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Evaluation of the C-alternatives for habitats and higher trophic levels

Report in the framework of the Integrated plan of the Upper Sea Scheldt

Joost Vanoverbeke, Amber Mertens, Alexander Van Braeckel and Gunther Van Ryckegem

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EVALUATION OF THE C-ALTERNATIVES FOR HABITATS AND HIGHER TROPHIC LEVELS

Report in the framework of the Integrated plan of the Upper Sea Scheldt

Vanoverbeke Joost, Mertens Amber, Van Braeckel Alexander and Van Ryckegem Gunther

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Abstract

The Integrated Plan of the Upper Sea Scheldt describes a set of morphological adjustments designed to improve the quality of the system by 2050. The intended improvements encompass, among others, ecological functioning, flood control, shipping and maintenance efforts. Within this context a number of alternative morphological adjustments have been designed with different degrees of impact on the current morphology: the C-alternatives (C1, C2, C3). In addition, different climate scenarios have been designed to assess the robustness of the effects against future climatic changes. In this report, we compare the predictions for habitats and higher trophic levels (Twaite shad (migratory fish) and Common teal (waterfowl)) for the different C-alternatives against predictions for the reference situation in 2050.

In general, tidal amplitude tends to decrease and surface area of shallow water and mudflats and marshes tends to increase in the C-alternatives compared to the C-reference, due to the inclusion of side channels, newly created CRTs (areas with controlled reduced tide) and managed realignments (depolderings). These evolutions follow the magnitude of adjustments to the reference bathymetry (alternative C3 > C2 > C1). Care should be taken, however, around stretches with strong alterations to the fairway, implemented to improve navigability. In these areas ecological conditions near the fairway may decrease (high water velocity, steep riverbanks, coastal squeezing). Reduced tidal amplitude also directly affects the relative contribution of different habitats with gains in subtidal area due to elevated low water levels, reductions in mudflat area due to squeezing into a shallower tidal window and reductions in marsh area due to lowered maximal water levels (desiccation and shift from estuarine habitat to terrestrial habitats). Sea level rise will strengthen the evolution of drowning of the lower mudflats but will temper the desiccation of the higher marshes.

Conditions are largely favorable for larval development of Twaite shad upstream of Dendermonde in the C-reference and alternative C1 and further improve in the C2 and C3 alternative due to higher levels of oxygen and reduced levels of suspended matter (SPM). Lack of sheltered areas with low water velocities around stretches with strong alterations to the fairway, however, entail an increased risk of flushing developing larvae to more downstream and less suitable areas. Moreover, oxygen levels around Antwerpen deteriorate in the C-alternatives, leading to unfavorable evolution of the suitability index in that region. Conditions for spawning are generally favorable in the Upper Sea Scheldt, including the region between Dendermonde and Tielrode, where most of the spawning is observed. There are indications that, as is today, oxygen levels can become too low around Antwerpen, creating a barrier for upstream migration of adults or downstream migration of juveniles. There is, however, relatively large uncertainty on the locally low levels of oxygen, and expert judgment estimates that evolutions with respect to oxygen will rather be neutral to slightly favorable. Yet, given the uncertainty, unfavorable evolutions associated with reduced levels of oxygen should not be totally neglected.

There is a positive evolution in the numbers of Common Teal when comparing the C-alternatives with the C-reference, due to the inclusion of large areas of newly created depolderings and CRTs, creating additional area of mudflats. Favorable evolutions are relatively largest in the more upstream region. Care should be taken, however, to the quality of the mudflats, which might be too low and too flat, hampering the generation of a favorable feeding window with high macrobenthic biomass.

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List of abbreviations

CRT = controlled reduced tide

SpD = spread in exposure (unflooded) time

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1 INTRODUCTION

The Integrated Plan of the Upper Sea Scheldt describes a set of morphological adjustments designed to improve the quality of the system by 2050. The intended improvements encompass, among others, aspects of ecology, flood control, shipping and maintenance efforts. Within this context a number of alternative morphological adjustments have been designed with different degrees of impact on the current morphology: the C-alternatives (IMDC 2021). These morphological alternatives rely on insights attained in previous iterations of morphological modeling and analyses (B-alternatives and building blocks, IMDC 2012, IMDC 2017). To evaluate the expected impact of alternative morphological adjustments on hydrodynamics, sediment transport, water quality and pelagic ecosystem, habitat quality and fauna and flora, a series of modeling tools have been developed to predict the effects of the alternatives on each of these system components (the modeling train; Figure 1-1) (see also 'Model instruments for the Integrated Plan Upper Seascheldt' (IMDC et al. 2015)). In addition, for each morphological alternative, different climate scenarios have been designed to assess the robustness of the effects under different magnitudes of future climatic changes.

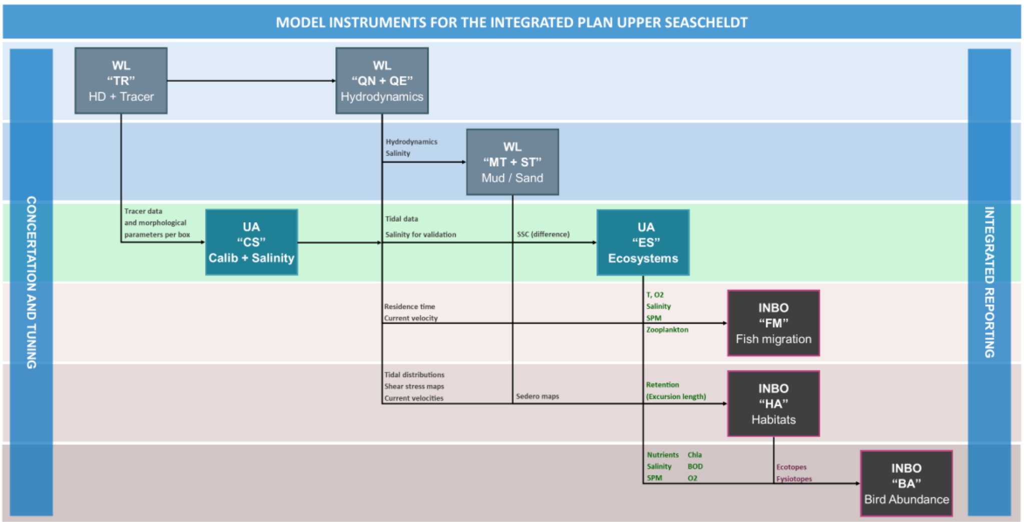

Figure 1-1: Sequence of calculations and data stream through the modeling train for the evaluation of the Integrated plan of the Upper Sea Scheldt.

In this report, we compare the predictions for habitats and higher trophic levels for the different C-alternatives (including the forks for different climate scenarios) against predictions for the reference situation in 2050. In doing so, we want to assess the ecological impact of each scenario and use this information to adjust the proposed fairway alternatives and mitigating measures to improve the ecological quality of the system.

Based on bathymetrical input and results from modeling of hydrodynamics and sediment transport (Figure 1-1; IMDC et al. 2015), the habitat model estimates the available area of sublittoral (submerged), littoral (mudflats) and supralittoral (marshes) habitats for each alternative bathymetry and climate scenario (Van Braeckel et al. 2