. The development target according to the grassland areas was reached satisfactorily. The area left to natural succession developed faster than expected. Also the aims for fish were reached one year after measure implementation already. However, the tidal waters at Vorder- and Hinterwerder were flooded longer than projected by the hydraulic models used. The hydraulic calculations undertaken during the planning stages should be analysed in order to improve the predictability of tidal influence on potential project areas at estuaries. This is crucial in order to estimate e.g. the degree of siltation and thus the maintenance effort to expect.
W-Cap.S.N.	Salt marsh vegetation developed as expected along the ditches and within the diked-out area. As a result of the measure implementation, the breeding bird population on the project area is labelled as important for the federal state of Lower Saxony.
H-Ch.N.	So far the site appears to be developing as expected as predicted in the EIA. Although not taken into account when determining the height of the new defence due to uncertainties involved in judging its long term sustainability, a strip of saltmarsh is expected to develop in front of the new (landward) sea defences. The monitoring has identified that species diversity has continued to rise at Chowder Ness over the five year monitoring period. Breeding birds have been specifically monitored at Chowder Ness. The number of species of breeding bird observed at these sites has been consistent across the five year monitoring period, with a five year average of seven species (range 6 to 8). Total numbers observed have also remained consistent. However, Chowder Ness managed realignment site was considered to be relatively small scale in relation to the estuary as whole (total area of 15ha, representing only 0.02% of the estuary's intertidal area and 0.01% of its spring tidal prism). As large lengths of sea wall were removed, the effects on estuarine tidal velocities, sedimentation and accretion, and water levels, were anticipated to be extremely localised and of a relatively small magnitude (ABPmer, 2004).

Moderately successful measures with a medium degree of target achievement:

Measure	Description degree of target achievement
E-Wr.B.	The new habitat developed in a favourable way, but adjustment of the site was needed. After the adjustment of the tidal creek the flow velocities in the river channel decreased and mudflats could evolve

	and thus provide food for the resting fish species.
E-Hahn.S.	The compensation target was quickly achieved. Two years after the western part was opened to the tide, broad freshwater mudflats had evolved and the area consists of 97% mudflats and 3% shallow water. The stocking of the *Oenanthe conioides* had increased significantly and the area seemed also a good feeding ground for resting bird species and species protected by the BHD. However, the measure was considered as being not sufficient as compensation because the RAMSAR target of 400 individuals of *Anas clypeata* were not achieved. The compensation obligations of the coherence targets of NATURA 2000 for the species *Anas clypeata* was finally achieved by the designation of an old unused harbour area were wide mudflats had evolved and the resting population of *Anas clypeata* reached the demanded amounts of about 400 individuals.
E-Sp.Sp.	In general, the measure was considered as a success, most biotopes developed well. The realignment had a positive effect on the conservation aims and stimulated the development of scarce and endangered species. Species diversity became enormous, and settlement of typical species took place on its own, eg. spores come with the tide very quickly. The area was also colonized by the endemic species Oenanthe conioides. However, one year after implementation, the little pond that should function as resting and spawning area for several fish species showed high sedimentation rates. Therefore the development target of establishing a permanently water filled realignment area could only be partly achieved.
S-Ket.	Monitoring results of the first year suggest that Ketenisse polder has the potential to develop towards a varied and normal functional intertidal area [35]. Succession stages of tidal marsh vegetation were observed and most apparent on the sections with a weak slope. However, based on wider monitoring results we conclude that the degree of target achievement is rather medium as a consequence of design problems. The old dike was not removed according to plan and as a result almost flat plateaus, with a steep slope towards the river were constructed instead of a gentle overall slope from the dike to the river. This had consequences for the habitat functions of the site. The steeper parts of the site showed net erosion and seemed less functional as habitat.
S-Pad.	In general, the restoration of the Paddebeek was a success to create a tidal wetland in the freshwater zone of the Sea Scheldt (Zeeschelde). By the inland shifting of the dike a small tidal area could develop in an area of the river Scheldt where mudflats and marshes are scarce. This is valuable for the connectivity of the tidal wetlands in this part of the Sea Scheldt (Zeeschelde). The constructed terraces were rapidly colonized by estuarine vegetation species. Because of the construction of terraces with life willow wicker, willow shrubs established very quickly, which accelerated vegetation succession and additionally stone rubble was not necessary to protect the new dike. Unfortunately the greater part of the old dike remained in place, hindering proper drainage, creek formation and colonisation. Additionally, the site has limited habitat functions for birds.
S-Paard.	Immediately after restoration (2004), the Paardenschor existed of 12ha bare mudflat. Under influence of the tidal floods twice a day with brackish water from the Scheldt, the Paardenschor rapidly transformed to a tidal wetland with a Good Ecological Potential [24], with clear creek formation in the mudflats and typical marsh vegetation at the higher areas (such as Common Glasswort (*Salicornia europaea*), Sea Aster (*Aster tripolium*) and Common Cordgrass (*Spartina anglica*)). The sediment is colonised by benthic invertebrates, predated on by water birds and fish. This type of low dynamic mudflats, relatively high in the tidal frame adds valuable foraging time and space for water birds. The initial tidal elevation and site slope were well chosen [36]. Overall there is net sedimentation, with local erosion in the developing creek network system. Creek network systems seem to establish without the specific excavation of a creek onset. However, its design could have been adapted to enhance its habitat functions for fish. Creek onset might have enhanced the habitat differentiation within the site and its suitability as fish habitat. The old dike could have been excavated more, but this might have led to erosion on the transition to the adjacent marsh (Schor Ouden Doel).
S-Heusd.	Overall, the restoration of the Heusden LO wetland succeeded in the aim to create an ecological valuable intertidal freshwater wetland. As a result of this design a site with a great variety of habitat types was created, with permanent pools, mudflats and all stages of typical tidal marsh vegetation. The vegetation gradient from low marsh to supratidal was uninterrupted because of the absence of fortifications. However, Initially the site only inundated at spring tides and it was not drained at low tide. Later two breaches to MLW were added where the old sluices used to be, connecting to ditches. It then had every aspect of a breached site with a strongly accentuated spring tide/neap tide differentiation in the inundation regime. Nevertheless, some areas remained inundated at low tide and the southern part where the sand stock for the dike construction works was not completely removed remained supratidal. Unfortunately the area was recently colonised by Floating marsh pennywort (*Hydrocotyle ranunculoides*), an invasive species. Chances are that this species will soon invade the complete tidal area.
W-Kl.P.	Although the tidal influence on the project area is restricted by three overflow barriers, the project area is regularly influenced by the tides and the appearance of several specific vegetation and fauna features

	of the brackish water zone of the Weser was confirmed by the monitoring results. However, the shallow water zone on the Kleinensieler Plate was strongly affected by siltation. Due to heightening the three overflow barriers, the amount of suspended matter entering the project was reduced significantly and siltation tendencies were slowed down. This means that –to the benefit of vegetation, fauna and water structures- less maintenance effort can be expected in the future.
H-Alk.	The site does appear to be acting as a nursery area for fish and is a significant feeding and roosting area for birds. In this respect, the development of the site appears to have been beneficial to this region of the estuary which is otherwise largely characterised by narrow mudflats with species poor communities and, in most areas, little vegetation. The Alkborough site has the dual aim of flood defence and compensation for habitat loss due to coastal squeeze (replacement of mudflat habitat). Given the site design, the elevation and the restricted flooding, it is however unlikely that this will be achieved in the long term and there is already evidence that the site will become vegetated and ceases to be fully inundated by high tides. This will mean that the site will not provide the 'like for like' habitat compensation. The rate of accretions was far greater than expected, also the development and usage of the site by birds highlighted a lack of understanding of how different species utilised the estuary as a whole.
H-PHS	After the first five year phase of monitoring data was reviewed and some results indicated that the site had not yet met some of the targets defined in the planning application. The site has achieved targets for habitat creation with typical saltmarsh species present, and usage by water birds as specified to compensate for lost habitats. The possible long-term development of the new mudflat into saltmarsh is likely to reduce the available habitat for benthic invertebrates and foraging birds, although additional saltmarsh may provide high tide refuges for birds, as well as roosting and nesting sites. Compensation for lost borrow pit and soke dyke habitats by translocation appears to have been successful with water vole, vegetation and freshwater invertebrate communities establishing. Accretion and saltmarsh development is however greater than originally expected and it is suggested that the site will become dominated by saltmarsh within a few years. The percentage cover of saltmarsh has increased dramatically and many areas are no longer fully inundated by high tides. In the long term, it may not continue to provide 'like for like' direct compensatory habitat. Discussions are on-going with Natural England to determine what level, if any, of management is required to ensure the site continues to meet its targets and possibly include the habitat within the designated site. Despite clear progress towards developing a benthic invertebrate community, this aspect, as expected, is lagging in terms of meeting targets, and the density of birds using the site is much lower than was the case on the sites lost for which they are compensating.

2) Safety

The second target for MR measures is safety. Three TIDE MRMs have a development target related to safety (Table 2-1):

- At **E-Sp.B.** the target was to reduce tidal energy (hydraulic effect) and thus, reduce the so called 'Tidal pumping effect'. Additionally, the expected benefit of the measures is the generation of approximately 1.1 Mio m³ of additional tidal volume. Although the measure is not implemented and monitored yet, it is already expected that dredging will be necessary every 4 or 5 years to keep the function.
- At **S-Lip.** the target was to create a Flood Control Area (FCA), and additionally to combine it with nature creation. Although it is only a small scale pilot project, it proved to be successful to combine nature creation in a flood control area by using a Controlled Reduced Tide with a high inlet and low outlet sluice.
- At **H-Alk.** the target was to reduce the impact of sea level rise and to allow wildlife to adapt to sea level rise. It is calculated that with the implementation of the Alkborough flats, the water level of the Humber could be reduced at extreme water levels by more than 150 mm (for a flood event with a 0.5 per cent chance of happening in any year, or 1 flood event in 200 years). However, it is anticipated that the site will become well vegetated and cease to be fully inundated by high tides. This means on the long term, that the flood water storage capacity will decrease. But on the other side, it is positive for marsh development and the elevation is important to reduce the impact of sea level rise.

3) Research

Three of the TIDE MRM examples are explicitly executed as a pilot project and hence for research purposes (Table 2-1):

- **S-Lip.** was executed in 2006 to study if sustainable ecological structures and functions could develop in a Flood Control Area with Controlled Reduced Tide (FCA-CRT), which are qualitatively and quantitatively similar to outer dike intertidal habitat. The results would deliver valuable input for all other planned FCA-CRT such as Kruibeke-Bazel-Rupelmonde. Based on the Lippenbroek pilot project, a lot of scientific insight was generated with respect to FCA-CRT and with intertidal mudflat and marsh in general. The pilot test proved that also an embanked area that is not suitable for basic managed realignment (because it is situated too low in reference to the water levels in the estuary) can be restored by a FCA with CRT. Therefore this technique increases the number of suitable sites and avoids problems with suboptimal tidal regimes and the need for artificial site elevation.

- **W-VorHin** is a pilot project for several similar compensation measures implemented after 1997 (e.g. TIDE measures **W-Kl.P.** and **W-Ronn.S.**). The measure site developed well and it is considered as a flagship measure. The tidal waters at the site were however flooded longer than projected by the hydraulic models used. The hydraulic calculations undertaken during the planning stages should be analysed in order to improve the predictability of tidal influence on potential project areas at estuaries. This is crucial in order to estimate e.g. the degree of siltation and thus the maintenance effort to expect.
- **H-PHS** was the first managed realignment site on the Humber estuary and therefore limited information was available to fully predict how the site would develop. The site development was not successful at all aspects: The rate of accretions was far greater than expected, also the development and usage of the site by birds highlighted a lack of understanding of how different species utilised the estuary as a whole. To improve the knowledge about MRMs, one of the overall targets was to monitor progress over a 10 year period. The monitoring programme implemented has proven to be a sound basis for observing the development of the site and assessing the progress towards achieving targets. The data sets generated during this study have been a powerful resource in developing understanding of processes and considerations in managed realignment habitat creation and contribute to current best practice. The data produced enables monitoring to assess if the habitat is developing into 'functional intertidal habitat' as required under the Habitats Regulation (planning condition). The output aids design, aims and techniques deployed in future schemes. The outcome of saltmarsh and mudflat development at Paull Holme Strays and the resulting composition of the invertebrate and bird communities will provide an important basis for the design and monitoring of further realignment schemes along the Humber Estuary.

4) Recreation

Only two of the TIDE cases explicitly mention recreation in the targets (Table 2-1):

- At **E-Sp.B.** a ‘tidal park’ was planned to introduce the tidal influenced landscape to a wide-ranging public.
- At **H-Alk.** one of the targets was to provide a focus for education and access opportunities for local communities.

2.2. Implementation techniques

2.2.1.How are managed realignments executed?

Managed realignment is the introduction of a tidal regime in formerly un-flooded areas. In general three techniques to re-align an area are known:

1. **Dike breach and defence removal**: A dike breach consists of one or more breaches in the dike, which could be accidental or forced. A defence removal is understood as an extreme situation of a dike breach: the complete (or partial) removal of the old dike.
2. **Land excavation**: If an embanked area is too highly elevated, breaching the old dike would not introduce floods in the area. Therefore the area could be excavated to bring it under estuarine influence. Floods are important for the development of a wetland ecosystem with flat habitats and marshes. This is mostly used for areas that were artificially elevated in history and hence lost the connection with the estuary. Secondly, land excavation is also used for “marsh rejuvenation”. In large natural wetlands, a process of altering sedimentation and erosion is responsible for transformations from mudflat to marsh and further to higher areas with a very low flood rate. Cliff formation and erosion can set back this development so that the cycle of marsh formation can start over. In smaller areas the space for this natural dynamism is missing and many natural processes are restricted: marsh edges are often artificially protected against erosion. Land excavation is then a solution to change marshes into mudflats or at least lower the marshes to increase the flood rate.
3. **RTE**: **Regulated Tidal Exchange** is organized by different techniques such as sluices, shaft, pipes and valves which are capable to control the tide in the area. By controlling the tide, realignment measures can also be executed on very low elevated areas (which would be much more flooded under the natural estuarine regime).

Deciding on the most appropriate realignment technique depends on the objectives of the measures and specific environmental characteristics of the measure site, but also the financial resources and the political context. The objective of the measure determines what habitat types have to be developed. Some examples: to create a feeding area for waders, mudflats are needed, but to protect an adjacent seawall, marsh development is needed.

2.2.2.Inter-estuarine comparison of TIDE examples

Of the TIDE examples, about half is implemented by a dike breach and the other half by defence removal (Figure 2-2). And, also in half of the examples this was combined with land lowering. Only one example is implemented by a Reduced Tidal Exchange (RTE): **S-Lip.**.

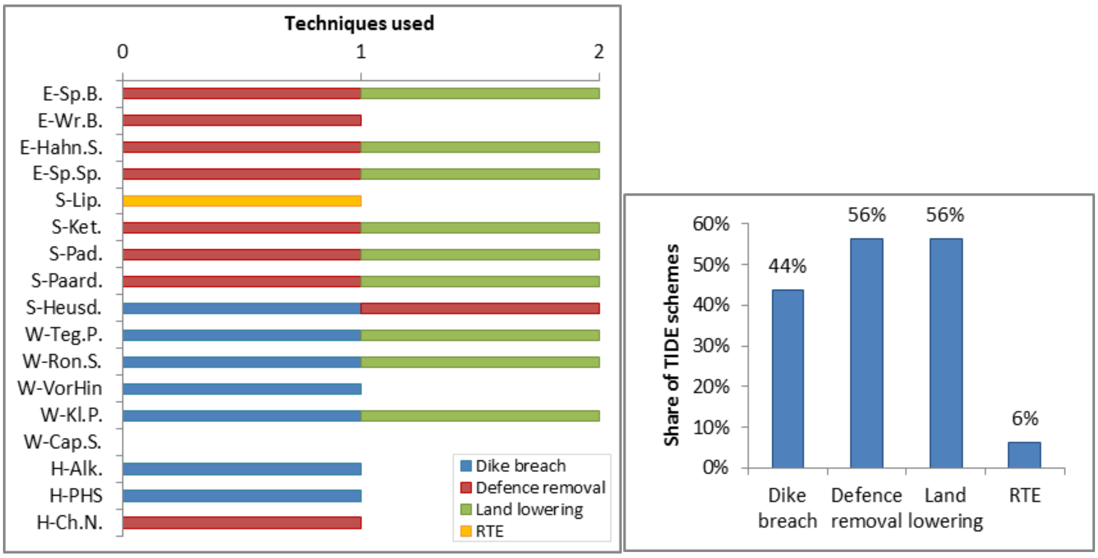

Figure 2-2. Left panel: Overview implementation techniques used for the different TIDE examples. Right panel: share of TIDE examples implemented with the different techniques.

Since the technique of defence removal only differs from a dike breach in the size of the breach, the breach size of the TIDE examples was compared and also related to the implementation technique. For all the examples, breach size ranges from 3m to 2650m (Figure 2-3) and the average breach size for measures implemented with a dike breach is 59 m and with a defence removal 1093 m. So indeed, the implementation technique defence removal corresponds with a substantially wider breach ($F(1,11)=9{,}04$; $p=0.012$).

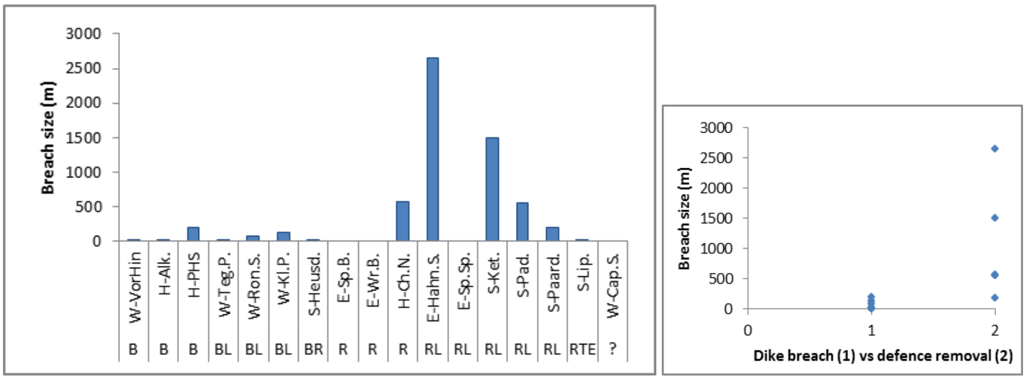

Figure 2-3. Link between implementation technique and the breach size (m): overview per measure (Left panel), distribution of breach size for measures with dike breach versus defence removal (Right panel). Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), RTE.

1) Overview measures with a dike breach

Measure	Description of the dike breach
S-Heusd	The old dike was lowered to mean high water level and two breaches to mean low water level were excavated where the old drainage sluices used to be.
W-Tegl.P.	Summer dikes were opened by several breaches and buildings, streets and supply lines were deconstructed to initiate the development of mudflat structures, creek systems, shallow water zones and tidal reeds.
W-Ronn.S.	A dike breach, with an overflow barrier (a sill) of 80m wide and levelled 0.5m under MLWL, guarantees a permanent minimum water level of 2m within the shallow water zone.
W-VorHin	The summer dike was partly deconstructed and an in- and outlet structure was installed in order to increase the tidal influence on the project area. The summer dike was enforced, i.e. breached dike will not be allowed to erode so as to not affect navigation.
W-Kl.P.	Three sill breaches were installed: two breaches connected directly with the estuary and one breach

	connected with a side arm.
H-Alk.	A dike breach of 20m wide was made and enforced with a boulder sill. Also, the defence was lowered over 1.5 km.
H-PHS	Two breaches in the old sea wall (protecting the former agricultural land from inundation) were made in order to maximise incursion and drainage whilst avoiding high velocities of a single breach: one breach at the eastern side (50m wide) and one at the western side (150m wide) of the site, approximately 1.5km apart from each other. No sill protection was placed on the breaches.

2) Overview measures with defence removal

Measure	Description defence removal
E-Sp.B.	This measure is still under construction: the dike is already removed, but the land lowering is not finished yet.
E-Wr.B.	The position of the dyke was changed in order to create a tidal creek of approx. 400m length (flow through system) in combination with an island of 300×40 m². This resulted in an outer dike area with an open creek system (open at both sides).
E-Hahn.S.	The implementation included a defence removal over 2,650m (West bay: 63ha and 1.300m opening; East bay: 39ha and 1.050m opening).
E-Sp.Sp.	The dike was replaced landwards (higher elevation) and a vegetated band exist between the project area and the river. The site is located immediately at the river with one opening from the river to the tidal creek in the project area (combined in- and out-let). The water enters/leaves via a tidal creek and flows to a shallow water area in the centre of the project area. A sill was placed at the opening of the creek in order to permanently ensure a certain water level and to prevent erosion within the area.
S-Ket.	The summer dike (central zone D-E) was partly excavated and the rubble of the summer dike and the dumped material was removed. The winter dike (from the north to the south) was elevated and broadened (to Sigma height and -width) to separate the wetland from the hinterland.
S-Pad.	The dike was shifted landwards (new dike at Sigma height) and the old dike was excavated. Where the old dike was removed, the substrate was reinforced with gabions (schanskorven) and a small stone rubble dike. Only at the ends, the dike was reinforced with stone rubble. Unfortunately the greater part of the old dike remained in place, hindering proper drainage, creek formation and colonisation. To allow some drainage several stones should be removed.
S-Paard.	The new dike was constructed next to the old dike and afterwards the old dike was excavated.
S-Heusd.	The old dike was lowered to mean high water level and two breaches to mean low water level were excavated where the old drainage sluices used to be. The dike needed to be elevated and broadened to Sigma requirement. Because there is no shipping in this area and because dynamics are low, the new dike was not reinforced with stone rubble.
H-Ch.N.	The existing seawall (defence) was removed over a length of 570m and some 200m remain. The removal was executed in a series of stages: (1) removing the rear of the embankment, (2) the concrete wave return, the bitumen and rock face, and (3) the overall lowering of the embankment. This removal, rather than the creation of solitary breaches, was chosen for a number of reasons: • It improves connectivity with the wider estuary; • It more closely recreates the type of environments that existed prior to the land claim; • It enables the whole cross sectional area of the estuary including the realignment site, to respond to estuary wide changes; and • It increases energy levels within the site, thereby improving the likelihood that mudflat habitat will be maintained (as mudflat creation was the main objective of the site). At the 15ha Chowder Ness site, new flood defences were created at the rear of the site to a minimum height of 6.7m above Ordnance Datum Newlyn (ODN).

3) Overview measures with land lowering

Measure	Description of land lowering
E-Sp.B.	This measure is still under construction: the dike is already removed, but the land lowering is not finished yet.
E-Hahn.S.	The land lowering consisted of the excavation of a 5m soil layer: 1.5 Mio. m³ sand used for land claim for Airbus extension.
E-Sp.Sp.	Some land lowering was executed to restructure the new area to create areas of permanent water

	(lagoons). In addition, some of the excavated material was used to create high areas above mean high water level (sill).
S-Ket.	The plan was to level the area with a weak slope to slightly under MHWL. Overall, initial elevation was slightly higher than planned, i.e. less material was removed. The original design to create a gentle slope had to be altered ultimately resulting in large variation in height and slope leaving supratidal vegetated parts (a plateau), lower bare mud and a rather steep slope along the summer dike remnants.
S-Pad.	With the land lowering, a global gradient of the Paddebeek wetland of 3.7% was created.
S-Paard.	The area itself was lowered and a faint slope was created between 5m TAW and the level of the mudflat already in front of it, to create a good situation for marsh formation.
W-Tegl.P.	A considerable excavation was necessary in order to meet the requirements for regularly flooded tidal habitats and tidally influenced standing water bodies. Additionally, a connection to the river was realized by creating a new creek system in the north and expanding an existing creek system in the south of the project area. Small tidally influenced standing water bodies were created (5 lagoons).
W-Ronn.S.	The land lowering consisted of the excavation of dumped dredge spoil (370.000 m³).
W-Kl.P.	The land lowering consisted of the excavation of dumped dredge spoil, grading to create lagoon and intertidal habitats. By forming the banks of the shallow water area, the site specific conditions for the settlement of different structured reeds were created. In order to promote the development of perennial and ruderal meadows and woods, small scale site specific differences were initiated by irregular surface design. The lagoon was created in 2000 but needed dredging in 2004 due to higher than expected sedimentation.

4) Other specific design aspects

In the next part, special design aspects of TIDE examples are described.

4.1) Link between design and habitat creation

i) Initial elevation (relative to tidal range)

From the Spadenländer Spitze case in the Elbe estuary (**E-Sp.Sp.**) it was concluded that for a good design the creation of different elevation levels with respect to the tide is important in order to create an area with the most possible tidal dynamics. Flat areas with little depressions below mean high water are very important for the establishment of creeks, serving as a habitat for *Oenanthe conioides*, waders and - after extension - also for juvenile fish.

Also in other cases the importance of the initial site elevation and the topography of the site were discussed.

- At the Heusden marsh (**S-Heusd.**) for instance the topography of the restored site was not altered and consequently the site was initially only inundated at spring tides and couldn't properly be drained at low tide. Adaptations to the site design were needed to differentiate the inundation regimes and hence improve the variety of habitat types.
- At Paul Holme Strays (**H-PHS**), resulting elevation has been demonstrated to be critical to rates and locations of vegetation development. The development of the site which has profound implications for rates and types of habitat creation was mainly affected by the sediment load in the Humber estuary and the limited exposure of the site. Both factors closely correspond to the site elevation and the corresponding inundation.

Site development and accretion also slow down at saltmarsh elevations, limited to only a few cm at most over 5 years (conclusion from the Chowder Ness case (**H-Ch.N.**)).

ii) Slope

From the Ketenisse case (**S-Ket.**) a clear correlation between the slope of the area and sedimentation/erosion was concluded (sedimentation at weak slopes until 2.5% and erosion at steeper slopes from 2.5%). The Ketenisse area was levelled in 2002 with a weak slope below mean high water level, creating the optimal starting conditions for the development of intertidal mudflats and marshes. However, at the extreme ends of the site the slopes are too steep and net erosion took place. As a consequence, those parts seemed less functional as habitat. The difference in slope corresponds to the two intertidal habitat types: flat habitat (slope < 2.5%), and steep habitat (slope > 2.5%).

iii) Dynamics on the site

Habitat development is also linked with the dynamics in the area:

- The low dynamic mudflats of the Paardenschor (**S-Paard.**), located relatively high in the tidal frame, are colonised by benthic invertebrates and add valuable foraging time and space for water birds. However, its design was less suitable as a habitat for fish.
- In the case of Paul Holme Strays (**H-PHS**), sustainability of mudflat habitats appears to be limited by the lack of exposure at this site. The sustainability of mudflat habitats corresponds with the accretion rate. The lowest accretion rates are thought to be characterised by a wide connection to the estuary (essentially a very wide breach); exposure to significant fetch from the predominant wind direction; and relatively high flows due to its proximity to the main Humber navigation channel and the Humber Bridge (the latter constriction causing higher flows). However, exposure at this site is a trade-off with erosion and losses of natural saltmarsh along the frontage of the remaining sea defence and cost implications.

iv) Drainage and creek network

Drainage system and creek network development also got special attention in the frame of site design:

- At Paardenschor (**S-Paard.**), creek network systems seem to establish without the specific excavation of a creek onset. However, creek onset might have enhanced the habitat differentiation within the site and its suitability as fish habitat.
- In the case of Spadenländer Spitze (**E-Sp.Sp.**), the special design of tidal creeks has turned out as superfluous; the tidal dynamics were too dominant. It turned out to be more important to have prevented the area of human disturbance.
- In the Paul Holme Strays case (**H-PHS**), hydrodynamic changes with the development of drainage systems have also been demonstrated to be critical for vegetation and benthic invertebrate community development and impact strongly on bird usage.
- The compensation measure Tegeler Plate (**W-Tegl.P.**) showed that it is principally possible to create self-preserving tidal creek systems within highly dynamical estuaries. One crucial point for the successful development of tidally influenced habitats on the Tegeler Plate was the creation of suitable site specific conditions by means of hydraulic engineering works. However, the conditions for achieving self-preserving creek systems should be analysed in detail. The results from the Tegeler Plate are at least supposed to be helpful in view of future measure planning and implementation processes.

v) Other aspects

- The deeper areas of the shallow water zone in the Vorder- und Hinterwerder (**W-VorHin**) are designed to improve the situation for fish and to serve as sediment traps to slow down the expected siltation.

<u>4.2) Unique design</u>

i) Flood Control Area with Controlled Reduced Tide (FCA-CRT construction)

The Lippenbroek case in the Scheldt estuary (**S-Lip.**) proved that tidal marsh restoration with a FCA-CRT construction can happen very fast and spontaneously. Some lessons learned:

- The inundation curve is different than in natural intertidal areas (duration is longer, and has three phases: ebb, stagnant and flood) but this does not obstruct the colonisation by fauna and flora.
- The inlet sluice has to be situated sufficiently high to allow sufficient differences in inflow duration and volume and thus to create a large variation in inundation frequencies and water levels in the polder.
- Initial terrestrial vegetation slowed down the establishment of estuarine species. It is therefore recommended to remove initial terrestrial vegetation before opening the side.

- Although the area is very small, this pilot project proved the potential effect on the water quality.

ii) Terraces

At the Paddebeek case in the Scheldt estuary (**S-Pad.**) terraces were constructed at different heights. A positive result came from the life willow wickers, used to construct the terraces. As a consequence, willow shrubs established very quickly, which accelerated vegetation succession in the site. The constructed terraces were rapidly colonized by estuarine vegetation species: pioneer communities of Vaucheria (*Vaucheria sp.*), Water speedwell (*Veronica anagallis-aquatica*), Cursed buttercup (*Ranunculus sceleratus*), etc., followed by helofytes like Alkali Bulrush (*scirpus maritimus*), Common Reed (*Phragmites australis*), Common Bulrush (*Typha latifolia*) en Reed Sweet Grass (*Glyceria maxima*).

In addition, there was no need to use stone rubble (boulders) to protect the new dike, except for the edges.

4.3) Negative experiences with un-complete implementation

In the case of Paddebeek (**S-Pad.**) the old dike was excavated and the substrate was reinforced with gabions (schanskorven) and a small stone rubble dike. Only at the ends, the dike was reinforced with stone rubble. However, the greater part of the old dike remained in place and the removed boulders were piled up between two terraces hindering proper drainage, creek formation and colonisation. To allow some drainage some of the boulders (stones) should still be removed.

Also at the Paardenschor (**S-Paard.**) the old dike could have been excavated more, but on the other hand this might have led to erosion on the transition to the adjacent marsh (Schor Ouden Doel).

At the Ketenisse marsh (**S-Ket.**), it was planned to level the area with a weak slope but in the end the slopes at the extreme ends of the site are too steep causing net erosion by which these zones seemed less functional as habitat. In the central part two aspects of the final design differed significantly from the original plan:

- Some areas, where the topsoil was not useful as construction material for dikes, were not excavated below mean high water level and remained almost supratidal.
- The old dike was not removed according to plan and as a result almost flat plateaus with a steep slope towards the river were constructed instead of a gentle overall slope from the dike to the river.

This had consequences for the habitat development of the site. At T-0 higher vegetation was already in place including supratidal as well as tidal marsh vegetation. Some of it died off, whilst in other places it remained and served as a ‘source’ for typical fauna and flora elements.
The plateaus now provide low dynamic habitat, they silted up and a relatively rich macrobenthic invertebrate community was established, providing extra foraging and roosting space for birds.

If the central slope would have been realised according to plan sedimentation / erosion and habitat development would have been quite different. There would have been relatively less mudflat with a long exposure time; on the other hand habitat diversity and gradual transitions might have been more elaborate.

5) Examples where adjustments were needed

At Wrauster Bogen (**E-Wr.B.**), the monitoring outcomes showed that the slope steepness and high flow velocities in the creek prevented that mudflats could evolve. Also the water level in the creek proved to be too low for a permanent colonization by fish using the creek as resting and growing habitat. Erosion occurred at the creek banks and the slopes, resulting in transportation of materials (more silt and clay) from the creek into the Elbe estuary at low tide.
In order to promote sedimentation in the creek, a morphological rearrangement of the creek was executed in 1994 (three years after the initial implementation). One side of the creek was closed in order to decrease the flow current and a sill (30m wide and levelled 1m above MLWL) was placed in the other opening in order to prevent the complete drainage of the creek. In addition, also the slope of the embankments was flattened.

After the adjustment of the tidal creek a positive influence on the erosion and sedimentation processes was observed: the flow velocities in the river channel decreased and mudflats could evolve and thus provide food for the resting fish species. Therefore the rework led to favourable results concerning the achievement of the development targets. Also, it was concluded that a monitoring after the implementation phase is necessary in order to check whether the targeted results finally have been achieved.

At Heusden (**S-Heusd.**) the site design had led to the unfavourable situation that initially the site inundated at spring tides and that it was not drained at low tide. Later two breaches at MLW were added where the old sluices used to be. It then had every aspect of a breached site with a strongly accentuated spring tide / neap tide differentiation in the inundation regime. Nevertheless some areas remained inundated at low tide and the southern part, where the sand stock for the dike construction works was not completely removed, remained supratidal.
As a result of this design a site with a great variety of habitat types was created, with permanent pools, mudflats and all stages of typical tidal marsh vegetation. The altitude gradient from low marsh to supratidal was uninterrupted because of the absence of fortifications.

At Kleinensieler Plate (**W-Kl.P.**) the shallow water zone was strongly affected by siltation. Therefore two of three overflow barriers were heightened in 2005 (five years after the initial implementation). As a result, the amount of suspended matter entering the project area could be reduced significantly and siltation tendencies were slowed down. At the same time, the tidal influence on the project area was restricted. This means also that, to the benefit of vegetation, fauna and water structures, less maintenance effort can be expected in the future.

2.3. Habitat creation & compensation

Main question: Which habitat types are expected & created by executing MRMs?

MRMs mostly transform 'adjacent land' into estuarine habitats. For the TIDE cases, in total almost 1000 hectares of land is realigned. More specifically the previous land type was for instance arable (eg. S-Lip., H-PHS, H-Ch.N.), pasture (eg. S-Ket., H-PHS), or dredge spoil storage (eg. W-Kl.P.). The TIDE measures create between two and six of the different habitat types (Figure 2-4). The newly created habitats are mainly marsh land (48%) and intertidal flats (35%), but also intertidal steep habitat and subtidal habitats are created (Figure 2-4). The largest habitat creation was realised by the TIDE cases in the Weser and Humber (Figure 2-5). In the Humber this was mainly in the mesohaline zone and in the Weser in the oligohaline zone.

For compensation measures, there is however no additional habitat created because it was lost first somewhere else. For the TIDE cases, almost all created habitat surface is for compensation reasons and only 10% is newly created for other reasons (Figure 2-6).

The data about the habitat change by the measures is collected by a survey. Responsible authorities were asked to indicate for every measure the habitat surface per habitat type, before and after the implementation of the measure.

For the Humber, only three MRMs are included in this study.

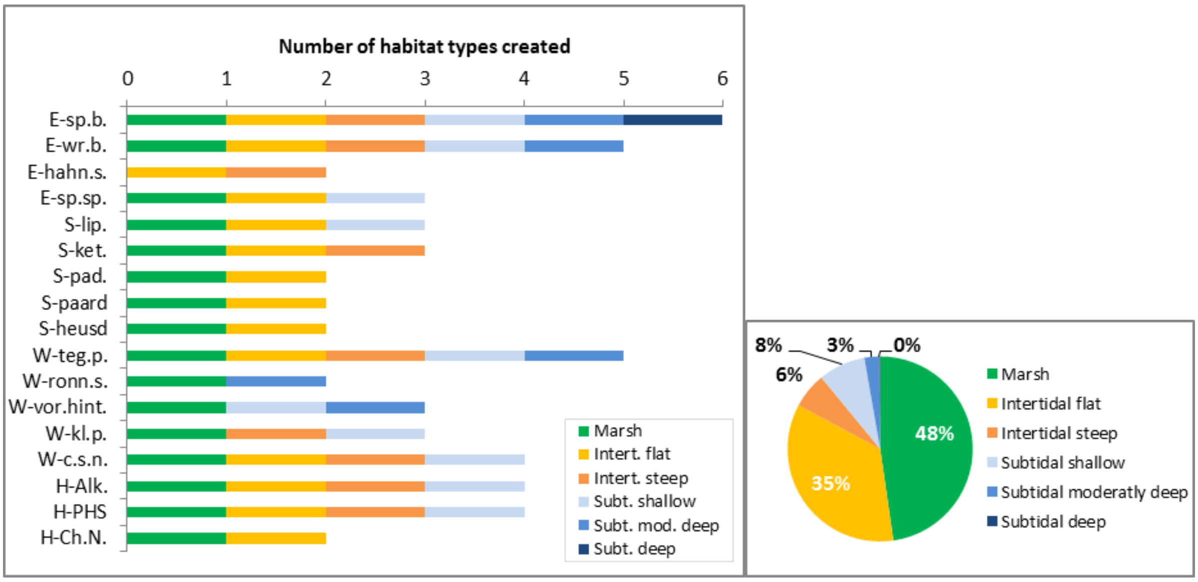

Figure 2-4. Left panel: Habitat types created per TIDE measure. Right panel: distribution of the total hectares of different habitat types created by the TIDE cases.

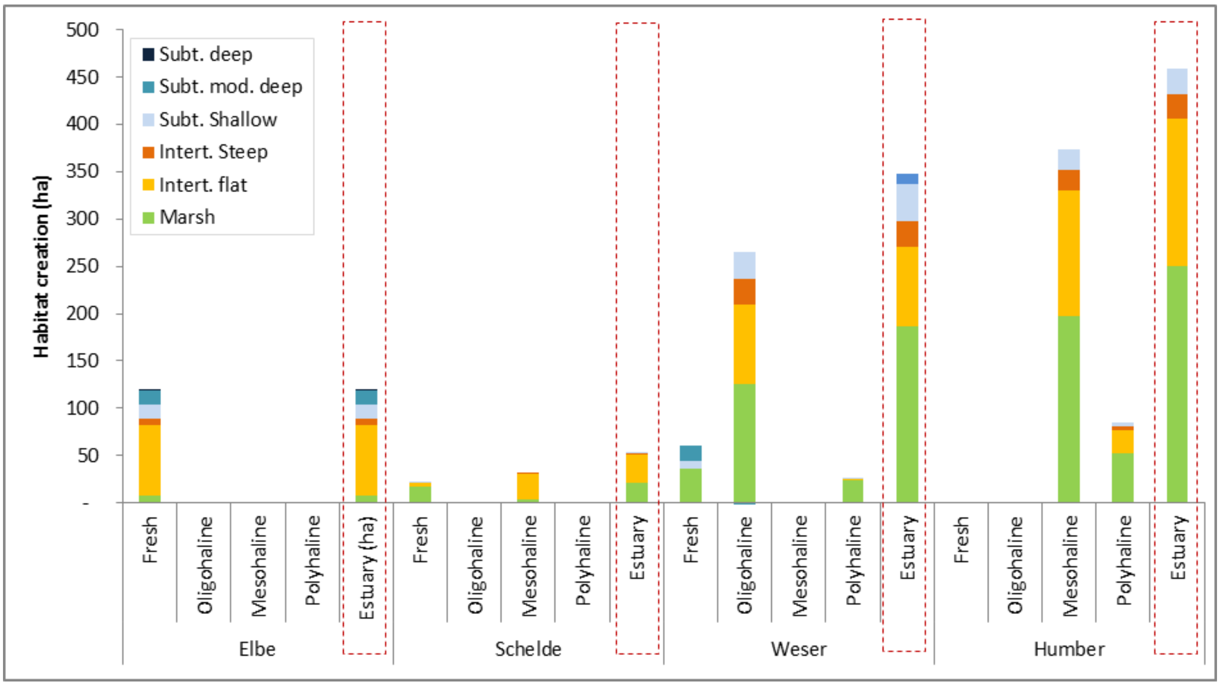

Figure 2-5. Overview habitat creation by the TIDE cases per estuary and per zone (in hectares)

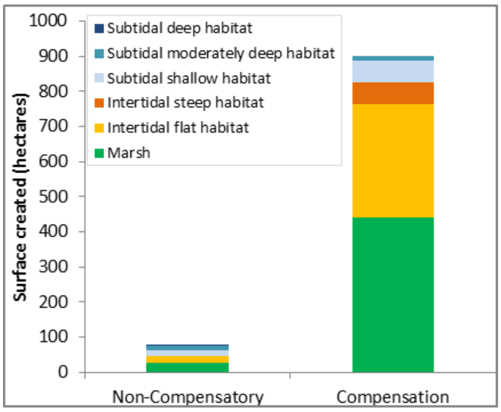

Figure 2-6. Overview habitat creation per habitat type by the TIDE compensation measures and non-compensatory measures

2.4. Monitoring program

Main question: Is the success of MRMs monitored?

The success of a measure is mostly analysed by monitoring different environmental characteristics. All TIDE examples do have a monitoring program. The duration of the monitoring program varies from 3 to 15 years. Since developments on levelled sites start shortly after the end of the works, it is important to monitor intensively in the early stages [35]. It is recommended to have a thorough monitoring within an annual programme for at least five years [37]. Long term monitoring records of many sites indeed suggest that the ecology of the realignment sites takes many years to pass from pioneer stages to a more stable ecology. After this period, the frequency of monitoring can generally be reduced when most sites become less dynamic and the colonisation phase is over and more stable flora and fauna are developing. However, there are examples where sites are still in transition after more than 12-15 years. It is not clear whether all sites will ever reach a state of equilibrium or achieve a similar physical and ecological status to adjacent areas in the main part of the estuary [37].

The parameters that are monitored in at least half of the TIDE examples are vegetation, accretion and sedimentation on site, invertebrates, birds and fish (Figure 2-7). This means that mostly the 'visible' biological aspects are monitored (the end users of a healthy system), but much less the underlying ecological/chemical/physical processes. This corresponds to the fact that many measures have been developed in response to the requirements of the Birds and Habitats Directives and hence the main focus of the monitoring is on birds and food sources for birds. Less work has been done on the physical changes which take place within and outside of the sites [37]. However, the latter is equally important to evaluate the success of a measure.

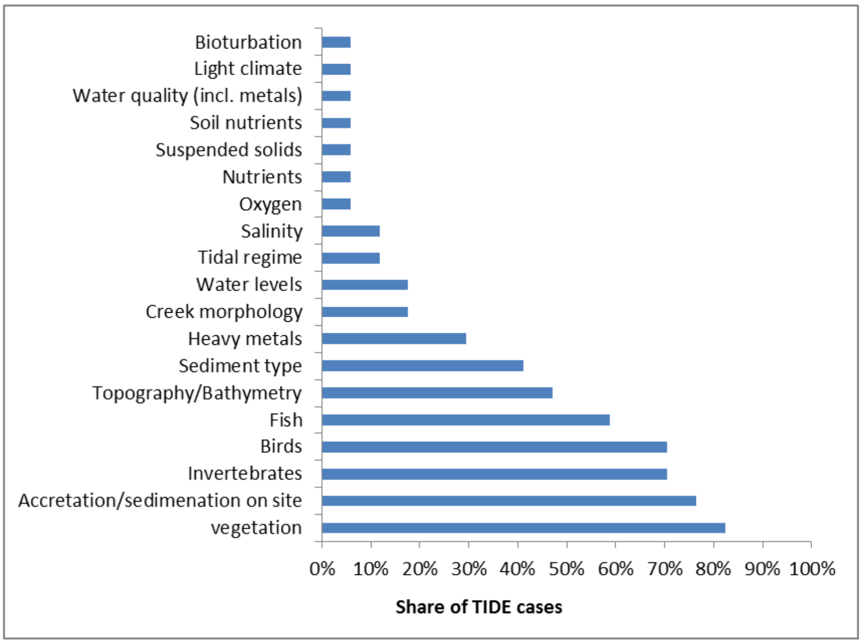

Figure 2-7. Share of TIDE MRM examples with the different parameters in the monitoring program

The monitored parameters are more or less in accordance to the key parameters that are recommended to add in all future managed realignment monitoring programmes [37]:

- Original ground levels
- Frequency of tidal inundation on all parts of the new intertidal areas
- Sedimentation at fixed monitoring points
- Changes in ground level across the site
- The nature of sediments in terms of particle size, organic content and moisture content
- Invertebrate colonisation of the intertidal sediments and water column
- Fisheries, in particular juveniles

- Use of the sites by birds
- Colonisation of bare substrates by vegetation including both algae and higher plants

For some Scheldt cases also the monitoring program was evaluated [35] and it was recommended to:

- start with the monitoring plan already in the planning phase with clear cost estimation and clear agreements on execution and reporting;
- make a clear distinction between "site success monitoring" and "impact verification monitoring";
- make a photographic survey on a yearly basis to improve interpretation of collected data;
- optimise the comparability of monitoring results of zoobenthos with that of other countries;
- monitoring of birds and fishes needs to be done from the beginning following fixed protocol;
- experimental research is needed to monitor benthic primary production; and
- investigate the monitoring of floristic quality of marsh vegetation.

2.5. Synergies and conflicts

Main question: Can managed realignment generate synergies? And, conflicts?

MRMs could generate many benefits in the field of flood management, environmental benefits and financial benefits [38].

- Benefits for flood management are about the reduction of the flood risk elsewhere in the system through changing the hydrodynamic conditions, the improvement of the flood risk condition in accordance with national legislation, the avoidance of uncontrolled abandonment of 'weak spots' in the dike, and the management of the effects of sea level rise over time.
- Environmental benefits come from an increase of the diversity and ecological richness of the area, an increase or management of the existing ecosystems in accordance with local/international legislation, a compensation for engineering works or long term processes such as coastal squeeze in accordance with local/international legislation, a creation of areas with a high recreational value for eco-tourism, and provision of nutrient and pollution sinks that purify the water.
- Financial benefits are related to the fact that it will require smaller defences due to wave attenuation on salt marsh, it will create a sustainable flood defence that will provide safety for a longer period of time, and it will lower the maintenance cost of the flood defence system as a whole.

Many stakeholders are also involved, with many synergetic but sometimes also conflicting interests. The main synergies and conflicts of the TIDE MRMs are summarised:

Synergies:

- Habitat creation and flood protection (**S-Lip., S-Pad., S-Heusd., W-Kl.P., H-Alk.**)
- Habitat creation and port development: The creation of estuarine habitats by implementing MRMs could give a justification for port development activities such as the creation of harbour docks (**S-Paard.**) and dredging activities inside the port (**E-Sp.B.**) or in the navigation channels.
- Habitat creation and recreation: at many cases positive effects on leisure and local recreation are observed:
  - At Spadenlander Bush (**E-Sp.B.**) positive effects are expected due to public footpaths along the newly built shore and a set of presentation boards to provide additional information concerning the new developed tidal influenced biotopes.
  - At Wrauster Bogen (**E-Wr.B.**) the implementation of the measure positively influenced the local fish population due to the generation of additional spawning and growing habitat for some species. This was good for local fishery activities.
  - The Lippenbroek case (**S-Lip.**) is included in touristic brochures by some municipalities.
  - At Ketenisse (**S-Ket.**) the creation of stairs over the dike is considered for watching birds behind a transparent wall, combined with information panels. The polder can also be visited during educative excursions (eg. bird watching day) by the local environmental association (Natuurpunt-WAL). Ketenisse is also favourable for cyclists with a nice cycle path along the flowery Scheldt dike. On the north side (in the direction of Liefkenshoek, along sections LHT and ABC) this cycle path is however not finished. At the downstream part (Fort Liefkenshoek) there is a tower with a nice view and a pub. This cycle route is also planned to be integrated in the Ecological InfraStructure cycle route (EIS-cycle rout) in the harbour area. The initiative to open the local service road is linked to the project 'the Antwerp harbour more environmentally friendly'.
  - At Kleinensieler Plate (**Kl.P.**) an 850m shore section north of the ferry terminal Kleinensiel is fully usable as beach again, after parts of the excavated material were spread. Here, no conflicts with tourism, leisure and local recreation appeared.

Conflicts:

- Corresponding to agriculture, only conflicts are observed, mostly because agricultural land disappeared at the benefit of estuarine habitat (**E-Sp.Sp., S-Pad., S-Paard, W-Tegl.P., W-Cap.S.N., H-Alk.**).

- Flood protection and local inhabitants: In some cases also some conflicts were observed because local inhabitants sometimes feared disadvantages from the flood protection (**E-Wr.B.**, **S-Lip.**). This conflict was however solved after both measures were carried out because it became clear that the high flood protection status could be kept.
- Nature development and recreation
  - After the implementation of the Hahnofer Sand measure (**E-Hahn.S.**) the area was designated as a nature protection area and therefore all hunting and fishing activities, even the hunting from the unprotected dyke area, were forbidden.
  - At Ketenisse (**S-Ket.**), recreation activities (eg. road for cyclers) are considered by some actors as a disturbance factor for resting and foraging birds.
  - At the area of Vorder- und Hinterwerder (**W-VorHin**), the general public was sceptical first because it has been a popular area for leisure, local recreation and tourism already before the compensation measure was implemented. But since the natural scenery improved significantly after measure implementation, positive effects on leisure, local recreation and tourism can be stated.
- Other conflicts
  - At Paul Holme Strays (**H-PHS**) there was some local opposition due to the change in land use, perceived increase in tourism, construction disturbance to residents and permanent footpath diversions. The environmental steering group helped to deal with the majority of the concerns raised and generally the site has now been accepted by the local community.
  - At Alkborough (**H-Alk.**) initial concerns from the local community were related to loss of agricultural land, removal of mature trees, and perceived increase in tourism.
  - At Tegeler Plate (**W-Tegl.P.**), conflicts regarding agriculture, tourism, leisure and local recreation can be stated and the site is almost inaccessible for people nowadays.

Conflicts are mainly caused by concerns of local inhabitants: Public acceptance by local stakeholders is in general limited. MR projects have the opportunity to combine different societal functions such as safety, agriculture, ecology and inhabitation in coastal defence schemes, but clarification on the success rate and the effectiveness of the provided estuarine restoration projects is often lacking. As a consequence, local communities fear disadvantages that are maybe irrelevant.

2.6. Costs and benefits of MR-measures

Main question: How cost-efficient are the TIDE MRMs?

Cost-efficiency is an import issue in the European Water Framework Directive. It was stated (in Article 11 of EU-WFD) that for the selection of a measure program also the cost-efficiency considerations should be taken into account in order to find the least expensive way of reaching the WFD objectives. Hence, the member states are obliged to apply the *cost recovery principle* and determine the most cost-effective combination of measures to achieve a good water status.

In the frame of this study, the costs and benefits of the TIDE MRM cases are compared and the cost-efficiency is calculated.

2.6.1.Implementation cost

The relative implementation cost (€/ha) is calculated per measure by dividing the total implementation cost (€) with the total restored surface (ha). It is important to state here that the total implementation cost was not available for all TIDE measures and hence for the others an estimation of the cost category was made (E-Wr.B., E-Sp.Sp., W-Tegl.P., W-Ronn.S., W-VorHin). For the calculations the average of the given cost category is used to reduce the amount of numbers in the text and in the graphs.

The average cost of the TIDE MRM cases amounts 280,000 €/ha, but a large range from 16,000 to 1.4 Mio €/ha was observed. Half of the measures (47%) cost however less than 100,000 €/ha, 35% between 0.1 Mio and 0.5 Mio €/ha and 18% more than 0.5 Mio €/ha. The most expensive measures are found in the Scheldt and the Elbe estuary, followed at a large distance by measures in the Humber and Weser (Figure 2-8).

The average relative implementation cost of the TIDE cases seems very high relative to other studies. For instance, according to the British OMReg study (managed realignment cases in U.K.), the average cost amounts 37,000 €/ha with the highest cost 139,000 €/ha [29].

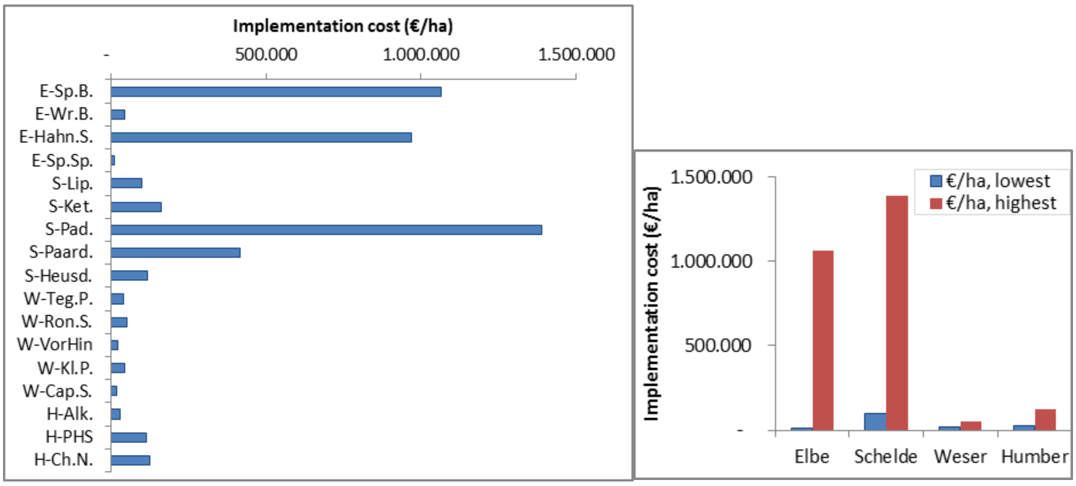

Figure 2-8. Left panel: Implementation cost per measure (€/ha). Right panel: The lowest and highest expensive example per estuary.

Three of the TIDE MRMs have a remarkably high relative implementation cost: Spadenlander Bush (E-Sp.B.), Hahnofer Sand (E-Hahn.S.), and Paddebeek (S-Pad.). Some possible explanations are found for the high cost of those measures:

- For Spadenlander Bush (**E-Sp.B.**), for which the work will start in November 2012, high costs are expected because a huge amount of heavy contaminated high-lying soil (over 2 Mio m³) has to be removed and treated in a special way. Extra costs will hence arise for the deposition of that material elsewhere.

- At Hahnofer Sand (**E-Hahn.S.**) also a lot of soils had to be removed to build the mudflats. The soil was not contaminated but the amount was huge (6 Mio m³).
- The cost of Paddebeek (**S-Pad.**) is part of the dike construction at a longer distance (between Schoonaardebrug and Paddebeek). Hence, the cost of 2.2 Mio € is most probably an overestimation. However, the implementation of the Paddebeek wetland consisted of the landward shift of the dike, the heightening of the dike to Sigma-height, realisation of three terraces, excavation of the old dike, and two breaches at the old dewatering sluices.

From those examples it is clear that aspects that determine the total implementation cost are very complex and highly dependent on the local situation. Therefore, direct comparison of measures according to costs is often not possible. This explains also the large range in the implementation cost between the cheapest and most expensive example. Indeed, the measures, although all MRMs, differ a lot in detail and therefore it is important to have a closer look at the actual work that have been carried out and point out why the implementation cost vary.

1) Size and year of implementation

Over the course of two decades there has been in general a clear shift from initial low-cost, small-scale, and relatively inexpensive trial projects to high-cost, larger projects that were designed to meet specific targets for habitat and flood alleviation [29]. For the TIDE cases, we see however no clear trend from small-scale to larger projects (R^2=0.0069; T=0.32; p=0.75) (Figure 2-9, a), but indeed the per hectare implementation cost tends to increase over time (however not significant: R^2=0.1314; T=1.5; p=0.15) (Figure 2-9, b). The schemes implemented after 2000 had higher per hectare implementation costs (Figure 2-10). Those were however still mostly small-scale projects.
It is expected that recent larger projects are accompanied by improved unit costs (i.e. 'economies of scale') because of enhanced efficiencies in the light of the lessons learned from previous projects. However, this could not be confirmed by the TIDE cases (R^2=0.0328; T=0.71; p=0.49) (Figure 2-9, c), and according to the British OMReg study this hypothesis was not true [29]. In this study it is stated that a number of large-scale projects are in the pipeline at present which will be relatively high cost projects due to their large size and/or novel complexities associated with their design and construction.

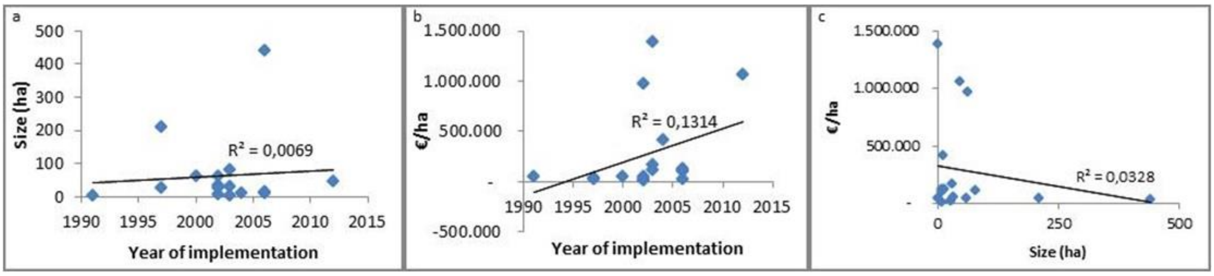

Figure 2-9. Evolution of measure size (a) and per hectare implementation cost (b) over time (1991-2012), and per hectare implementation cost linked with measure size (c).

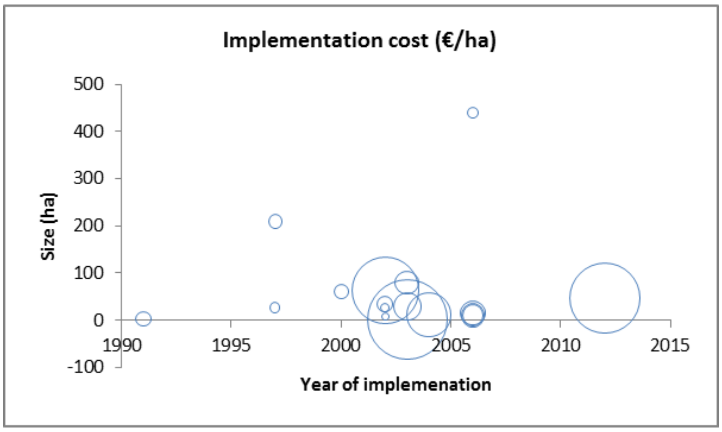

Figure 2-10. Implementation cost (€/ha) plotted against size and year.

2) Implementation technique: dike breach, defence removal, breach size and land removal

The average per hectare implementation cost is significantly higher for **defence removal compared to dike breach** ($F(1,13)=5,08$; $p=0,04$) (Figure 2-11). The average cost for dike breach amounts 60,000 €/ha (ranging from 20,000 to 120,000 €/ha), and for defence removal on average 500,000 €/ha (ranging from 10,000 to 1.4 Mio €/ha). The three most expensive cases are indeed implemented by a defence removal.

Since dike breach and defence removal mainly differ in the **breach size**, this was also compared in more detail. Breach size in the TIDE cases varies between 3m and 2650m. Compared with the per hectare implementation cost, this gives also a positive relationship (Figure 2-12). A larger breach size is more expensive (but not significant ($R^2=0.29$; $T=2.12$; $p=0.057$). The three most expensive cases have also a larger breach size.

In addition, also a higher relative implementation cost is expected for MRM with **land lowering**. Indeed, an important and costly issue in the case of land lowering is the removal and deposition of the removed soil (eg. E-Hahn.S.). More specifically this is very expensive in the case of contaminated soil (eg. E-Sp.B.). The average relative implementation cost for the TIDE MRM with land lowering is indeed higher (460,000 compared to 75,000 €/ha), however this is not significant ($F(1,13)=3.01$; $p=0.1$).

In many cases a **new defence** had to be constructed or existing defences had to be enforced/broadened/heightened (E-Wr.B., E-Sp.Sp., S-Lip., S-Pad., S-Ket., S-Paard., S-Heusd., W-Tegl.P., W-VorHin). Evidently, this means also additional costs.

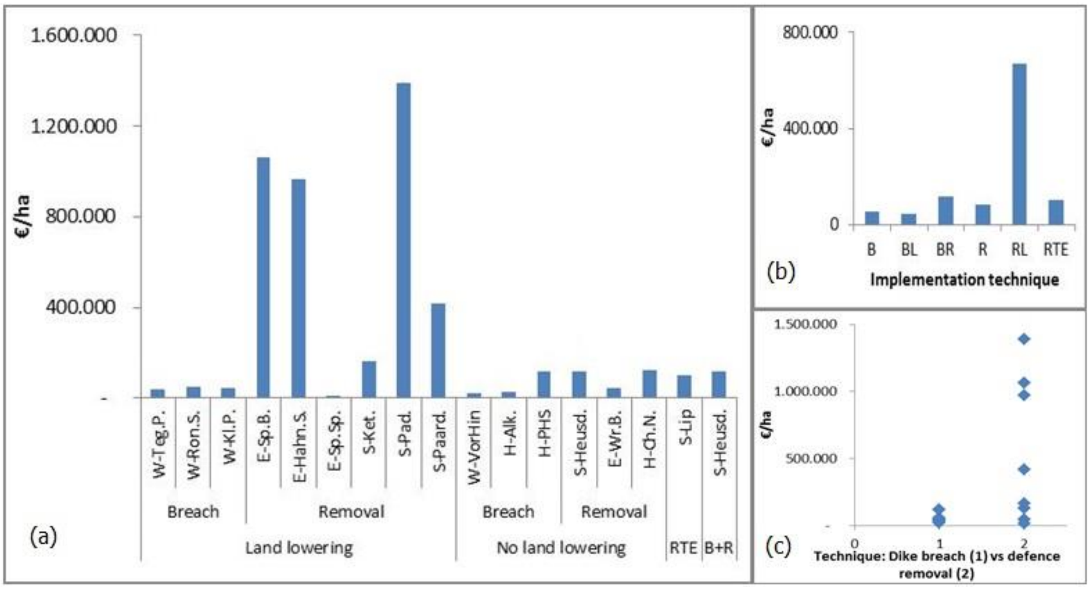

Figure 2-11. (a) Per hectare implementation cost related to the implementation technique: overview per measure, (b) average cost per implementation technique, and (c) spread of relative implementation cost for dike breach versus defence removal. Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), Reduced Tidal Exchange (RTE).

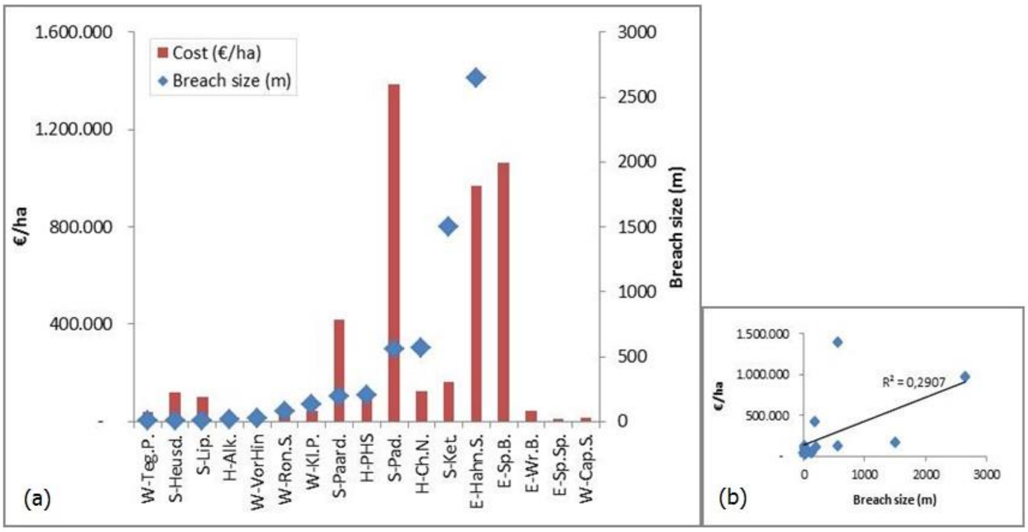

Figure 2-12. Per hectare implementation cost related to the breach size

3) Artificial creek dug: yes/now

Another design aspect that could impact the implementation cost is the artificial digging of a creek network. This is applied in 6 TIDE cases but this gives no clear difference in the relative implementation cost compared to the measures without an artificial creek system (F(1,15)=1,11; p=0,74) (Figure 2-13). Only one of the three most expensive TIDE cases will implement a creek system, the two others will not.

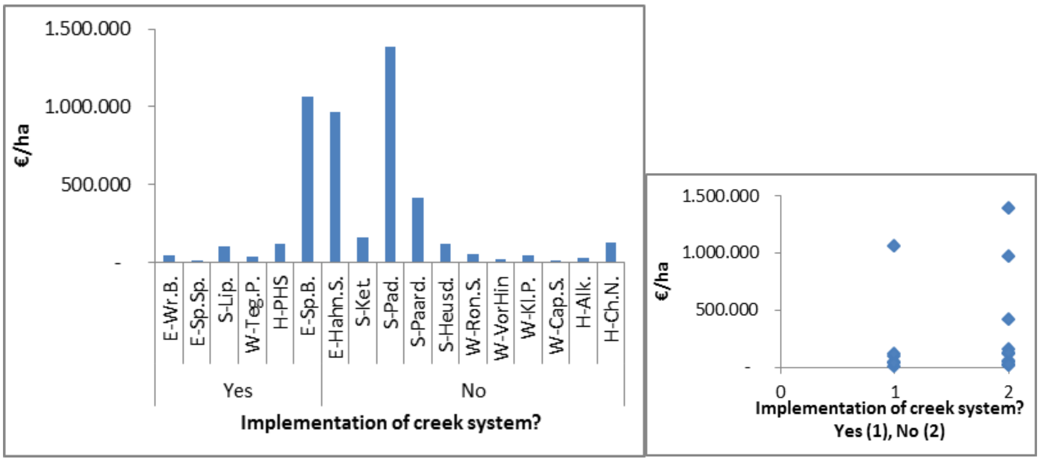

Figure 2-13. Relationship between the relative implementation cost and an artificial creek dug during the implementation

4) Other aspects

- In many cases the land was privately owned before and had to be purchased. Evidently, the land purchase price is also very location specific and could vary a lot between different places and within time.
- Costs for extensive pre investigations during the planning stages could also increase the total implementation cost. This is related with very location specific aspects such as the situation of the project area before measure implementation, costs for licensing, assessment, engineering, and mitigation requirements.
- During various phases (i.e. scheme design, impact assessment, planning and construction), also many obstacles could occur with the risk for increasing costs. Studying existing MR schemes could help to identify specific cost components.

Conclusions

The relative implementation cost of the TIDE MRM cases amounts 280,000 €/ha with a large range between 16,000 and 1.4 Mio. €/ha. For some measures, only a rough estimation was available. Three measures are considered as outliers with a remarkable high relative implementation cost, because a high amount of soil that had to be removed out of the area (E-Hahn.S.) and that had to be treated because of contamination (E-Sp.B.), or uncertainty about the total implementation cost (S-Padd.).

Different measure characteristics are studied to find reasons for the large variance in the relative implementation cost.

- Size and age: No significant relationship is observed between the relative implementation cost and the size of the measures, nor could we observe a temporal evolution in the relative implementation cost.
- Implementation techniques: A significant difference in the relative implementation cost is observed between the TIDE measures implemented by dike breach and by defence removal. The latter technique is, evidently, much more expensive. A positive relationship with the breach size was however not significant. Also, measures with land lowering are expected to be more expensive but this difference was not significant.
- Creek system implemented: Measures with the implementation of a creek system are expected to be more expensive but this difference was not observed for the TIDE cases.

Overall, only the difference between dike breach and defence removal is a significant reason for a variation in the relative implementation cost of the considered TIDE cases.

Critical note: By comparing measure characteristics with the relative implementation cost nothing could be concluded about the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and to be sustainable is more important when considering the measure design than the implementation cost.

2.6.2. Benefits of MRMs

MRMs are executed with the main benefit of enhanced defences and/or newly created coastal habitat. MR sites could obtain natural protection against recurring storm surges and sea level rise. MR sites could also preserve the resources coastal habitats provide. Both benefits correspond with the main measure objectives (nature conservation/creation, and safety). MRMs however also generate many more additional socio-economic benefits such as tourism, recreational and commercial fisheries, carbon sequestration and water quality improvements.

The ecosystem services concept could help to identify and estimate benefits MRMs could generate. Monetary evaluation of ES could support decision making to take into account more direct and indirect impacts of management activities [39]. The monetary valuation indicates the clear economic gains that can arise from managed realignment schemes and it also demonstrates that these projects can have a sound economic rationale. Additionally, the findings of the monetary valuation could be used to seek out new funding sources for future schemes which would help to address one of the key problems of funding MR implementation [29]. However no scientific consensus exists yet concerning how to express ES in monetary units and different outcomes will be obtained when using different approaches.

An easy approach is by using an economic value for different biomes and multiplying this with the surface of the different biomes that are created or destructed. This approach is initiated in the widely referenced paper of Costanza et al. in Nature in 1997 [40]. More recently (in 2012), a literature review is published by De Groot et al [41] on the economic value of the large biomes (such as 'Marine', 'Coastal systems' and 'Tropical forest'). In frame of this study, data from the latter study will be used to get an indication of the economic value of the MRMs. However, in the conclusions we have to bear in mind the constraints of this approach.

The TIDE MRM measures have an impact on two of the biomes from the study of De Groot et al. [41]: 'Coastal systems' and 'Coastal wetlands'.

- The first biome 'Coastal systems', with a monetary value of 28,917 Int.$/ha.y[1] [41], corresponds to the TIDE habitats 'subtidal deep habitat', 'subtidal moderately deep habitat', and 'subtidal shallow habitat'.
- The second biome 'Coastal wetlands', with a monetary value of 193,845 Int.$/ha.y[1] [41], corresponds to the TIDE habitats 'marshes' and 'intertidal flat and steep habitat'.

To calculate the monetary benefit of the TIDE measures, the values from de Groot et al. [41] are multiplied by the habitat change per habitat type (% of total measure size in ha). This means that the new habitat distribution is corrected for the situation before the measure was implemented. Within the TIDE project it was however decided not to count for adjacent land. But, as many MRM measures have transformed adjacent land into estuarine habitat, this implies that the disadvantages (i.e. costs) from the lost adjacent land (mostly agricultural land) are not corrected for in this analysis. This is a major assumption which has to be considered in the conclusions: the monetary value calculated here is an overestimation because it is limited to the benefits generated within the estuary itself without counting for the lost adjacent land.

The results show that the TIDE examples generate an average benefit of 133,000 € per hectare and year, ranging from 70,000 to 155,000 € per hectare and year (Figure 2-14). The difference in the annual benefit per hectare depends on the distribution between subtidal habitats on the one hand (which corresponds to the biome 'Coastal system') and intertidal and marsh habitat (which corresponds to the biome 'Coastal wetlands'). Indeed, from the literature review that we use here [41] it is concluded that the annual monetary benefits from subtidal habitats amounts only 15% of the monetary benefits from intertidal habitats and marshes [41]. Hence, the measures creating the largest share of intertidal habitats and marshes generate the largest annual benefit per hectare, i.e. monetary benefit generated within the estuary itself without counting for the lost adjacent land (often agricultural land).

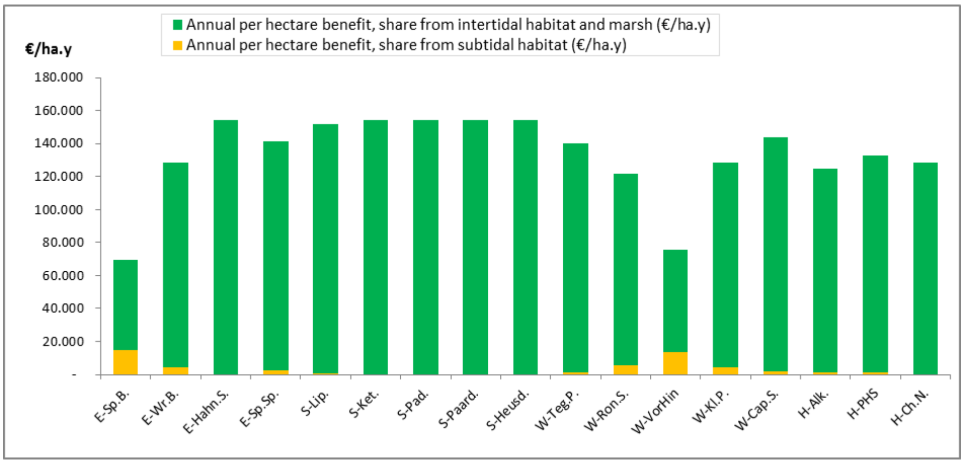

Figure 2-14. Annual monetary benefits per measure per hectare (€/ha.y), separating the monetary benefit from the subtidal habitats (shallow, moderately deep and deep) and the intertidal habitats (flat and steep) and marshes.

<u>Comparison between two approaches: global value versus local study (Alkborough case)</u>

The methodologies for the monetary valuation of ecosystem services are still highly discussed. In many projects the monetary valuation of ES is limited to the more obvious market services (eg. food provisioning and benefits of tourism). More attention should also be addressed to less tangible services (eg. nursery function and erosion prevention) to improve our understanding of the global benefits of the projects. Recently, some cases have been executed where a wider range of ecosystem services are valued for specific case studies also including the

[1] Figures expressed in international dollars cannot be converted to another country's currency using current market exchange rates; instead they must be converted using the country's PPP (purchasing power parity) exchange rate. 1 Int.$=1 USD. PPP for Belgium, Germany and UK is about 0.8 (1 Int.$ = 0.8€).

local context. For the Alkborough case (**H-Alk.**), the annual benefit from ecosystem services was estimated at £1.6 Mio per year [42] and the gross benefit value was estimated at almost £28 Mio (assuming that the benefits are generated during 25 years). With a scheme cost of £8.69 Mio this gives a benefit/cost ratio of 3.22:1, meaning a gross benefit of £3.22 by investing £1. This estimation is however much lower than the calculation based on the global estimates of the value of biomes and their services in monetary units [41]: annual benefit of 55 Mio €/y (44.65 £/y, conversion £=1.2319€).

A detailed overview of both approaches (Table 2-2) shows that there is a large discrepancy between both. Overall, the estimates from the local case study of Alkborough are much lower than the estimates based on the global value for the different biomes realised with Alkborough.

- The estimates from the Alkborough case could be considered as underestimation because not all ecosystem services were monetised because of a lag in knowledge about how to quantify and monetary value those services (such as Climate change, Air quality, fish recruitment [42]).
- The global estimates based on data from de Groot et al. [41], on the other hand, also need some critical consideration. An important constraint is that it is not adapted to the local circumstances. It gives the same value for all different types of coastal systems despite local characteristics, specific ecosystem quality and local demand. This is however determinative for the real delivery of ecosystem services (eg. the ES delivered by a dry or wet wetland will differ).

In the end, we assume that the real value of the ecosystem services delivered after the implementation of a measure will be in between both approaches. The approach with the global data is the quickest and most easy approach, but the case specific approach is however recommended because it is more accurate since the local context is included. A guidance document for ES valuation in an estuarine context will be developed in the frame of the TIDE project to improve our knowledge and to support managers in this exercise [22].

Table 2-2. Overview economic value of different ecosystem services due to the Alkborough case: based on two different approaches.

Value **Alkborough** (**£/y** ; **€/y**) (*)Conversion factor: £ = 1.2319€	Based on global data for biomes [41]	Based on local study [42]	
	€/y	£/y	€/y (*)
Provisioning services	**886 125**	**-3 255**	**-4 009**
Food	*354 816*	*- 28 075*	*-34 586*
Water	*342 707*	*- 5 000*	*-6 160*
Raw materials	*101 024*	*26 820*	*33 040*
Genetic resources	*2 816*	*3 000*	*3 696*
Medicinal resources	*84 762*		
Ornamental resources			
Regulating services	**48 753 531**	**423 220**	**521 365**
Air quality regulation			
Climate regulation	*26 734*	*14 553*	*17 928*
Disturbance moderation	*1 506 842*	*408 667*	*503 437*
Regulation of water flows			
Waste treatment	*45 654 400*		
Erosion prevention	*1 552 883*		
Nutrient cycling	*12 672*		
Pollination			
Biological control			
Habitat services	**4 832 643**	**757 598**	**933 285**
Nursery service	*3 001 891*		
Genetic diversity	*1 830 752*	*757 598*	*933 285*
Cultural services	**622 811**	**164 830**	**203 054**
Aesthetic information			
Recreation	*622 054*	*164 830*	*203 054*
Inspiration			
Spiritual development	*370*		
Cognitive development	*387*		
Total annual economic value	**55 095 110**	**1 342 393**	**1 653 694**

2.6.3. Cost-efficiency analysis

By comparing the cost of the measure with the annual benefits, the earn-back time is calculated (Figure 2-15). This gives the number of years that the measure should be operational before the total implementation cost is earned back. The average time to earn back the implementation cost for the TIDE MRM examples is 2.3 years, ranging from 0.1 years to 15 years.

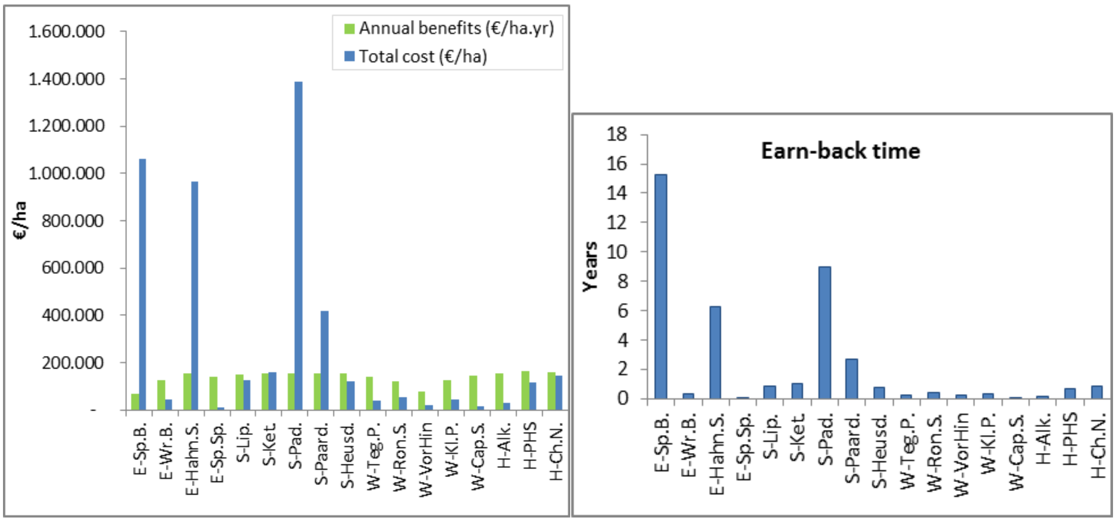

Figure 2-15. Left panel: Implementation cost (€/ha) and annual benefit per measure (€/ha.y). Right panel: Earn-back time for the TIDE MRM examples (in years)

Another way to evaluate the cost-efficiency of the measures is by calculating the benefit/cost ratio, i.e. the annual benefit generated for 1€ invested. For the TIDE cases this is on average 2.82 €/y for every 1€ invested, ranging from 0.07 to 13.35 €/y for every 1€ invested (Figure 2-16 left panel). This gives (evidently) the opposite result of the earn-back time: measures with a long earn-back time have a low benefit/cost ratio. However this relationship is not linear (Figure 2-16 right panel).

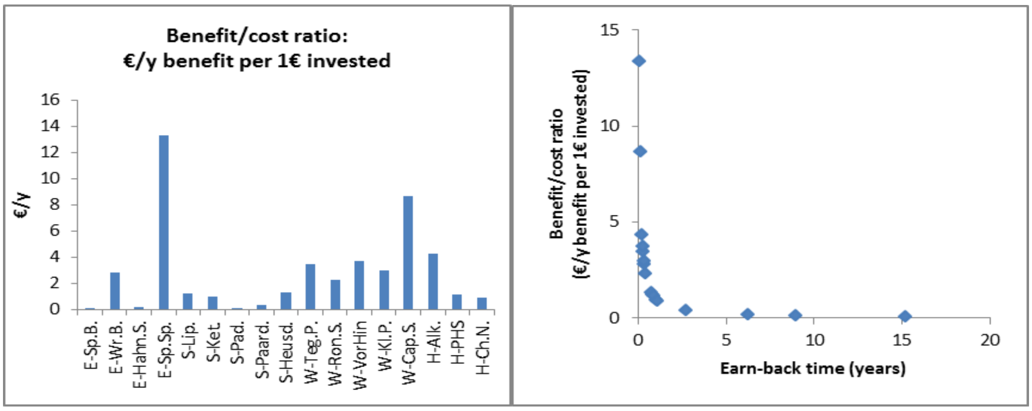

Figure 2-16. Left panel: Benefit/cost ratio for the TIDE MRMs. Right panel: Relationship between the earn-back time and the benefit/cost ratio.

Critical notes:

1. The earn-back time and benefit/cost ratio does however do not necessarily gives an indication of the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and the sustainability of the measure is more important than the cost efficiency when considering the measure design. The cost-efficiency of measures could be used as one of the decision criteria, but should not be used as the main argument.
2. In addition, the monetary benefits are an overestimation because it is not corrected for lost adjacent land.

2.7. Effectiveness based on ecosystem services (ES)-assessment

The effectiveness of the TIDE examples is analysed by comparing the targeted ES with the realised ES. The ES assessment is based on the general ES assessment for measures developed in the TIDE project [1, 23].

2.7.1. Targeted ES

For every TIDE measure, the targeted ES were indicated by the responsible authorities [1] from the list of the 20 selected estuarine ES [23]. The most common targeted ES for the TIDE MRMs is the category “Supporting and habitat services” (Table 2-3). Only in some cases this target is accompanied by one or more other targeted ES such as “Water for navigation”, “Water quantity regulation: dissipation of tidal and river energy”, “Regulation of extreme events: flood water storage”, “Erosion and sedimentation regulation by water bodies”, “Opportunities for recreation and tourism”, and “Information for cognitive development”.
This corresponds with the information gathered under section 2.1 Measure targets and degree of target achievement (Table 2-4). The development target “Safety” corresponds with the ES “Regulation of extreme events: flood water storage”, “Water quantity regulation: dissipation of tidal and river energy” and “Erosion and sedimentation regulation by water bodies”. The development targets “Habitat conservation and creation” and “compensation” both correspond with the ES “Supporting and habitat services”. Furthermore the development target “Access opportunities and education” corresponds with the cultural ES “Opportunities for recreation and tourism” and the research target corresponds with the cultural ES “Information for cognitive development”.

Table 2-3. Targeted ES per measure

Targeted ES ■	TIDE MRMs																
	Elbe				Scheldt					Weser					Humber		
Ecosystem services	Sp.B.	Wr.B.	Hahn.S.	Sp.Sp.	Lip.	Ket.	Pad.	Paard.	Heusd.	Tegl.P.	Ronn.S.	VorHin	Kl.P.	Cap.S.N.	Alk. (1)	PHS(1)	Ch.N.
P1 – Water for industrial use																	
P2 - Water for navigation	■																
P3 - Food: animals																	
R1 – Erosion and sedimentation regulation by water bodies										■		■					
R2 – Water quality regulation - reduction of excess loads coming from the catchment																	
R3 - Water quality regulation - transport of pollutants and excess nutrients																	
R4 - Water quantity regulation - drainage of river water																	
R5 - Erosion and sedimentation regulation by biological mediation																	
R6 - Water quantity regulation - transportation																	
R7 - Water quantity regulation - landscape maintenance																	
R8 - Climate regulation Carbon sequestration and burial																	
R9 - Water quantity regulation - Dissipation of tidal and river energy	■																■
R10 - Regulation of extreme events - wave reduction																	
R11 – Regulation of extreme events - water current reduction																	
R12 - Regulation of extreme events - flood water storage					■												■
S – Supporting and habitat services		■	■	■	■	■	■	■	■	■	■	■	■	■			■
C1 - aesthetic information																	
C2 - Inspiration for culture, art and design																	
C3 - Information for cognitive development					■												
C4 - Opportunities for recreation and tourism																	■

(1) Missing information

Table 2-4. Translation of measure targets in terms of ES

Target	Corresponding Ecosystem Service
Safety	R1 - Erosion and sedimentation regulation by water bodies R9 - Water quantity regulation: dissipation of tidal and river energy R12 - Reg. of extreme events: flood water storage
Habitat conservation/restoration	S - Supporting and habitat services (biodiversity)
Compensation	S - Supporting and habitat services (biodiversity)
Access opp. and education	C4 - Cult. Opportunities for recreation and tourism
Research	C3 - Cult. Information for cognitive development

2.7.2. Realised ES and beneficiaries

To analyse if the targeted ES are also realised, the results of the TIDE study Ecosystem Services is used [23]. In this study, the potential of each estuarine habitat type to deliver the different ecosystem services was scored. This is combined with the information about habitat change for every measure [1-19].

It is important to emphasize that this approach assumes an equal surface-supply relationship for all habitats and services [23]. This is however a simplification of the reality since differences exist in the quantity of this relationship: e.g. one hectare of tidal flat will not supply the same 'amount of benefit' for nutrient capture as of sedimentation regulation. Also, surface-supply curves might be linear, exponential, or saturated: e.g. more deep water will increase navigation service, but after a certain amount is reached and demand is met, the service will not further increase. Therefore ES calculations based on surfaces should be interpreted as an indication and interpreted with caution. This is mainly the case for services like water for navigation, wave reduction and water current reduction, which strongly depend on the form of the habitat (length-width, orientation along river, presence of bottlenecks,…).

The result is the **expected impact** of every measure on each ecosystem service. This is represented as a score from +3 (very positive expected impact) to -3 (very negative expected impact). From the general overview (Table 2-5), it is concluded that the TIDE MRMs have a slightly positive to very positive expected impact on at least 12 of the 20 considered ecosystem services.

- Provisioning services: expected impact is mostly neutral
- Regulating services: expected impact is neutral to very positive
- Supporting and habitat services: expected impact is positive to very positive
- Cultural services: expected impact is slightly positive to very positive

It is important to emphasise that this analysis has to be considered as a first but rough screening to check which ES are expected to be impacted by a certain measure. Managers should however first control this result with the local conditions of the measure. In the developed ES assessment for every habitat type one fixed score is determined for each ES without the possibility to diversify for local characteristics. For instance, if a measure site is not directly connected to the river you should be aware that several regulating services (such as dissipation of tidal and river energy and wave reduction) will be very limited. For more information on a correct interpretation of the results, see [1] §3.2.1.2 Impact on ecosystem services (ES).

The expected impact on the **targeted ES** is in most cases very positive (Table 2-5). On average, only 10% of the ES with a positive expected impact (slightly positive to very positive) are also targeted. This means that the MRMs are expected to **generate many co-benefits**!

Furthermore, also the expected impact among different **beneficiaries** is assessed. Two types of beneficiaries are included: one set of beneficiaries depending on the users' typology (direct[2]-indirect[3]-future[4] use), and one set of beneficiaries depending on the spatial scale (local, regional and global use). The expected contribution of each ES to the different beneficiaries is based on assigned values, see §3.2.1.2 Impact on ecosystem services (ES) in [1]. This analysis shows that the TIDE MRMs are mainly beneficial in an indirect way, at a longer term (for future use) and at a local and regional scale (Table 2-5).

[2] Direct use is obtained through a removable product in nature (i.e. timber, fish, water).
[3] Indirect use is obtained through a non-removable product in nature (i.e. sunset, waterfall).
[4] Future use (or option value) is the potential future ability to use a resource even though it is not currently used and the likelihood of future use is very low. This reflects the willingness to preserve an option for potential future use.

Table 2-5. Overview expected impact of the MRMs on the various ecosystem services; and beneficiaries. The targeted ES are indicated as an orange box.

ES assessment

Legend: expected impact*	
3	Very positive
2	Positive
1	Slightly positive
0	Neutral
-1	Slightly negative
-2	Negative
-3	Very negative

Targeted ES (orange box)

*: Indicative screening based on ES-supply surveys and estimated impact of measures on habitat quality and quantity. Quantitative socio-economic conclusions require local supply and demand data to complement this assessment.

Cat.: category Biology/ecology (B), Hydrology/morphology (H), combination of biology/ecology with hydrology/morphology (HB)

	Measures																
	E-Sp.B.	E-Wr.B	E-Hahn.S	E-Sp.Sp	S-Lip.	S-Ket.	S-Pad.	S-Paard	S-Heusd	W-Tegl.P	W-Ronn.S	W-VorHin	W-Kl.P.	W-Cap.S.N	H-Alk.	H-PHS	H-Ch.N.
Zone	Fresh	Fresh	Fresh	Fresh	Fresh	Meso	Fresh	Meso	Fresh	Oligo	Fresh	Fresh	Fresh	Poly	Meso	Poly	Meso
Cat.	HB	B	B	B	HB	B	B	B	B	B	HB	HB	B	B	HB	B	B
Ecosystem services:																	
P1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
P2	**1**	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
P3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
R1	3	3	3	3	3	2	3	3	3	**3**	3	**3**	3	3	2	3	2
R2	1	3	1	3	3	1	3	2	3	2	3	2	3	3	2	3	1
R3	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0
R4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R5	1	2	2	2	2	1	2	2	2	2	2	1	2	3	2	3	1
R6	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
R7	1	2	2	2	2	1	2	2	2	3	2	1	2	3	2	2	1
R8	1	3	2	3	3	1	3	2	3	3	2	2	2	3	2	3	1
R9	**1**	0	1	0	0	1	0	2	0	2	0	0	0	1	1	1	**2**
R10	0	1	1	1	1	1	1	2	1	2	1	0	1	2	1	1	1
R11	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1
R12	1	0	1	3	**3**	1	3	0	3	3	2	1	2	1	1	1	**0**
S	3	**3**	**3**	**3**	**3**	**2**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	3	3	**2**
C1	2	3	2	3	3	1	3	3	3	3	2	2	2	3	2	2	2
C2	3	3	2	2	2	2	2	3	2	3	2	2	2	3	2	2	2
C3	3	3	2	2	**2**	1	2	2	2	3	2	2	2	3	2	2	1
C4	2	2	1	2	2	1	2	2	2	2	2	2	2	3	2	3	**1**
Beneficiaries:																	
DU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IDU	2	2	2	3	2	1	2	2	2	2	2	2	2	3	2	2	1
FU	3	3	3	3	3	2	3	3	3	3	3	2	3	3	3	3	2
LU	2	3	2	3	3	1	2	2	3	2	2	2	2	3	2	2	1
RU	2	2	1	3	2	1	2	1	2	2	2	1	1	2	1	2	1
GU	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1

Ecosystem services:

P1: Water for industrial use
P2: Water for navigation
P3: Food: Animals

R1: Erosion and sedimentation regulation by water bodies
R2: Water quality regulation: reduction of excess loads coming from the catchment
R3: Water quality regulation: transport of pollutants and excess nutrients
R4: Water quantity regulation: drainage of river water
R5: Erosion and sedimentation regulation by biological mediation
R6: Water quantity regulation: transportation
R7: Water quantity regulation: landscape maintenance
R8: Climate regulation: Carbon sequestration and burial
R9: Water quantity regulation: dissipation of tidal and river energy
R10: Regulation extreme events or disturbance: Wave reduction
R11: Regulation extreme events or disturbance: Water current reduction
R12: Regulation extreme events or disturbance: Flood water storage

S: "biodiversity"

C1: Aesthetic information
C2: Inspiration for culture, art and design
C3: Information for cognitive development
C4: Opportunities for recreation & tourism

Beneficiaries:

DU: Direct use
IDU: Indirect use
FU: Future use

LU: Local use
RU: Regional use
GU: Global use

2.8. Conclusions part 1: General aspects of MRMs

In this study, 17 Managed Realignment Measures from the four TIDE estuaries (Elbe, Scheldt, Weser, Humber) are analysed and compared [1-19].

Introduction of the TIDE measures

- Zonation: Half of the TIDE MRMs is located in the freshwater zone and the other half is spread along the three other salinity zones according to the Venice System (mesohaline, oligohaline and polyhaline) [21].
- Age: The studied TIDE MRMs are all implemented in the last 21 years.
- Size: The average size of the TIDE MRMs is 63 ha, ranging from 1.6 ha to 440 ha. However, only two cases are larger than 100 ha.

Comparison of general aspects of MRMs

- Measure targets: Habitat conservation/restoration/creation is the most common target for the TIDE MRMs. Only a few cases combine this conservation target with a safety target (flood storage capacity), research target, and/or recreation opportunities. Half of the cases are driven by a compensation reason.
- Degree of target achievement: Almost half of the measures are considered to have a high degree of target achievement and the other part a medium degree meaning that not all targets are completely reached. However in some cases it was proved that the degree of target achievement could be improved by making some adaptations to the MR site.
- Implementation technique: Half of the TIDE cases are implemented by dike breach and half by defence removal (large dike breach), with a dike breach between 3m and 2650m. Another type of estuarine habitat restoration is by Reduced Tidal Exchange (RTE). Within TIDE we have only one RTE example (S-Lip.). In half of the measures, the dike breach or defence removal is combined with land lowering. In many cases it was proven that different design aspects such as initial site elevation, slope of the area and hydrodynamics do influence habitat development and the success of the measure. In some cases the initial design was not optimal, but adaptations to the site were possible to improve the success of the measure.
- Habitat creation and compensation: The tide MRMs together transformed about 1000 hectares adjacent land into estuarine habitat, consisting mainly of marsh land and intertidal flat habitat. For the TIDE cases, about 90% of the created habitat surface (approx. 900 ha) was however implemented for compensation reasons meaning that it is not really new habitat because it was lost first somewhere else.
- Monitoring program: All TIDE MRMs have a monitoring program with a duration between 3 to 15 years. The parameters that are mostly monitored (in at least half of the TIDE cases) are: vegetation, accretion and sedimentation on site, invertebrates, birds and fish.
- Synergies and conflicts: MRMs generate many synergies between nature, flood protection, port development, recreation, and natural resources, but also conflicts occur with agriculture and local inhabitants.

Costs and benefits: MRMs are **expensive** but could also generate **large benefits**.

- Relative implementation cost: The relative implementation cost of the TIDE MRM cases amounts 280,000 €/ha with a large range between 16,000 and 1.4 Mio. €/ha. For some measures, only a rough estimation was available. Three TIDE MRMs are considered as outliers with a remarkable high relative implementation cost, because a high amount of soil that had to be removed out of the area (E-Hahn.S.) and that had to be treated because of contamination (E-Sp.B.), or uncertainty about the total implementation cost (S-Padd.). Furthermore, different measure characteristics are studied to find reasons for the large variance in the relative implementation cost.
    - Size and age: No significant relationship is observed between the relative implementation cost and the size of the measures, nor could we observe a temporal evolution in the relative implementation cost.
    - Implementation techniques: A significant difference in the relative implementation cost is observed between the TIDE measures implemented by dike breach and by defence removal.

The latter technique is, evidently, much more expensive. A positive relationship with the breach size was however not significant. Furthermore, measures with land lowering are expected to be more expensive but this difference was also not significant.

  - Creek system implemented: Measures with the implementation of a creek system are expected to be more expensive but this difference was not observed for the TIDE cases.
  - Overall it is not possible to give a clear indication about what causes a higher or lower relative implementation cost. It depends too much on local conditions.
  - **Critical note**: By comparing measure characteristics with the relative implementation cost nothing could be concluded about the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and to be sustainable is more important when considering the measure design than the implementation cost.

- Benefits: Benefits of the measures are studied based on the ecosystem services concept. No scientific consensus exists yet on the monetary valuation of ES. Different approaches are explored with often also different outcomes. A simple approach was applied to get a rough idea of the order of magnitude of the monetary benefits of the MRMs. A recent overall literature review with global monetary data for different biomes was used and multiplied with the habitat creation in the MRMs. Based on this approach, the TIDE examples generate an average benefit of 133,000 € per hectare and year, ranging from 70,000 to 155,000 € per hectare and year. The monetary benefit calculated here is however an overestimation because it is limited to the benefits generated within the estuary itself without counting for the lost adjacent land.
  - A more detailed approach to calculate the local benefits of a measure is however recommended. Therefore, a guidance document is developed to support managers and decision makers in how to quantify and monetary value the changes in ecosystem services specifically for the study site [22].

- Cost-efficiency analysis:
  - Earn-back time: The average time that the measure should be operational before the total implementation cost is earned back amounts for the TIDE MRMs on average 2.3 years, ranging from 0.1 years to 15 years.
  - Benefit/cost ratio: The benefit/cost ratio for the TIDE cases is on average 2.82:1, meaning a benefit of 2.82 €/y for every 1€ invested. The benefit/cost ratio for the TIDE cases ranges from 0.07 to 13.35 €/y for every 1€ invested.
  - **Critical note**: The earn-back time and benefit/cost ratio both give an indication of the cost-efficiency of a measure, assuming that the measure targets are met completely. However, in reality the latter assumption is rarely the situation. It is therefore recommended to first check the success of measures to meet the development targets and additionally the cost-efficiency estimate could be used to make a selection between measures that are expected to be successful.

ES-assessment (based on the TIDE ES study [23]):

- Targeted ES: For every measure, the development targets are translated into ES terms to identify the targeted ES. Most TIDE MRMs target the supporting and habitat services. In a few cases, this target is combined with a regulating service (flood water storage, dissipation of tidal and river energy), and/or a cultural services (opportunities for recreation and tourism, and information for cognitive development).
- Realised ES: The TIDE MRMs have a positive expected impact (from slightly positive to very positive) on at least 12 of the 20 considered ES. The expected impact on the targeted ES is in most cases very positive. On average, only 10% of the ES with a positive expected impact (slightly positive to very positive) are also targeted. This means that the MRMs are expected to generate many co-benefits!
- Beneficiaries: The TIDE MRMs are mainly beneficial in an indirect way, at a longer term (for future use), and at a local and regional scale.

3. Part 2: Optimisation of MRMs with a focus on the sedimentation rate

The second part of the TIDE Management Realignment study will focus on issues related to the sedimentation rate and specific site selection and site design aspects that could influence the sedimentation rate on the managed realignment sites. It is expected that this is strongly related with the success of those measures.

3.1.Sedimentation rate in MRM sites and CRTs

3.1.1. Sedimentation rate TIDE cases

The sedimentation rate of 12 (out of 17) TIDE MR sites is available (Figure 3-1) and is mainly based on measurements but also modelled results in case of **E-Sp.B.**. For the remaining cases, the sedimentation rate is missing because it was not monitored (**E-Hahn.S.**, **W-Ronn.S.**, and **W-Cap.S.N.**), or data was not found/not provided (**E-Wr.B.** and **W-Tegl.P.**). For Hahnofer Sand (**E-Hahn.S.**) for instance it was stated in the monitoring document that sedimentation did occur, however without monitoring sedimentation rates.
For some cases only the average was available for single years without a range of highest and lowest. For other cases an average over different years was calculated, giving a (misleading) constant trend in the yearly average sedimentation rate.

Accretion is observed on all TIDE sites (with data of sedimentation rate available), but also erosion was observed at some spots (**S-Ket.**, **S-Heusd.**, **H-PHS**). Erosion was also observed at Spadenlander Spitze (**E-Sp.Sp.**) at the banks in the first 2 years after implementation but this has changed since. The overall average sedimentation rate on the TIDE MR sites is 9 cm/yr, with the highest sedimentation rate measured at parts of the Kleinensieler Plate (75 cm/yr, **W-Kl.P.**) and the strongest erosion in some parts of Ketenisseschor (-30 cm/yr, **S-Ket.**). The average accretion at Kleinensieler Plate (**W-Kl.P.**) is very high compared to all other TIDE cases, and without **W-Kl.P.** the overall average sedimentation rate is only 5 cm/yr.

In general, the sedimentation rate is highest immediately after implementation and then levels off after some years. This is also observed at different TIDE cases (**S-Lip.**, **S-Ket.**, **S-Pad.**, **W-Kl.P.**, **H-Alk.**, **H-PHS**), but also the opposite trend is observed (**S-Paard.**). In some cases the sedimentation rate also has changed as a consequence of site adaptations (**E-Wr.B.**, **S-Heusd.** and **W-Kl.P.**).

In this part of the study, different site aspects will be analysed for their influence on the sedimentation rate on the site. For the further analysis, an overall average per site will be used without indicating the temporal trend (Figure 3-2).

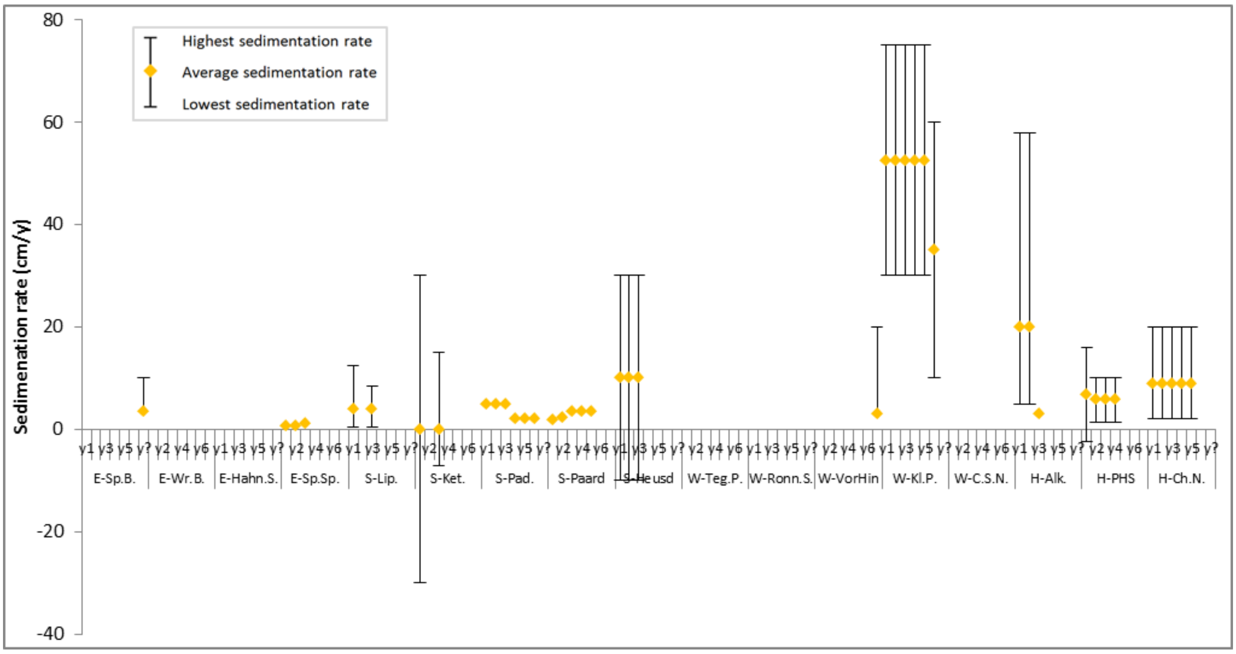

Figure 3-1. Temporal trend of the average sedimentation rate per TIDE MRM, with indication of the highest and lowest measured (or modelled) sedimentation rate as error bars. Evolution in the first years (y1-y6) after the implementation, 'y?' if the data of the sedimentation rate was not clear.

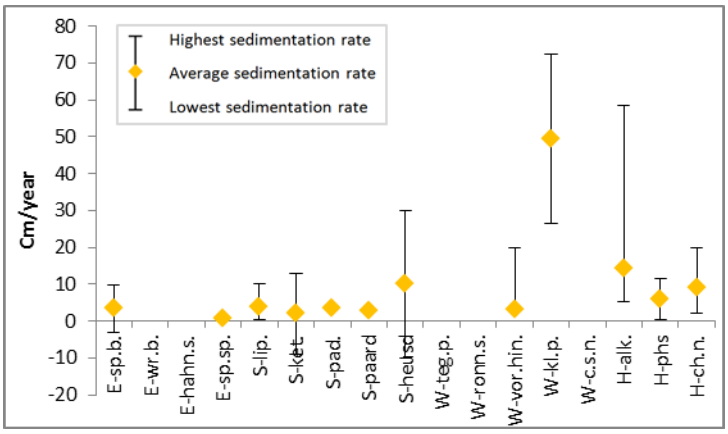

Figure 3-2. Average sedimentation rate per TIDE MRM, with indication of the highest and lowest measured (or monitored) sedimentation rate as error bars.

3.1.2. Management problems related to the sedimentation rate

Managers have to deal with sedimentation and erosion processes in the MR sites as it is part of the natural dynamics of the estuary. In practice dealing with these processes however seems to cause some difficulties because of the complexity of the processes. The sedimentation rate is not constant and evolves at a spatial and temporal scale, eg. depending on the habitat type (higher sedimentation rate on mudflats and lower on marshes and very limited on high marshes). This on its turn depends on eg. hydro- and morphodynamics in the estuary or erosion in the catchment.

To begin with, sedimentation is desired for habitat development. Tidal marshes are widely recognized as net sinks of sediment, which leads, in the long term, to vertical rise or growth of tidal marsh platforms [34]. Changes in elevation are crucial for the colonization and evolution of tidal marsh ecosystems [30]. The input of marine sediments enables the advancement of typical marsh morphology and marsh soil, which in turn promotes the establishment of estuarine vegetation and fauna. A conceptual model was developed about how the elevation of a subsided site is anticipated to evolve in response to estuarine sedimentation processes, from subtidal to intertidal mudflat, to initial mudflat colonization by salt-tolerant marsh plants (pioneer mudflat colonization), to ultimately a fully mature vegetated marsh plain (Figure 3-3 a, from [28]). This trend was confirmed by different case studies (Figure 3-3 b, from [28]).

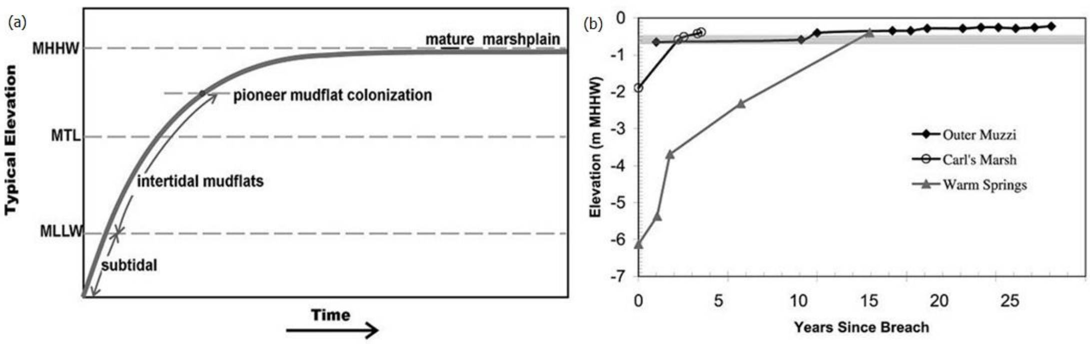

Figure 3-3. (a) Conceptual model of tidal marsh plain evolution with time since breaching. MHHW, mean higher high water; MTL, mean tide level; MLLW, mean lower low water. From [28]. (b) Evolutionary trajectories of three sites and approximate Spartina *colonization elevation (represented by the shaded bar). Elevations are presented relative to MHHW, the approximate predicted marsh plain elevation. From [28].*

Sediment import also ensures that the site would continue to increase in elevation as sea levels rise. The study of Paul Holmes Strays (H-PHS) for instance clearly demonstrated the fundamental importance of the underlying process of sediment accretion to intertidal habitat and ecosystem development. It was concluded that this process drives succession towards mature saltmarsh habitat that compensates for sea level rise and is, therefore, a key factor controlling the rate of development of the fauna and flora communities these habitats support.

The sedimentation rate itself has also a function for different ecosystem services, such as burying nutrients and pollutants. Also, the development of marshes generates additional ecosystem services. Marshes act as natural defence for hinterland and dikes. A wide marsh zone is also a natural defence against waves and erosion. These barriers could also be climate change proof if the sediment supply is high enough so the marshes could follow the increasing sea water levels [30, 34].

Conversely there could also be associated negative implications to sediment import. Excessive sedimentation is to be avoided in a flood storage polder, as this leads to decreased water storage capacity and hence the safety effect of the area (buffering effect for flooding) [30].

Depending on the measure targets, the evolution in habitat types (from shallow water to mudflats to marshes) could also be unwanted. In some cases for instance shallow water area is targeted (eg. to attract fish species and birds), but if this area silts up the measure is not successful anymore. The sedimentation and erosion processes are however difficult to predict for a certain realignment site and hence also the evolution in habitat types. The evolution to other habitat types is hence not always according to the objectives of the area (eg. if

shallow water or mudflats are the target) and therefore (high) sedimentation rates is in practice often considered as a problem.
The evolution to mature marshes also diminishes habitat diversity with changing species diversity and changing supply of ecosystem services since the supplied services differ between different habitat types.

Sedimentation and erosion processes could have a substantial impact on the success of a realignment measure both positive and negative. It is however a complex issue and difficult to predict and anticipate on in practice. Although for many measures some modelling work on this topic was done in the planning stage, the reality after measure implementation turned out to be different and does not always suit the development goals. However, if it turns out that we put goals that require a system which is not in equilibrium this might be more a problem of setting the goal than of the sedimentation rate that is "too high". Meaning: the project might be in the wrong place, the objectives might be unrealistic or the design of the project might be suboptimal.
The MRM study aims to answer these three questions: Is the project in the right place?; Are the objectives realistic?; Is the design of the project optimal?. The conclusions of this analysis could then be used as recommendations for new projects to improve the site selection, defining the objectives and the design of the project and hence improve the overall success of the measure.

__TIDE cases__

For all TIDE cases, the opinions on the local sedimentation rates are collected (Table 3-1). This is based on the measure descriptions and monitoring results from the basic analysis reports of every TIDE measure.

It turns out that the sedimentation rate is indeed considered as a problem in some cases (also problems with erosion), but in many other cases it is not considered as a problem or it is even considered as beneficial. Three cases are not described here because no real issues related to the sedimentation rate were described (**S-Pad.**), or because information was missing (**W-Ronn.S.** and **W-Cap.S.N.**).

Table 3-1. Overview of the measure targets and if sediment related problems were observed for the different TIDE measures.

		Measures																
		E-Sp.B.	E-Wr.B.	E-Hahn.S.	E-Sp.Sp.	S-Lip.	S-Ket.	S-Pad.	S-Paard.	S-Heusd.	W-Tegl.P.	W-Ronn.S.	W-VorHin	W-Kl.P.	W-Cap.S.N.	H-Alk.	H-PHS	H-Ch.N.
Measure targets	Habitat*	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Safety and transportation	X				X										X		
Observed problem(s)	with accretion?	- (red)	- (red)	-	-	-			-	-	+		- (red)	- (red)		+ (green)	+ (green)	+ (green)
	with erosion?		- (red)		-		- (red)		+ (green)		+ (green)							

Legend:	
- (red)	Unwanted trend (considered as a problem for the success of the MRM)
-	Unwanted trend (not considered as a problem for the success of the MRM)
+ (green)	Unwanted trend but with positive effects (considered as beneficial)
+	Unwanted trend but with positive effects (not considered as beneficial)

*) Habitat conservation, creation, restoration; and/or habitat compensation

In 5 cases, problems are described related to the sedimentation rate, where it was "too high" (accretion) or "too low" (erosion). More specifically, two different problems are observed: siltation of tidal water areas and too strong erosion for habitat development.

- *__Siltation of tidal water areas.__* In three cases, besides wetlands (marshes and intertidal habitat) also subtidal habitat was developed (E-Sp.B., W-VorHin, W-Kl.P.). The tidal water area was however silting up quite rapidly (or expected to be in case of E-Sp.B.). This has negative consequences for example for maintaining the water storage capacity. In case of **W-VorHin** the water storage capacity had decreased by 13% after 6 years. For **E-Sp.B.** it is expected that dredging will be needed every 4 or 5 years to keep the function. In case of **W-Kl.P.** the problems related to the sedimentation rate were already expected during the planning stage because the site is located in a turbidity zone of the Weser river. Therefore some adaptations to the site were made in the beginning (maintenance dredging and heightening of overflow barriers) in order to decrease the entry of suspended particulate matter (SPM), reducing the amount of sedimentation and leading to a consolidation of the bed substratum.

- *Too strong erosion for habitat development.* Two cases address the issue of too strong erosion (E-Wr.B. and S-Ket.). In case of **E-Wr.B.**, flow velocity in the creek was too strong for the development of mudflats. Therefore some site adaptations were made (closing one side of the creek and flattening the slope of the embankment), after which the area silted up completely. At the Ketenisse schor (**S-Ket.**) erosion was strong at the zones with a steep slope, causing limited habitat development in those parts of the site.

Also in 6 other cases unwanted evolutions related to the sedimentation rate occurred but here it was not considered to be a real problem for the success of the measure.

- *Siltation of tidal water areas.* At **E-Hahn.S.**, siltation of the shallow water area took place but overall the measure was successful to create mudflats (the area consists of 3% shallow water and 97% mudflats). However, the sedimentation rate was not monitored in the area, the accretion was only observed. At **E-Sp.Sp.** the sedimentation and erosion patterns within the measure were very divers due to the exposed situation between the Dove- and Northern Elbe. One year after implementation, the little pond that should function as resting and spawning area for several fish species showed high sedimentation rates. Therefore the development target of establishing a permanently water filled realignment area could only be partly achieved. In addition, some erosion was observed at the shore of the creek. But in the general, the measure was considered as a success because most biotopes developed well.
- *Mudflats evolve to marshes.* At **S-Lip.**, the sedimentation rate in the area is higher than expected which causes a fast flattening of the area. The topography of the site determines how the water will be spread; causing different flooding frequencies and hence different habitat types will develop (mudflats will become vegetated). However, the measure succeeded in creating a diverse wetland. Additionally, if the site elevates, storage capacity could be lost in the long run which is a problem since this area is developed as a flood control area. Hence, regarding the safety function the long term accretion could become a problem.
- In the case of Tegeler Plate (**W-Tegl.P.**) the sedimentation rate was lower and slower than expected. Heightening in areas of low current on the banks and endings of the creeks was observed, but was expected to be worse because the measure is located in the turbidity zone of the river Weser.
- At Paardenschor (**S-Paard.**), overall there is net sedimentation but large spatial differences were observed. The sedimentation rate is higher in the north-western part (low hydrodynamic in the shadow of the Schor van Oude Doel) and smaller in the southern part of the Paardenschor (high hydrodynamic, turbulence, waves, etc. in the opening to the Scheldt).
- At Heusden (**S-Heusd.**) also some interesting conclusions were made concerning the sedimentation. It was observed that the sedimentation is strongly related to elevation and therefore also with flood frequency and flood duration. Hence, sedimentation is stronger in the lower parts and lower at higher elevated parts.

To conclude, sedimentation related issues were also described as being beneficial in 5 cases.

- *Accretion is also important.* At Chowder Ness (**H-Ch.N.**) the import of fine marine sediments and hence elevation of the area was considered to be positive for site development (for mudflat invertebrates and saltmarsh plants) and also to ensure that the site would continue to increase in elevation as sea levels rise.
- *Erosion is important for the development of a creek network system*. In two cases (**S-Paard.** and **W-Tegl.P.**) local erosion was observed in the context of the development of a creek network system,

which is considered to be an important aspect for the site development (to create a good drainage system).

- *Mudflats evolve in marshes.* In two cases (H-Alk. and H-PHS), the evolution of mudflats into marsh land was observed and initially considered to be a problem because it was not according to the measure target but in the end the marsh land was also recognised as a valuable and priority habitat which made the measure successful.
    - The site of Alkborough (**H-Alk.**) became vegetated rapidly as it was also expected given the site design, the elevation and the restricted flooding. But this proved to result also in ecological valuable habitat: nursery area for fish and significant feeding and roosting area for birds. In this respect, the development of the site appears to have been beneficial to this region of the estuary which is otherwise largely characterized by narrow mudflats with species poor communities and, in most areas, little vegetation.
    - At **H-PHS**, even the lowest elevation sites were after five years beginning to show initial signs of colonisation by plants and, therefore, if this pattern of warping-up continues it is likely that the majority of the mudflat habitat of the north of the site will succeed to saltmarsh. It is considered that this evolution has negative implications because if the newly created mudflat eventually develops into saltmarsh then the habitat available to benthic invertebrates, and hence to foraging birds that rely on intertidal benthos, may be reduced in the longer term. However, saltmarsh habitats are also a valuable BAP priority habitat, and are in decline along other parts of the British coastline. Additional saltmarsh may provide high tide refuges for birds, as well as roosting and nesting sites.

The two latter cases illustrate that it is beneficial to be flexible with the measure targets because of the unpredictability of the very dynamic estuary. Very precise targets, such as the creation of a certain area of shallow water area or mudflats at a certain spot, tend to be very hard to realise in the dynamic context of an estuary. Many cases (discussed above) show that the dynamic sedimentation and erosion processes could obstruct this type of measure targets, even not considering all other estuarine processes.

In the context of the sedimentation rate, the combination of habitat creation and improvement of the safety function seems certainly possible but could be difficult to maintain. At Spadenlander Bush (**E-Sp.B.**), it is expected that dredging will be needed every 4 or 5 years to keep the safety function. In contrast, at Lippenbroek (**S-Lip.**) and Alkborough (**H-Alk.**), both implemented in 2006, no urgent problems related to the water storage capacity were observed. However, it is recognised that some problems are possible if the sedimentation rate is high on the long run.

Another topic is the trade-off that was observed in some cases, because the evolution in the sedimentation rate could be beneficial for some aspects of the site development but negative for others. At Kleinensieler Plate (**W-Kl.P.**) for instance, the aim to let the brackish water fauna benefit required a location that was under the influence of the turbidity zone. The rapid sedimentation however diminishes the entire shallow water habitats within a few years after realisation. In the case of Paul Holmes Strays (**H-PHS**), the sustainability of mudflat habitats appeared to be limited by the lack of exposure at this site which is however a trade-off with erosion and losses of natural saltmarsh along the frontage of the remaining sea defence and cost implications. Also the evolution of mudflats into marsh land implicates some trade-offs. If the newly created mudflat eventually develops into saltmarsh, then the habitat available to benthic invertebrates, and hence to foraging birds that rely on intertidal benthos, may be reduced in the longer term. But on the other hand, saltmarsh habitats are also a valuable BAP Priority habitat, and are in decline along other parts of the British coastline. Additional saltmarsh may provide high tide refuges for birds, as well as roosting and nesting sites.

In summary it could be stated that sedimentation rate is required but could also cause problems, depending on the specific measure objectives (Table 3-2). The targets habitat conservation and habitat compensation require high sedimentation rate, at least in the initial stage, for habitat and vegetation development. Furthermore, high sedimentation rate could be required or problematic depending on the targeted habitat type(s). To realise wetlands with mudflats and marshes, accretion is required. But if for instance a shallow water area is targeted, silting up of this area is considered as problematic. For the target safety, high sedimentation rate is problematic to maintain the water storage capacity. The success for the other targets (research and recreation) is less depending on the sedimentation rate.

Table 3-2. Link between the measure targets and if a high sedimentation rate is required or problematic.

Measure targets	High sedimentation rate
1. Habitat conservation, restoration	→ **Required** for (initial) vegetation development → **Required** or **problematic** depending on the targeted habitat type(s)
2. Habitat compensation	→ **Required** or **problematic** depending on the targeted habitat type(s)
3. Safety	→ **Problematic** for storage capacity
4. Research	/
5. Access and education	/

3.2. Optimisation regarding the sedimentation rate: MRM site selection and site design

Managers have to deal with the unpredictability of the estuary but this does however not mean that managers do not have the possibility to improve the success of the measure and for example reduce the need to dredge the sites. The following hypothesis is addressed in this study: the sedimentation rate on the site can be influenced by controlling the site location and site design, and hence the success of the measure could be improved.

Different aspects of the MRsite are studied in this part of the report to analyse their relationship with the sedimentation rate on the site. It is the aim of this study to better understand the link between the MRsites (both the location within the estuary and the design of the site) and the sedimentation rate and to formulate recommendations to enable managers to improve the selection and design of the site and hence the success of the measure.

When managing an estuary it is important to understand the dynamic character of it. Translation from [43]: *The evolution of restoration projects depends on preconditions defined by interacting factors determined by the local characteristics of the system and the design of the restored area (location of the area along the estuary, history, physical dimensions, topography and geology). The preconditions control the physical processes in the area (sedimentation and erosion), determining for creek development, soil development and changes in the water storage capacity. They are also responsible for ecosystem responses, modelling the structural characteristics of the area and fulfilling ecosystem functions (temporal processes). The main structural characteristics are soil texture, biogeochemics, habitat development and species response (species diversity, density/cover, and biomass). The main ecosystem functions are biochemical functions, primary and secondary production. Biotics and abiotics influence each other constantly in a dynamic environment forming repeatedly dynamic equilibrium situations. If changes occur on one of the key factors or processes, the development will adapt proportionally, even in an area in a dynamic equilibrium. Intervention in the development of an area could be realised by adaptive management of the design depended factors.*

A range of key physical processes and morphological parameters are defined that need to be considered [44]. This includes the morphological regime (topography: level and gradient; and presence of morphological features: such as creeks and deltas); the hydrodynamic regime (tidal levels and range, tidal prism, tidal current velocities, tidal asymmetry, and wave action); and the sediment regime (sediment composition, sediment budgets, and sediment transport: bed load and suspended load).

To analyse the determining factors of the sedimentation rate, a first difference is made in this study between outer-dike and inner-dike areas, which depend on the connection to the river (with or without a construction). In the second part the impact of the <u>location of the area within the estuary</u> on the sedimentation rate is analysed. This includes the location in the different estuarine zones and related salinity, SPM and turbidity zones, location at a river bend, and hydrodynamics in the site. Finally, the impact of <u>design characteristics</u> of the site on the sedimentation rate is studied: initial elevation and inundation, slope of the area, and opening to the river.

3.2.1. Inner-dike versus outer-dike sites

Regarding the sedimentation rate on the site, an important distinction has to be made between inner-dike and outer-dike sites (Table 3-3). In this study, outer-dike sites are defined as the areas that are under direct influence of the river and hence under influence of the full tidal range. The inner-dike sites are defined as areas with a hydraulic constriction by a (narrow) construction (eg. sluice, sill or overflow barrier) in between the site and the estuary, resulting in a damped tidal range on the site. It is expected that the sedimentation and erosion processes will differ between outer- and inner-dike sites due to the different site conditions, depending on water depth, residence time, concentration of suspended matter in the water column, erosion forces etc.. The Kleinensieler Plate is an example for a measure with more or less outer-dike character at the beginning which later on has been converted into an inner-dike site. By this water exchange, sediment entry and sedimentation rate has decreased significantly.

Table 3-3. Overview inner-dike and outer-dike TIDE MRMs

	Elbe	Scheldt	Weser	Humber
Inner-dike[1]		S-Lip.	W-Ronn.S. W-VorHin W-Kl.P.	
Outer-dike[2]	E-Sp.B. E-Wr.B. E-Hahn.S. E-Sp.Sp.	S-Ket. S-Pad. S-Paard. S-Heusd.	W-Tegl.P. W-Cap.S.N.	H-Alk. H-PHS H-Ch.N.

1) *Inner-dike sites*: with a (narrow) construction between the river (eg. sluice, sill, overflow barrier…)
2) *Outer-dike sites*: in direct contact to the river

Theory: sedimentation on inner-dike vs outer-dike sites, and CRT vs natural tidal marsh

Inner-dike areas are characterised by restricted tidal exchange (significant damping of tidal action) because of the hydraulic constriction of a narrow levee breach or small inlet channel. This reduces the volume of sediment entering the site on the flood tide, proportionally to the reduction in tidal prism, extending the time of evolution [28]. Damped tides could also inhibit vegetation colonization by increasing the inundation period at low elevations. Over time those impacts will however change because scouring action tends to enlarge the constrictions on the tidal exchange, eventually restoring full tidal exchange (a full tidal range within the site).

In case of a CRT[5], the potential for sedimentation is higher because the environment inside is less dynamic and the tidal cycle is modified with longer stagnant phases. As a consequence, the elevation change is higher in a CRT marsh compared to a natural marsh [30]. This is in addition also a consequence of absent (or limited) eroding processes in the area because drainage is limited. Within the area, temporal variations in marsh sedimentation rates exist due to variations in tidal inundation (frequency, height, duration) and seasonal variations in suspended sediment supply [30]. High elevated sites have low rates in surface elevation increase, low mean water depths and elevation change rates do not change rapidly. Low elevated sites, only in the CRT marsh, have initially high rates in surface elevation increase. Consequently these sites get less flooded with time, and elevation change rates progressively decrease.

In case of a natural tidal marsh, the variations in sediment deposition are explained by the tidal inundation (frequency, height, duration), the distance from the creeks and the distance from the marsh edge [30]. The higher a marsh platform is located in the tidal frame, the less it is inundated and the smaller the increase in elevation is, and furthermore the sedimentation rate is typically highest close to channels and decreases with increasing distance from channels (i.e., increasing distance from sediment source) [30]. On a CRT marsh however, only the tidal inundation parameter (i.e. mean water depth) influences the sediment deposition. Distance from creeks and distance from marsh edge (i.e. inlet sluice) play a minor role.

[5] A CRT (Controlled Reduced Tide, such as **S-Lip.**) is a special case of inner-dike areas. The special tidal regime is initiated through a culvert in the embankment. Hence, the tidal curve is strongly deformed with lower and longer inundations. In this way tidal water levels are significantly lowered so that a CRT marsh can develop on formerly embanked land with a lower elevation than the natural tidal marshes (ca. 3 m lower in case of S-Lip.).

A CRT has the advantage that by managing sluice dimensions and volumes of water exchange, the safety function could be improved (e.g. by reducing volumes of water and sediment import) and it also may force the restoration of the CRT marsh towards a specific stage in marsh succession (e.g. the lost lower marshes of the Scheldt estuary) [30].

TIDE cases

In case of the TIDE measures, the average sedimentation rate in the inner-dike examples is higher compared to the outer-dike sites: 18.67 cm/year versus 5.78 cm/year (but this difference is not significant: F(1,10)=2,42; p=0,15) (Figure 3-4 a, b). However this involves only three inner-dike cases with the sedimentation rate available, including the outlier **W-Kl.P.**. Without the outlier W-Kl.P., the average sedimentation rate in the outer-dike examples (5.78 cm/yr) is higher compared to the inner-dike examples (3.5 cm/yr), however not significant (F(1,9)=0,48; p=0,51) (Figure 3-4 c).

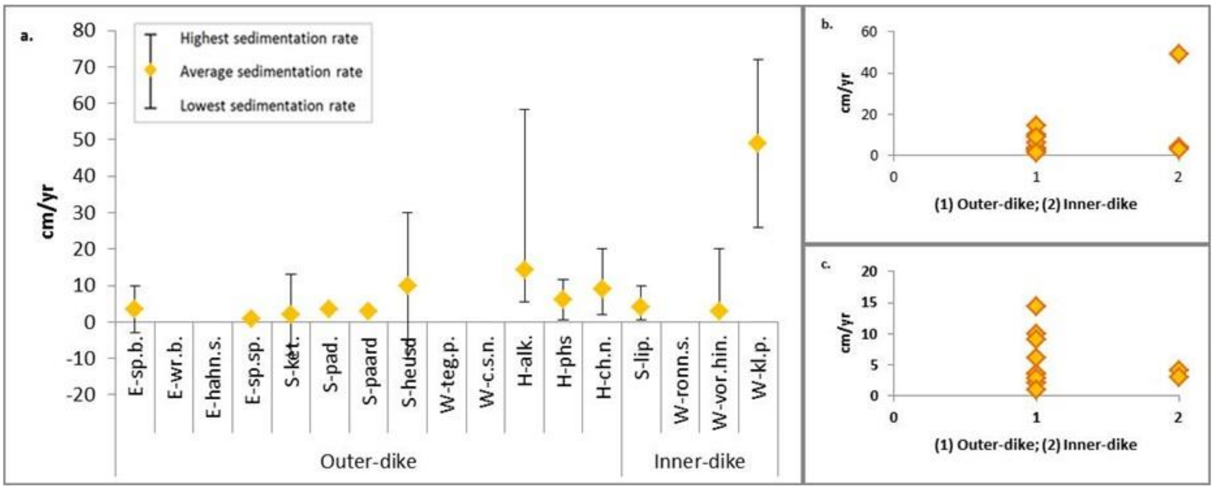

Figure 3-4. (a) Average sedimentation rate of outer-dike and inner-dike TIDE MRM, with indication of the highest and lowest measured (or monitored) sedimentation rate as error bars. (b) Difference between the average sedimentation rates of outer-dike versus inner-dike sites. (c) Difference between the average sedimentation rates of outer-dike versus inner-dike sites exclusive the outlier W-Kl.P..

3.2.2. Factors related to the location of the site in the estuary

3.2.2.1. Estuarine zones (TIDE-km)

The average sedimentation rate is not related to the location of the site along the estuary (relation with TIDE-km is not significant: $R^2=0.0014$; $T=0.12$; $p=0.91$), nor to the location in a certain estuarine zone (freshwater, oligohaline, mesohaline or polyhaline) (Figure 3-5).

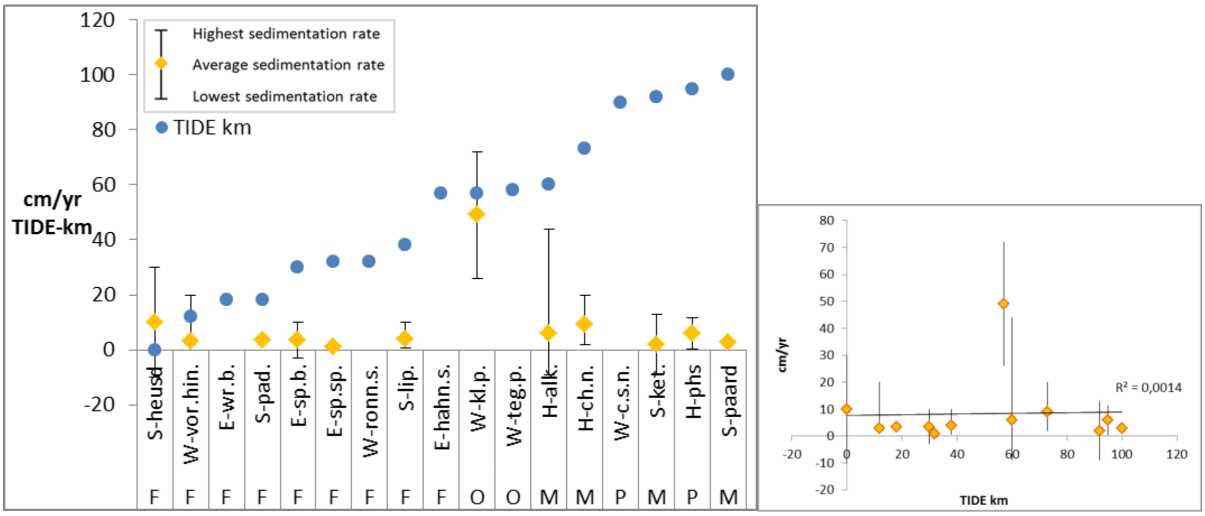

Figure 3-5. (a) Average sedimentation rate for the TIDE cases along the estuary (TIDE-km) and with indication of the zone Freshwater (F), Oligohaline (O), Mesohaline (M), Polyhaline (P). (b) Correlation between average sedimentation rate and the TIDE-km.

3.2.2.2. Turbidity zone: sediment load in the river (near the measure site)

The physical evolution of a subsided restored site to a vegetated marsh depends, besides many other factors, on the sediment supply (Figure 3-6). Long-term average suspended sediment concentrations brought into the site with the flood tide are influenced by the long-term sediment budget of the estuary and by the proximity of the site to the estuarine circulation turbidity maxima or proximity to extensive intertidal mudflats where sediment can be locally re-suspended by wave action. Sediment concentrations tend to be lowest for interior marshes, furthest from the estuarine sediment supply [28].

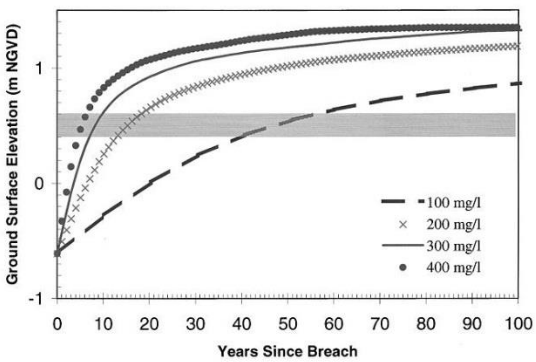

Figure 3-6. Effect of suspended sediment concentration on marshplain evolution over time for a site sheltered from wind wave action. Shaded bar identifies the approximate Spartina *colonization elevation. Prediction is based on tides at the Presidio, no sea level rise and 550 kg/m³ dry density of inorganics typical for San Francisco Bay. NGVD, National Geodetic Vertical Datum, is a vertical datum fixed at the mean sea level of 1929. From [28].*

TIDE cases

The Suspended Particulate Matter (SPM) data is based on measurements in the river near the project areas [45]. The accuracy of the SPM data depends on the distance between the measure point and the project area. Therefore, this data is corrected if local data was available [11, 13, 14]. But even with local data, it is not guaranteed that all suspended matter also enters the project area. This is even more true for inner-dike areas because the volume of sediment entering the site on the flood tide is reduced proportionally to the reduction in tidal prism [28]. At least for the inner-dike areas, but also for the outer-dike areas, the SPM data is hence to be considered as an over-estimation.

Overall, the average SPM near the TIDE cases amounts 200 mg/l, ranging from 38 mg/l (**E-Wr.B.** & **E-Sp.Sp.**) to 700 mg/l (**W-Tegl.P.** & **W-Kl.P.**) (Figure 3-7). The latter cases are indeed located in the turbidity zone of the Weser river, i.e. influenced by the tide of water with high rates of suspended sediment. As expected, the sedimentation rate is higher at sites with high SPM (R^2=0,68; T=4,6; p<0,001) and also without the outlier W-Kl.P. (R^2=0,62; T=3,8; p=0,0039). The same relationship is also observed both for outer-side areas (R^2=0,62; T=3,36; p=0,012) and inner-side areas (R^2=0,99; T=84,85; p=0,0075) (Figure 3-8). However, due to a very small sample size we have to be careful to make overall conclusions.

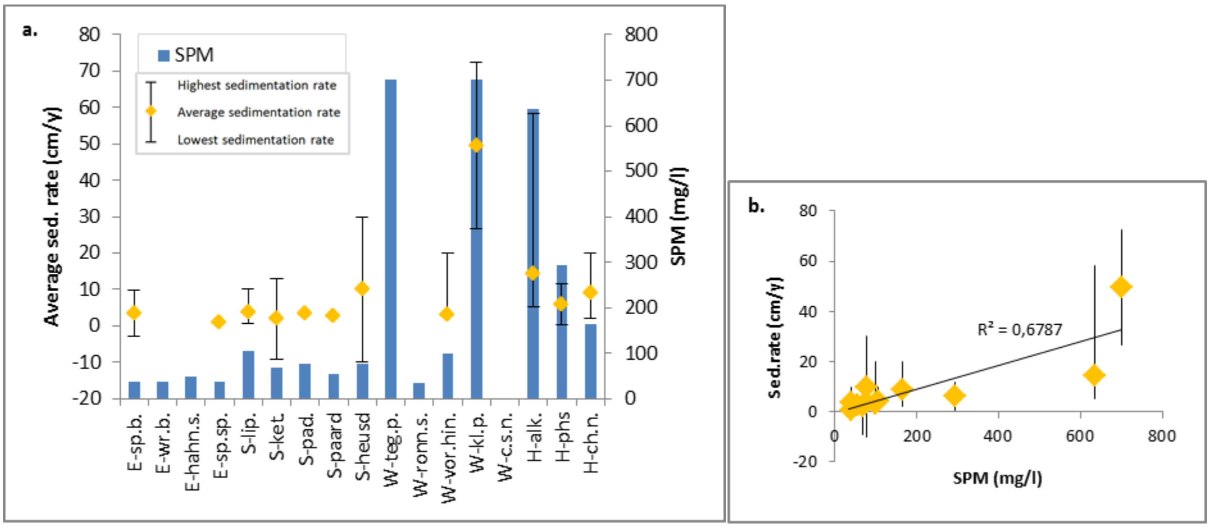

Figure 3-7. (a) SPM and sedimentation rate for all TIDE examples. (b) Correlation between SPM and the average sedimentation rate on the site.

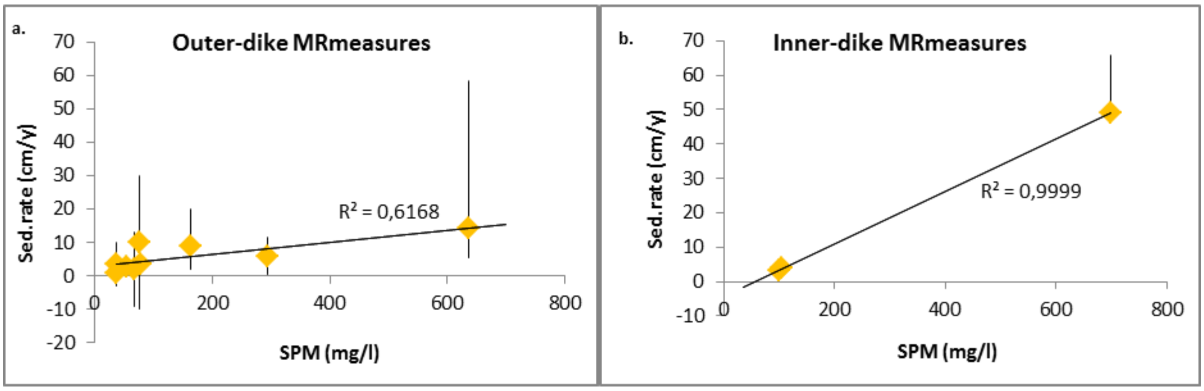

Figure 3-8. Correlation between SPM and the sedimentation rate on the outer-dike (a) and inner-dike (b) sites.

3.2.2.3. Located at a river bend (inner or outer side)?

It is expected that the sedimentation rate will be higher at sites located at the inner side of a river bend versus at the inner side, because here current velocity is lower. This is however mainly expected for outer-dike sites because these sites are under full influence of the river.

For the TIDE outer-dike measures, the average sedimentation rate amounts 5.70 cm/y. TIDE outer-dike measures located at the outer or inner side of a river bend have a similar average sedimentation rate (difference is not significant: $F(1,5)=0{,}16$; $p=0{,}71$) (Figure 3-9). However, the sample range is very small (only measures with data on average sedimentation rate available): two measures located at the outer side, five measures at the inner side and two measures partially inner and outer side of a river bend. Hence, based on the TIDE examples we are not able to make conclusions about the link between the location of an MRM site at a river bend and the average sedimentation rate.

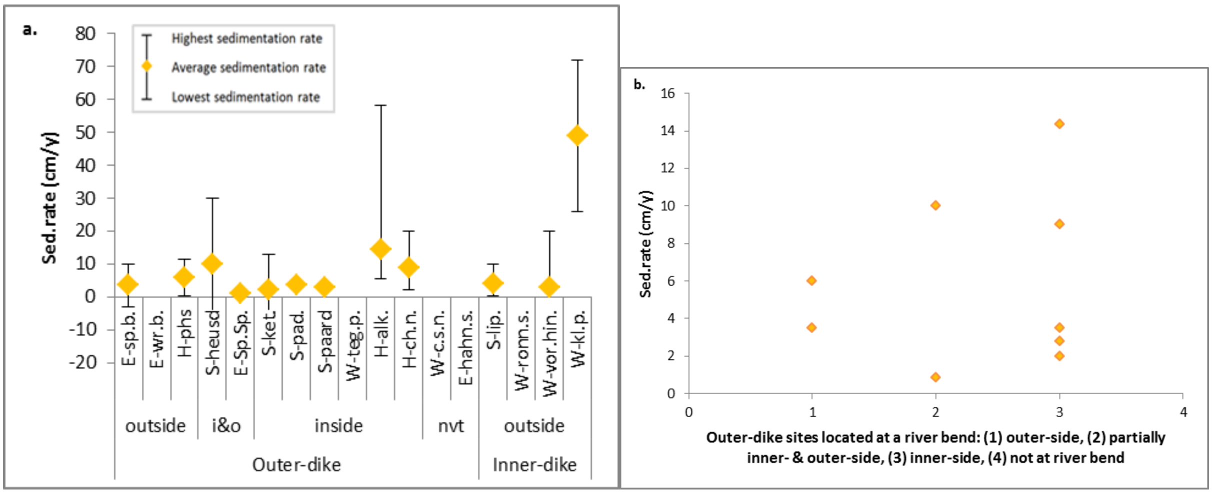

Figure 3-9. (a) Sedimentation rate of outer-dike and inner-dike measures located at the outer-side or inner-side of a river bend. 'i&o': measures located partially at the inner- & outer-side of a river bend. 'nvt': measures not located at a river bend. (b) Difference between sedimentation rate and the location of outer-dike measures at a river bend: (1) outer-side, (2) partially inner- & outer-side, (3) inner-side, (4) not at river bend.

Link with SPM

It was already shown that the sedimentation rate on the site is higher in case of higher SPM inflow, both for outer-dike and inner-dike measures (Figure 3-8). In case of the outer-dike measures this relationship is not observed for the sites located at the outer-side of a river bend ($R^2=0{,}087$; $T=0{,}44$; $p=0{,}70$), but it is observed for the sites located at the inner-side of a river bend ($R^2=0{,}64$; $T=2{,}98$; $p=0{,}03$) (Figure 3-10). Hence, even for sites located at the inner-side of a river bend (where current velocity is high), sedimentation rate will be higher in case of higher SPM.

It is not possible to make conclusions from the TIDE outer-dike sites located at the outer-side of a river bend because the sample range is very small and all cases have low SPM values.

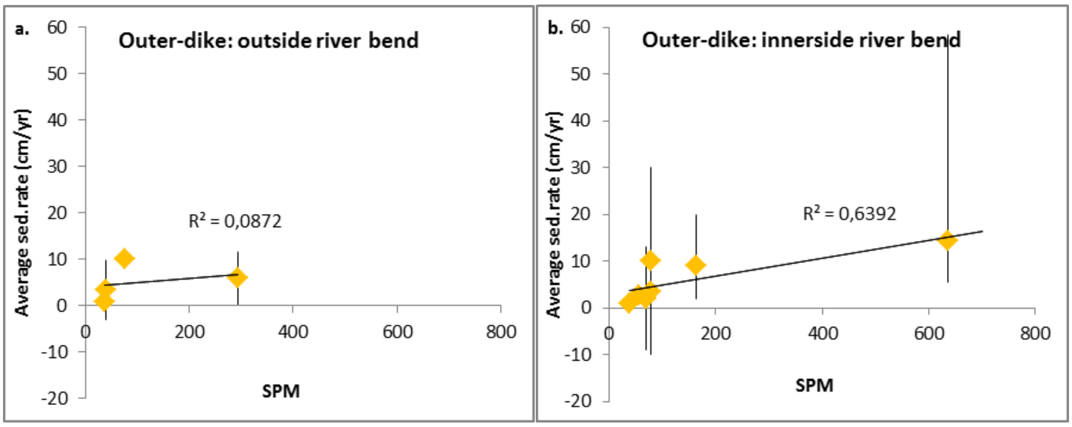

Figure 3-10. Correlation between SPM and sedimentation rate of outer-dike measures: located at the outer-side (a) or at the inner-side (b) of a river bend.

3.2.2.4. Hydrodynamics in the area

The exposure of the realignment area to the turbulence of the estuary (eg. wave action from tidal, wind and from ships) also proved to influence the sedimentation and erosion patterns in the area [28]. Areas with too high tidal dynamism, for example, could be characterised by inadequate sedimentation which could lead to only bare mudflats without marsh development. In contrast, sheltered zones and depressions could face high sedimentation rates by which mudflats disappear and only marshes remain.

TIDE cases

At Ketenisse (**S-Ket.**) it was observed that the sedimentation rate was directly proportional to shelter (width of the area on open tidal areas and distance from the breach in breached areas). Net sedimentation was monitored at lower and sheltered areas (depressions) and erosion at exposed intertidal areas. The latter zones also corresponded to areas with a steep slope (at shorelines and cliff).

Also at Paardenschor (**S-Paard.**) the inverse link between sedimentation rates and the hydrodynamics in the area was observed. Higher sedimentation rates were monitored at the low hydrodynamic zones (in the shadow of the Schor van Oude Doel) and smaller sedimentation rates in high hydrodynamic zones with turbulence, waves etc. (in the opening to the Scheldt) (Figure 3-11).

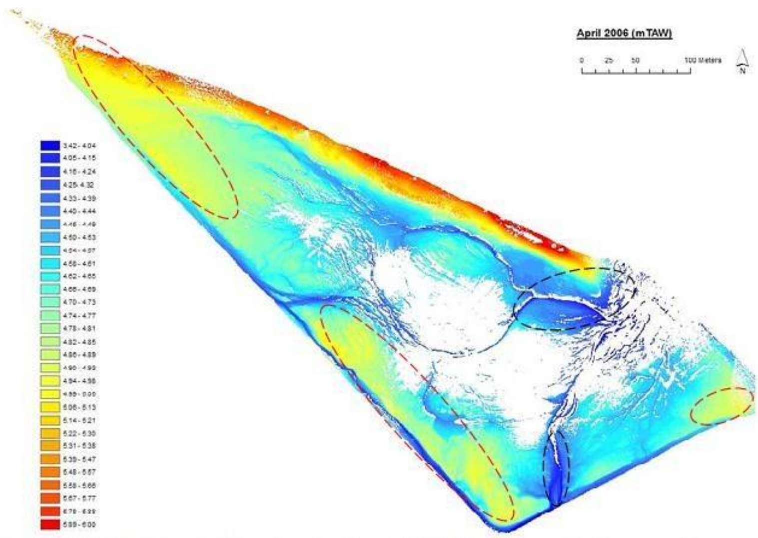

Figure 3-11. 3D-picture of the Paardenschor in April 2006. The red circled zones are elevated relatively high corresponding to low hydrodynamic zones, the black circled zones low corresponding to high hydrodynamic zones. [24]

A similar conclusion came from Chowder Ness (**H-CH.N.**) where the lowest accretion rates were thought to be characterised by: a wide connection to the estuary (essentially a very wide breach); exposure to significant fetch from the predominant wind direction; and relatively high flows due to its proximity to the main Humber navigation channel and the Humber Bridge (the latter constriction causing higher flows).

A Controlled Reduced Tide (CRT), such as Lippenbroek (**S-Lip.**), is special in many ways. A clear relationship between sedimentation and hydrodynamics was observed. Because this CRT is completely embanked and with reduced tide, dynamism in the area is low and it risks more sedimentation. Also, during the stagnant phase (typical for a CRT, cf. Figure 3-14) the water is stable for some hours and suspended matter can deposit.

Also at Paul Holmes Strays (**H-PHS**) the more sheltered nature of the mudflat inside the realignment was indicated as reason for higher accretion at lower elevations compared to the same elevations outside the realignment, i.e. 'settling-tank' effect of accretion.

3.2.3. Factors related to the design of the site

Sedimentation and erosion processes on MR sites are the overall result of the wider estuarine context (cf. part 3.2.2 Factors related to the location of the site in the estuary), but also of characteristics of the restored site itself. In many cases it is illustrated that sedimentation and erosion processes strongly vary between study areas as well as in the different zones of one area, depending on a combination of different characteristics. At Ketenisse (**S-Ket.**) for instance, there is overall net sedimentation, but in some zones net erosion takes place and in other zones no sedimentation or erosion is observed. It was proven that in this particular case the differences in zones with erosion and sedimentation are closely linked with the slope of the different zones. Erosion took place at a large exposed intertidal area characterised by a steep slope (consequence of the construction work), as well at the shoreline and at the top of the cliff. Net sedimentation occurred at the lower and sheltered areas; at these areas some depressions filled up relatively quickly. Only at the supratidal areas (close to the dike), little change occurred.

Overall, following site characteristics are considered as determining for global and local sedimentation and erosion processes: initial elevation (lower vs higher zones), inundation (flood frequency and duration high vs low), slope (weak vs steep), opening to the river and hydrodynamics in the area, vegetation at the site, drainage and creek system development.

3.2.3.1. Site topography: elevation and inundation

Elevation appears to be the main influence on patterns of accretion and saltmarsh vegetation, with implications for benthic invertebrate diversity and hence bird usage of the site. In general, sedimentation is stronger in the lower parts and lower in the more elevated parts (**S-Lip.**, **S-Pad.**, **S-Heusd.**, **H-PHS**). This inverse relationship between elevation and accretion rates inside the realignment site is a consequence of the tidal regime in the area, i.e. lower parts will be flooded more frequent and for a longer time and hence more sediment could be deposited [25, 34] (Figure 3-12 a). It is proved that there is a positive relationship between inundation frequency and the accretion rate and hence with elevation (Figure 3-12 b, Figure 3-13). At Lippenbroek (**S-Lip.**), the highest sedimentation rate was observed at sites inundated around 85% of the time (Figure 3-12 b). At Alkborough (**H-Alk.**), low sedimentation accretion was observed at areas with low predicted inundation (with 100 inundations per year), and high sedimentation accretion at areas with high predicted inundation (with more than 500 inundations per year).

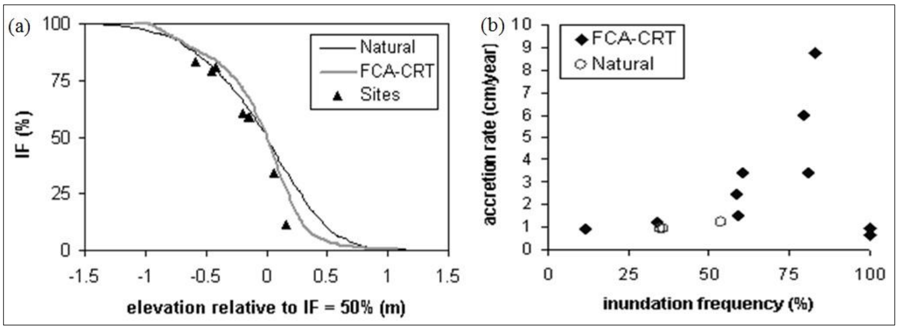

Figure 3-12. (a) Inundation frequencies in the adjacent marsh and in the pilot CRT in function of elevation. Elevation is expressed relative to the level corresponding with an IF of 50%. Based on tidal data for the period March 2006 – March 2008, this IF corresponds to 5.63 m TAW on the reference marsh and 3.02 m TAW in the CRT. Black triangles represent the different research sites in the CRT. (b) Average accretion rate in function of IF at the three sites on the adjacent marsh (reference sites at "De Plaat") and at all sites in the pilot CRT. Two sites have an IF of 100% (site 8 and 9), both are located in an intertidal pool. Source: [25].

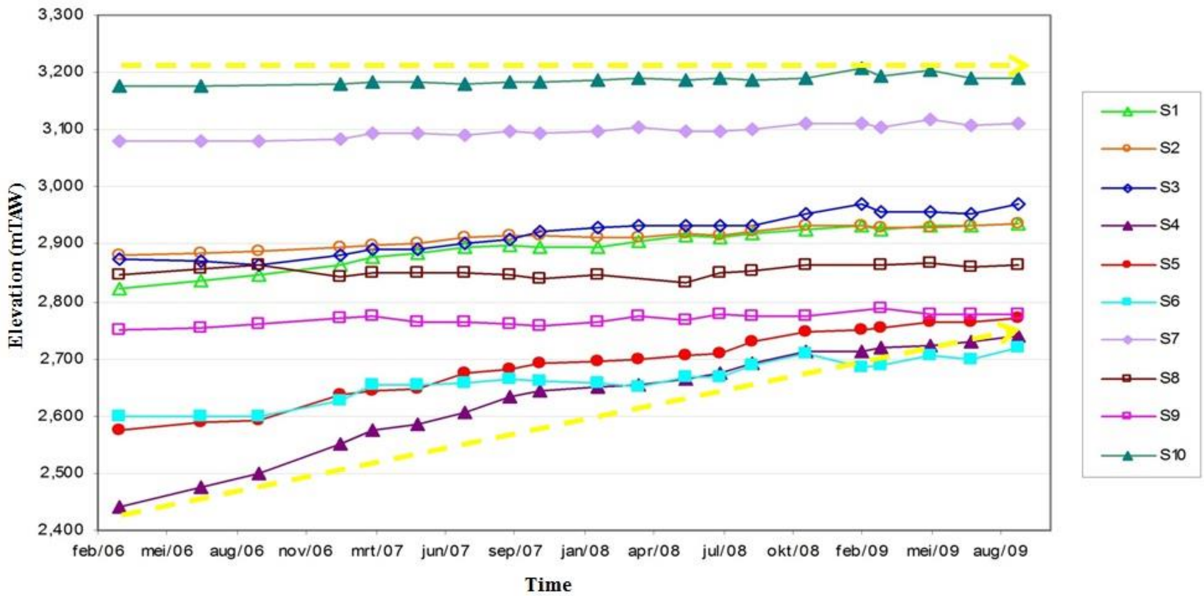

Figure 3-13. Comparison of sedimentation in the time at the 10 sites of Lippenbroek, February 2006-August 2009: elevation changes (m TAW) [25, 26]. Lower sites (eg. 4 and 5) are characterised by higher sedimentation rates and hence elevate much more over time than higher sites (eg. 7 and 10), indicated by the yellow arrows.

The elevation of the area in relation to mean high water level is hence important for the sedimentation rate and hence the habitat development on the site.

- Areas that are located much lower than mean high water level are quasi constantly flooded. Those areas will develop as mudflats and vegetation development is not possible. Marsh development is however still possible, if sediment supply is 'high' and local conditions make sediment deposition possible. But this process could last for some years, time that is not always available if marsh loss has to be compensated for. Failing marsh development in realignment projects is often caused by an inappropriate elevation of the area. The project sites are often located to low. An elevation at mean high water level is considered as an optimal condition for realignments. Old polders are often located much lower as a consequence of increasing water levels and alignment of the areas.
- In contrast, areas that are located above mean high water level show very little geomorphological changes. But also in those areas, very local patterns of accretion and erosion are possible for instance due to resistant layers on the surface.

<u>**Outer-dike versus inner-dike sites**</u>

The tidal influence proofed to be an important aspect regarding sedimentation and erosion processes on the site and hence also for habitat and vegetation development. In this prospect, it is however important to make a difference between outer-dike and inner-dike measures. In natural marshes (outer-dike), an increase in elevation would lead to a decrease in flooding frequency and a consequent gradual decrease in sedimentation. This is however not the case for inner-dike measures. Indeed, by the construction of inner-dike measures the water inflow is restricted (by any kind of construction such as small breach, sill, sluice, or overflow barrier) meaning that inundation in the first place depends on the water inflow in the area (discharge). The tidal range on inner-dike sites will hence also be smaller compared to the tidal range in the river, depending on the dimensions of the inflow (Figure 3-14, Figure 3-15). The distribution of the water in the area depends however also on the elevation of the area; water depth will be larger at lower laying areas. Consequently, the relationship between inundation and sedimentation rate is similar as outer-dike natural areas (Figure 3-12 a). The difference is that inundation will not change correspondingly to changes in elevation, as it is the case in outer-dike natural areas. This is true if the discharge remains constant. In some cases however the dimensions of the opening to the river could change and consequently also the discharge, for instance due to erosion or sedimentation processes at the entrance.

A Controlled Reduced Tide (CRT) is a special case of an inner-dike measure where the inflow and outflow regime is highly controlled. The pilot project Lippenbroek (**S-Lip.**) proved that by implementing a CRT with high inlet and low outlet, a high variation of inundation frequencies is possible. This simulates a traditional spring-neap tide cycle which is however characterised by a restricted tidal range and a stagnant phase in the cycle (Figure 3-14, Figure 3-15). An important condition however is that the inlet construction has to be high enough (4.70 m at Lippenbroek) because only then enough variation in the water entering duration and –volume to enable the high variation in water levels in the polder. As a consequence, this technique makes it possible to create an intertidal habitat in low elevated areas not suitable for the traditional realignment because then the area would be flooded all the time (located much lower than MHWL). This is very useful, since many old polders are located very low due to increasing water levels and historical land reclamations.

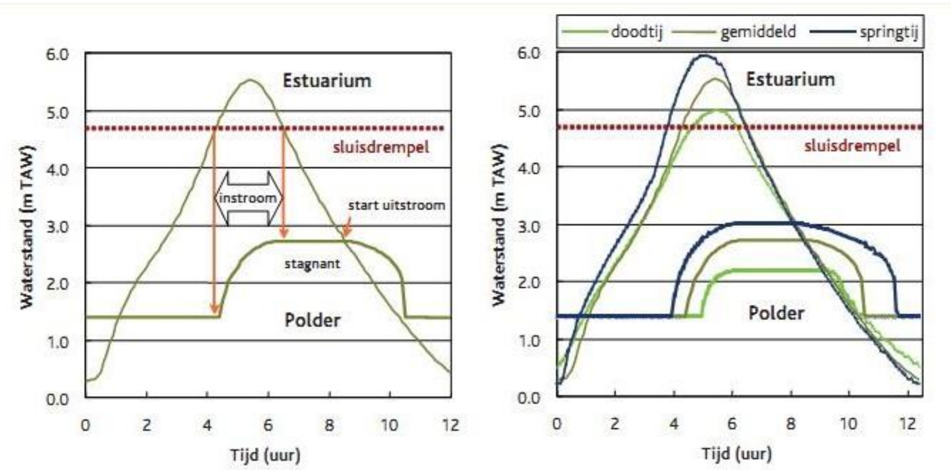

Figure 3-14. Modelling (1D) of the tide in CRT Lippenbroek for an average tide, with indication of in-stream and out-stream. The tidal difference between the end of the in-stream and the start of the out-stream results in a stagnant phase. The right panel visualises the same modelling for neap-, average- and spring tide. Only with a high inlet culvert the difference in in-stream will be large enough to result in large spring-neap tide variation. Source: [46].

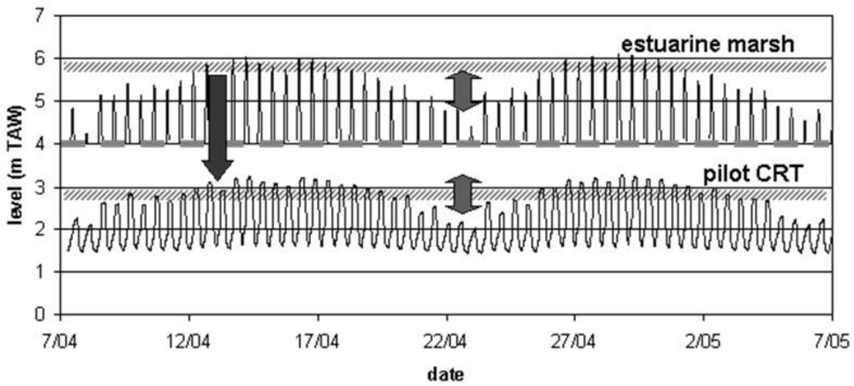

Figure 3-15. Tidal waves in Scheldt and the pilot CRT (Lippenbroek). Hatched areas indicate the elevation of the adjacent marsh and the mean surface elevation of the polder. The big arrow indicates the reduction of the high water levels by about 3 m. The smaller arrows show that the difference between HW spring tide and HW neap tide is preserved in the CRT. Note that for the tidal curve of the Scheldt, only the upper parts (above 4 m TAW) are shown. Source: [25].

TIDE cases: elevation relative to tidal frame

The initial site elevation is only meaningful in relation to the tidal range, because this determines the tidal regime and inundation in the area, and hence the sediment inflow, the possibility for sedimentation and consequently habitat and vegetation development.

Data on the initial site elevation (both lowest and highest point of the area) and the tidal regime (MHWL and MLWL) is collected for all TIDE cases (Figure 3-16, Figure 3-18). Data on the initial site elevation is gathered from the project description and monitoring results [2-19]. Data on the tidal range, MHWL and MLWL are based on the TIDE hydro- and geomorphology study [45]. Unfortunately, the data set is not complete for all measures. For some cases, data on site elevation is missing (**E-Hahn.S.**, **S-Heusd.**, **W-Cap.S.N.**, **W-Ronn.S.**) or incomplete (**S-Paard.**, **H-Alk.**, **W-VorHin**).

Outer-dike sites

The average tidal range for all outer-dike TIDE cases is **3.9 m**, ranging from 2.9 m (**E-Wr.B.** and **S-Pad.**) to 5.17 m (**S-Paard.**).

- The *average MHWL* is 3.3 m TAW (or m NN, or m OD), ranging from 1.6 m TAW (**W-Cap.S.N.**) to 5.25 m TAW (**S-Paard.**).
- The *average MLWL* is -0.6 m TAW (or m NN, or m OD), ranging from -2.2 m TAW (**H-PHS**) to 2.43 m TAW (**S-Heusd.**).

Only at the Scheldt cases, MLWL is positive (above 0 m TAW). In all other cases, MLWL is negative. Also MHWL is highest at the Scheldt cases. The tidal regime is similar at the three other estuaries. Also per estuary, clear similarities in the tidal regime are observed (Figure 3-16).

The elevation of most TIDE cases is situated around MHWL, which is also considered to be the optimal condition for realignments (Figure 3-16: orange circles). At two cases (**E-Sp.B.**, **E-Sp.Sp.**), the lowest point of the area is however much lower, i.e. situated around MLWL indicating the existence of areas permanently covered with water (Figure 3-16: purple circle).

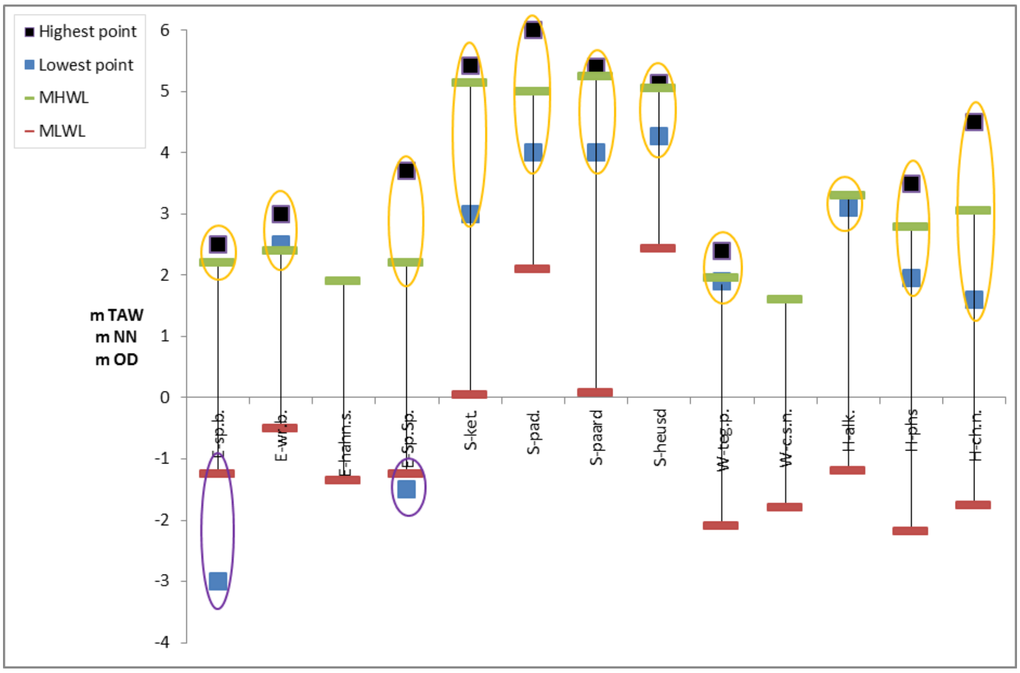

Figure 3-16. Initial site elevation of the outer-dike TIDE MRMs (lowest and highest point in the MR site) and tidal amplitude (MHWL and MLWL).The orange circles indicate sites located around MHWL. The purple circle indicates a site with the lowest point around MLWL.

Link with the sedimentation rate

S-Paard.: Spatial differences in erosion and sedimentation patterns are observed at **S-Paard.**, with higher accretion at the zones that were initially lowest in elevation and vice versa (Figure 3-17). This pattern is however not true for the two deepest points, i.e. drainage channels characterised by erosion.

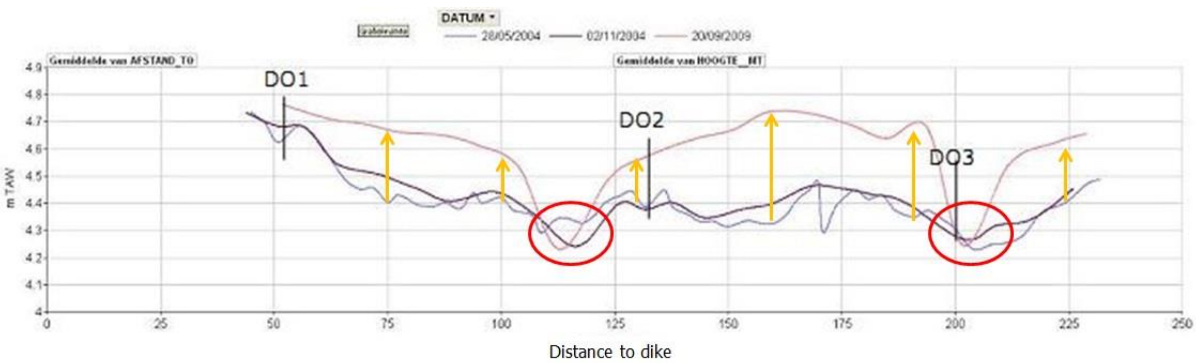

Figure 3-17. Changes in elevation (orange arrows) at Paardenschor between 2004 and 2009. The drainage channels (with erosion) are indicated by a red circle.

Inner-dike sites

The different characteristics of inner-dike sites results in the need to compare the elevation of the area with the tidal regime on the site which will be restricted compared to the tidal regime of the river. For Lippenbroek (**S-Lip.**) the tidal range on the site is 1.3 m, which is much smaller than the 5.5 m of the Scheldt near the Lippenbroek site. This large difference is also observed for the other TIDE inner-dike measures (Figure 3-18 a). The average tidal range for all inner-dike TIDE cases is **0.76 m**, ranging from 0.15 m (**W-Kl.P.**) to 1.3 m (**S-Lip.**). This is indeed much lower compared to the tidal regime for outer-dike cases.

The data of the MHWL and MLWL on the site is however lacking for most of the inner-dike cases. The tidal range is therefore plotted in between the tidal range off site (in the river) to illustrate the large difference (Figure 3-18 b). Only for **S-Lip.**, the data is complete and the elevation of the site is also situated around MHWL (Figure 3-18 b: orange circle), as it is also the case for most outer-dike measures (Figure 3-16).

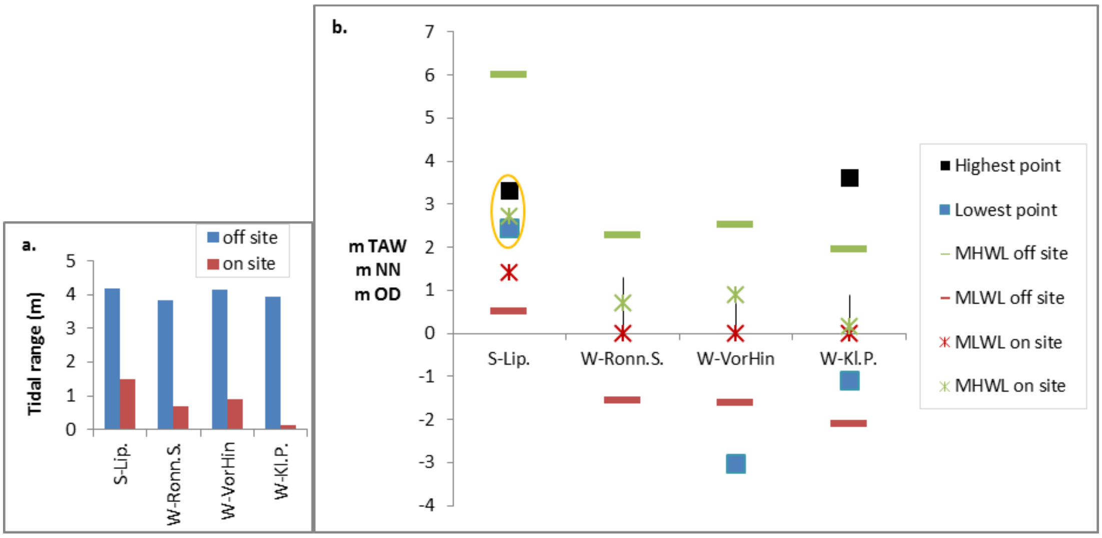

Figure 3-18. (a) Mean tidal range for inner-dike areas (off site versus on site). (b) Initial site elevation of inner-dike TIDE MRMs (lowest and highest point) and tidal amplitude (MHWL and MLWL) both off site and on site.

Link with the sedimentation rate

S-Lip.: The inverse relationship between elevation and sedimentation rate was already illustrated for S-Lip. (Figure 3-13). The lowest elevated zones (site numbers 4, 5, 6) are characterised by the largest elevation increase. This corresponds to the spatial variation in the sedimentation rate (Figure 3-19). Furthermore, no net accretion was monitored at sites in the tidal pool (site numbers 8 and 9).

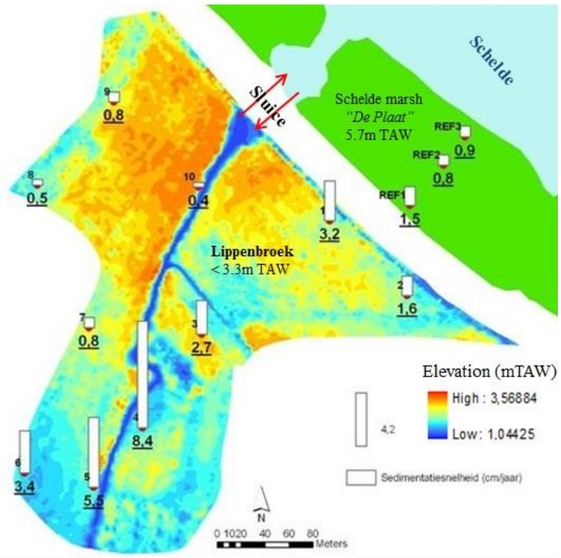

Figure 3-19. Spatial variation in sedimentation rate (cm/year) at Lippenbroek and the adjacent reference site (marsh "De Plaat"). The little numbers indicate the SET sites the underlined numbers is the sedimentation rate. Sedimentation rates are counted for the period between March 2006 and September 2009. The morphology of Lippenbroek is represented based on the digital elevation model of Flanders for the original polder (before the introduction of CRT in March 2006). [26]

W-VorHin: The global distribution of shallow and deeper water areas did not basically change between 2004 and 2010. However, within the shallow water zones and ponds, the water depth decreased locally up to 1 m between 2004 and 2010 (Figure 3-20). This resulted in a decrease in the water volume in the area at tidal low tide: decrease with 615m³ between 2004 and 2006, and with 7267m³ between 2006 and 2010 [47]. Only pond 1 (at the entrance to the area) is not affected by siltation.

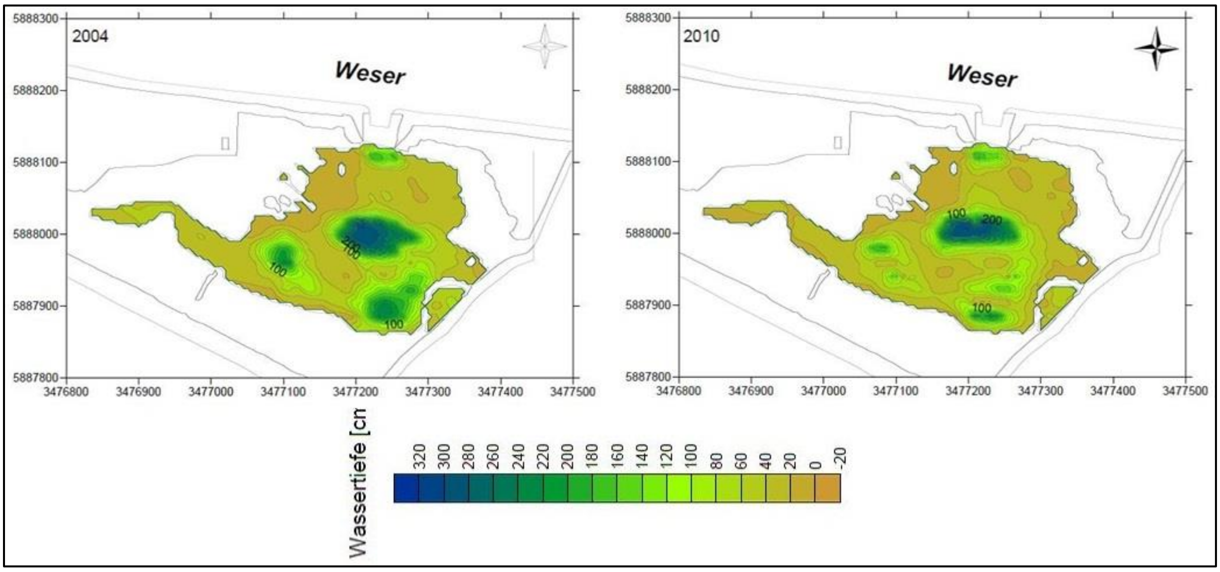

Figure 3-20. Water depth in the Vordern- und Hinterwerder in 2004 and 2010 [47]

W-Kl.P.: Although the tidal influence on the project area is restricted by three overflow barriers (invert at -0.5 MHWL), the project area is regularly influenced by the tides. This resulted in a strong accretion of the lagoon, with accretion of more than 2m at the deepest spots (Figure 3-21). The deepest zones of the lagoon were deeper than 1m NN in 2000, but in 2002 no zones deeper than 1m NN existed anymore and the share of shallow water increased a lot. This was also the reason why the lagoon needed dredging in 2004 to restore the deeper subtidal habitat.

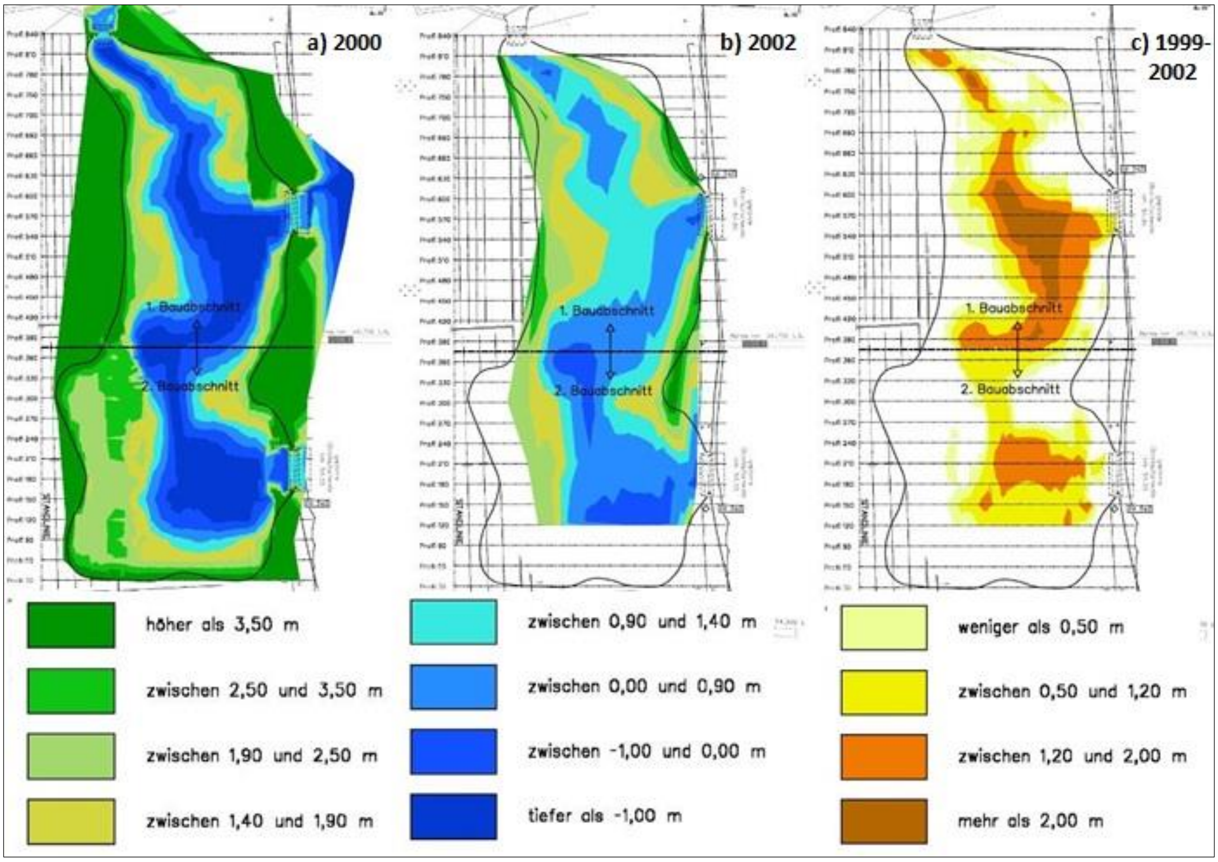

Figure 3-21. Topography and bathymetry (elevation in m NN) at Kleinensieler Plate: (a) in 2000; (b) in 2002; (c) difference between 1999 and 2002: largest difference in the deepest zones.

<u>Conclusion Site topography: elevation and inundation</u>

A general conclusion on the impact of the initial elevation of the area relative to the tidal range and the average sedimentation rate on the site is however not possible based on the TIDE examples (Figure 3-22, Figure 3-23). However, clear differences are observed between the local sedimentation rate and the spatial variance in site elevation within the study areas. Overall, the different TIDE cases showed that lower areas of the site are more vulnerable for higher sedimentation rates.

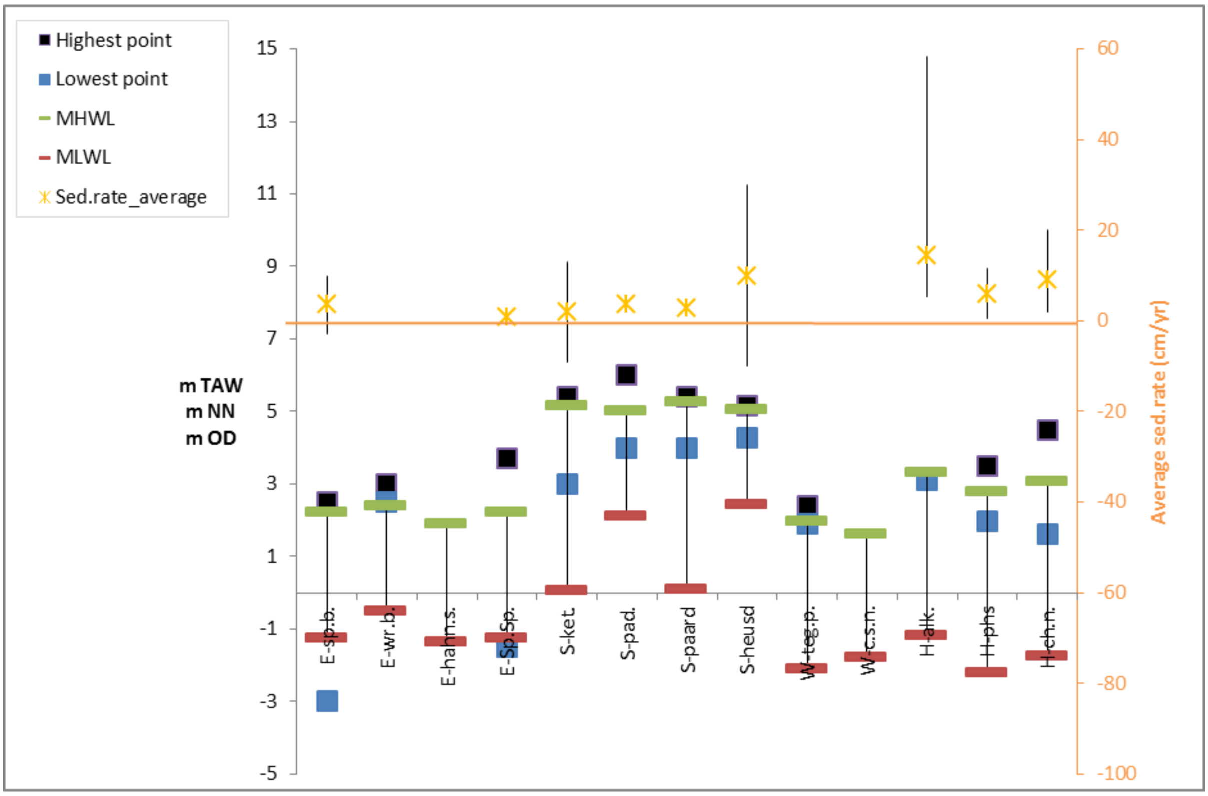

Figure 3-22. Initial site elevation of the outer-dike TIDE MRMs (lowest and highest point) and tidal amplitude (MHWL and MLWL), in combination with the average sedimentation rate with indication of max/min measured sedimentation rates.

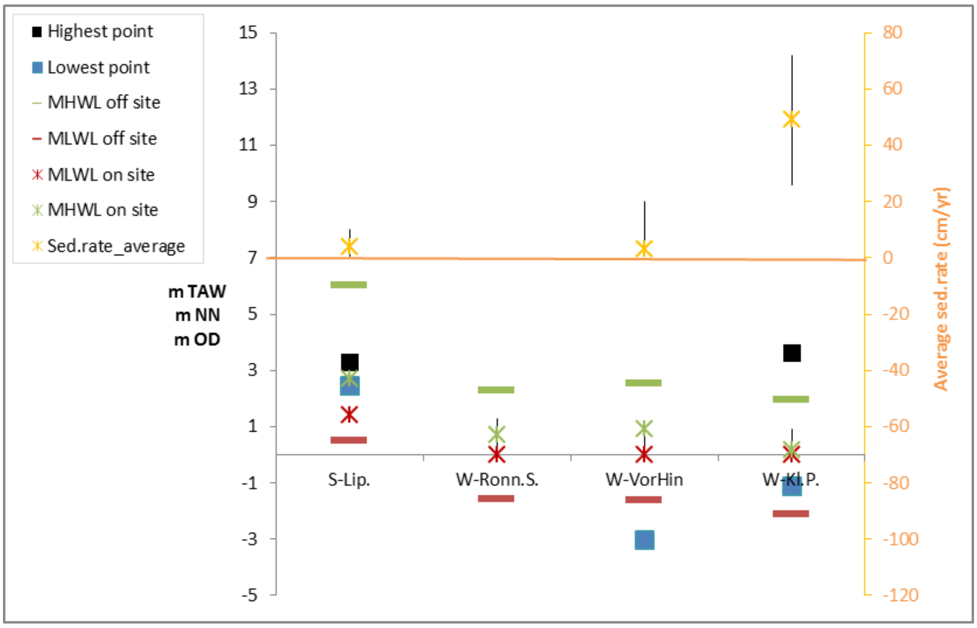

Figure 3-23. Initial site elevation of the inner-dike TIDE MRMs (lowest and highest point) and tidal amplitude (MHWL and MLWL), in combination with the average sedimentation rate with indication of max/min measured sedimentation rates.

3.2.3.2. Slope

An extra element of the elevation determining the sedimentation rate is the combination with the slope of the area. This is illustrated by the cases **S-Ket.** and **S-Pad.**.

S-Ket.: Based on the sedimentation-erosion measurements in the different zones of Ketenisse and some geomorphological variables, a causal relation was only observed between the percentage of slope grade of the mudflat and the intensity of sedimentation/erosion [36, 43]. A steeper slope corresponds with less sedimentation (Figure 3-24). A sedimentation shift to erosion from a critical slope grade of 2.5% or more was determined [36]. Areas with a steep slope of 2.5% or more (Tide habitat type 'intertidal steep habitat') were subject to erosion. Net sedimentation was observed in the zones under MHWL with a gentle slope less than 2.5% (TIDE habitat type 'intertidal flat habitat'). Depressions acted as sediment traps and filled relatively quickly.
As a consequence of the construction work at Ketenisse, the area consists of steep parts (with much erosion) and a flat plateau with sedimentation.

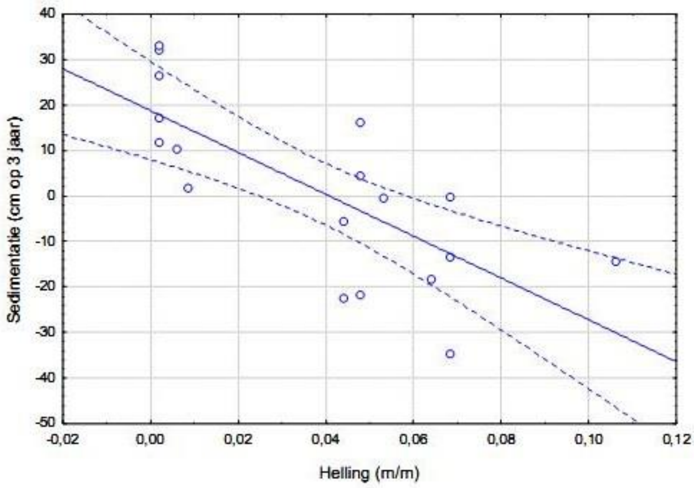

Figure 3-24. Relationship between sedimentation / erosion and overall slope on Ketenisse the first 3 years after levelling [36].

S-Pad.: The global gradient of the Paddebeek wetland is 3.7%, consisting of two steep zones (highest part close to the dike and lowest part close to the river) and one flat zone in the central part. Net sedimentation was only observed at the flat central part of the area [36, 43]. This observation confirms the conclusion from the S-Ket. case.

Overall, the sedimentation rate strongly depends on the slope of the area, with more sedimentation at flat areas (intertidal flat habitat with a slope less than 2.5%) and less sedimentation or even erosion at steep areas (intertidal steep habitat starting from a slope of 2.5%).

3.2.3.3. Opening to the river

The opening from the realignment site to the river could impact many processes which also influence the sedimentation and erosion processes. The **dimensions of the breach** (width and elevation), in relation to the tidal prism in the site and in the estuary, will (partially) determine the current and water levels, hence also inundation and correspondingly also the sediment inflow and accretion rates. This is also closely linked to the realised habitat types and hence the habitat objectives.

An important aspect of the breach is the breach **size** (width); this also corresponds to sites with a dike breach or with defence removal (to consider as a large dike breach). An inverse correlation between the average sedimentation rate and the breach size (both absolute and relative to site surface) is observed, however not significant both with the outlier W-Kl.P. (Figure 3-25: a. absolute breach size R^2=0,06; T=-0,71; p=0,49; and b. relative breach size R^2=0,04; T=-0,61; p=0,55) and without the outlier W-Kl.P. (Figure 3-26: a. absolute breach size R^2=0,15; T=-1,13; p=0,29; and b. R^2=0,07; T=-0,75; p=0,47).

Although not significant, the sedimentation rate tends to be higher when the breach is smaller. At first sight, this result seems contra-intuitive because a wide breach means more inflow of water and hence more sediment entering the area. But a wide breach also generates a faster drainage of the area, creating larger currents and more material is transported back to the river again. In case of a smaller opening, less material will enter the area but also a larger share will remain in the area because the outflow is much slower creating a longer inundation and hence more sediment disposal.

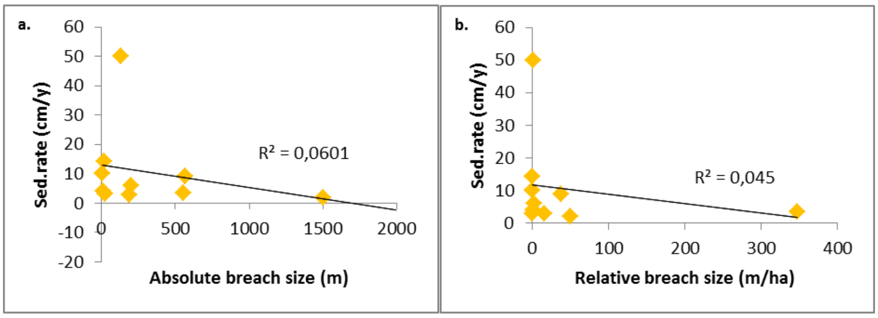

Figure 3-25. Correlation between average sedimentation rate and breach size: (a) absolute breach size and (b) relative breach size to site surface.

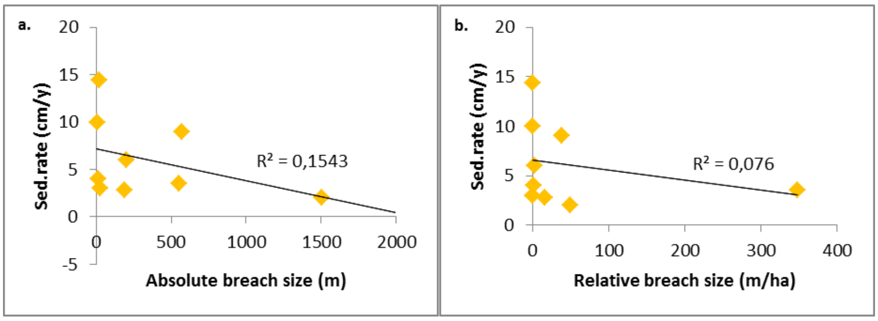

Figure 3-26. Correlation between average sedimentation rate and breach size: (a) absolute breach size and (b) relative breach size to site surface. Without outlier W-Kl.P.

The **elevation** of the breach is another characteristic with a potential impact on the sedimentation and erosion processes because it (partially) determines to which extend the site is under influence of the tidal prism. Lower elevated inflow corresponds with a larger water volume flowing into the area bringing in also more suspended material; but the water could also leave the area faster by which deposition will be limited. Indeed, a positive but not significant relationship is observed for the TIDE measures (Figure 3-27: a. relative to MHWL R^2=0,089; T=0,82; p=0,43; and b. relative to MLWL R^2=0,012; T=0,29; p=0,77). Without the outlier W-Kl.P. an inverse but also not significant relationship is observed (Figure 3-28: a. relative to MHWL R^2=0,23; T=-1,35; p=0,22; and b. relative to MLWL R^2=0,17; T=-1,1; p=0,31).

At Kleinensieler Plate (W-Kl.P.) accretion was very high especially in the shallow water area. To limit the sediment inflow, and also to initiate flow within the shallow water area, two of three overflow barriers were indeed heightened after 5 years. As a result, the tidal range and by this the amount of suspended matter entering the project area could be reduced significantly and siltation tendencies were slowed down.

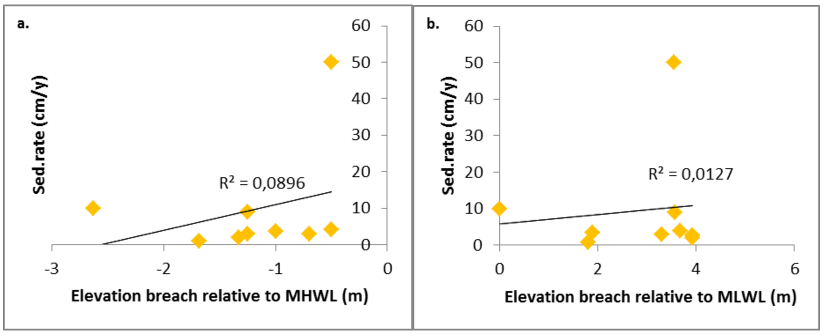

Figure 3-27. Correlation between sedimentation rate and elevation of the inlet relative to (a) MHWL and (b) MLWL.

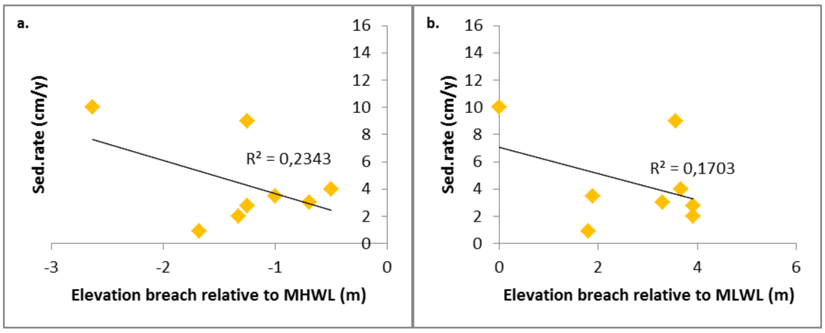

Figure 3-28. Correlation between sedimentation rate and elevation of the inlet relative to (a) MHWL and (b) MLWL. Without outlier W-Kl.P.

The elevation of the in- and outlet also determines the **drainage** opportunities of the site; if the outflow is too high in elevation drainage of the area could be hampered. At Heusden (S-Heusd.) the site design had led to the unfavourable situation that initially the site was inundated at spring tides only and was not drained properly at low tide. In a later stage, two breaches to MLWL were created to improve drainage. It also resulted in a strongly accentuated spring tide/neap tide differentiation in the inundation regime. As a result of this design a site with a great variety of habitat types was created, with permanent pools, mudflats and all stages of typical tidal marsh vegetation.

At Lippenbroek (S-Lip.), a special inlet/outlet system with a high inlet and low outlet was constructed and proved to be optimal to simulate the tidal regime, i.e. controlled reduced tide. The high inlet lets in the top of the tidal wave, but do create neap and spring tides. Fine-tuning of the invert levels is possible with the possibility to create the optimal conditions in the area, increasing the opportunity to create targeted habitat types.

The **number of breaches** could also influence sedimentation and erosion processes. With only one opening, the area functions as a **reservoir** with in- and outflow through the same opening. With multiple openings a **flow through** the area is possible changing the sedimentation and erosion processes; less sedimentation but possibly also more erosion can occur. The latter situation was the case at Wrauster Bogen (E-Wr.B.). At this site, the slope steepness and high flow velocities in the creek prevented that mudflats could evolve. Also the water level in the creek proved to be too low for a permanent colonization by fish to use the creek as resting and growing habitat. Erosion occurred at the creek banks and the slopes, resulting in the transportation of materials (more silt and clay) from the creek into the Elbe estuary at low tide. In order to promote sedimentation in the creek, a morphological rearrangement of the creek was executed three years after the initial implementation. One side of the creek was closed in order to decrease the flow current and a sill (30m wide and levelled 1m above MLWL) was placed in the other opening in order to prevent the complete drainage of the creek. In addition, also the slope of the embankments was flattened. After the adjustment of the tidal creek a positive influence on the erosion and sedimentation processes was observed: the flow velocities in the river channel decreased and mudflats could evolve and thus provide food for the resting fish species. Therefore the rework led to favourable results concerning the achievement of the development targets.

At Chowder Ness (**H-Ch.N.**) the choice for a defence removal rather than solitary breaches was extensively motivated. It was stated that it improves connectivity with the wider estuary; it more closely recreates the type of environments that existed prior to the land claim; it enables the whole cross sectional area of the estuary including the realignment site, to respond to estuary wide changes; and it increases energy levels within the site, thereby improving the likelihood that mudflat habitat will be maintained (as mudflat creation was the main objective of the site).

As the dimensions of the breach are important for the development of the area, much attention is addressed during the planning phase to create optimal dimensions. For specific measures it might be necessary that at a long term perspective **dimensions remain stable**. For instance, sedimentation and erosion processes could, depending on the dynamics, enlarge or diminish the opening, changing the hydromorphological characteristics in the area. To improve the stability, breaches are frequently enforced by a sill. Also a sluice system (such as in Lippenbroek) could offer a solution, because the dimensions are constructed in detail and fine-tuning is possible.

In principle, wherever practicable a measure should aim at a dynamic estuary-specific development of a site. Within such a site one might have both, sedimentation and erosion processes. For example, by forming the opening to the river and by designing the morphology within the measure site (meandering creeks, tidal pools etc.) the coexistence of sedimentation and erosion zones/processes can be furthered.

Overall, the dike breach forms an important aspect of the site design, influencing also sedimentation and erosion processes. Optimal breach dimensions depend on the development targets which is closely linked with sedimentation and erosion processes. It is important to realize that a more or less proportion of suspended material that enters the area will also be disposed there and not turn back to the river. Hence, to control sedimentation in the area it might be crucial to control the inflow of suspended material. From the TIDE cases it is concluded that sedimentation is lower when the breach is wider and higher in elevation (compared to MHWL and MLWL). A higher elevated opening could however hamper proper drainage of the area, but this could be solved with extra breaches to MLWL (cf. **S-Heusd.**). Creating optimal conditions, corresponding to the development targets, is easier with a sluice construction with culverts at different heights by which fine-tuning is possible (cf. **S-Lip.**).

3.3. Conclusions part 2: Optimisation of MRMs with a focus on the sedimentation rate

The second part of the MRM report focusses on issues related to the sedimentation rate at MR sites. Sedimentation and erosion processes have an important role in the development of MR sites and hence in the success of the MRMs. It is however a complex issue and difficult to predict and anticipate on in practice. Although for many measures some modelling work on this topic was done in the planning stage, the reality after measure implementation turned out to be different and does not always suit the development goals. In some TIDE cases the sedimentation rate was therefore considered as a problem, e.g. because tidal water areas silted up quickly due to unexpectedly high sedimentation rates or because habitat development was curtailed due to unexpectedly strong erosion. However, if the situation arises where we require a system which is not in equilibrium this might be more a problem of setting the goal than of the sedimentation rate that is “too high”. Meaning: the project might be in the wrong place, the objectives might be unrealistic or the design of the project might be suboptimal.

Managers have to deal with the unpredictability of the dynamic estuarine system but this does however not mean that managers do not have the possibility to improve the success of the measure and for example reduce the need to dredge the sites. Different aspects of the MRsites are studied to analyse their relationship with the sedimentation rate on the site. It is the aim of this study to better understand the link between the MRsites (both the location within the estuary and the design of the site) and the sedimentation rate and to formulate recommendations to enable managers to improve the selection and design of the site and hence the success of the measure.

a. Sedimentation rate TIDE cases

In general, the sedimentation rate is highest immediately after implementation and then levels off after some years. The overall average sedimentation rate on the TIDE MR sites is 9 cm/yr, with the highest sedimentation rate measured at parts of the Kleinensieler Plate (75 cm/yr, **W-Kl.P.**) and the strongest erosion in some parts of Ketenisseschor (-30 cm/yr, **S-Ket.**). The average accretion at Kleinensieler Plate (**W-Kl.P.**) is very high compared to all other TIDE cases, and without **W-Kl.P.** the overall average sedimentation rate is only 5 cm/yr.

b. Impact of site selection and site design aspects on the sedimentation rate

<u>1. Outer-dike vs inner-dike measures</u>

A first difference is made between outer-dike and inner-dike areas. In this study, <u>outer-dike sites</u> are defined as the areas that are under direct influence of the river and hence under influence of the full tidal range. Most TIDE cases are outer-dike sites. The <u>inner-dike sites</u> are defined as areas with a hydraulic constriction by a (narrow) construction (eg. sluice, sill or overflow barrier) in between the site and the estuary, resulting in a dampened tidal range on the site. A special case of inner-dike measures is a Controlled Reduced Tide (CRT), of which one example is analysed within TIDE (**S-Lip.**). It is expected that the sedimentation and erosion processes will differ between outer- and inner-dike sites due to the different site conditions, depending on water depth, residence time, concentration of suspended matter in the water column, erosion forces etc.. The Kleinensieler Plate is an example for a measure with more or less outer-dike character at the beginning which later on has been converted into an inner-dike site. By this water exchange, sediment entry and sedimentation rate has decreased significantly.
Indeed, based on the TIDE measures no significant relationship was found between the average sedimentation rate at the MR site and whether the site is located outer- or inner-dike.

<u>2. Factors related to the location of the MR site in the estuary</u>

Overall, the following location characteristics are considered as determining both global and local sedimentation and erosion processes: salinity gradient (TIDE-km and estuarine zone), Suspended Particulate Matter (SPM) and turbidity maximum, location at inner or outer side of a river bend, and hydrodynamics in the area.

i. Salinity gradient (TIDE-km and estuarine zone)
The first factor is the location of the MR site along the **salinity gradient**: at a certain TIDE-km or certain estuarine zone (freshwater, oligohaline, mesohaline and polyhaline). No relation with the average sedimentation rate at the MR site was found.

ii. Suspended Particulate Matter (SPM) and turbidity maximum
The second factor is the **SPM** near the MR site and the location of the site at a **turbidity maximum**. For the TIDE cases, the average SPM amounts 200 mg/l, ranging from 38 mg/l to 700 mg/l. As expected, the sedimentation rate is higher at sites with a high SPM supply.

iii. Location at inner or outer side of a river bend
The third factor is the location of the MR site at the **inner or outer side of a river bend**. It is expected that the sedimentation rate will be higher at sites located at the inner side of a river bend, because here current velocity is lower. This is however mainly expected for outer-dike sites because only these sites are under full influence of the river. Based on the TIDE data we are not able to verify this assumption (small dataset).

iv. Hydrodynamics in the area
Sedimentation and erosion processes are also influenced by the **exposure of the area** to the turbulence of the estuary: tidal wave action (large in case of a wide connection to the estuary; essentially a very wide breach); wave action from wind (large in case of exposure to significant fetch from the predominant wind direction); and wave action from ships (large in case of relatively high waves from ships). Firstly, it is possible to select a location along the estuary that is more exposed or sheltered to the hydrodynamic turbulences (e.g. close to the navigation channel will give more ship waves). Secondly, it is also possible to influence the hydrodynamics in the measure site by adapting the site design, e.g. by the size of the opening to the river.

Highly exposed zones with high tidal dynamisms could be characterised by inadequate sedimentation or even erosion which could lead to only bare mudflats without marsh development. In contrast, sheltered zones, depressions and completely embanked inner-dike areas (such as a CRT) could be characterised by higher sedimentation rates by which mudflats could disappear and only marshes remain.

<u>3. Factors related to the design of the MR site</u>

Overall, the following site characteristics are considered as determining both global and local sedimentation and erosion processes: initial elevation (lower vs higher zones), inundation (flood frequency and duration high vs low), slope (weak vs steep), opening to the river, vegetation at the site, drainage and creek system development.

i. Site topography: elevation and inundation
Spatial **differences in elevation** in the area will have an influence on spatial patterns of accretion and saltmarsh vegetation, with implications for the habitat development on the site such as benthic invertebrate diversity and bird usage of the site. It has previously been shown that an inverse relationship exists between elevation and accretion rates inside the realignment site. This is a consequence of the tidal regime in the area, i.e. lower parts will be flooded more frequent and for a longer time and hence more sediment could be deposited. It is proved that there is a positive relationship between inundation (frequency and duration) and the accretion rate and hence with elevation. This is also observed at the TIDE cases: sedimentation rates are higher at the lower areas (e.g. **S-Lip**. and **W.Kl.P.**).

Inappropriate elevation could result in specific site objectives (e.g. marsh development) not being met. Areas that are located much lower than mean high water level (MHWL) for example are quasi constantly flooded and hence vegetation development is difficult. Old polders, frequently used as project sites, are however often located much lower than MHWL as a consequence of increasing water levels and alignment of the areas. In general, an **elevation of the site at MHWL** is considered as an optimal condition for realignments. The elevation of most TIDE cases is indeed situated around MHWL.

ii. Slope

A causal relationship exists between the percentage of slope grade of the mudflat and the intensity of sedimentation and erosion: flat areas are characterised by more sedimentation and steep areas by less sedimentation or even erosion. In the TIDE example **S-Ket.,** a sedimentation shift to erosion from a **critical slope grade of 2.5%** or more was determined. This also corresponds to the difference between the TIDE habitat types intertidal flat habitat (slope rate <2.5%) and intertidal steep habitat (slope rate >2.5%).

iii. Opening to the river

The connection of the site with the river proved to influence the sedimentation and erosion processes in the site. The **dimensions of the opening (width and elevation)** will (partially) determine to which extent the site is under influence of the tidal prism. In addition, this will influence currents and water levels in the site and hence also the inundation and correspondingly the sediment inflow and the accretion rates. A larger opening (wider and/or low in elevation) can correspond with a larger water volume flowing in the area potentially bringing in also more suspended material. In addition, it is expected that a more or less proportion of suspended material that enters the area will also be deposited there and not return to the river. Hence, to control the sedimentation in the area it might be crucial to control the inflow of suspended material. From the TIDE cases no clear relationship was observed between the average sedimentation rate and the breach size (both absolute and relative to site surface), nor with the elevation of the opening. However, in the TIDE case **W-Kl.P.** the overflow barriers were heightened to reduce tidal range and by this the amount of suspended matter entering the project area and indeed siltation tendencies were slowed down (see above). In another TIDE case (**S-Heusd**) it occurred however that the elevation of the opening was too high to properly drain the area, but this was solved by making an extra breach at MLWL.

As the dimensions of the breach are important for the development of the area, much attention is addressed during the planning phase to create optimal dimensions. For specific measures it might be necessary that at a long term perspective **dimensions remain stable**. For instance, sedimentation and erosion processes could, depending on the dynamics, enlarge or diminish the opening and change the hydromorphological characteristics in the area. To improve the stability, breaches are frequently enforced by a sill. Also a sluice system (such as in case of the FCA-CRT **S-Lip.**) could offer a solution, because the dimensions are constructed in detail and fine-tuning is possible.

Another aspect of the opening to the river is the **number of breaches**. If only one breach connects the site to the river, the site will function as a reservoir which will cause a different hydrodynamic situation compared to a site with at least two openings by which the site will function as a flow through (e.g. **S-Lip.** with high inlet and low outlet to improve the flow through characteristic). In a flow through case, hydrodynamics will be higher causing less sedimentation. However, flow current could also be too strong causing strong erosion obstructing habitat development. This was the case in the TIDE example **E-Wr.B.** where one site of the creek had to be closed to stop erosion and make habitat development possible.

In principle, wherever practicable a measure should aim at a dynamic estuary-specific development of a site. Within such a site one might have both, sedimentation and erosion processes. For example, by forming the opening to the river and by designing the morphology within the measure site (meandering creeks, tidal pools etc.) the coexistence of sedimentation and erosion zones/processes can be furthered.

Recommendations part 2:

Overall, managers have several possibilities to control, at least to a certain extent, the sedimentation in the MR site and hence improve the success of the MRM. In the **site selection** phase, it is advised to take into account the location of the turbidity maximum in the estuary, the SPM concentrations along the estuary and the location of river bends. In the **designing** phase, many factors could be controlled: outer- or inner dike area with full or dampened tidal influence; initial elevation of the area relative to the tidal prism; elevation differences within the MR site to improve habitat diversity; the slope of the area (a slope of 2.5% and more has to be avoided to make habitat development possible); sheltered sites have higher sedimentation rates compared to exposed sites; and with a larger opening more suspended matter could enter the area and could hence be deposited.

4. Part 3: General recommendations for successful MRMs

The overall success of a MRM depends on the possibility to meet the different development targets. Hence the targets have to be specific, measurable and achievable within the context of the project [27]. MRMs executed in an estuary have to deal with the dynamic and complex context of the estuary. Biotic and abiotic factors of the estuary interact constantly, ultimately resulting in a dynamic equilibrium situation. When intervening in the estuary, e.g. by implementing a MRM, the system is disturbed will evolve towards a new dynamic equilibrium. For a successful MRM, the development targets have to be in accordance with what can be expected to become the new situation in the long term. The manager has however also the opportunity to guide the development of the MR site towards a targeted equilibrium situation by a well-considered design and location. When understanding the impacts of a MRM it will become easier to manipulate the ecological and hydromorphological processes in such a way that the MRM will evolve to the targeted equilibrium situation. In practice it is however difficult to predict the resulting equilibrium situation when implementing a certain measure and hence if this will be in accordance with the development targets.

4.1. Realistic goals: dynamic and with time trajectory

To limit the unpredictability of the success of MRMs it is recommended to formulate **dynamic goals with a time trajectory** that corresponds to the perceived and predicted changes in the project area and in the estuary, rather than a fixed target without temporal consideration. That implies that the goals do not only contain a qualitative description of the desired situation (eg. which habitat types and which species communities), but also a time frame to reach the target (eg. at year t, t+10 and t+20) [27]. Since the development of the restoration project does not end after the completion of the engineering phase, it is recommended to incorporate realistic predictions of the time frame of evolution in tidal wetland restoration planning [28]. Existing and on-going projects in similar conditions could be used as reference to estimate the evolution of habitat development and to determine feasible performance criteria for different habitats.

Formulating dynamic goals (eg. marshland with mudflats and creek development) has to follow from the understanding of both the ecological and the hydromorphological changes [27]. As sedimentation, erosion and the development of the vegetation are natural processes of the restored estuarine habitats, changes will occur (eg. mudflat will evolve to marsh). The character of the estuarine habitat will therefore inevitably change. The goals of restoration projects should hence be formulated with the ecological and the hydromorphological (desired and undesired) changes in mind because they are intrinsic aspects of the estuarine habitats. This means that it is advised to target certain habitat types and species communities, but not in quantitative terms (exact number of hectares of each habitat type or exact number of species).

Nevertheless, it is obvious that many natural processes within the big North Sea estuaries are considerably disturbed. Therefore one probably has to accept that the safeguarding of specific habitat functions (also at MR sites) will require here and there some maintenance.

4.2. Optimisation of measure success

4.2.1. Overall success

To optimise the success of the MRMs it is recommended to start in the planning phase with incorporating lessons learned from previous and on-going projects. Indeed, the general knowledge on how to develop realignment sites has already been greatly advanced through practical experiences in many case studies. **Knowledge sharing** could be improved by an iterative approach, i.e. follow and further develop best practices established in the past. The evaluation of previous and on-going projects will provide valuable information on the short- and long-term development of restoration projects. This could help to understand the impact of management interventions on overall developments and this can also indicate which other tools are required to guide restoration projects towards their goals [27]. A deeper going analysis of comparable successful measures realized under similar conditions could also minimize the risk of associated problems (eg. additional maintenance effort after measure implementation; reconstruction of overflow barriers; etc.). Exchange of experiences, also across estuaries, is hence necessary to improve the overall success of MRMs and this TIDE report aims to be a first step in that direction.

The success of MRMs also depends on the pre- and post-project **monitoring**.

- This is indeed necessary in order to check whether the targeted results finally have been achieved. And more important to identify unwanted changes or a lack of change in certain aspects for which interventions may be required to steer the development in the aimed direction [27].
- Adaptive management, both during and after implementation, forms an important part of the management strategy to improve the overall success of the restoration project.
- Previous and on-going projects could also help to identify which factors are important to monitor, as well as identifying which monitoring techniques should be used.
- Regarding the success of MRMs, it is recommended to consider (at least) tidal prism, breach design (and breach flow speeds), the role of site morphology in delivering particular habitats, and how future accretion may influence site development [29].
- The time-scale of the monitoring program has to follow the time-frame of project and hence of the development goals. Because long-term monitoring is in practice often difficult to establish within the project, it is recommended to incorporate the monitoring and possibly the evaluation in a regular long-term monitoring program [27].

MRMs generate many ecosystem services and many synergies, but also conflicts between different stakeholders could occur. An effective, clear, honest and early **communication strategy** with the public, stakeholders and regulators is hence also a key aspect in the overall success of MRMs. It is indeed important to optimise the social support for the measure: by securing landowner involvement and allow sufficient time for landowner negotiations [29], by emphasizing the multiple socio-economic benefits of the measure, and if necessary by explaining that the design has changed as far as possible to minimise negative effects on public.

4.2.2. Success related to sedimentation issues

The success of MRMs depends, among many others, on the **induced sedimentation and erosion processes** [30] because these processes are key factors in realising most development goals, i.e. to ensure a site is at the right elevation and receives sufficient tidal inundation for habitat development and for flood storage capacity. However, the real sedimentation and erosion processes on the site are not always in favour of the development goals. When sedimentation rates are higher or lower than expected this could be a disadvantage for certain goals. Reduction of the sedimentation rate in the realignment site could be beneficial to meet for instance the goal flood water storage and additionally this could also reduce the need for maintenance efforts in the future which is then beneficial for vegetation, fauna and water structures.
The presented study (part 2) illustrates that by considering certain aspects of the **site selection and design**, the expected sedimentation and erosion processes could be manipulated to a certain extent in favour of specific development goals. A first recommendation is to evaluate existing and on-going projects to use one or several reference states from a comparable setting (in terms of geomorphology, tidal range and elevation) as basis to establish the design on a target state for the restoration site [27]. Furthermore, the conclusions from the presented study (part 2) could be used as guideline for optimal site selection and design. Depending on the development goals (habitat development and/or safety), the sedimentation and erosion processes could be guided in a favourable way by designing certain site aspects in a specific way. For many realignment sites the development goals are however a combination of the development of different habitat types. It is therefore recommended to adapt the design of different zones of the site in favour of the different goals. This means a large spatial variation in elevation, slope, etc.
An overall rule for designing realignment sites should be to **minimise land manipulation** and work with the existing topography as far as possible. It is hence recommended to maximise the advantage from natural physical and vegetative processes and natural sources from the site (e.g. materials for dike enforcement). Furthermore, the extent of any landform manipulation must be justified due to the consideration of project objectives, the potential gains and the likely cost [29].
Overall, it is important to keep always in mind that the estuary is a highly dynamic ecosystem and the most important rule for successful management is to **work with the system, not against it**!

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6. Appendix 1: Data overview TIDE MRmeasures

Table 6-1. Data overview part 1: General information

M nr.	TIDE nr.	Est.[1]	Measure name	Code	Year of impl.	Size	TIDE-km[2]	Zone[3]	Cat.[4]	Target[5]	Type[6]	Method[7]	Total impl. Cost[1]
						ha	km						€[9]
1	1	E	Spadenlander Busch/Kreetsand	E-Sp.B.	2012	47	30	F	HB	HS	O	RL	50.000.000
2	7	E	Realignment Wrauster Bogen	E-Wr.B.	1991	2,2	18	F	B	H	O	R	(100.000)
3	8	E	Compensation measure Hahnöfer Sand	E-Hahn.S.	2002	63	57	F	B	HC	O	RL	(61.000.000)
4	9	E	Spadenlander Spitze	E-Sp.Sp.	2002	8	32	F	B	H	O	RL	(85.000)
5	13	S	Lippenbroek FCA-CRT	S-Lip.	2006	10	38	F	HB	HS	I	RTE	1.000.000
6	15	S	Ketenisse wetland	S-Ket.	2003	30	92	M	B	HC	O	RL	(4.800.000)
7	16	S	Paddebeek wetland	S-Pad.	2003	1,6	18	F	B	H	O	RL	2.200.000
8	17	S	Paardenschor wetland	S-Paard.	2004	12	100	M	B	HC	O	RL	5.000.000
9	18	S	Heusden LO wetland	S-Heusd.	2006	10	0	F	B	H	O	BR	(1.200.000)
10	24	W	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.	1997	210	58	O	B	HC	O	BL	(8.400.000)
11	25	W	Shallow water area Rönnebecker Sand	W-Ron.S.	2002	34	32	F	B	HC	I	BL	(1.800.000)
12	26	W	Tidal habitat Vorder- und Hinterwerder	W-VorHin	1997	27	12	F	B	HC	I	B	(550.000)
13	27	W	Shallow water zone Kleinensieler Plate	W-Kl.P.	2000	60	57	F	B	HC	I	BL	2.600.000
14	28	W	Cappel-Süder-Neufeld	W-Cap.S.N.	2002	27	90	P	B	HC	O		450.000
15	30	H	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.	2006	440	60	M	HB	HSC	O	B	12.500.000
16	31	H	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS	2003	80	95	P	B	HC	O	B	(9.000.000)
17	33	H	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.	2006	15	73	M	B	HC	O	R	(1.800.000)

1) Estuary: Elbe (E), Scheldt (S), Weser (W), Humber (H)
2) TIDE-km: 0 km is location most downstream where tidal influence is still measured
3) Zone in the estuary: freshwater zone (F), Oligohaline zone (O), Mesohaline zone (M), Polyhaline zone (P)
4) Category: Hydrology & morphology (H), Biology & ecology (B), combined hydrology/morphology and biology/ecology (HB)
5) Target: Safety flood defence (S), Habitat conservation/restoration (H); compensation target (C)
6) Type: inner dike area (I), outer dike area (O)
7) Method: Dike breach (B), defence removal (R), land lowering (L), Reduced Tidal Exchange (RTE)
8) Total implementation cost: cost data between brackets is rough estimation
9) Transformation for UK measures (H-Alk, H-PHS, H-Ch.N.): £ = 1.2319 €

Table 6-2. Data overview part 2: Sedimentation rate and related issues

TIDE nr.	Code name	Sedimentation rate: average (min. to max.)	SPM[1]	River bend[2]	Tidal amplitude: tidal range (MLWL; MHWL)	Initial elevation: Lowest point in the area	Initial elevation: Highest point in the area	Breach dimensions: Width	Breach dimensions: Invert
		cm/y	g/l	O, I	m (m TAW/NN/OD)	m TAW/NN/OD	m TAW/NN/OD	m	m TAW/NN/OD
1	E-Sp.B.	3.5 (max.10)	39	O	3.45 (-1.25; 2.20)	-3	2.5		
7	E-Wr.B.		38	O	2.9 (-0.5; 2.4)	2.5	3	30	0.5
8	E-Hahn.S.	*Not monitored*	49	N	3.26 (-1.36; 1.9)			2650	
9	E-Sp.Sp.	0.88	38	OI	3.45 (-1.25; 2.20)	-1.5	3.7		0.5
13	S-Lip.	4 (0.5 to 8.5)	105	O	1.3 (1.4; 2.7)	2.45	3.3	14,15	4.8
15	S-Ket.	2 (-7 to +15)	69	I	5.1 (0.04; 5.14)	3	5.42	1502	4
16	S-Pad.	3.5	78	I	2.9 (2.1, 5.0)	4	6	556	4
17	S-Paard.	2.8	55	I	5.17 (0.08, 5.25)	4	5.4	190	4
18	S-Heusd.	10 (-10 to +30)	77	OI	2.63 (2.43, 5.06)	4.27	5.14	6	2.43
24	W-Tegl.P.		700	I	3.95 (-2.1; 1.95)	1.9	2.4	3	
25	W-Ron.S.		35	O	0.7 (;)			80	1.16
26	W-VorHin	3 (max. 20)	100	O	0.9 (;)	-3.03		25	1.7
27	W-Kl.P.	50 (10 to 75)	700	O	0.15 (;)	-1.1	3.6	130	1.45
28	W-Cap.S.			N	3.4 (-1.8; 1.6)				
30	H-Alk.	14 (5 to 58)	635	I	4.5 (-1.2; 3.3)	3.1		20	
31	H-PHS	6 (-2.5 to 16)	294	O	4.98 (-2.19; 2.79)	1.95	3.49	200	
33	H-Ch.N.	9 (2 to 20)	163	I	4.82 (-1.77; 3.05)	1.6	4.5	570	1.8

1) SPM: Suspended Particulate Matter (in g/l)
2) River bend: located at the outer side (O) or inner side (I) of a river bend, partially inner- and outer-side (OI), or not at a river bend (N)
Grey box: missing data

7. Appendix 2: Additional Humber measures

By Nancy Pinnington and Susan Manson, Environment Agency, UK (The responsible authors for including three additional Humber measures).

With this appendix, the authors would like to add three more Humber measures to the comparison: Welwick, Kilnsea and Donna Nook. In part 1 (general aspects of MRMs), data for the three additional Humber measures are added in the analysis. For part 2 (regarding sedimentation rates), the authors were unable to add information on the three additional Humber measures, as not much information is available for Welwick on sedimentation rates and Kilnsea and Donna Nook monitoring results are not available as these measures are still being implemented and monitoring has not yet commenced.

Summary

In the first part, general aspects of the 20 MRMs (Table 0-1) are analysed and compared. The second part focusses on the sedimentation rate on MR sites and determining site selection and site design aspects. Overall, the aim of this report is to conclude with recommendations for future nature restoration measures hence improve the success of estuarine management.

Table 7-1. List of the 17 TIDE managed realignment measures. Basic information and effectiveness analysis of the measures is available in the respective measure reports [2-19]

TIDE nr.	Estuary	Measure name	Code
1	Elbe	Spadenlander Busch/Kreetsand	E-Sp.B.
7	Elbe	Realignment Wrauster Bogen	E-Wr.B.
8	Elbe	Compensation measure Hahnöfer Sand	E-Hahn.S.
9	Elbe	Spadenlander Spitze	E-Sp.Sp.
13	Scheldt	Lippenbroek FCA-CRT	S-Lip.
15	Scheldt	Ketenisse wetland	S-Ket.
16	Scheldt	Paddebeek wetland	S-Pad.
17	Scheldt	Paardenschor wetland	S-Paard.
18	Scheldt	Heusden LO wetland	S-Heusd.
24	Weser	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.
25	Weser	Shallow water area Rönnebecker Sand	W-Ronn.S.
26	Weser	Tidal habitat Vorder- und Hinterwerder	W-VorHin
27	Weser	Shallow water zone Kleinensieler Plate	W-Kl.P.
28	Weser	Cappel-Süder-Neufeld	W-Cap.S.N.
30	Humber	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.
31	Humber	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS
33	Humber	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.
34	Humber	Welwick: Creation of 54ha of intertidal mud, saltmarsh and grassland.	H-Wel.
35	Humber	Kilnsea Wetlands (formerly Beacon Lagoons): Bringing 70ha of wetland SSSI back into favourable condition and providing 43ha of functional replacement coastal wetland habitat.	H-Ki.W.
38	Humber	Donna Nook: Transformation of 130ha of agricultural land into a mosaic of saltmarsh, mudflats, creeks and small islands.	H-Do.N.

Part 1: General aspects of Managed Realignment Measures (MRMs)

The 20 TIDE MRMs are all implemented in the last 21 years. The average size of the TIDE MRM is 68ha, ranging from 1.6 ha to 440 ha (Figure 0-1). However, only four cases are larger than 100 ha. Half of the TIDE MRMs are located in the freshwater zone and the other half is spread along the three other salinity zones according to the Venice System (mesohaline, oligohaline and polyhaline) [21].

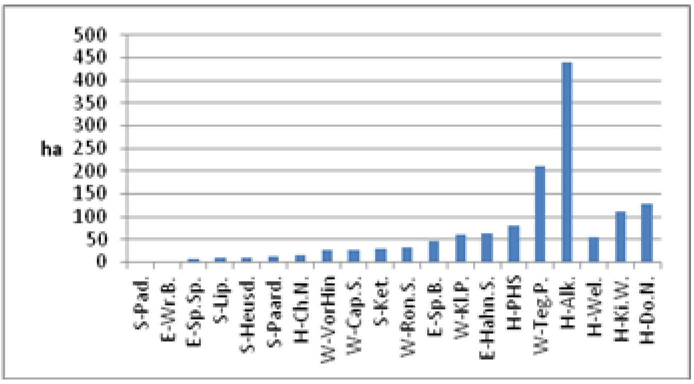


Figure 7-1. Restored surface

The MRM have been implemented **for different reasons**. The most common measure target is habitat conservation, restoration or creation. Only a few cases combine this conservation target with a safety target (flood storage capacity), research target, and/or recreation opportunities. Half of the cases are driven by a compensation reason. The degree of target achievement is overall high: almost half of the measures are considered to have a high degree of target achievement, the other part a medium degree meaning that not all targets are completely reached. However in some cases it was proved that the degree of target achievement could be improved by making some adaptations to the MR site.

An MRM could be executed **by different techniques**. Half of the TIDE cases are implemented by dike breach and half by defence removal (large dike breach), with a dike breach between 3m and 2650m (Figure 0-2). Another type of estuarine habitat restoration is by Reduced Tidal Exchange (RTE). Within TIDE we have only one RTE example (**S-Lip.**). In half of the measures, the dike breach or defence removal is combined with land lowering. In many cases it was proven that different design aspects such as initial site elevation, slope of the area and hydrodynamics do influence habitat development and the success of the measure. In some cases the initial design was not optimal, but adaptations to the site were possible to improve the success of the measure.

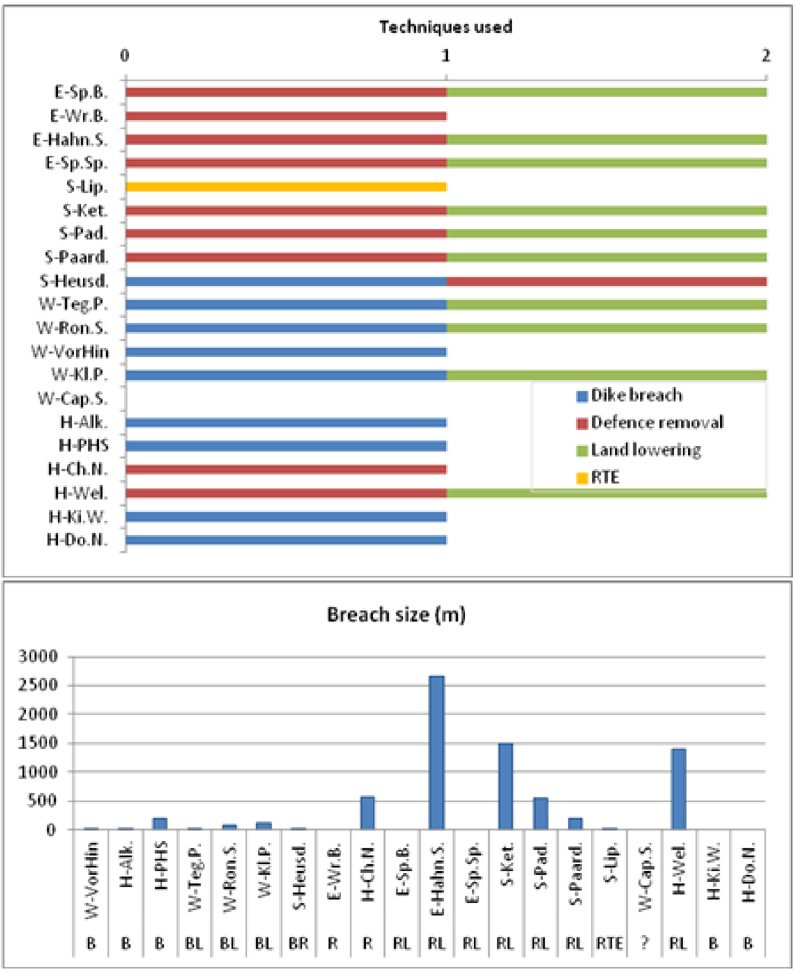
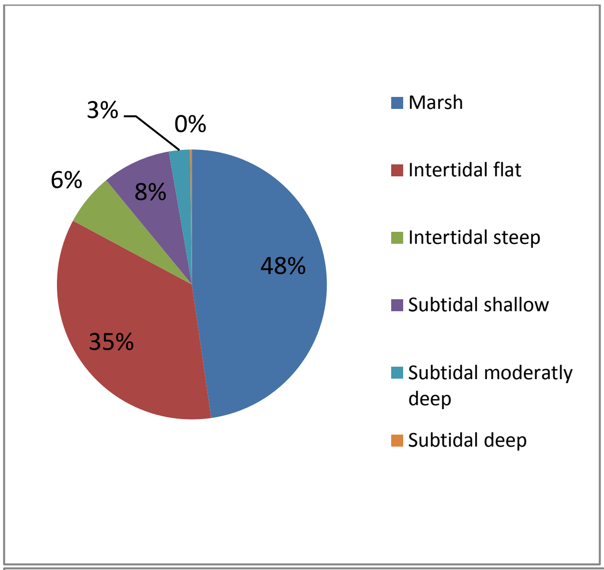


Figure 7-2. Overview implementation techniques used for the different TIDE examples (LEFT), and link between implementation technique and breach size (m) (RIGHT). Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), RTE.

The TIDE MRMs together transformed about 1000 hectares **adjacent land into estuarine habitat**, consisting mainly of marsh land and intertidal flat habitat (Figure 0-3). For the TIDE cases, about 90% of the created habitat surface (approx. 900 ha) was however implemented for compensation reasons meaning that it is not really new habitat because it was lost first somewhere else.



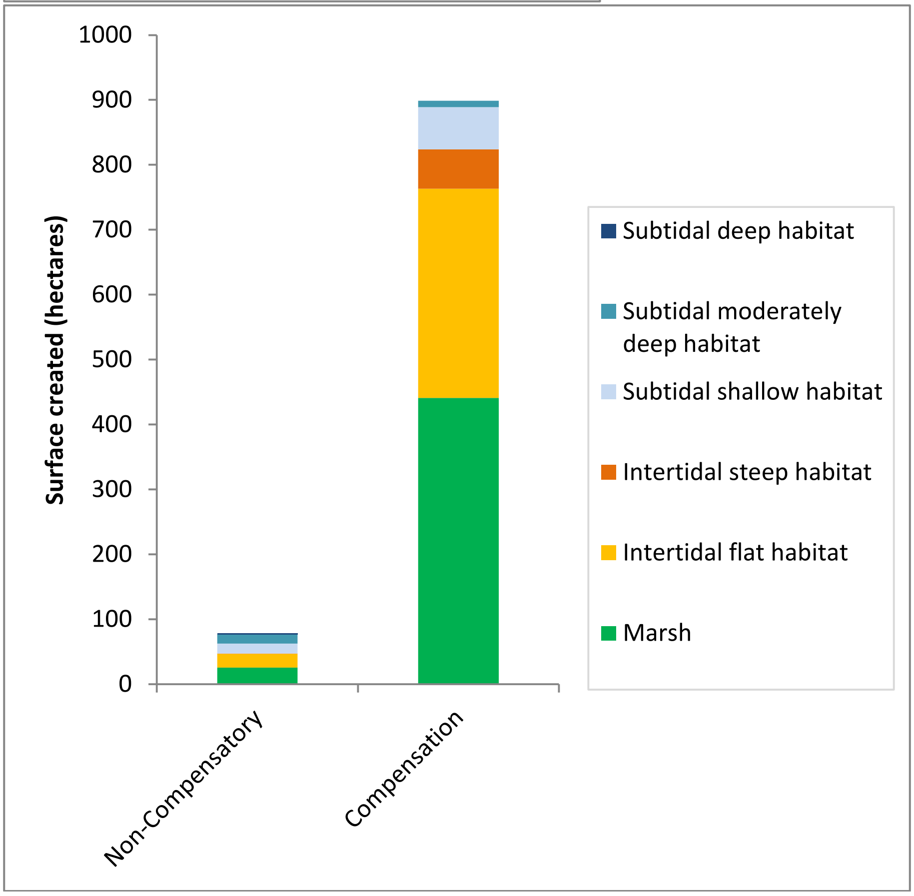


Figure 7-3. Distribution of different habitat types created by the TIDE cases (Left), and overview habitat creation per habitat type by the TIDE compensation measures and non-compensatory measures (Right).

Most TIDE MRMs have a **monitoring program** with a duration between 3 to 15 years. The parameters mostly monitored (in at least half of the TIDE cases) are: vegetation, accretion and sedimentation on site, invertebrates, birds and fish.

MRMs generate many **synergies** between nature, flood protection, port development, recreation and natural resources, but also **conflicts** with agriculture and local inhabitants.

MRMs are **expensive** but could also generate **large benefits**. The **relative implementation cost** of the TIDE MRM cases amounts 250,000 €/ha with a large range between 2,000 and 1.4 Million €/ha. For some measures, only a rough estimation was available.

- Three TIDE MRMs are considered as outliers with a remarkable high relative implementation cost, because of a high amount of soil that had to be removed out of the area (**E-Hahn.S.**) and that had to be treated because of contamination (**E-Sp.B.**), or uncertainty about the total implementation cost (**S-Pad.**).
- Furthermore, different measure characteristics are studied to find reasons for the large variance in the relative implementation cost.
    - Size and age: No significant relationship is observed between the relative implementation cost and the size of the measures, nor could we observe a temporal evolution in the relative implementation cost.
    - Implementation techniques: A significant difference in the relative implementation cost is observed between the TIDE measures implemented by dike breach or by defence removal. The latter technique is, evidently, much more expensive. A positive relationship with the breach size was however not significant. Furthermore, measures with land lowering are expected to be more expensive but this difference was also not significant.
    - Creek system implemented: Measures with the implementation of a creek system are expected to be more expensive but this difference was not observed for the TIDE cases.
- Overall it is not possible to give a clear indication about what causes a higher or lower relative implementation cost. It depends too much on local conditions.
- **Critical note**: By comparing measure characteristics with the relative implementation cost nothing could be concluded about the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and to be sustainable is more important when considering the measure design than the implementation cost.

Besides the implementation cost of the measures, also the **benefits** are studied based on the Ecosystem Services (ES) concept. However, no scientific consensus exists yet on the monetary valuation of ES. Different approaches are explored with often also different outcomes.

- A simple approach was applied to get a rough idea of the order of magnitude of the monetary benefits of the MRMs. A recent overall literature review with global monetary data for different biomes was used and multiplied with the habitat creation in the MRMs. Based on this approach, the TIDE examples generate an average annual per hectare benefit of 133,000 €/ha.y, ranging from 70,000 to 155,000 €/ha.y. The monetary benefit calculated here is however an overestimation because it is limited to the benefits generated within the estuary itself without counting for the lost adjacent land.
- A more detailed approach to calculate the local benefits of a measure is however recommended. Therefore, a guidance document is developed to support managers and decision makers in how to quantify and monetary value the changes in ecosystem services specifically for the study site [22].

By comparing the costs and benefits of the measures, the **cost-efficiency** of the TIDE cases is analysed.

- The first method is the earn-back time, i.e. the average time that the measure should be operational before the total implementation cost is earned back. For the TIDE MRMs this amounts on average 2.3 years, ranging from 0.1 year to 15 years.
- The second method is the benefit/cost ratio, i.e. the annual benefit generated for every 1€ invested. For the TIDE cases the benefit/cost ratio is on average 2.82:1, meaning a benefit of 2.82 €/y for every 1€ invested. The benefit/cost ratio for the TIDE cases ranges from 0.07 to 13.35 €/y for every 1€ invested.
- The earn-back time and benefit/cost ratio both give an indication of the cost-efficiency of a measure, assuming that the measure targets are met completely. However, in reality the latter assumption is rarely the situation. It is therefore recommended to first check the success of measures to meet the development targets and additionally the cost-efficiency estimate could be used to make a selection between measures that are expected to be successful.

In the final section, the results of an **ES assessment** for the MRMs are analysed (based on the TIDE ES study [23]).

- In a first part, the target ES are indicated per measure based on the development targets (Table 0-2). Most TIDE MRMs target the supporting and habitat services. In a few cases, this target is combined with a regulating service (flood water storage, dissipation of tidal and river energy), and/or a cultural services (opportunities for recreation and tourism, and information for cognitive development).
- The TIDE MRMs have a positive expected impact (from slightly positive to very positive) on at least 12 of the 20 considered ecosystem services.
- The expected impact on the targeted ES is in most cases very positive. On average, only 10% of the ES with a positive expected impact (slightly positive to very positive) are also targeted. This means that the MRMs are expected to generate many co-benefits!
- Regarding the beneficiaries, the TIDE MRMs are mainly beneficial in an indirect way, at a longer term (for future use), and at a local and regional scale.

Table 7-2. Translation of measure targets in terms of ES

Target	**Corresponding Ecosystem Service**
Safety	R1 - Erosion and sedimentation regulation by water bodies R9 - Water quantity regulation: dissipation of tidal and river energy R12 - Reg. of extreme events: flood water storage
Habitat conservation/restoration	S - Supporting and habitat services (biodiversity)
Compensation	S - Supporting and habitat services (biodiversity)
Access opp. and education	C4 - Cult. Opportunities for recreation and tourism
Research	C3 - Cult. Information for cognitive development

7.1.Introduction of the TIDE Managed Realignment Measures (MRM)

Almost half of all TIDE measures are Managed Realignment Measures (MRM), spread over the four TIDE estuaries: four examples in the Elbe, five in the Scheldt, seven in the Weser and six in the Humber (Table 1-1).

For the purpose of this study, the TIDE cases are presented shortly by comparing chosen basic aspects such as years implemented and size. In addition, a picture of each measure is added. For a more detailed description of these measures, see the overall measure report [1] and the individual measures reports [2-19].

Table 7-3. List of the 20 TIDE managed realignment measures with chosen basic information.

TIDE nr.	Estuary	Measure name	Code	Year of impl.	Size (ha)	Cat. [1]	Zonation [2] (in TIDE-km)			
							F	O	M	P
1	Elbe	Spadenlander Busch/Kreetsand	E-Sp.B.	2012	47	BH	30			
7	Elbe	Realignment Wrauster Bogen	E-Wr.B.	1991	2,2	B	18			
8	Elbe	Compensation measure Hahnöfer Sand	E-Hahn.S.	2002	63	B	57			
9	Elbe	Spadenlander Spitze	E-Sp.Sp.	2002	8	B	32			
13	Scheldt	Lippenbroek FCA-CRT	S-Lip.	2006	10	BH	38			
15	Scheldt	Ketenisse wetland	S-Ket.	2003	30	B			92	
16	Scheldt	Paddebeek wetland	S-Pad.	2003	1,6	B	18			
17	Scheldt	Paardenschor wetland	S-Paard.	2004	12	B			100	
18	Scheldt	Heusden LO wetland	S-Heusd.	2006	10	B	0			
24	Weser	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.	1997	210	B		58		
25	Weser	Shallow water area Rönnebecker Sand	W-Ronn.S.	2002	34	B	32			
26	Weser	Tidal habitat Vorder- und Hinterwerder	W-VorHin	1997	27	B	12			
27	Weser	Shallow water zone Kleinensieler Plate	W-Kl.P.	2000	60	B		57		
28	Weser	Cappel-Süder-Neufeld	W-Cap.S.N.	2002	27	B				90
30	Humber	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.	2006	440	BH			60	
31	Humber	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS	2003	80	B				95
33	Humber	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.	2006	15	B			73	
34	Humber	Welwick: Creation of 54ha of intertidal mud, saltmarsh and grassland.	H-Wel.	2006	54	B	54			
35	Humber	Kilnsea Wetlands (formerly Beacon Lagoons): Bringing 70ha of wetland SSSI back into favourable condition and providing 43ha of functional replacement coastal wetland habitat.	H-Ki.W.	2011/2012	113	B	113			
38	Humber	Donna Nook: Transformation of 130ha of agricultural land into a mosaic of saltmarsh, mudflats, creeks and small islands.	H-Do.N.	2012/2013	130	B		130		

1) **Category**: Biology/ecology (B), hydrology/morphology (H), combination of biology/ecology with hydrology/morphology (HB)

2) **Zonation**: freshwater zone (F), Oligohaline zone (O), mesohaline zone (M), and polyhaline zone (P) [21]

Pictures of the 17 TIDE Managed Realignment Measures planned or implemented at Elbe (E), Scheldt (S), Weser (W) and Humber (H):

E-Sp.-B.

E-Wr.B.

E-Hahn.S.

E-Sp.Sp.

S-Lip.

S-Ket.

S-Pad.

S-Paard.

S-Heusd.



W-Tegl.P.

W-Ronn.S.

W-VorHin



W-Kl.P.

W-Cap.S.N.

H-Alk.



H-PHS

H-Ch.N.

H-Wel.



H-Ki.W.

H-Do.N.


1) Zonation

Half of the TIDE MRMs are located in the freshwater zone (55%), followed by the mesohaline zone (20%), and only few TIDE examples are located in the oligohaline (15%) and polyhaline (10%) zones. The spatial distribution of the measures along the four estuaries is visualised in Figure 1-1. The TIDE MRM are however only a sample and hence not to be seen as a representation of all MRMs along the four estuaries.

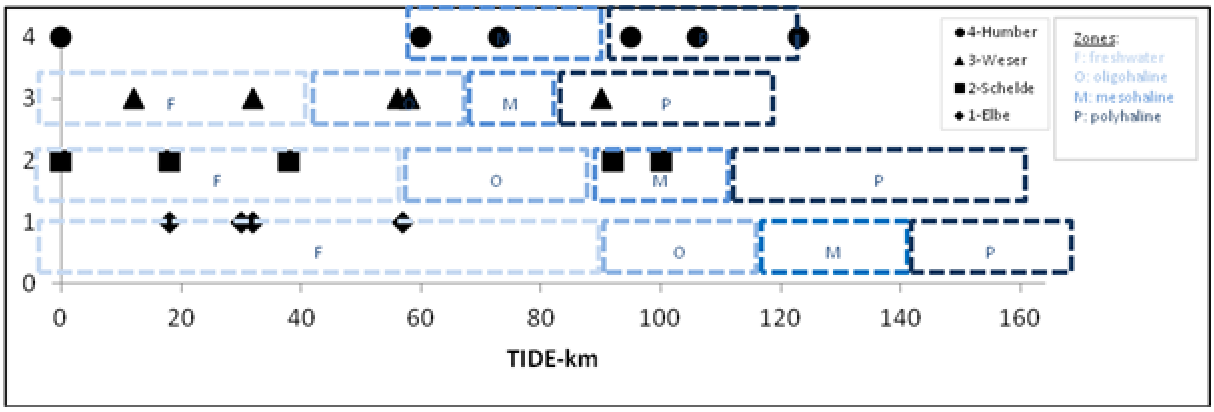


Figure 7-4. Distribution of the TIDE MRMs along the four estuaries (in TIDE-km, based on the salinity gradient [21]).

2) Age (Years implemented in 2012)

The TIDE MRMs are all implemented in the last 21 years (Figure 1-2). The oldest TIDE example was implemented in 1991 (**E-Wr.B.**) and the most recent TIDE example is planned for 2013 (**H-Do.N.**).

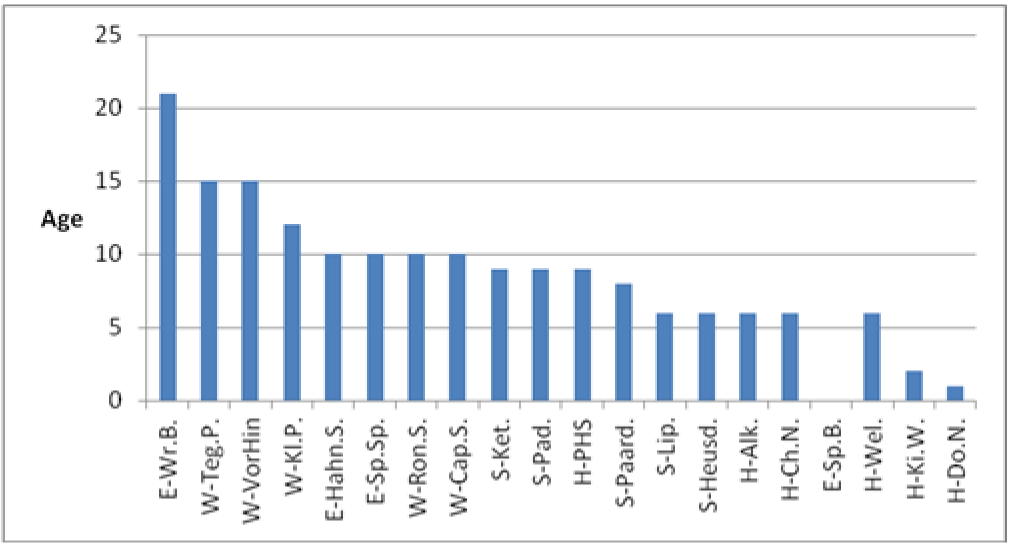


Figure 7-5. Number of years that each TIDE case is implemented in 2012.

3) Size (ha)

The average size of the TIDE MRM is 68 ha (Figure 1-3), ranging from 1.6 ha (**S-Pad.**) to 440 ha (**H-Alk.**) and only four cases are larger than 100 ha (**W-Tegl.P., H-Alk., H-Ki.W. and Do.N.**).). No temporal trend was observed in the size of the MRM.

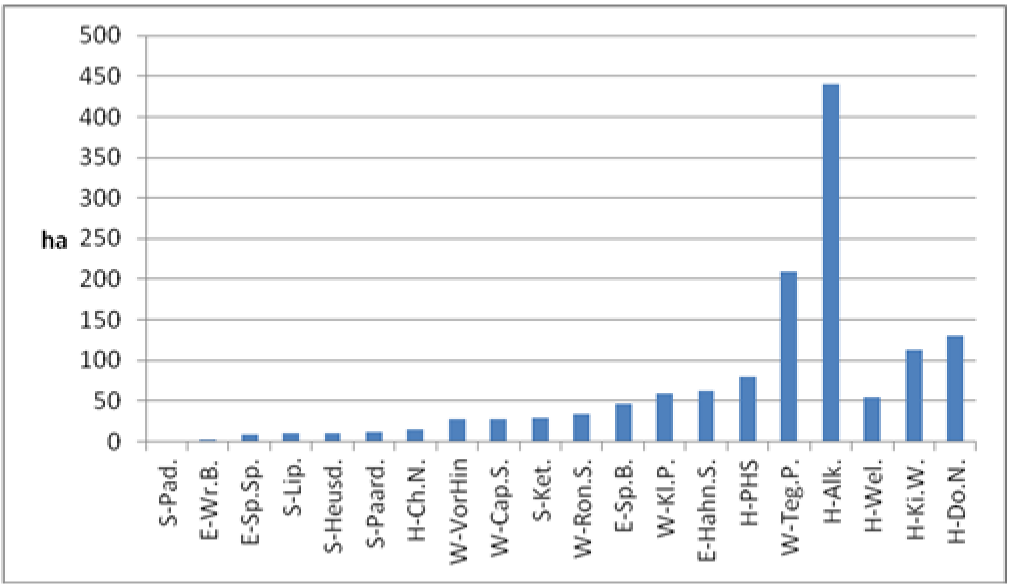


Figure 7-6. Restored surface

7.2.Part 1: General aspects of MRM

A general definition of a managed realignment measure is made in this part of the study by comparing different topics of the 20 TIDE MRM examples. The topics that are described here are: (1) measure targets, (2) implementation techniques, (3) habitat creation, (4) monitoring program, (5) synergies and conflicts, (6) impact on ecosystem services and (7) costs and benefits.

7.2.1. Measure targets and degree of target achievement

Main question: Why are MRMs executed? And, are MRMs successful in achieving these targets?

During history, many dikes were breached accidently by the tide. In some cases it was decided not to repair the dike but let the tide enter the adjacent land. This is called an **accidental realignment**. This happened when the benefits of the lost land were valued less than the costs to repair the dike. The land under tidal influence develops to wetlands and could also supply additional benefits. During last decades, accidental realignments are rare because adjacent lands have a high value and dikes are therefore mostly repaired.

Also managed realignment (MR) is a frequently used measure in estuarine management. The oldest form of managed realignment is probably as part of the **military strategy**. A realignment area was used as a permanent buffer against the enemy.

More recent MR measures have other targets: safety, nature compensation or nature restoration [31-33].

- **Safety**: MR measures proved to be useful as cost effective coastal defence and for flood protection. The safety aspect of MRMs consists of different aspects:
    - Marshes form a natural protection for adjacent land and dikes. Marshes act as a barrier against waves and erosion. This barrier could also be climate change proof if the marshes grow equally with increasing sea water levels [30, 34].
    - The MR area offers flood water storage capacity by allowing water to reclaim the land at high tide and in times of flooding (new tidal volume).
    - The MR area also reduces the energy of the incoming tidal wave because the water is spread over a larger area (energy dissipation).

- **Habitat compensation**: MRMs are often used to compensate for protected habitats that were lost elsewhere (hence no extra habitat is created). Wetlands have an important ecological value and are often protected by international, European and local legislation (Water Framework Directive, Habitat and Bird Directive, Ramsar, Natura 2000, red list for species).
- **Habitat conservation/restoration/ creation**: MRMs improve the natural scenery by upgrading the ecological characteristic landscape of the estuary region. This means the development and re-establishing of functioning intertidal and ecological valuable habitat, as resting, feeding and breeding area for aquatic flora and fauna. This involves the improvement of specific estuarine gradients (from aquatic to terrestrial) and functions such as the chemical condition (oxygen, nutrients, self-purifying power) and morphological condition (sedimentation-erosion processes and creek formation). Important biotopes for aquatic flora and fauna to develop and restore are shallow water areas, marsh habitat (eg. saltmarsh), intertidal mudflat structures, natural floodplain habitats (floodplain forest), tidal reeds, creek systems, sandy shores, bushes, and wide grasslands.
- Most MR measures are executed for a combination of targets and combined with secondary targets such as **recreation and tourism**.

The number of targets per MRM varies between 1 and 4. All TIDE examples have habitat conservation as one of the main development target (Figure 2-1). More than half of the TIDE examples are driven by a compensation reason, mostly linked with port development, flood defence schemes and compensation requirements for sea level rise. Three of the more recent examples have the aim to combine habitat conservation with safety (extra tidal volume). Three examples are implemented as pilot project and therefore have a research aim. Only five of the most recent examples explicitly mentioned the improvement of access opportunities and recreation as a target.

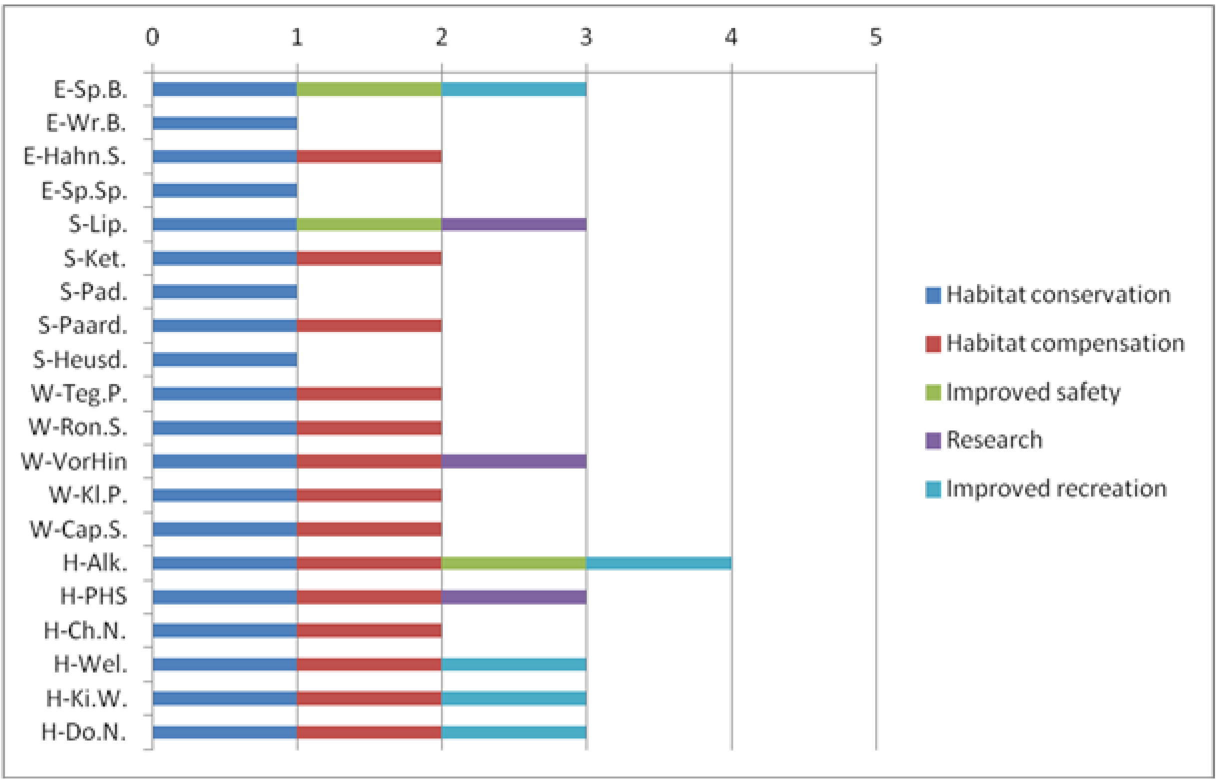


Figure 7-7. Overview of the measure targets per TIDE MRM (LEFT) and number of schemes with each target (RIGHT)

The measure targets could be linked with the TIDE measure categories. All TIDE MRMs belong to the "biology/ecology" category, and a few explicitly combine the category "biology/ecology" with "hydrology/morphology" (see also §4.1 in [1]). This corresponds with the fact that all cases have habitat conservation as a main target, and only a few examples aim to combine this with a safety target.

In the following part, the different measure targets will be explained in more details for the TIDE cases as well as the degree of target achievement for all the measures (Table 2-1).

Table 7-4. Overview measure targets and degree of target achievement per measure. Degree of target achievement: low (0), medium (+), high (+++).

TIDE nr.	Measure	Number of years implemented	Habitat conservation, creation, restoration				Safety	Research	Recreation
			1. Processes	2. Habitat	3. Specie	4. Compensation			
1	E-Sp.B.	0	+++	+++	+++		+++		+++
7	E-Wr.B.	21		+	+				
8	E-Hahn.S.	10		+	+	0			
9	E-Sp.Sp.	10	+	+	+				
13	S-Lip.	6		+++			+++	+++	
15	S-Ket.	9	+			+			
16	S-Pad.	9	+	+					
17	S-Paard.	8	+	+		+			
18	S-Heusd.	6	+	+					
24	W-Tegl.P.	15	+++	+++		+++			
25	W-Ronn.S.	10	+++	+++		+++			
26	W-VorHin	15	+++	+++		+++		+	
27	W-Kl.P.	12	+			+			
28	W-Cap.S.N.	10			+++	+++			
31	H-Alk.	6		+		+	+++		+++
32	H-PHS	9		+	+	+		+++	
33	H-Ch.N.	6	+++	+++	+++	+++			
34	H-Wel.	6	+++	+++	+++	+++			+++
35	H-Ki.W.	2	+++	+++	+++	+++			+++
38	H-Do.N.	1	+++	+++	+++	+++			+++

1) Habitat conservation/restoration/creation

All TIDE examples aim to conserve, restore or create estuarine habitat. The concretisation of this target is diverse and four main types could be distinguished (Table 2-1):

5. Target to improve estuarine processes such as sedimentation processes, creek formation, and soil development.
6. Target to create a specific habitat (freshwater or brackish) such as valuable habitats like mudflats, marsh habitat, shallow water habitat, reed, meadows and floodplain forest.
7. Target to support specific species by creating habitat for certain fauna and flora, e.g. the 'Elbe Water Dropwort' (*Oenanthe conioides*) (**E-Sp.B.**, **E-Hahn.S.**, **E-Sp.Sp.**),the 'Northern Shoveler' (*Anas clypeata*) (**E-Hahn.S.**) and key invertebrate species, such as Ragworm (*Hediste diversicolor*), Bristle Worm (*Pygospio elegans*), Mud Shrimp (*Corophium volutator*), Baltic tellin Clam (*Macoma balthica*), Laver Spire Shell (*Hydrobia ulvae*) and Worm (*Streblospio shrubsolii*) (**H-Wel.)**
8. Compensation targets: Many of the TIDE MRMs are driven by compensation targets (Table 2-1), mainly related to lost habitats due to port development. All TIDE MRMs from the Weser are compensation measures, i.e. habitat compensation is the driver for measure implementation. But also in the other estuaries, different MRMs are driven by compensation targets e.g. to compensate for port facilities, flood defence works and industry development (**E-Hahn.S.**, **S-Ket.**, **S-Paard.**, **H-Ch.N.**, **H-Wel. and H-Do.N.**).
9. Sea level rise: Also, there are requirements for the provision of compensatory habitat due to coastal erosion losses (**H-Ki.W.**).

Degree of target achievement?

Half of the measures are considered to have a high degree of target achievement regarding habitat conservation, the other part of the measures are considered to have a medium degree of target achievement meaning that not all targets are completely reached (Table 2-1). Only one measure (**E-Hahn.S.**) was not able to realise all compensation targets. Also, the achievement of target measures for **H-Ki.W.** and **H-Do.N.** are not yet fully known as this measure is still in the process of being implemented.

Successful measures with a high degree of target achievement:

Measure	Description degree of target achievement
E-Sp.B.	The measure is not implemented and monitored yet. Though the achievement of the different development targets are considered to be as high as estimated as described in the planning approval

	documents.
S-Lip.	Lippenbroek started functioning as freshwater intertidal habitat since the introduction in March 2006 and hence was successful. Tidal marsh restoration with a FCA-CRT construction can happen very fast and spontaneously. The inundation curve is different than in natural intertidal areas (duration is longer, and has three phases: ebb, stagnant and flood) but this does not obstruct the colonization by fauna and flora.
W-Tegl.P.	The available monitoring results show that the development targets defined for the compensation measure are fully reachable until the end of the 15 year runtime of the monitoring program. In summary, the measures realized on the Tegeler Plate represent a sustainable habitat development which contributes to restore the lower part of the river Weser which is strongly affected by human activities. W-Tegl.P. also showed that it is principally possible to create self-preserving tidal creek systems within highly dynamical estuaries.
W-Ronn.S.	The available monitoring results show that the development targets defined for the compensation measure are fully reachable until the end of the 10 year runtime of the monitoring program.
W-VorHin	The compensation measure 'Tidal habitat Vorder- und Hinterwerder' is a flagship measure, because several experienced partners worked together during the planning and implementation stages, the social status of nature conservation was very strong at that time and there were no conflicting plans to be considered. The development target according to the grassland areas was reached satisfactorily. The area left to natural succession developed faster than expected. Also the aims for fish were reached one year after measure implementation already. However, the tidal waters at Vorder- and Hinterwerder were flooded longer than projected by the hydraulic models used. The hydraulic calculations undertaken during the planning stages should be analysed in order to improve the predictability of tidal influence on potential project areas at estuaries. This is crucial in order to estimate e.g. the degree of siltation and thus the maintenance effort to expect.
W-Cap.S.N.	Salt marsh vegetation developed as expected along the ditches and within the diked-out area. As a result of the measure implementation, the breeding bird population on the project area is labelled as important for the federal state of Lower Saxony.
H-Ch.N.	So far the site appears to be developing as expected as predicted in the EIA. Although not taken into account when determining the height of the new defence due to uncertainties involved in judging its long term sustainability, a strip of saltmarsh is expected to develop in front of the new (landward) sea defences. The monitoring has identified that species diversity has continued to rise at Chowder Ness over the five year monitoring period. Breeding birds have been specifically monitored at Chowder Ness. The number of species of breeding bird observed at these sites has been consistent across the five year monitoring period, with a five year average of seven species (range 6 to 8). Total numbers observed have also remained consistent. However, Chowder Ness managed realignment site was considered to be relatively small scale in relation to the estuary as whole (total area of 15ha, representing only 0.02% of the estuary's intertidal area and 0.01% of its spring tidal prism). As large lengths of sea wall were removed, the effects on estuarine tidal velocities, sedimentation and accretion, and water levels, were anticipated to be extremely localised and of a relatively small magnitude (ABPmer, 2004).
H-Wel.	So far the site appears to be developing as expected. The specific target for Welwick was to create intertidal habitat to compensate for that lost through ABP port development on the Humber Estuary. The scheme was breached in June 2006 and appears to be performing as predicted at this early stage, with saltmarsh development and bird usage already evident. In the medium to long term, the monitoring results will be compared with the objectives of the site to determine the success of the scheme.

Moderately successful measures with a medium degree of target achievement:

Measure	Description degree of target achievement
E-Wr.B.	The new habitat developed in a favourable way, but adjustment of the site was needed. After the adjustment of the tidal creek the flow velocities in the river channel decreased and mudflats could evolve and thus provide food for the resting fish species.
E-Hahn.S.	The compensation target was quickly achieved. Two years after the western part was opened to the tide, broad freshwater mudflats had evolved and the area consists of 97% mudflats and 3% shallow water. The stocking of the *Oenanthe conioides* had increased significantly and the area seemed also a good feeding ground for resting bird species and species protected by the BHD. However, the measure was considered as being not sufficient as compensation because the RAMSAR target of 400 individuals of *Anas clypeata* were not achieved. The compensation obligations of the coherence targets of NATURA 2000 for the species *Anas clypeata* was finally achieved by the designation of an old unused harbour area were wide mudflats had evolved and the resting population of *Anas clypeata* reached the demanded amounts of about 400 individuals.
E-Sp.Sp.	In general, the measure was considered as a success, most biotopes developed well. The realignment had a positive effect on the conservation aims and stimulated the development of scarce and endangered

	species. Species diversity became enormous, and settlement of typical species took place on its own, eg. spores come with the tide very quickly. The area was also colonized by the endemic species Oenanthe conioides. However, one year after implementation, the little pond that should function as resting and spawning area for several fish species showed high sedimentation rates. Therefore the development target of establishing a permanently water filled realignment area could only be partly achieved.
S-Ket.	Monitoring results of the first year suggest that Ketenisse polder has the potential to develop towards a varied and normal functional intertidal area [35]. Succession stages of tidal marsh vegetation were observed and most apparent on the sections with a weak slope. However, based on wider monitoring results we conclude that the degree of target achievement is rather medium as a consequence of design problems. The old dike was not removed according to plan and as a result almost flat plateaus, with a steep slope towards the river were constructed instead of a gentle overall slope from the dike to the river. This had consequences for the habitat functions of the site. The steeper parts of the site showed net erosion and seemed less functional as habitat.
S-Pad.	In general, the restoration of the Paddebeek was a success to create a tidal wetland in the freshwater zone of the Sea Scheldt (Zeeschelde). By the inland shifting of the dike a small tidal area could develop in an area of the river Scheldt where mudflats and marshes are scarce. This is valuable for the connectivity of the tidal wetlands in this part of the Sea Scheldt (Zeeschelde). The constructed terraces were rapidly colonized by estuarine vegetation species. Because of the construction of terraces with life willow wicker, willow shrubs established very quickly, which accelerated vegetation succession and additionally stone rubble was not necessary to protect the new dike. Unfortunately the greater part of the old dike remained in place, hindering proper drainage, creek formation and colonisation. Additionally, the site has limited habitat functions for birds.
S-Paard.	Immediately after restoration (2004), the Paardenschor existed of 12ha bare mudflat. Under influence of the tidal floods twice a day with brackish water from the Scheldt, the Paardenschor rapidly transformed to a tidal wetland with a Good Ecological Potential [24], with clear creek formation in the mudflats and typical marsh vegetation at the higher areas (such as Common Glasswort (*Salicornia europaea*), Sea Aster (*Aster tripolium*) and Common Cordgrass (*Spartina anglica*)). The sediment is colonised by benthic invertebrates, predated on by water birds and fish. This type of low dynamic mudflats, relatively high in the tidal frame adds valuable foraging time and space for water birds. The initial tidal elevation and site slope were well chosen [36]. Overall there is net sedimentation, with local erosion in the developing creek network system. Creek network systems seem to establish without the specific excavation of a creek onset. However, its design could have been adapted to enhance its habitat functions for fish. Creek onset might have enhanced the habitat differentiation within the site and its suitability as fish habitat. The old dike could have been excavated more, but this might have led to erosion on the transition to the adjacent marsh (Schor Ouden Doel).
S-Heusd.	Overall, the restoration of the Heusden LO wetland succeeded in the aim to create an ecological valuable intertidal freshwater wetland. As a result of this design a site with a great variety of habitat types was created, with permanent pools, mudflats and all stages of typical tidal marsh vegetation. The vegetation gradient from low marsh to supratidal was uninterrupted because of the absence of fortifications. However, Initially the site only inundated at spring tides and it was not drained at low tide. Later two breaches to MLW were added where the old sluices used to be, connecting to ditches. It then had every aspect of a breached site with a strongly accentuated spring tide/neap tide differentiation in the inundation regime. Nevertheless, some areas remained inundated at low tide and the southern part where the sand stock for the dike construction works was not completely removed remained supratidal. Unfortunately the area was recently colonised by Floating marsh pennywort (*Hydrocotyle ranunculoides*), an invasive species. Chances are that this species will soon invade the complete tidal area.
W-Kl.P.	Although the tidal influence on the project area is restricted by three overflow barriers, the project area is regularly influenced by the tides and the appearance of several specific vegetation and fauna features of the brackish water zone of the Weser was confirmed by the monitoring results. However, the shallow water zone on the Kleinensieler Plate was strongly affected by siltation. Due to heightening the three overflow barriers, the amount of suspended matter entering the project was reduced significantly and siltation tendencies were slowed down. This means that –to the benefit of vegetation, fauna and water structures- less maintenance effort can be expected in the future.
H-Alk.	The site does appear to be acting as a nursery area for fish and is a significant feeding and roosting area for birds. In this respect, the development of the site appears to have been beneficial to this region of the estuary which is otherwise largely characterised by narrow mudflats with species poor communities and, in most areas, little vegetation. The Alkborough site has the dual aim of flood defence and compensation for habitat loss due to coastal squeeze (replacement of mudflat habitat). Given the site design, the elevation and the restricted flooding, it is however unlikely that this will be achieved in the long term and there is already evidence

	that the site will become vegetated and ceases to be fully inundated by high tides. This will mean that the site will not provide the 'like for like' habitat compensation. The rate of accretions was far greater than expected, also the development and usage of the site by birds highlighted a lack of understanding of how different species utilised the estuary as a whole.
H-PHS	After the first five year phase of monitoring data was reviewed and some results indicated that the site had not yet met some of the targets defined in the planning application. The site has achieved targets for habitat creation with typical saltmarsh species present, and usage by water birds as specified to compensate for lost habitats. The possible long-term development of the new mudflat into saltmarsh is likely to reduce the available habitat for benthic invertebrates and foraging birds, although additional saltmarsh may provide high tide refuges for birds, as well as roosting and nesting sites. Compensation for lost borrow pit and soke dyke habitats by translocation appears to have been successful with water vole, vegetation and freshwater invertebrate communities establishing. Accretion and saltmarsh development is however greater than originally expected and it is suggested that the site will become dominated by saltmarsh within a few years. The percentage cover of saltmarsh has increased dramatically and many areas are no longer fully inundated by high tides. In the long term, it may not continue to provide 'like for like' direct compensatory habitat. Discussions are on-going with Natural England to determine what level, if any, of management is required to ensure the site continues to meet its targets and possibly include the habitat within the designated site. Despite clear progress towards developing a benthic invertebrate community, this aspect, as expected, is lagging in terms of meeting targets, and the density of birds using the site is much lower than was the case on the sites lost for which they are compensating.

Measures with an as of yet unknown degree of target achievement:

Measure	Description degree of target achievement
H-Ki.W.	There are currently no details available regarding the effectiveness of the measure according to the development targets.
H-Don.N.	There are currently no details available regarding the effectiveness of the measure according to the development targets.

2) Safety

The second target for MR measures is safety. Three TIDE MRMs have a development target related to safety (Table 2-1):

- At **E-Sp.B.** the target was to reduce tidal energy (hydraulic effect) and thus, reduce the so called 'Tidal pumping effect'. Additionally, the expected benefit of the measures is the generation of approximately 1.1 Mio m³ of additional tidal volume. Although the measure is not implemented and monitored yet, it is already expected that dredging will be necessary every 4 or 5 years to keep the function.
- At **S-Lip.** the target was to create a Flood Control Area (FCA), and additionally to combine it with nature creation. Although it is only a small scale pilot project, it proved to be successful to combine nature creation in a flood control area by using a Controlled Reduced Tide with a high inlet and low outlet sluice.
- At **H-Alk.** the target was to reduce the impact of sea level rise and to allow wildlife to adapt to sea level rise. It is calculated that with the implementation of the Alkborough flats, the water level of the Humber could be reduced at extreme water levels by more than 150 mm (for a flood event with a 0.5 per cent chance of happening in any year, or 1 flood event in 200 years). However, it is anticipated that the site will become well vegetated and cease to be fully inundated by high tides. This means on the long term, that the flood water storage capacity will decrease. But on the other side, it is positive for marsh development and the elevation is important to reduce the impact of sea level rise.

3) Research

Three of the TIDE MRM examples are explicitly executed as a pilot project and hence for research purposes (Table 2-1):

- **S-Lip.** was executed in 2006 to study if sustainable ecological structures and functions could develop in a Flood Control Area with Controlled Reduced Tide (FCA-CRT), which are qualitatively and quantitatively similar to outer dike intertidal habitat. The results would deliver valuable input for all other planned FCA-CRT such as Kruibeke-Bazel-Rupelmonde. Based on the Lippenbroek pilot project, a lot of scientific insight was generated with respect to FCA-CRT and with intertidal mudflat and marsh in general. The pilot test proved that also an embanked area that is not suitable for basic managed realignment (because it is situated too low in reference to the water levels in the estuary) can be restored by a FCA with CRT. Therefore this technique increases the number of suitable sites and avoids problems with suboptimal tidal regimes and the need for artificial site elevation.

- **W-VorHin** is a pilot project for several similar compensation measures implemented after 1997 (e.g. TIDE measures **W-Kl.P.** and **W-Ronn.S.**). The measure site developed well and it is considered as a flagship measure. The tidal waters at the site were however flooded longer than projected by the hydraulic models used. The hydraulic calculations undertaken during the planning stages should be analysed in order to improve the predictability of tidal influence on potential project areas at estuaries. This is crucial in order to estimate e.g. the degree of siltation and thus the maintenance effort to expect.
- **H-PHS** was the first managed realignment site on the Humber estuary and therefore limited information was available to fully predict how the site would develop. The site development was not successful at all aspects: The rate of accretions was far greater than expected, also the development and usage of the site by birds highlighted a lack of understanding of how different species utilised the estuary as a whole. To improve the knowledge about MRMs, one of the overall targets was to monitor progress over a 10 year period. The monitoring programme implemented has proven to be a sound basis for observing the development of the site and assessing the progress towards achieving targets. The data sets generated during this study have been a powerful resource in developing understanding of processes and considerations in managed realignment habitat creation and contribute to current best practice. The data produced enables monitoring to assess if the habitat is developing into 'functional intertidal habitat' as required under the Habitats Regulation (planning condition). The output aids design, aims and techniques deployed in future schemes. The outcome of saltmarsh and mudflat development at Paull Holme Strays and the resulting composition of the invertebrate and bird communities will provide an important basis for the design and monitoring of further realignment schemes along the Humber Estuary.

4) Recreation

Five of the TIDE cases explicitly mention recreation in the targets (Table 2-1):

- At **E-Sp.B.** a ‘tidal park’ was planned to introduce the tidal influenced landscape to a wide-ranging public.
- At **H-Alk.** one of the targets was to provide a focus for education and access opportunities for local communities.
- At **H-Wel.** opportunities for recreation and tourism were provided through the site becoming a tourist and bird watching attraction.
- At **H-Ki.W.** opportunities for recreation and tourism were provided through the site becoming a tourist and bird watching attraction.
- At **H-Don.N.** opportunities for recreation and tourism were provided through new footpath provisions.

7.2.2. Implementation techniques

How are managed realignments executed?

Managed realignment is the introduction of a tidal regime in formerly un-flooded areas. In general three techniques to re-align an area are known:

1. **Dike (embankment) breach and defence removal**: A dike breach consists of one or more breaches in the dike, which could be accidental or forced. A defence removal is understood as an extreme situation of a dike breach: the complete (or partial) removal of the old dike.
2. **Land excavation**: If an embanked area is too highly elevated, breaching the old dike would not introduce floods in the area. Therefore the area could be excavated to bring it under estuarine influence. Floods are important for the development of a wetland ecosystem with flat habitats and marshes. This is mostly used for areas that were artificially elevated in history and hence lost the connection with the estuary. Secondly, land excavation is also used for “marsh rejuvenation”. In large

natural wetlands, a process of altering sedimentation and erosion is responsible for transformations from mudflat to marsh and further to higher areas with a very low flood rate. Cliff formation and erosion can set back this development so that the cycle of marsh formation can start over. In smaller areas the space for this natural dynamism is missing and many natural processes are restricted: marsh edges are often artificially protected against erosion. Land excavation is then a solution to change marshes into mudflats or at least lower the marshes to increase the flood rate.

3. **RTE**: **Regulated Tidal Exchange** is organized by different techniques such as sluices, shaft, pipes and valves which are capable to control the tide in the area. By controlling the tide, realignment measures can also be executed on very low elevated areas (which would be much more flooded under the natural estuarine regime).

Deciding on the most appropriate realignment technique depends on the objectives of the measures and specific environmental characteristics of the measure site, but also the financial resources and the political context. The objective of the measure determines what habitat types have to be developed. Some examples: to create a feeding area for waders, mudflats are needed, but to protect an adjacent seawall, marsh development is needed.

Inter-estuarine comparison of TIDE examples

Of the TIDE examples, about half is implemented by a dike breach and the other half by defence removal (Figure 2-2). And, also in half of the examples this was combined with land lowering. Only one example is implemented by a Reduced Tidal Exchange (RTE): **S-Lip.**.

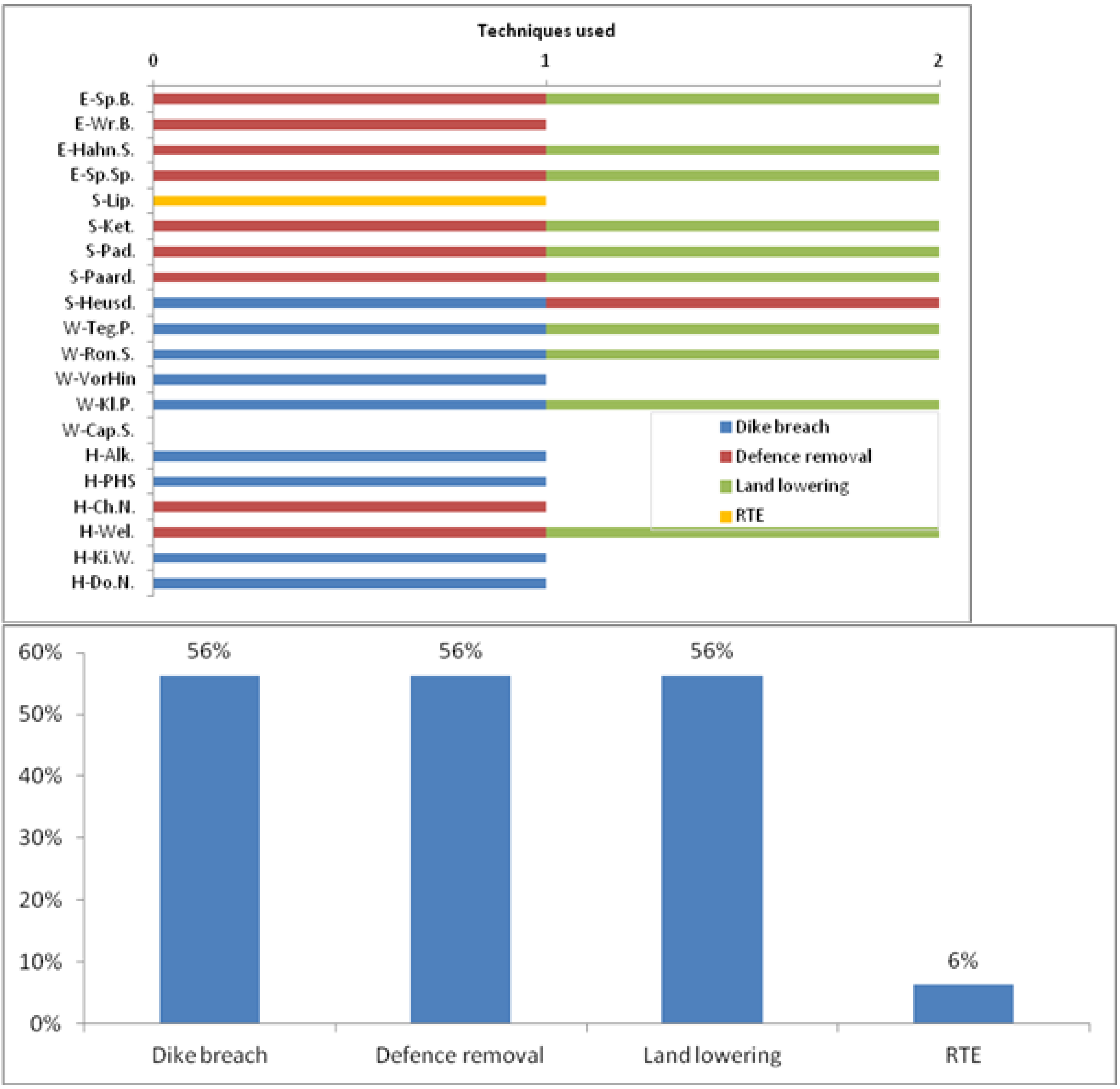
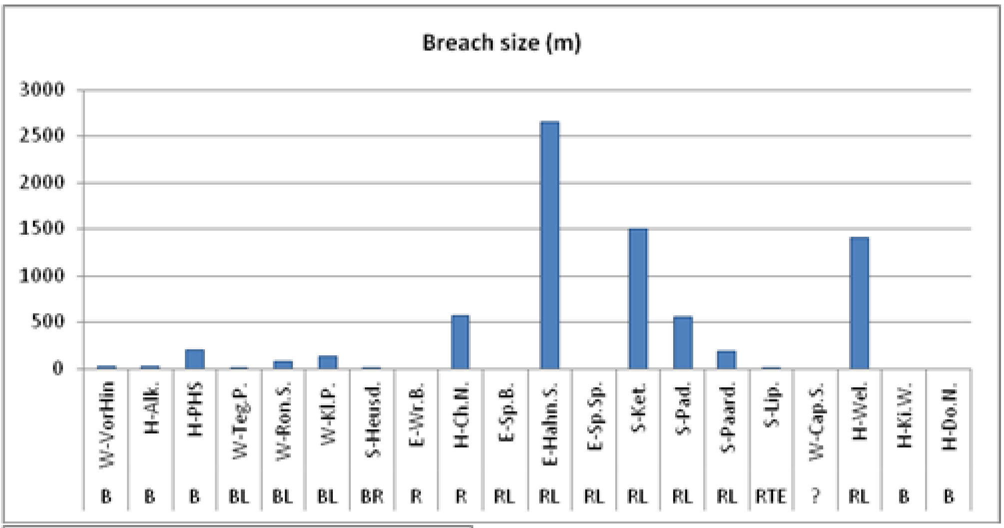


Figure 7-8. Left panel: Overview implementation techniques used for the different TIDE examples. Right panel: share of TIDE examples implemented with the different techniques.

Since the technique of defence removal only differs from a dike breach in the size of the breach, the breach size of the TIDE examples was compared and also related to the implementation technique. For all the examples, breach size ranges from 3m to 2650m (Figure 2-3) and the average breach size for measures implemented with a dike breach is 66m and with a defence removal 982m. So indeed, the implementation technique defence removal corresponds with a substantially wider breach ($F(1,11)=9,04$; $p=0.012$).



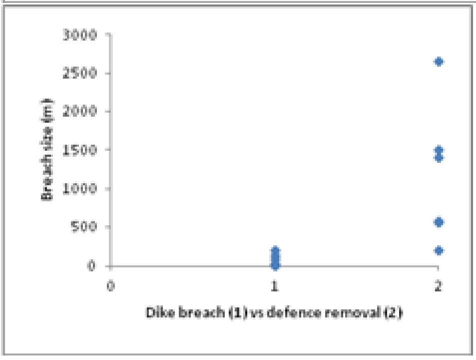


Figure 7-9. Link between implementation technique and the breach size (m): overview per measure (Left panel), distribution of breach size for measures with dike breach versus defence removal (Right panel). Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), RTE.

1) Overview measures with a dike breach

Measure	Description of the dike breach
S-Heusd	The old dike was lowered to mean high water level and two breaches to mean low water level were excavated where the old drainage sluices used to be.
W-Tegl.P.	Summer dikes were opened by several breaches and buildings, streets and supply lines were deconstructed to initiate the development of mudflat structures, creek systems, shallow water zones and tidal reeds.
W-Ronn.S.	A dike breach, with an overflow barrier (a sill) of 80m wide and levelled 0.5m under MLWL, guarantees a permanent minimum water level of 2m within the shallow water zone.
W-VorHin	The summer dike was partly deconstructed and an in- and outlet structure was installed in order to increase the tidal influence on the project area. The summer dike was enforced, i.e. breached dike will not be allowed to erode so as to not affect navigation.
W-Kl.P.	Three sill breaches were installed: two breaches connected directly with the estuary and one breach connected with a side arm.
H-Alk.	A dike breach of 20m wide was made and enforced with a boulder sill. Also, the defence was lowered over 1.5 km.
H-PHS	Two breaches in the old sea wall (protecting the former agricultural land from inundation) were made in order to maximise incursion and drainage whilst avoiding high velocities of a single breach: one breach at the eastern side (50m wide) and one at the western side (150m wide) of the site, approximately 1.5km apart from each other. No sill protection was placed on the breaches.
H-Kil.W.	The breach is planned for summer 2013, so exact details are not yet known.
H-Do.N.	The breach is planned for April-June 2013, so exact details are not yet known.

2) Overview measures with defence removal

Measure	Description defence removal
E-Sp.B.	This measure is still under construction: the dike is already removed, but the land lowering is not finished yet.
E-Wr.B.	The position of the dyke was changed in order to create a tidal creek of approx. 400m length (flow through system) in combination with an island of 300×40 m². This resulted in an outer dike area with an open creek system (open at both sides).
E-Hahn.S.	The implementation included a defence removal over 2,650m (West bay: 63ha and 1.300m opening; East bay: 39ha and 1.050m opening).
E-Sp.Sp.	The dike was replaced landwards (higher elevation) and a vegetated band exist between the project area and the river. The site is located immediately at the river with one opening from the river to the tidal creek in the project area (combined in- and out-let). The water enters/leaves via a tidal creek and flows to a shallow water area in the centre of the project area. A sill was placed at the opening of the creek in order to permanently ensure a certain water level and to prevent erosion within the area.
S-Ket.	The summer dike (central zone D-E) was partly excavated and the rubble of the summer dike and the dumped material was removed. The winter dike (from the north to the south) was elevated and broadened (to Sigma height and -width) to separate the wetland from the hinterland.
S-Pad.	The dike was shifted landwards (new dike at Sigma height) and the old dike was excavated. Where the old dike was removed, the substrate was reinforced with gabions (schanskorven) and a small stone rubble dike. Only at the ends, the dike was reinforced with stone rubble. Unfortunately the greater part of the old dike remained in place, hindering proper drainage, creek formation and colonisation. To allow some drainage several stones should be removed.
S-Paard.	The new dike was constructed next to the old dike and afterwards the old dike was excavated.
S-Heusd.	The old dike was lowered to mean high water level and two breaches to mean low water level were excavated where the old drainage sluices used to be. The dike needed to be elevated and broadened to Sigma requirement. Because there is no shipping in this area and because dynamics are low, the new dike was not reinforced with stone rubble.
H-Ch.N.	The existing seawall (defence) was removed over a length of 570m and some 200m remain. The removal was executed in a series of stages: (1) removing the rear of the embankment, (2) the concrete wave return, the bitumen and rock face, and (3) the overall lowering of the embankment. This removal, rather than the creation of solitary breaches, was chosen for a number of reasons: • It improves connectivity with the wider estuary; • It more closely recreates the type of environments that existed prior to the land claim; • It enables the whole cross sectional area of the estuary including the realignment site, to respond to estuary wide changes; and • It increases energy levels within the site, thereby improving the likelihood that mudflat habitat will be maintained (as mudflat creation was the main objective of the site). At the 15ha Chowder Ness site, new flood defences were created at the rear of the site to a minimum height of 6.7m above Ordnance Datum Newlyn (ODN).
H-Wel.	The existing seawall was removed over a length of 1400m and reprofiling of the land was undertaken to increase the extent of lower areas where mudflat could develop, as the site was largely too high. It was reprofiled from around 2.8m ODN, some 0.4m below the level of the Mean High Water Spring (MHWS) tides, to a minimum height of 6.1 ODN.

3) Overview measures with land lowering

Measure	Description of land lowering
E-Sp.B.	This measure is still under construction: the dike is already removed, but the land lowering is not finished yet.
E-Hahn.S.	The land lowering consisted of the excavation of a 5m soil layer: 1.5 Mio. m³ sand used for land claim for Airbus extension.
E-Sp.Sp.	Some land lowering was executed to restructure the new area to create areas of permanent water (lagoons). In addition, some of the excavated material was used to create high areas above mean high water level (sill).
S-Ket.	The plan was to level the area with a weak slope to slightly under MHWL. Overall, initial elevation was slightly higher than planned, i.e. less material was removed. The original design to create a gentle slope had to be altered ultimately resulting in large variation in height and slope leaving supratidal vegetated parts (a plateau), lower bare mud and a rather steep slope along the summer dike remnants.

S-Pad.	With the land lowering, a global gradient of the Paddebeek wetland of 3.7% was created.
S-Paard.	The area itself was lowered and a faint slope was created between 5m TAW and the level of the mudflat already in front of it, to create a good situation for marsh formation.
W-Tegl.P.	A considerable excavation was necessary in order to meet the requirements for regularly flooded tidal habitats and tidally influenced standing water bodies. Additionally, a connection to the river was realized by creating a new creek system in the north and expanding an existing creek system in the south of the project area. Small tidally influenced standing water bodies were created (5 lagoons).
W-Ronn.S.	The land lowering consisted of the excavation of dumped dredge spoil (370.000 m³).
W-Kl.P.	The land lowering consisted of the excavation of dumped dredge spoil, grading to create lagoon and intertidal habitats. By forming the banks of the shallow water area, the site specific conditions for the settlement of different structured reeds were created. In order to promote the development of perennial and ruderal meadows and woods, small scale site specific differences were initiated by irregular surface design. The lagoon was created in 2000 but needed dredging in 2004 due to higher than expected sedimentation.
H-Wel.	The existing seawall was removed over a length of 1400m and reprofiling of the land was undertaken to increase the extent of lower areas where mudflat could develop, as the site was largely too high. It was reprofiled from around 2.8m ODN, some 0.4m below the level of the Mean High Water Spring (MHWS) tides, to a minimum height of 6.1 ODN.

4) Other specific design aspects

In the next part, special design aspects of TIDE examples are described.

4.1) Link between design and habitat creation

i) Initial elevation (relative to tidal range)

From the Spadenländer Spitze case in the Elbe estuary (**E-Sp.Sp.**) it was concluded that for a good design the creation of different elevation levels with respect to the tide is important in order to create an area with the most possible tidal dynamics. Flat areas with little depressions below mean high water are very important for the establishment of creeks, serving as a habitat for *Oenanthe conioides*, waders and - after extension - also for juvenile fish.

Also in other cases the importance of the initial site elevation and the topography of the site were discussed.

- At the Heusden marsh (**S-Heusd.**) for instance the topography of the restored site was not altered and consequently the site was initially only inundated at spring tides and couldn't properly be drained at low tide. Adaptations to the site design were needed to differentiate the inundation regimes and hence improve the variety of habitat types.
- At Paul Holme Strays (**H-PHS**), resulting elevation has been demonstrated to be critical to rates and locations of vegetation development. The development of the site which has profound implications for rates and types of habitat creation was mainly affected by the sediment load in the Humber estuary and the limited exposure of the site. Both factors closely correspond to the site elevation and the corresponding inundation.
- At Welwick (**H-Wel.**), accretionary trends were found, showing an average difference between 2007 and 2011 of +14cm. The degree of accretion was found to have decreased over time. The main change in elevation took place in the initial year following the breach, with typical elevations increasing by between 0 and 50cm between 2006 and 2007. The change in elevation in subsequent years has decreased, although increases of up to 40cm have still been observed at some locations across the site between the 2009 and 2011 surveys. Over the survey period, the majority of change in elevation (accretion) has occurred in lowest (seaward) parts of the site, which were around 1.5 to 1.75mODN in 2007 - with changes in elevation of the order of 10-40cm. Erosion was initially noted in the creeks, and continually towards the rear of the site within the created saline lagoons. The latter should, however, be viewed with a degree of caution as the presence of standing water can reduce the accuracy of the LiDAR data. The higher elevations (above ca. 2.75mODN) have barely, or not at all, been subject to a net gain in elevation. Saltmarsh vegetation has generally established in areas above 2.5 to 3mODN (2.5mODN is approximately 50cm above the MHWN level). Most of the mudflat areas below 2mODN remain un-vegetated.

Site development and accretion also slow down at saltmarsh elevations, limited to only a few cm at most over 5 years (conclusion from the Chowder Ness case (**H-Ch.N.**)).

ii) Slope

From the Ketenisse case (**S-Ket.**) a clear correlation between the slope of the area and sedimentation/erosion was concluded (sedimentation at weak slopes until 2.5% and erosion at steeper slopes from 2.5%). The Ketenisse area was levelled in 2002 with a weak slope below mean high water level, creating the optimal starting conditions for the development of intertidal mudflats and marshes. However, at the extreme ends of the site the slopes are too steep and net erosion took place. As a consequence, those parts seemed less functional as habitat. The difference in slope corresponds to the two intertidal habitat types: flat habitat (slope < 2.5%), and steep habitat (slope > 2.5%).

iii) Dynamics on the site

Habitat development is also linked with the dynamics in the area:

- The low dynamic mudflats of the Paardenschor (**S-Paard.**), located relatively high in the tidal frame, are colonised by benthic invertebrates and add valuable foraging time and space for water birds. However, its design was less suitable as a habitat for fish.
- In the case of Paul Holme Strays (**H-PHS**), sustainability of mudflat habitats appears to be limited by the lack of exposure at this site. The sustainability of mudflat habitats corresponds with the accretion rate. The lowest accretion rates are thought to be characterised by a wide connection to the estuary (essentially a very wide breach); exposure to significant fetch from the predominant wind direction; and relatively high flows due to its proximity to the main Humber navigation channel and the Humber Bridge (the latter constriction causing higher flows). However, exposure at this site is a trade-off with erosion and losses of natural saltmarsh along the frontage of the remaining sea defence and cost implications.
- At Welwick (**H-Wel.**), saltmarsh colonised the site very rapidly, covering some 28ha within two years of the site being inundated. The extent of saltmarsh has also continued to increase since this time, although the rate of expansion has decreased as time has elapsed. Species diversity has also been fairly consistent over the years monitored to date and average abundance has increased rapidly and, although variable, is still continuing to increase four years post inundation of this site.

iv) Drainage and creek network

Drainage system and creek network development also got special attention in the frame of site design:

- At Paardenschor (**S-Paard.**), creek network systems seem to establish without the specific excavation of a creek onset. However, creek onset might have enhanced the habitat differentiation within the site and its suitability as fish habitat.
- In the case of Spadenländer Spitze (**E-Sp.Sp.**), the special design of tidal creeks has turned out as superfluous; the tidal dynamics were too dominant. It turned out to be more important to have prevented the area of human disturbance.
- In the Paul Holme Strays case (**H-PHS**), hydrodynamic changes with the development of drainage systems have also been demonstrated to be critical for vegetation and benthic invertebrate community development and impact strongly on bird usage.
- The compensation measure Tegeler Plate (**W-Tegl.P.**) showed that it is principally possible to create self-preserving tidal creek systems within highly dynamical estuaries. One crucial point for the successful development of tidally influenced habitats on the Tegeler Plate was the creation of suitable site specific conditions by means of hydraulic engineering works. However, the conditions for achieving self-preserving creek systems should be analysed in detail. The results from the Tegeler Plate are at least supposed to be helpful in view of future measure planning and implementation processes.

v) Other aspects

- The deeper areas of the shallow water zone in the Vorder- und Hinterwerder (**W-VorHin**) are designed to improve the situation for fish and to serve as sediment traps to slow down the expected siltation.

4.2) Unique design

i) Flood Control Area with Controlled Reduced Tide (FCA-CRT construction)

The Lippenbroek case in the Scheldt estuary (**S-Lip.**) proved that tidal marsh restoration with a FCA-CRT construction can happen very fast and spontaneously. Some lessons learned:

- The inundation curve is different than in natural intertidal areas (duration is longer, and has three phases: ebb, stagnant and flood) but this does not obstruct the colonisation by fauna and flora.
- The inlet sluice has to be situated sufficiently high to allow sufficient differences in inflow duration and volume and thus to create a large variation in inundation frequencies and water levels in the polder.
- Initial terrestrial vegetation slowed down the establishment of estuarine species. It is therefore recommended to remove initial terrestrial vegetation before opening the side.
- Although the area is very small, this pilot project proved the potential effect on the water quality.

ii) Terraces

At the Paddebeek case in the Scheldt estuary (**S-Pad.**) terraces were constructed at different heights. A positive result came from the life willow wickers, used to construct the terraces. As a consequence, willow shrubs established very quickly, which accelerated vegetation succession in the site. The constructed terraces were rapidly colonized by estuarine vegetation species: pioneer communities of Vaucheria (*Vaucheria sp.*), Water speedwell (*Veronica anagallis-aquatica*), Cursed buttercup (*Ranunculus sceleratus*), etc., followed by helofytes like Alkali Bulrush (*scirpus maritimus*), Common Reed (*Phragmites australis*), Common Bulrush (*Typha latifolia*) en Reed Sweet Grass (*Glyceria maxima*).

In addition, there was no need to use stone rubble (boulders) to protect the new dike, except for the edges.

4.3) Negative experiences with un-complete implementation

In the case of Paddebeek (**S-Pad.**) the old dike was excavated and the substrate was reinforced with gabions (schanskorven) and a small stone rubble dike. Only at the ends, the dike was reinforced with stone rubble. However, the greater part of the old dike remained in place and the removed boulders were piled up between two terraces hindering proper drainage, creek formation and colonisation. To allow some drainage some of the boulders (stones) should still be removed.

Also at the Paardenschor (**S-Paard.**) the old dike could have been excavated more, but on the other hand this might have led to erosion on the transition to the adjacent marsh (Schor Ouden Doel).

At the Ketenisse marsh (**S-Ket.**), it was planned to level the area with a weak slope but in the end the slopes at the extreme ends of the site are too steep causing net erosion by which these zones seemed less functional as habitat. In the central part two aspects of the final design differed significantly from the original plan:

- Some areas, where the topsoil was not useful as construction material for dikes, were not excavated below mean high water level and remained almost supratidal.
- The old dike was not removed according to plan and as a result almost flat plateaus with a steep slope towards the river were constructed instead of a gentle overall slope from the dike to the river.

This had consequences for the habitat development of the site. At T-0 higher vegetation was already in place including supratidal as well as tidal marsh vegetation. Some of it died off, whilst in other places it remained and served as a ‘source’ for typical fauna and flora elements.
The plateaus now provide low dynamic habitat, they silted up and a relatively rich macrobenthic invertebrate community was established, providing extra foraging and roosting space for birds.

If the central slope would have been realised according to plan sedimentation / erosion and habitat development would have been quite different. There would have been relatively less mudflat with a long exposure time; on the other hand habitat diversity and gradual transitions might have been more elaborate.

5) Examples where adjustments were needed

At Wrauster Bogen (**E-Wr.B.**), the monitoring outcomes showed that the slope steepness and high flow velocities in the creek prevented that mudflats could evolve. Also the water level in the creek proved to be too low for a permanent colonization by fish using the creek as resting and growing habitat. Erosion occurred at the creek banks and the slopes, resulting in transportation of materials (more silt and clay) from the creek into the Elbe estuary at low tide.
In order to promote sedimentation in the creek, a morphological rearrangement of the creek was executed in 1994 (three years after the initial implementation). One side of the creek was closed in order to decrease the flow current and a sill (30m wide and levelled 1m above MLWL) was placed in the other opening in order to prevent the complete drainage of the creek. In addition, also the slope of the embankments was flattened.
After the adjustment of the tidal creek a positive influence on the erosion and sedimentation processes was observed: the flow velocities in the river channel decreased and mudflats could evolve and thus provide food for the resting fish species. Therefore the rework led to favourable results concerning the achievement of the development targets. Also, it was concluded that a monitoring after the implementation phase is necessary in order to check whether the targeted results finally have been achieved.

At Heusden (**S-Heusd.**) the site design had led to the unfavourable situation that initially the site inundated at spring tides and that it was not drained at low tide. Later two breaches at MLW were added where the old sluices used to be. It then had every aspect of a breached site with a strongly accentuated spring tide / neap tide differentiation in the inundation regime. Nevertheless some areas remained inundated at low tide and the southern part, where the sand stock for the dike construction works was not completely removed, remained supratidal.

As a result of this design a site with a great variety of habitat types was created, with permanent pools, mudflats and all stages of typical tidal marsh vegetation. The altitude gradient from low marsh to supratidal was uninterrupted because of the absence of fortifications.

At Kleinensieler Plate (**W-Kl.P.**) the shallow water zone was strongly affected by siltation. Therefore two of three overflow barriers were heightened in 2005 (five years after the initial implementation). As a result, the amount of suspended matter entering the project area could be reduced significantly and siltation tendencies were slowed down. At the same time, the tidal influence on the project area was restricted. This means also that, to the benefit of vegetation, fauna and water structures, less maintenance effort can be expected in the future.

7.2.3. Habitat creation & compensation

Main question: Which habitat types are expected & created by executing MRMs?

For the Humber, only three MRMs are included in this study.

MRMs mostly transform 'adjacent land' into estuarine habitats. For the TIDE cases, in total almost 1000 hectares of land is realigned. More specifically the previous land type was for instance arable/agricultural (e.g. S-Lip., H-PHS, H-Ch.N. and H-Don.N.), pasture (e.g. S-Ket. and H-PHS), or dredge spoil storage (eg. W-Kl.P.). The TIDE measures create between two and six of the different habitat types (Figure 2-4). The newly created habitats are mainly marsh land (48%) and intertidal flats (35%), but also intertidal steep habitat and subtidal habitats are created (Figure 2-4). The largest habitat creation was realised by the TIDE cases in the Weser and Humber (Figure 2-5). In the Humber this was mainly in the mesohaline zone and in the Weser in the oligohaline zone.

For compensation measures, there is however no additional habitat created because it was lost first somewhere else. For the TIDE cases, almost all created habitat surface is for compensation reasons and only 10% is newly created for other reasons (Figure 2-6).

The data about the habitat change by the measures is collected by a survey. Responsible authorities were asked to indicate for every measure the habitat surface per habitat type, before and after the implementation of the measure.

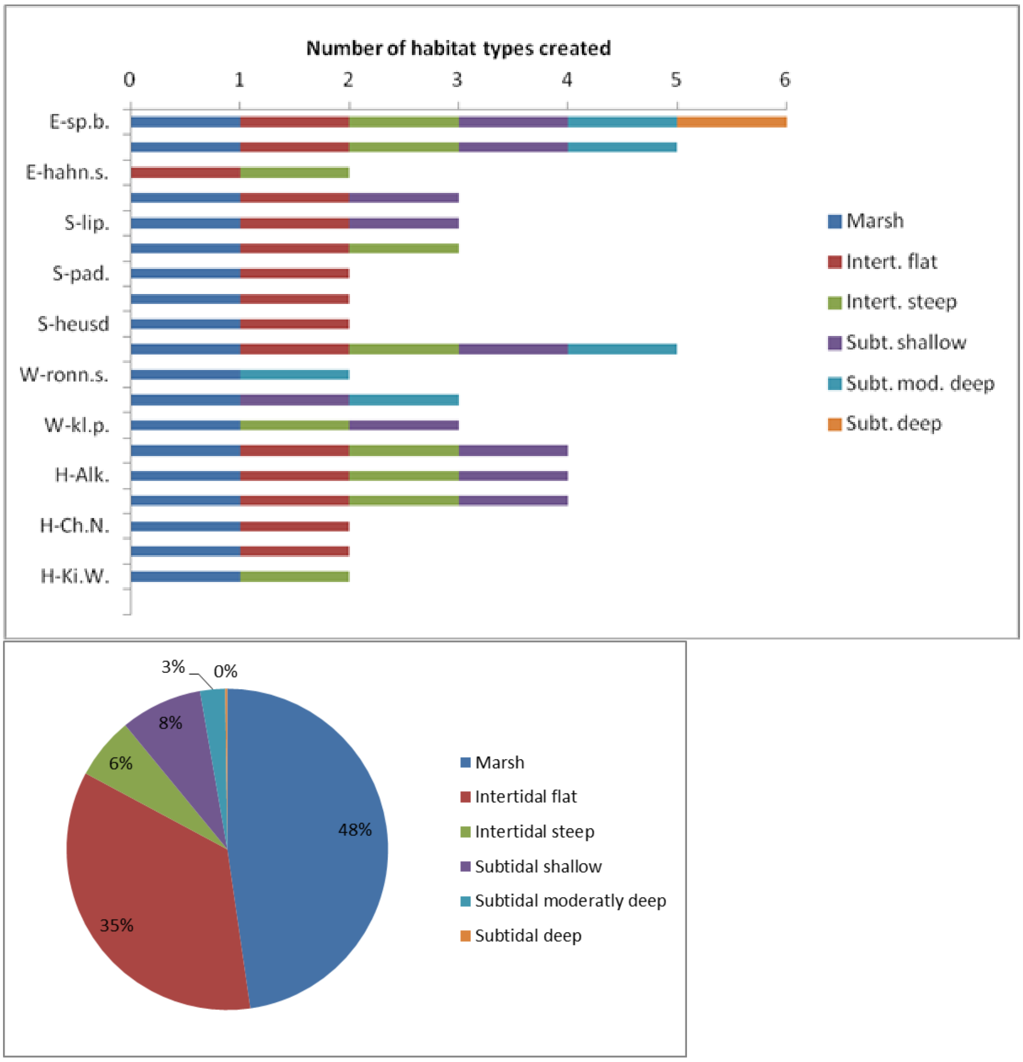


Figure 7-10. Left panel: Habitat types created per TIDE measure. Right panel: distribution of the total hectares of different habitat types created by the TIDE cases.

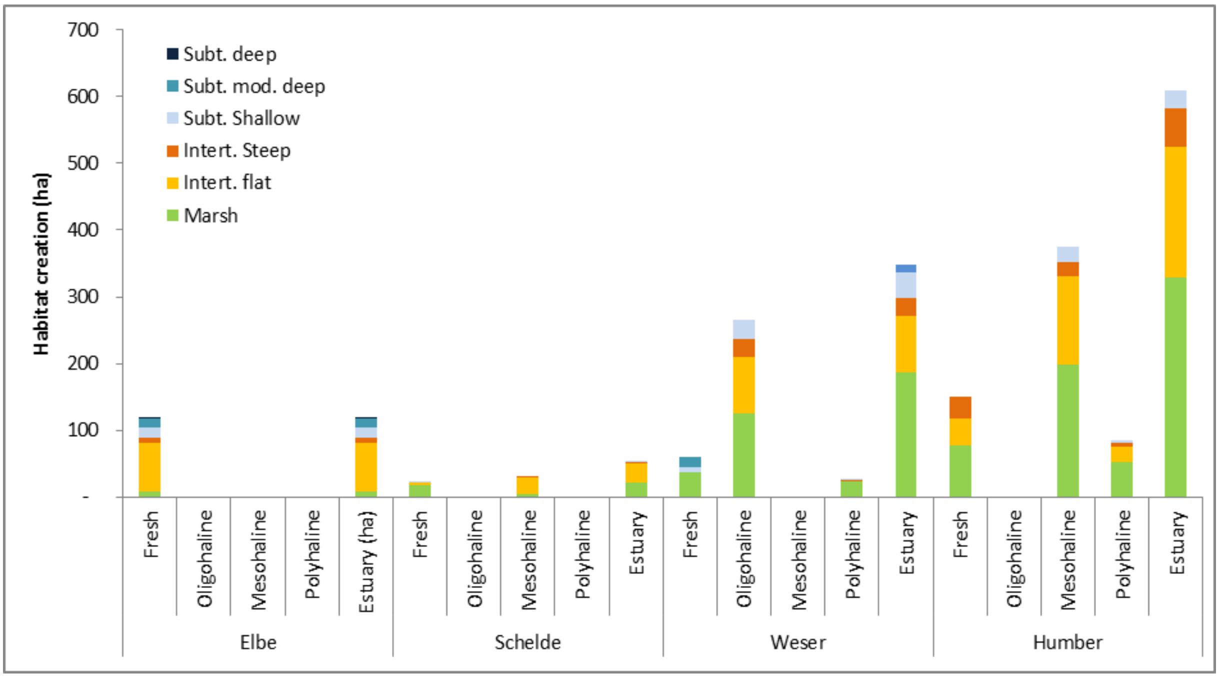


Figure 7-11. Overview habitat creation by the TIDE cases per estuary and per zone (in hectares)

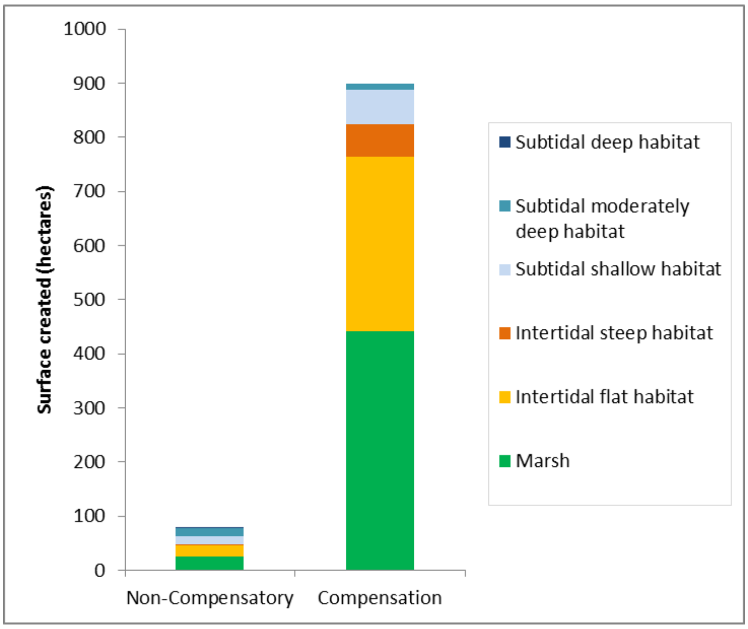


Figure 7-12. Overview habitat creation per habitat type by the TIDE compensation measures and non-compensatory measures

7.2.4. Monitoring program

Main question: Is the success of MRMs monitored?

The success of a measure is mostly analysed by monitoring different environmental characteristics. All TIDE examples do have a monitoring program. The duration of the monitoring program varies from 3 to 15 years. Since developments on levelled sites start shortly after the end of the works, it is important to monitor intensively in the early stages [35]. It is recommended to have a thorough monitoring within an annual programme for at least five years [37]. Long term monitoring records of many sites indeed suggest that the ecology of the realignment sites takes many years to pass from pioneer stages to a more stable ecology. After this period, the frequency of monitoring can generally be reduced when most sites become less dynamic and the colonisation phase is over and more stable flora and fauna are developing. However, there are examples where sites are still in transition after more than 12-15 years. It is not clear whether all sites will ever reach a state of equilibrium or achieve a similar physical and ecological status to adjacent areas in the main part of the estuary [37].

The parameters that are monitored in at least half of the TIDE examples are vegetation, accretion and sedimentation on site, invertebrates, birds and fish (Figure 2-7). This means that mostly the 'visible' biological aspects are monitored (the end users of a healthy system), but much less the underlying ecological/chemical/physical processes. This corresponds to the fact that many measures have been developed in response to the requirements of the Birds and Habitats Directives and hence the main focus of the monitoring is on birds and food sources for birds. Less work has been done on the physical changes which take place within and outside of the sites [37]. However, the latter is equally important to evaluate the success of a measure.

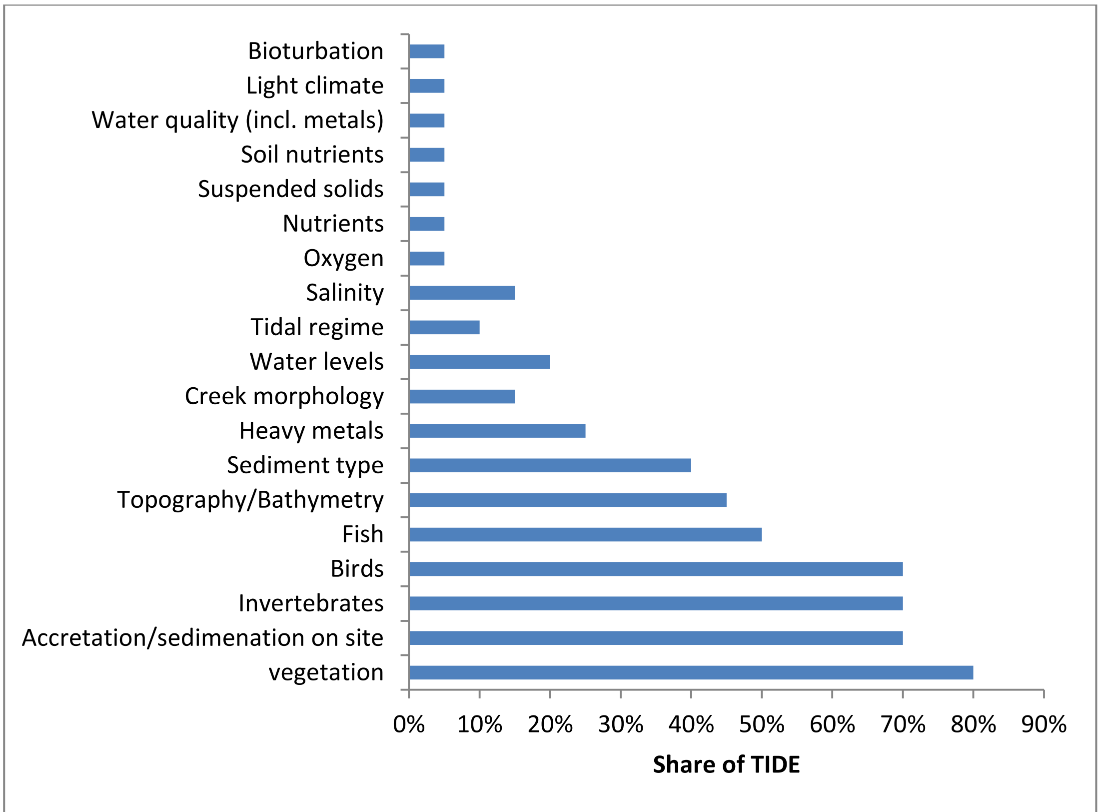


Figure 7-13. Share of TIDE MRM examples with the different parameters in the monitoring program

The monitored parameters are more or less in accordance to the key parameters that are recommended to add in all future managed realignment monitoring programmes [37]:

- Original ground levels;
- Frequency of tidal inundation on all parts of the new intertidal areas;
- Sedimentation at fixed monitoring points;
- Changes in ground level across the site;
- The nature of sediments in terms of particle size, organic content and moisture content;
- Invertebrate colonisation of the intertidal sediments and water column;
- Fisheries, in particular juveniles;
- Use of the sites by birds; and
- Colonisation of bare substrates by vegetation including both algae and higher plants.

For some Scheldt cases also the monitoring program was evaluated [35] and it was recommended to:

- Start with the monitoring plan already in the planning phase with clear cost estimation and clear agreements on execution and reporting;
- Make a clear distinction between "site success monitoring" and "impact verification monitoring";
- Make a photographic survey on a yearly basis to improve interpretation of collected data;
- Optimise the comparability of monitoring results of zoobenthos with that of other countries;
- Monitoring of birds and fishes needs to be done from the beginning following fixed protocol;
- Experimental research is needed to monitor benthic primary production; and
- Investigate the monitoring of floristic quality of marsh vegetation.

7.2.5. Synergies and conflicts

Main question: Can managed realignment generate synergies? And, conflicts?

MRMs could generate many benefits in the field of flood management, environmental benefits and financial benefits [38].

- Benefits for flood management are about the reduction of the flood risk elsewhere in the system through changing the hydrodynamic conditions, the improvement of the flood risk condition in accordance with national legislation, the avoidance of uncontrolled abandonment of 'weak spots' in the dike, and the management of the effects of sea level rise over time.
- Environmental benefits come from an increase of the diversity and ecological richness of the area, an increase or management of the existing ecosystems in accordance with local/international legislation, a compensation for engineering works or long term processes such as coastal squeeze in accordance with local/international legislation, a creation of areas with a high recreational value for eco-tourism, and provision of nutrient and pollution sinks that purify the water.
- Financial benefits are related to the fact that it will require smaller defences due to wave attenuation on salt marsh, it will create a sustainable flood defence that will provide safety for a longer period of time, and it will lower the maintenance cost of the flood defence system as a whole.

Many stakeholders are also involved, with many synergetic but sometimes also conflicting interests. The main synergies and conflicts of the TIDE MRMs are summarised:

Synergies:

- Habitat creation and flood protection (**S-Lip., S-Pad., S-Heusd., W-Kl.P., H-Alk.** and **H-Kil.W.**)
- Habitat creation and port development: The creation of estuarine habitats by implementing MRMs could give a justification for port development activities such as the creation of harbour docks (**S-Paard., H-Wel.** and **H-Don.N.**) and dredging activities inside the port (**E-Sp.B.**) or in the navigation channels.
- Habitat creation and recreation: at many cases positive effects on leisure and local recreation are observed:
    - At Spadenlander Bush (**E-Sp.B.**) positive effects are expected due to public footpaths along the newly built shore and a set of presentation boards to provide additional information concerning the new developed tidal influenced biotopes.
    - At Wrauster Bogen (**E-Wr.B.**) the implementation of the measure positively influenced the local fish population due to the generation of additional spawning and growing habitat for some species. This was good for local fishery activities.
    - The Lippenbroek case (**S-Lip.**) is included in touristic brochures by some municipalities.
    - At Ketenisse (**S-Ket.**) the creation of stairs over the dike is considered for watching birds behind a transparent wall, combined with information panels. The polder can also be visited during educative excursions (eg. bird watching day) by the local environmental association (Natuurpunt-WAL). Ketenisse is also favourable for cyclists with a nice cycle path along the flowery Scheldt dike. On the north side (in the direction of Liefkenshoek, along sections LHT and ABC) this cycle path is however not finished. At the downstream part (Fort Liefkenshoek) there is a tower with a nice view and a pub. This cycle route is also planned to be integrated

in the Ecological InfraStructure cycle route (EIS-cycle rout) in the harbour area. The initiative to open the local service road is linked to the project 'the Antwerp harbour more environmentally friendly'.
  - At Kleinensieler Plate (**Kl.P.**) an 850m shore section north of the ferry terminal Kleinensiel is fully usable as beach again, after parts of the excavated material were spread. Here, no conflicts with tourism, leisure and local recreation appeared.
  - At Welwick (**H-Wel.**) intertidal habitat creation to compensate for losses associated with port development was implemented, which had additional benefits of providing opportunities for recreation and tourism through becoming a tourist and bird watching attraction.

Conflicts:

- Corresponding to agriculture, only conflicts are observed, mostly because agricultural land disappeared at the benefit of estuarine habitat (**E-Sp.Sp., S-Pad., S-Paard, W-Tegl.P., W-Cap.S.N., H-Alk.**).
- Flood protection and local inhabitants: In some cases also some conflicts were observed because local inhabitants sometimes feared disadvantages from the flood protection (**E-Wr.B.**, **S-Lip.** and **H-Don/N.**). This conflict was however solved after both measures were carried out because it became clear that the high flood protection status could be kept.
- Nature development and recreation
  - After the implementation of the Hahnofer Sand measure (**E-Hahn.S.**) the area was designated as a nature protection area and therefore all hunting and fishing activities, even the hunting from the unprotected dyke area, were forbidden.
  - At Ketenisse (**S-Ket.**), recreation activities (eg. road for cyclers) are considered by some actors as a disturbance factor for resting and foraging birds.
  - At the area of Vorder- und Hinterwerder (**W-VorHin**), the general public was sceptical first because it has been a popular area for leisure, local recreation and tourism already before the compensation measure was implemented. But since the natural scenery improved significantly after measure implementation, positive effects on leisure, local recreation and tourism can be stated.
- Other conflicts
  - At Paul Holme Strays (**H-PHS**) there was some local opposition due to the change in land use, perceived increase in tourism, construction disturbance to residents and permanent footpath diversions. The environmental steering group helped to deal with the majority of the concerns raised and generally the site has now been accepted by the local community.
  - At Alkborough (**H-Alk.**) initial concerns from the local community were related to loss of agricultural land, removal of mature trees, and perceived increase in tourism.
  - At Tegeler Plate (**W-Tegl.P.**), conflicts regarding agriculture, tourism, leisure and local recreation can be stated and the site is almost inaccessible for people nowadays.

Conflicts are mainly caused by concerns of local inhabitants: Public acceptance by local stakeholders is in general limited. MR projects have the opportunity to combine different societal functions such as safety, agriculture, ecology and inhabitation in coastal defence schemes, but clarification on the success rate and the effectiveness of the provided estuarine restoration projects is often lacking. As a consequence, local communities fear disadvantages that are maybe irrelevant.

7.2.6. Costs and benefits of MR-measures

Main question: How cost-efficient are the TIDE MRMs?

Cost-efficiency is an import issue in the European Water Framework Directive. It was stated (in Article 11 of EU-WFD) that for the selection of a measure program also the cost-efficiency considerations should be taken into account in order to find the least expensive way of reaching the WFD objectives. Hence, the member states are obliged to apply the *cost recovery principle* and determine the most cost-effective combination of measures to achieve a good water status.

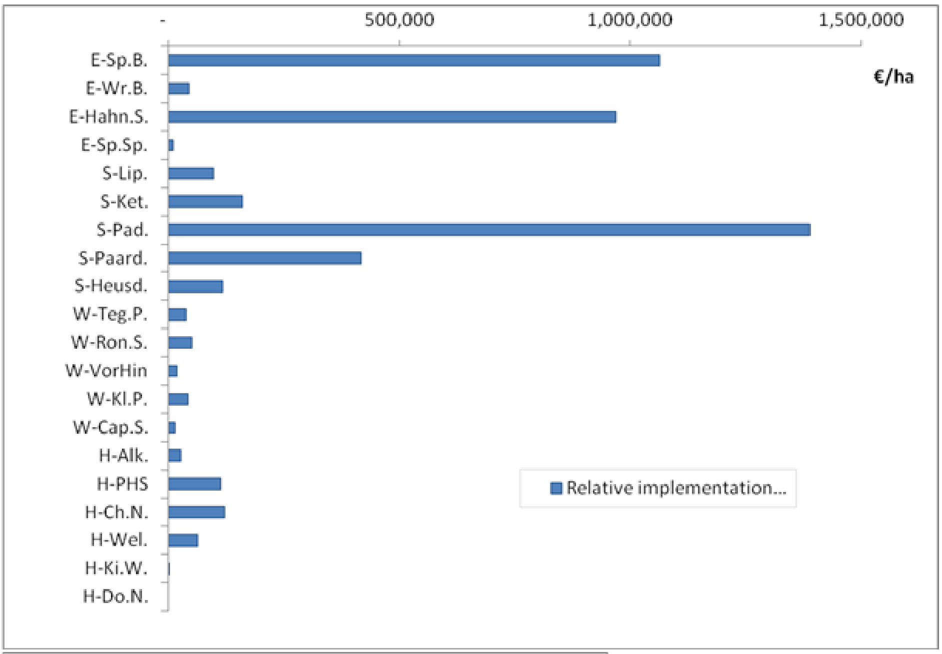
In the frame of this study, the costs and benefits of the TIDE MRM cases are compared and the cost-efficiency is calculated.

Implementation cost

The relative implementation cost (€/ha) is calculated per measure by dividing the total implementation cost (€) with the total restored surface (ha). It is important to state here that the total implementation cost was not available for all TIDE measures and hence for the others an estimation of the cost category was made (**E-Wr.B.**, **E-Sp.Sp.**, **W-Tegl.P.**, **W-Ronn.S.**, **W-VorHin.** and H-Do.N.). For the calculations the average of the given cost category is used to reduce the amount of numbers in the text and in the graphs.

The average cost of the TIDE MRM cases amounts 250,000 €/ha, but a large range from 2,000 to 1.4 Mio €/ha was observed. Slightly over half of the measures (55%) cost less than 100,000 €/ha, 30% between 0.1 Mio and 0.5 Mio €/ha and 15% more than 0.5 Mio €/ha. The most expensive measures are found in the Scheldt and the Elbe estuary, followed at a large distance by measures in the Humber and Weser (Figure 2-8).

The average relative implementation cost of the TIDE cases seems very high relative to other studies. For instance, according to the British OMReg study (managed realignment cases in U.K.), the average cost amounts 37,000 €/ha with the highest cost 139,000 €/ha [29].



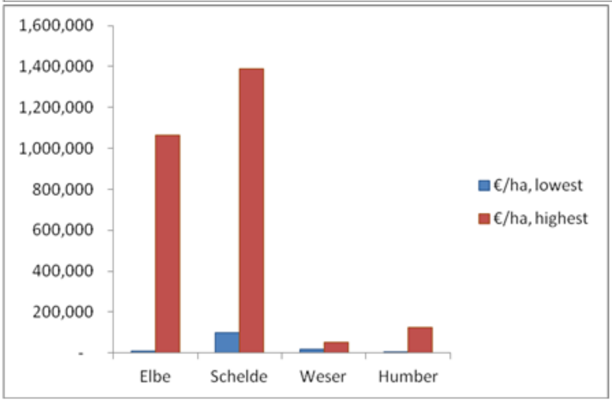


Figure 7-14. Left panel: Implementation cost per measure (€/ha). Right panel: The lowest and highest expensive example per estuary.

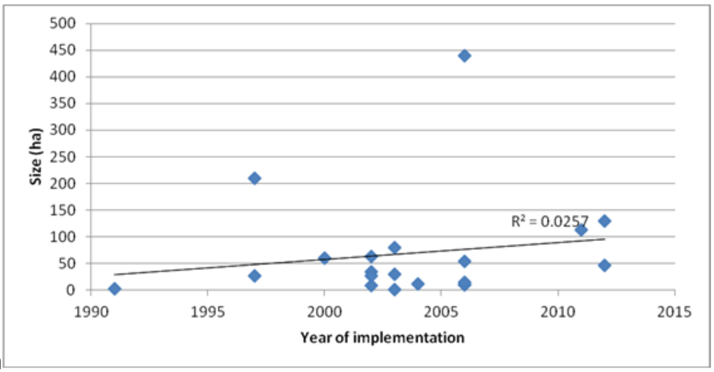
Three of the TIDE MRMs have a remarkably high relative implementation cost: Spadenlander Bush (E-Sp.B.), Hahnofer Sand (E-Hahn.S.), and Paddebeek (S-Pad.). Some possible explanations are found for the high cost of those measures:

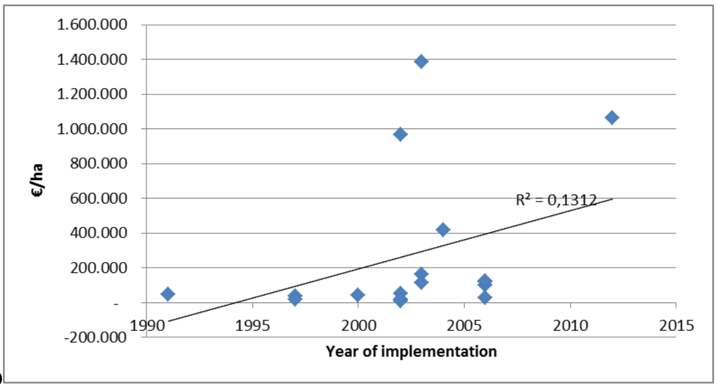
- For Spadenlander Bush (**E-Sp.B.**), for which the work will start in November 2012, high costs are expected because a huge amount of heavy contaminated high-lying soil (over 2 Mio m^3) has to be removed and treated in a special way. Extra costs will hence arise for the deposition of that material elsewhere.
- At Hahnofer Sand (**E-Hahn.S.**) also a lot of soils had to be removed to build the mudflats. The soil was not contaminated but the amount was huge (6 Mio m^3).
- The cost of Paddebeek (**S-Pad.**) is part of the dike construction at a longer distance (between Schoonaardebrug and Paddebeek). Hence, the cost of 2.2 Mio € is most probably an overestimation. However, the implementation of the Paddebeek wetland consisted of the landward shift of the dike, the heightening of the dike to Sigma-height, realisation of three terraces, excavation of the old dike, and two breaches at the old dewatering sluices.

From those examples it is clear that aspects that determine the total implementation cost are very complex and highly dependent on the local situation. Therefore, direct comparison of measures according to costs is often not possible. This explains also the large range in the implementation cost between the cheapest and most expensive example. Indeed, the measures, although all MRMs, differ a lot in detail and therefore it is important to have a closer look at the actual work that have been carried out and point out why the implementation cost vary.

1) Size and year of implementation

Over the course of two decades there has been in general a clear shift from initial low-cost, small-scale, and relatively inexpensive trial projects to high-cost, larger projects that were designed to meet specific targets for habitat and flood alleviation [29]. For the TIDE cases, we see however no clear trend from small-scale to larger projects (R^2=0.0069; T=0.32; p=0.75) (Figure 2-9, a), but indeed the per hectare implementation cost tends to increase over time (however not significant: R^2=0.1314; T=1.5; p=0.15) (Figure 2-9, b). The schemes implemented after 2000 had higher per hectare implementation costs (Figure 2-10). Those were however still mostly small-scale projects.
It is expected that recent larger projects are accompanied by improved unit costs (i.e. 'economies of scale') because of enhanced efficiencies in the light of the lessons learned from previous projects. However, this could not be confirmed by the TIDE cases (R^2=0.0328; T=0.71; p=0.49) (Figure 2-9, c), and according to the British OMReg study this hypothesis was not true [29]. In this study it is stated that a number of large-scale projects are in the pipeline at present which will be relatively high cost projects due to their large size and/or novel complexities associated with their design and construction.

a 



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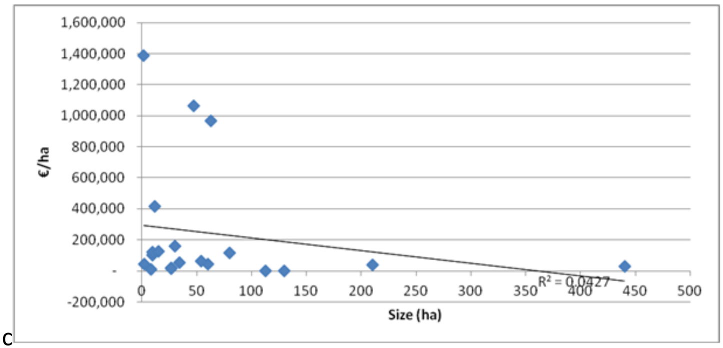


c

Figure 7-15. Evolution of measure size (a) and per hectare implementation cost (b) over time (1991-2012), and per hectare implementation cost linked with measure size (c).

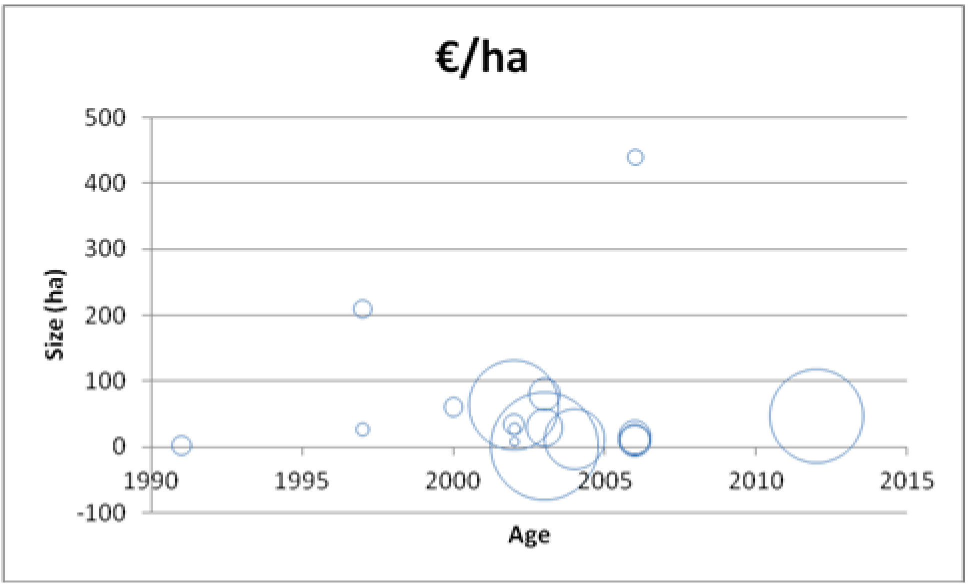


Figure 7-16. Implementation cost (€/ha) plotted against size and year.

2) Implementation technique: dike breach, defence removal, breach size and land removal

The average per hectare implementation cost is significantly higher for **defence removal compared to dike breach** (F(1,13)=5,08; p=0,04) (Figure 2-11). The average cost for dike breach amounts 85,000 €/ha (ranging from 20,000 to 125,000 €/ha), and for defence removal on average 42,000 €/ha (ranging from 10,.000 to 1.4 Mio €/ha). The three most expensive cases are indeed implemented by a defence removal.

Since dike breach and defence removal mainly differ in the **breach size**, this was also compared in more detail. Breach size in the TIDE cases varies between 3m and 2650m. Compared with the per hectare implementation cost, this gives also a positive relationship (Figure 2-12). A larger breach size is more expensive (but not significant (R^2=0.29; T=2.12; p=0.057). The three most expensive cases have also a larger breach size.

In addition, also a higher relative implementation cost is expected for MRM with **land lowering**. Indeed, an important and costly issue in the case of land lowering is the removal and deposition of the removed soil (eg. E-Hahn.S.). More specifically this is very expensive in the case of contaminated soil (eg. E-Sp.B.). The average relative implementation cost for the TIDE MRM with land lowering is indeed higher (460.000 compared to 75.000 €/ha), however this is not significant ($F(1,13)=3.01$; $p=0.1$).

In many cases a **new defence** had to be constructed or existing defences had to be enforced/broadened/heightened (E-Wr.B., E-Sp.Sp., S-Lip., S-Pad., S-Ket., S-Paard., S-Heusd., W-Tegl.P., W-VorHin). Evidently, this means also additional costs.

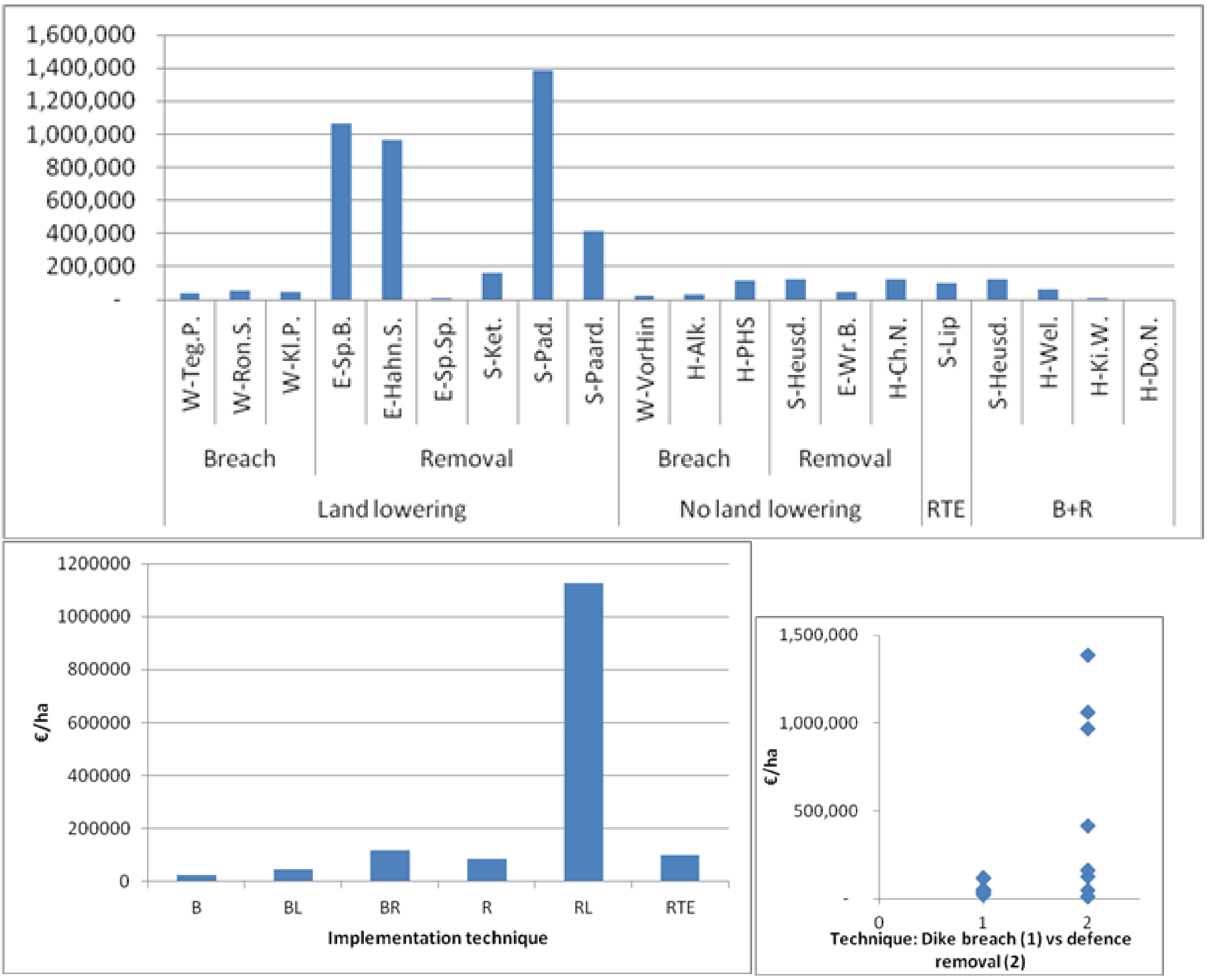


Figure 7-17. (a) Per hectare implementation cost related to the implementation technique: overview per measure, (b) average cost per implementation technique, and (c) spread of relative implementation cost for dike breach versus defence removal. Implementation techniques: dike breach (B), dike breach + land lowering (BL), dike breach + defence removal (BR), defence removal (R), defence removal + land lowering (RL), Reduced Tidal Exchange (RTE).

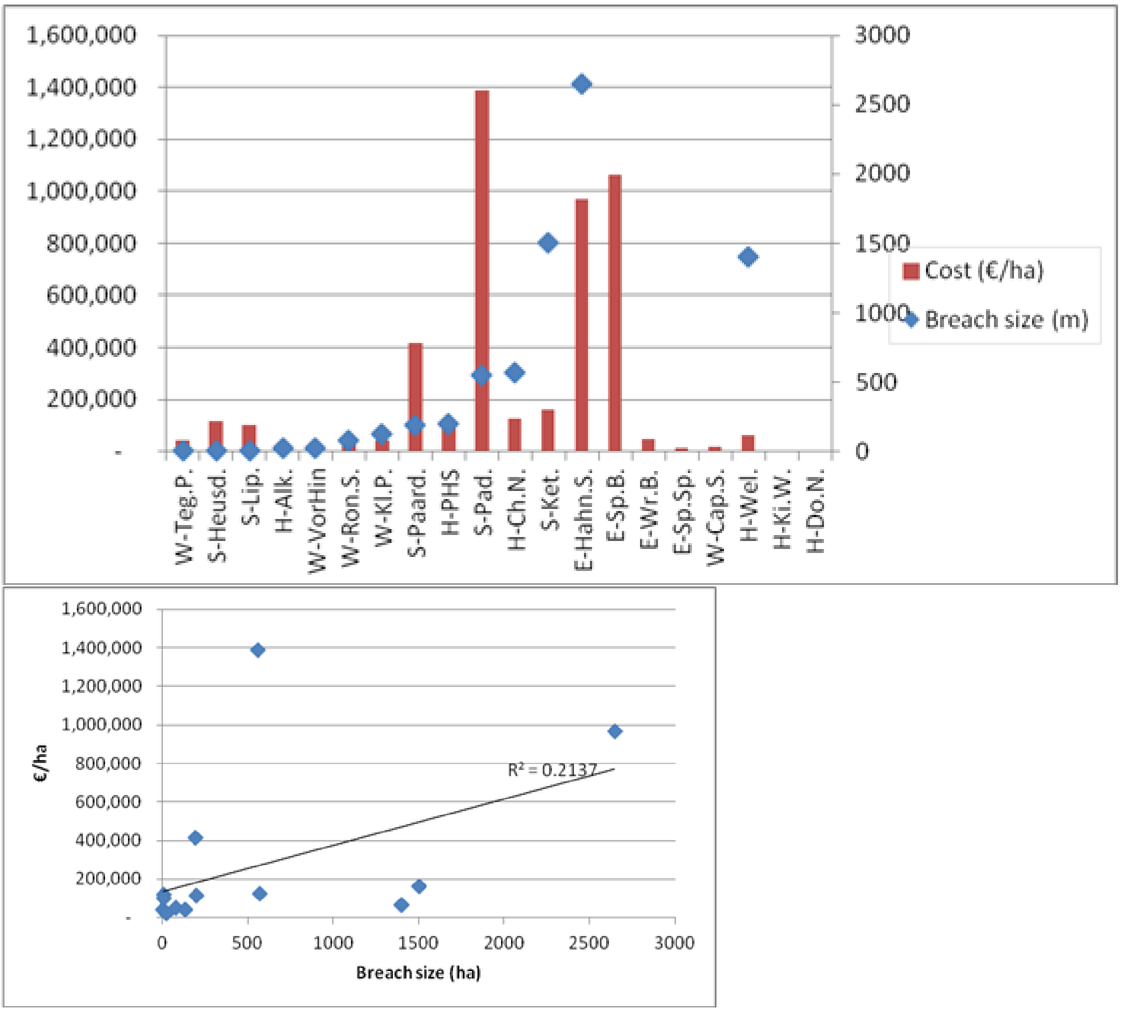
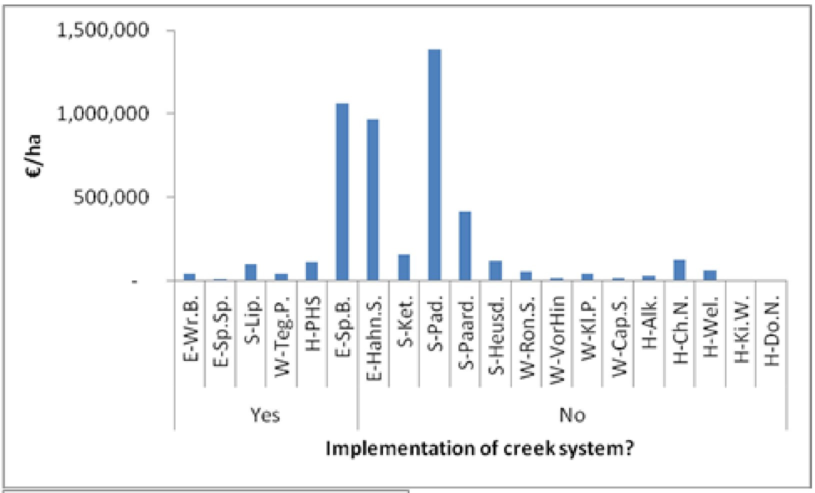


Figure 7-18. Per hectare implementation cost related to the breach size

3) Artificial creek dug: yes/no

Another design aspect that could impact the implementation cost is the artificial digging of a creek network. This is applied in 6 TIDE cases but this gives no clear difference in the relative implementation cost compared to the measures without an artificial creek system (F(1,15)=1,11; p=0,74) (Figure 2-13). Only one of the three most expensive TIDE cases will implement a creek system, the two others will not.



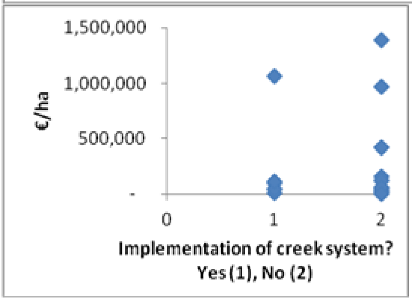


Figure 7-19. Relationship between the relative implementation cost and an artificial creek dug during the implementation

4) Other aspects

- In many cases the land was privately owned before and had to be purchased. Evidently, the land purchase price is also very location specific and could vary a lot between different places and within time.
- Costs for extensive pre investigations during the planning stages could also increase the total implementation cost. This is related with very location specific aspects such as the situation of the project area before measure implementation, costs for licensing, assessment, engineering, and mitigation requirements.
- During various phases (i.e. scheme design, impact assessment, planning and construction), also many obstacles could occur with the risk for increasing costs. Studying existing MR schemes could help to identify specific cost components.

Conclusions

The relative implementation cost of the TIDE MRM cases amounts 250,000 €/ha with a large range between 2,000 and 1.4 Mio. €/ha. For some measures, only a rough estimation was available. Three measures are considered as outliers with a remarkable high relative implementation cost, because a high amount of soil that had to be removed out of the area (E-Hahn.S.) and that had to be treated because of contamination (E-Sp.B.), or uncertainty about the total implementation cost (S-Padd.).

Different measure characteristics are studied to find reasons for the large variance in the relative implementation cost.

- Size and age: No significant relationship is observed between the relative implementation cost and the size of the measures, nor could we observe a temporal evolution in the relative implementation cost.
- Implementation techniques: A significant difference in the relative implementation cost is observed between the TIDE measures implemented by dike breach and by defence removal. The latter technique is, evidently, much more expensive. A positive relationship with the breach size was

however not significant. Also, measures with land lowering are expected to be more expensive but this difference was not significant.

- Creek system implemented: Measures with the implementation of a creek system are expected to be more expensive but this difference was not observed for the TIDE cases.

Overall, only the difference between dike breach and defence removal is a significant reason for a variation in the relative implementation cost of the considered TIDE cases.

Critical note: By comparing measure characteristics with the relative implementation cost nothing could be concluded about the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and to be sustainable is more important when considering the measure design than the implementation cost.

Benefits of MRMs

MRMs are executed with the main benefit of enhanced defences and/or newly created coastal habitat. MR sites could obtain natural protection against recurring storm surges and sea level rise. MR sites could also preserve the resources coastal habitats provide. Both benefits correspond with the main measure objectives (nature conservation/creation, and safety). MRMs however also generate many more additional socio-economic benefits such as tourism, recreational and commercial fisheries, carbon sequestration and water quality improvements.

The ecosystem services concept could help to identify and estimate benefits MRMs could generate. Monetary evaluation of ES could support decision making to take into account more direct and indirect impacts of management activities [39]. The monetary valuation indicates the clear economic gains that can arise from managed realignment schemes and it also demonstrates that these projects can have a sound economic rationale. Additionally, the findings of the monetary valuation could be used to seek out new funding sources for future schemes which would help to address one of the key problems of funding MR implementation [29]. However no scientific consensus exists yet concerning how to express ES in monetary units and different outcomes will be obtained when using different approaches.

An easy approach is by using an economic value for different biomes and multiplying this with the surface of the different biomes that are created or destructed. This approach is initiated in the widely referenced paper of Costanza et al. in Nature in 1997 [40]. More recently (in 2012), a literature review is published by De Groot et al [41] on the economic value of the large biomes (such as ‘Marine’, ‘Coastal systems’ and ‘Tropical forest’). In frame of this study, data from the latter study will be used to get an indication of the economic value of the MRMs. However, in the conclusions we have to bear in mind the constraints of this approach.

The TIDE MRM measures have an impact on two of the biomes from the study of De Groot et al. [41]: ‘Coastal systems’ and ‘Coastal wetlands’.

- The first biome ‘Coastal systems’, with a monetary value of 28,917 Int.$/ha.y[6] [41], corresponds to the TIDE habitats ‘subtidal deep habitat’, ‘subtidal moderately deep habitat’, and ‘subtidal shallow habitat’.
- The second biome ‘Coastal wetlands’, with a monetary value of 193,845 Int.$/ha.y[1] [41], corresponds to the TIDE habitats ‘marshes’ and ‘intertidal flat and steep habitat’.

To calculate the monetary benefit of the TIDE measures, the values from de Groot et al. [41] are multiplied by the habitat change per habitat type (% of total measure size in ha). This means that the new habitat distribution is corrected for the situation before the measure was implemented. Within the TIDE project it was however decided not to count for adjacent land. But, as many MRM measures have transformed adjacent land into estuarine habitat, this implies that the disadvantages (i.e. costs) from the lost adjacent land (mostly

[6] Figures expressed in international dollars cannot be converted to another country's currency using current market exchange rates; instead they must be converted using the country's PPP (purchasing power parity) exchange rate. 1 Int.$=1 USD. PPP for Belgium, Germany and UK is about 0.8 (1 Int.$ = 0.8€).

agricultural land) are not corrected for within this analysis. This is a major assumption which has to be considered in the conclusions: the monetary value calculated here is an overestimation because it is limited to the benefits generated within the estuary itself without counting for the lost adjacent land.

The results show that the TIDE examples generate an average annual benefit per hectare of 133,000 €/ha.y, ranging from 70,000 to 155,000 €/ha.y (Figure 2-14). The difference in the annual benefit per hectare depends on the distribution between subtidal habitats on the one hand (which corresponds to the biome 'Coastal system') and intertidal and marsh habitat (which corresponds to the biome 'Coastal wetlands'). Indeed, from the literature review that we use here [41] it is concluded that the annual monetary benefits from subtidal habitats amounts only 15% of the monetary benefits from intertidal habitats and marshes [41]. Hence, the measures creating the largest share of intertidal habitats and marshes generate the largest annual benefit per hectare, i.e. monetary benefit generated within the estuary itself without counting for the lost adjacent land (often agricultural land).

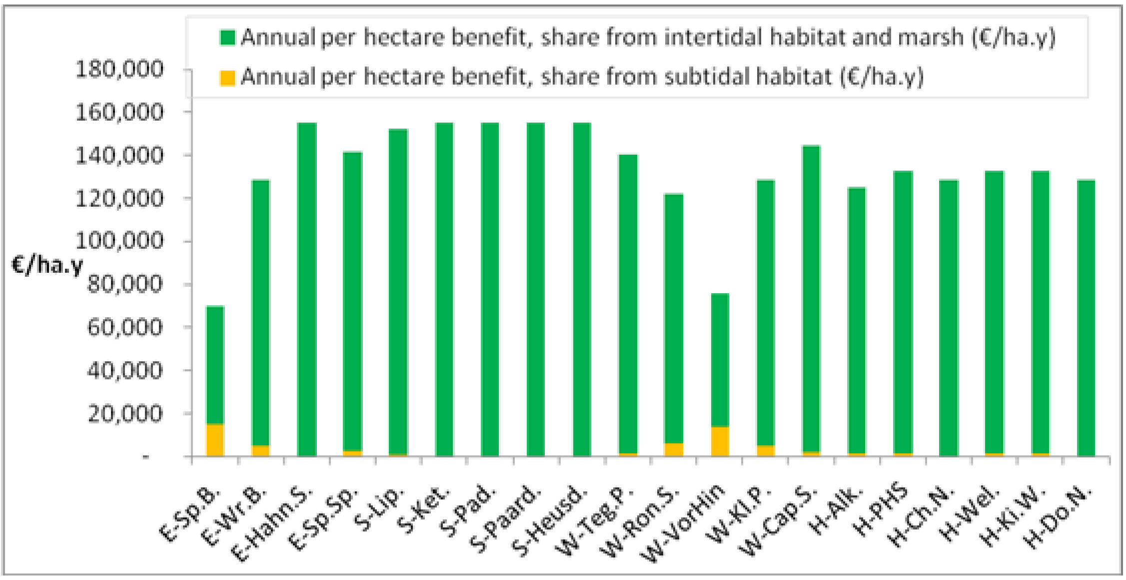


Figure 7-20. Annual monetary benefits per measure per hectare (€/ha.y), separating the monetary benefit from the subtidal habitats (shallow, moderately deep and deep) and the intertidal habitats (flat and steep) and marshes.

<u>Comparison between two approaches: global value versus local study (Alkborough case)</u>

The methodologies for the monetary valuation of ecosystem services are still highly discussed. In many projects the monetary valuation of ES is limited to the more obvious market services (e.g. food provisioning and benefits of tourism). More attention should also be addressed to less tangible services (e.g. nursery function and erosion prevention) to improve our understanding of the global benefits of the projects. Recently, some cases have been executed where a wider range of ecosystem services are valued for specific case studies also including the local context. For the Alkborough case (**H-Alk.**), the annual benefit from ecosystem services was estimated at £1.6 Mio per year [42] and the gross benefit value was estimated at almost £28 Mio (assuming that the benefits are generated during 25 years). With a scheme cost of £8.69 Mio this gives a benefit/cost ratio of 3.22:1, meaning a gross benefit of £3.22 by investing £1. This estimation is however much lower than the calculation based on the global estimates of the value of biomes and their services in monetary units [41]: annual benefit of 55 Mio €/y (44.65 £/y, conversion £=1.2319€).

A detailed overview of both approaches (Table 2-2) shows that there is a large discrepancy between both. Overall, the estimates from the local case study of Alkborough are much lower than the estimates based on the global value for the different biomes realised with Alkborough.

- The estimates from the Alkborough case could be considered as underestimation because not all ecosystem services were monetised because of a lag in knowledge about how to quantify and monetary value those services (such as Climate change, Air quality, fish recruitment [42]).

- The global estimates based on data from de Groot et al. [41], on the other hand, also need some critical consideration. An important constraint is that it is not adapted to the local circumstances. It gives the same value for all different types of coastal systems despite local characteristics, specific ecosystem quality and local demand. This is however determinative for the real delivery of ecosystem services (eg. the ES delivered by a dry or wet wetland will differ).

In the end, we assume that the real value of the ecosystem services delivered after the implementation of a measure will be in between both approaches. The approach with the global data is the quickest and most easy approach, but the case specific approach is however recommended because it is more accurate since the local context is included. A guidance document for ES valuation in an estuarine context will be developed in the frame of the TIDE project to improve our knowledge and to support managers in this exercise [22].

Table 7-5. Overview economic value of different ecosystem services due to the Alkborough case: based on two different approaches.

Value **Alkborough** (£/y ; €/y) (*)Conversion factor: £ = 1.2319€	Based on global data for biomes [41]	Based on local study [42]	
	€/y	£/y	€/y (*)
Provisioning services	**886 125**	**-3 255**	**-4 009**
Food	*354 816*	*- 28 075*	*-34 586*
Water	*342 707*	*- 5 000*	*-6 160*
Raw materials	*101 024*	*26 820*	*33 040*
Genetic resources	*2 816*	*3 000*	*3 696*
Medicinal resources	*84 762*		
Ornamental resources			
Regulating services	**48 753 531**	**423 220**	**521 365**
Air quality regulation			
Climate regulation	*26 734*	*14 553*	*17 928*
Disturbance moderation	*1 506 842*	*408 667*	*503 437*
Regulation of water flows			
Waste treatment	*45 654 400*		
Erosion prevention	*1 552 883*		
Nutrient cycling	*12 672*		
Pollination			
Biological control			
Habitat services	**4 832 643**	**757 598**	**933 285**
Nursery service	*3 001 891*		
Genetic diversity	*1 830 752*	*757 598*	*933 285*
Cultural services	**622 811**	**164 830**	**203 054**
Aesthetic information			
Recreation	*622 054*	*164 830*	*203 054*
Inspiration			
Spiritual development	*370*		
Cognitive development	*387*		
Total annual economic value	**55 095 110**	**1 342 393**	**1 653 694**

Cost-efficiency analysis

By comparing the cost of the measure with the annual benefits, the earn-back time is calculated (Figure 2-15). This gives the number of years that the measure should be operational before the total implementation cost is earned back. The average time to earn back the implementation cost for the TIDE MRM examples is 2.3 years, ranging from 0.1 years to 15 years.

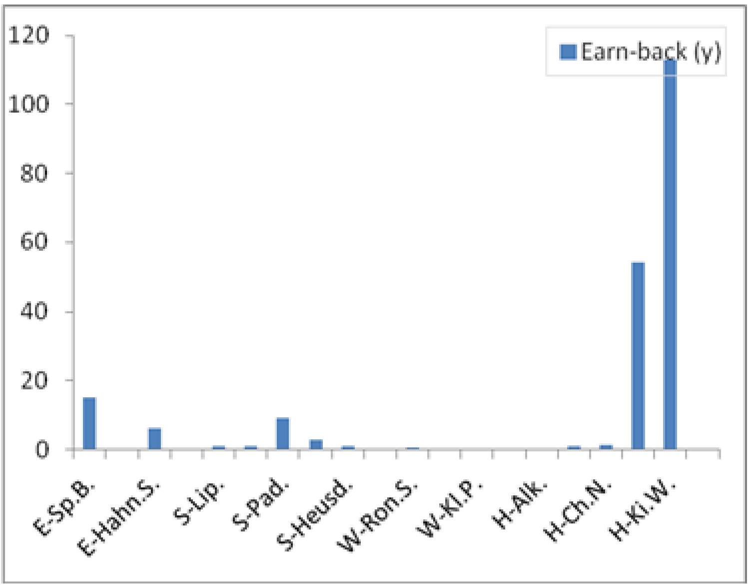


Figure 7-21. Left panel: Implementation cost (€/ha) and annual benefit per measure (€/ha.y). Right panel: Earn-back time for the TIDE MRM examples (in years)

Another way to evaluate the cost-efficiency of the measures is by calculating the benefit/cost ratio, i.e. the annual benefit generated for 1€ invested. For the TIDE cases this is on average 2.82 €/y for every 1€ invested, ranging from 0.07 to 13.35 €/y for every 1€ invested (Figure 2-16 left panel). This gives (evidently) the opposite result of the earn-back time: measures with a long earn-back time have a low benefit/cost ratio. However this relationship is not linear (Figure 2-16 right panel).

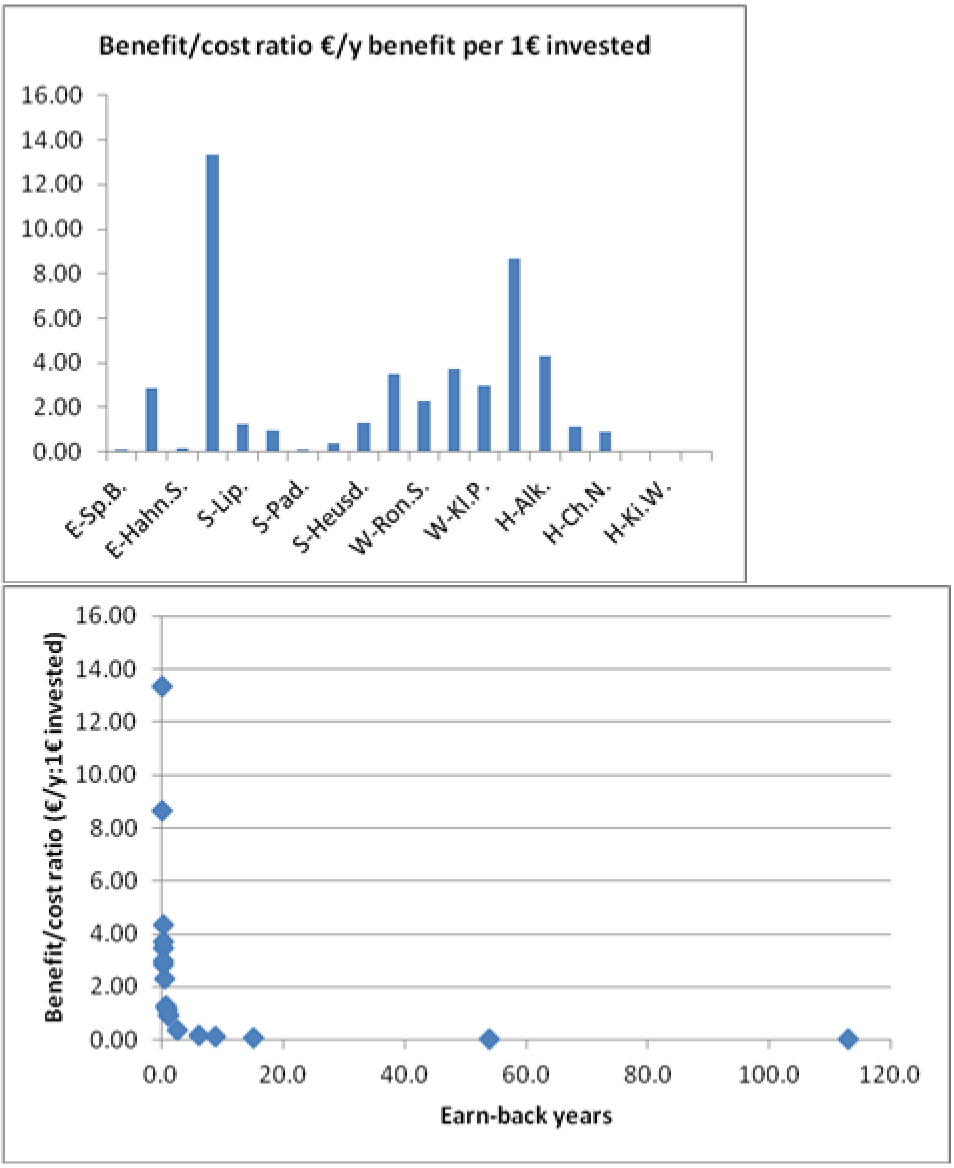


Figure 7-22. Left panel: Benefit/cost ratio for the TIDE MRMs. Right panel: Relationship between the earn-back time and the benefit/cost ratio.

Critical notes:

1. The earn-back time and benefit/cost ratio does however do not necessarily gives an indication of the success of the measure. Indeed, the effectiveness of the measure to reach the objectives/requirements and the sustainability of the measure is more important than the cost efficiency when considering the measure design. The cost-efficiency of measures could be used as one of the decision criteria, but should not be used as the main argument.
2. In addition, the monetary benefits are an overestimation because it is not corrected for lost adjacent land.

7.2.7. Effectiveness based on ecosystem services (ES)-assessment

The effectiveness of the TIDE examples is analysed by comparing the targeted ES with the realised ES. The ES assessment is based on the general ES assessment for measures developed in the TIDE project [1, 23].

Targeted ES

For every TIDE measure, the targeted ES were indicated by the responsible authorities [1] from the list of the 20 selected estuarine ES [23]. The most common targeted ES for the TIDE MRMs is the category "Supporting and habitat services" (Table 2-3). Only in some cases this target is accompanied by one or more other targeted ES such as "Water for navigation", "Water quantity regulation: dissipation of tidal and river energy", "Regulation of extreme events: flood water storage", "Erosion and sedimentation regulation by water bodies", "Opportunities for recreation and tourism", and "Information for cognitive development".

This corresponds with the information gathered under section 2.1 Measure targets and degree of target achievement (Table 2-4). The development target "Safety" corresponds with the ES "Regulation of extreme events: flood water storage", "Water quantity regulation: dissipation of tidal and river energy" and "Erosion and sedimentation regulation by water bodies". The development targets "Habitat conservation and creation" and "compensation" both correspond with the ES "Supporting and habitat services". Furthermore the development target "Access opportunities and education" corresponds with the cultural ES "Opportunities for recreation and tourism" and the research target corresponds with the cultural ES "Information for cognitive development".

Table 7-6. Targeted ES per measure

Targeted ES ■	TIDE MRMs																
	Elbe				Scheldt					Weser					Humber		
Ecosystem services	Sp.B.	Wr.B.	Hahn.S.	Sp.Sp.	Lip.	Ket.	Pad.	Paard.	Heusd.	Tegl.P.	Ronn.S.	VorHin	Kl.P.	Cap.S.N.	Alk. (1)	PHS (1)	Ch.N.
P1 – Water for industrial use																	
P2 - Water for navigation	■																
P3 - Food: animals																	
R1 – Erosion and sedimentation regulation by water bodies										■		■					
R2 – Water quality regulation - reduction of excess loads coming from the catchment																	
R3 - Water quality regulation - transport of pollutants and excess nutrients																	
R4 - Water quantity regulation - drainage of river water																	
R5 - Erosion and sedimentation regulation by biological mediation																	
R6 - Water quantity regulation - transportation																	
R7 - Water quantity regulation - landscape maintenance																	
R8 - Climate regulation Carbon sequestration and burial																	
R9 - Water quantity regulation - Dissipation of tidal and river energy	■																■
R10 - Regulation of extreme events - wave reduction																	
R11 – Regulation of extreme events - water current reduction																	
R12 - Regulation of extreme events - flood water storage					■												■
S – Supporting and habitat services		■	■	■	■	■	■	■	■	■	■	■	■	■			■
C1 - aesthetic information																	
C2 - Inspiration for culture, art and design																	
C3 - Information for cognitive development					■												
C4 - Opportunities for recreation and tourism																	■

(1) Missing information

Table 7-7. Translation of measure targets in terms of ES

Target	Corresponding Ecosystem Service
Safety	R1 - Erosion and sedimentation regulation by water bodies R9 - Water quantity regulation: dissipation of tidal and river energy R12 - Reg. of extreme events: flood water storage
Habitat conservation/restoration	S - Supporting and habitat services (biodiversity)
Compensation	S - Supporting and habitat services (biodiversity)
Access opp. and education	C4 - Cult. Opportunities for recreation and tourism
Research	C3 - Cult. Information for cognitive development

Realised ES and beneficiaries

To analyse if the targeted ES are also realised, the results of the TIDE study Ecosystem Services is used [23]. In this study, the potential of each estuarine habitat type to deliver the different ecosystem services was scored. This is combined with the information about habitat change for every measure [1-19].

It is important to emphasize that this approach assumes an equal surface-supply relationship for all habitats and services [23]. This is however a simplification of the reality since differences exist in the quantity of this relationship: e.g. one hectare of tidal flat will not supply the same 'amount of benefit' for nutrient capture as of sedimentation regulation. Also, surface-supply curves might be linear, exponential, or saturated: e.g. more deep water will increase navigation service, but after a certain amount is reached and demand is met, the service will not further increase. Therefore ES calculations based on surfaces should be interpreted as an indication and interpreted with caution. This is mainly the case for services like water for navigation, wave reduction and water current reduction, which strongly depend on the form of the habitat (length-width, orientation along river, presence of bottlenecks,…).

The result is the **expected impact** of every measure on each ecosystem service. This is represented as a score from +3 (very positive expected impact) to -3 (very negative expected impact). From the general overview (Table 2-5), it is concluded that the TIDE MRMs have a slightly positive to very positive expected impact on at least 12 of the 20 considered ecosystem services.

- Provisioning services: expected impact is mostly neutral
- Regulating services: expected impact is neutral to very positive
- Supporting and habitat services: expected impact is positive to very positive
- Cultural services: expected impact is slightly positive to very positive

It is important to emphasise that this analysis has to be considered as a first but rough screening to check which ES are expected to be impacted by a certain measure. Managers should however first control this result with the local conditions of the measure. In the developed ES assessment for every habitat type one fixed score is determined for each ES without the possibility to diversify for local characteristics. For instance, if a measure site is not directly connected to the river you should be aware that several regulating services (such as dissipation of tidal and river energy and wave reduction) will be very limited. For more information on a correct interpretation of the results, see [1] §3.2.1.2 Impact on ecosystem services (ES).

The expected impact on the **targeted ES** is in most cases very positive (Table 2-5). On average, only 10% of the ES with a positive expected impact (slightly positive to very positive) are also targeted. This means that the MRMs are expected to **generate many co-benefits**!

Furthermore, also the expected impact among different **beneficiaries** is assessed. Two types of beneficiaries are included: one set of beneficiaries depending on the users' typology (direct[7]-indirect[8]-future[9] use), and one set of beneficiaries depending on the spatial scale (local, regional and global use). The expected contribution of each ES to the different beneficiaries is based on assigned values, see §3.2.1.2 Impact on ecosystem services (ES) in [1]. This analysis shows that the TIDE MRMs are mainly beneficial in an indirect way, at a longer term (for future use) and at a local and regional scale (Table 2-5).

Table 7-8. Overview expected impact of the MRMs on the various ecosystem services; and beneficiaries. The targeted ES are indicated as an orange box.

[7] Direct use is obtained through a removable product in nature (i.e. timber, fish, water).
[8] Indirect use is obtained through a non-removable product in nature (i.e. sunset, waterfall).
[9] Future use (or option value) is the potential future ability to use a resource even though it is not currently used and the likelihood of future use is very low. This reflects the willingness to preserve an option for potential future use.

ES assessment

Legend: expected impact*	
3	Very positive
2	Positive
1	Slightly positive
0	Neutral
-1	Slightly negative
-2	Negative
-3	Very negative

Targeted ES

*: Indicative screening based on ES-supply surveys and estimated impact of measures on habitat quality and quantity. Quantitative socio-economic conclusions require local supply and demand data to complement this assessment.

Cat.: category Biology/ecology (B), Hydrology/morphology (H), combination of biology/ecology with hydrology/morphology (HB)

	Measures																
	E-Sp.B.	E-Wr.B	E-Hahn.S	E-Sp.Sp	S-Lip.	S-Ket.	S-Pad.	S-Paard	S-Heusd	W-Tegl.P	W-Ronn.S	W-VorHin	W-Kl.P.	W-Cap.S.N	H-Alk.	H-PHS	H-Ch.N.
Zone	Fresh	Fresh	Fresh	Fresh	Fresh	Meso	Fresh	Meso	Fresh	Oligo	Fresh	Fresh	Fresh	Poly	Meso	Poly	Meso
Cat.	HB	B	B	B	HB	B	B	B	B	B	HB	HB	B	B	HB	B	B
Ecosystem services:																	
P1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
P2	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
P3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
R1	3	3	3	3	3	2	3	3	3	3	3	3	3	3	2	3	2
R2	1	3	1	3	3	1	3	2	3	2	3	2	3	3	2	3	1
R3	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0
R4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R5	1	2	2	2	2	1	2	2	2	2	2	1	2	3	2	3	1
R6	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
R7	1	2	2	2	2	1	2	2	2	3	2	1	2	3	2	2	1
R8	1	3	2	3	3	1	3	2	3	3	2	2	2	3	2	3	1
R9	1	0	1	0	0	1	0	2	0	2	0	0	0	1	1	1	2
R10	0	1	1	1	1	1	1	2	1	2	1	0	1	2	1	1	1
R11	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1
R12	1	0	1	3	3	1	3	0	3	3	2	1	2	1	1	1	0
S	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	2
C1	2	3	2	3	3	1	3	3	3	3	2	2	2	3	2	2	2
C2	3	3	2	2	2	2	2	3	2	3	2	2	2	3	2	2	2
C3	3	3	2	2	2	1	2	2	2	3	2	2	2	3	2	2	1
C4	2	2	1	2	2	1	2	2	2	2	2	2	2	3	2	3	1
Beneficiaries:																	
DU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IDU	2	2	2	3	2	1	2	2	2	2	2	2	2	3	2	2	1
FU	3	3	3	3	3	2	3	3	3	3	3	2	3	3	3	3	2
LU	2	3	2	3	3	1	2	2	3	2	2	2	2	3	2	2	1
RU	2	2	1	3	2	1	2	1	2	2	2	1	1	2	1	2	1
GU	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1

Ecosystem services:

P1: Water for industrial use
P2: Water for navigation
P3: Food: Animals

R1: Erosion and sedimentation regulation by water bodies
R2: Water quality regulation: reduction of excess loads coming from the catchment
R3: Water quality regulation: transport of pollutants and excess nutrients
R4: Water quantity regulation: drainage of river water
R5: Erosion and sedimentation regulation by biological mediation
R6: Water quantity regulation: transportation
R7: Water quantity regulation: landscape maintenance
R8: Climate regulation: Carbon sequestration and burial
R9: Water quantity regulation: dissipation of tidal and river energy
R10: Regulation extreme events or disturbance: Wave reduction
R11: Regulation extreme events or disturbance: Water current reduction
R12: Regulation extreme events or disturbance: Flood water storage

S: “biodiversity”

C1: Aesthetic information
C2: Inspiration for culture, art and design
C3: Information for cognitive development
C4: Opportunities for recreation & tourism

Beneficiaries:

DU: Direct use
IDU: Indirect use
FU: Future use

LU: Local use
RU: Regional use
GU: Global use

7.3. Data overview 20 TIDE MRmeasures

Table 7.2-1. Data overview part 1: General information

M nr.	TIDE nr.	Est.[1]	Measure name	Code	Year of impl.	Size	TIDE-km[2]	Zone[3]	Cat.[4]	Target[5]	Type[6]	Method[7]	Total impl. Cost[!]
						ha	km						€[9]
1	1	E	Spadenlander Busch/Kreetsand	E-Sp.B.	2012	47	30	F	HB	HS	O	RL	50.000.000
2	7	E	Realignment Wrauster Bogen	E-Wr.B.	1991	2,2	18	F	B	H	O	R	(100.000)
3	8	E	Compensation measure Hahnöfer Sand	E-Hahn.S.	2002	63	57	F	B	HC	O	RL	(61.000.000)
4	9	E	Spadenlander Spitze	E-Sp.Sp.	2002	8	32	F	B	H	O	RL	(85.000)
5	13	S	Lippenbroek FCA-CRT	S-Lip.	2006	10	38	F	HB	HS	I	RTE	1.000.000
6	15	S	Ketenisse wetland	S-Ket.	2003	30	92	M	B	HC	O	RL	(4.800.000)
7	16	S	Paddebeek wetland	S-Pad.	2003	1,6	18	F	B	H	O	RL	2.200.000
8	17	S	Paardenschor wetland	S-Paard.	2004	12	100	M	B	HC	O	RL	5.000.000
9	18	S	Heusden LO wetland	S-Heusd.	2006	10	0	F	B	H	O	BR	(1.200.000)
10	24	W	Tegeler Plate – Development of tidally influenced brackish water habitats	W-Tegl.P.	1997	210	58	O	B	HC	O	BL	(8.400.000)
11	25	W	Shallow water area Rönnebecker Sand	W-Ron.S.	2002	34	32	F	B	HC	I	BL	(1.800.000)
12	26	W	Tidal habitat Vorder- und Hinterwerder	W-VorHin	1997	27	12	F	B	HC	I	B	(550.000)
13	27	W	Shallow water zone Kleinensieler Plate	W-Kl.P.	2000	60	57	F	B	HC	I	BL	2.600.000
14	28	W	Cappel-Süder-Neufeld	W-Cap.S.N.	2002	27	90	P	B	HC	O		450.000
15	30	H	Alkborough Managed Realignment and flood storage: Creation of ~440 a of intertidal habitat	H-Alk.	2006	440	60	M	HB	HSC	O	B	12.500.000
16	31	H	Paull Holme Strays Managed Realignment: creation of ~80 ha of intertidal habitat	H-PHS	2003	80	95	P	B	HC	O	B	(9.000.000)
17	33	H	Creation of ~13 ha of intertidal habitat at Chowder Ness	H-Ch.N.	2006	15	73	M	B	HC	O	R	(1.800.000)
18	34	H	Welwick: Creation of 54ha of intertidal mud, saltmarsh and grassland.	H-Wel.	2006	54	106	F	B	HC	O	RL	3.496.136
19	35	H	Kilnsea Wetlands (formerly Beacon Lagoons): Bringing 70ha of wetland SSSI back into favourable condition and providing 43ha of functional replacement coastal wetland habitat.	H-Ki.W.	2011/2012	113	N/A	F	B	HC	O	B	233.075
20	38	H	Donna Nook: Transformation of 130ha of agricultural land into a mosaic of saltmarsh, mudflats, creeks and small islands.	H-Do.N.	2012/2013	130	122.6	O	B	HC	O	B	Unknown

1) <u>Estuary</u>: Elbe (E), Scheldt (S), Weser (W), Humber (H)
2) <u>TIDE-km</u>: 0 km is location most downstream where tidal influence is still measured
3) <u>Zone</u> in the estuary: freshwater zone (F), Oligohaline zone (O), Mesohaline zone (M), Polyhaline zone (P)
4) <u>Category</u>: Hydrology & morphology (H), Biology & ecology (B), combined hydrology/morphology and biology/ecology (HB)

5) Target: Safety flood defence (S), Habitat conservation/restoration (H); compensation target (C)
6) Type: inner dike area (I), outer dike area (O)
7) Method: Dike breach (B), defence removal (R), land lowering (L), Reduced Tidal Exchange (RTE)
8) Total implementation cost: cost data between brackets is rough estimation
9) Transformation for UK measures (H-Alk, H-PHS, H-Ch.N.): £ = 1.2319 €

Table 1.1-2. Data overview part 2: Sedimentation rate and related issues

TIDE nr.	Code name	Sedimentation rate: average (min. to max.)	SPM[1]	River bend[2]	Tidal amplitude: tidal range (MLWL; MHWL)	Initial elevation: Lowest point in the area	Initial elevation: Highest point in the area	Breach dimensions: Width	Breach dimensions: Invert
		cm/y	g/l	O, I	m (m TAW/NN/OD)	m TAW/NN/OD	m TAW/NN/OD	m	m TAW/NN/OD
1	E-Sp.B.	3.5 (max.10)	39	O	3.45 (-1.25; 2.20)	-3	2.5		
7	E-Wr.B.		38	O	2.9 (-0.5; 2.4)	2.5	3	30	0.5
8	E-Hahn.S.	*Not monitored*	49	N	3.26 (-1.36; 1.9)			2650	
9	E-Sp.Sp.	0.88	38	OI	3.45 (-1.25; 2.20)	-1.5	3.7		0.5
13	S-Lip.	4 (0.5 to 8.5)	105	O	1.3 (1.4; 2.7)	2.45	3.3	14,15	4.8
15	S-Ket.	2 (-7 to +15)	69	I	5.1 (0.04; 5.14)	3	5.42	1502	4
16	S-Pad.	3.5	78	I	2.9 (2.1, 5.0)	4	6	556	4
17	S-Paard.	2.8	55	I	5.17 (0.08, 5.25)	4	5.4	190	4
18	S-Heusd.	10 (-10 to +30)	77	OI	2.63 (2.43, 5.06)	4.27	5.14	6	2.43
24	W-Tegl.P.		700	I	3.95 (-2.1; 1.95)	1.9	2.4	3	
25	W-Ron.S.		35	O	0.7 (;)			80	1.16
26	W-VorHin	3 (max. 20)	100	O	0.9 (;)	-3.03		25	1.7
27	W-Kl.P.	50 (10 to 75)	700	O	0.15 (;)	-1.1	3.6	130	1.45
28	W-Cap.S.			N	3.4 (-1.8; 1.6)				
30	H-Alk.	14 (5 to 58)	635	I	4.5 (-1.2; 3.3)	3.1		20	
31	H-PHS	6 (-2.5 to 16)	294	O	4.98 (-2.19; 2.79)	1.95	3.49	200	
33	H-Ch.N.	9 (2 to 20)	163	I	4.82 (-1.77; 3.05)	1.6	4.5	570	1.8
34	H-Wel.	*Lack of information*							
35	H-Ki.W.	*Not yet monitored*							
38	H-Do.N.	*Not yet monitored*							

1) SPM: Suspended Particulate Matter (in g/l)
2) River bend: located at the outer side (O) or inner side (I) of a river bend, partially inner- and outer-side (OI), or not at a river bend (N)
Grey box: missing data

The end.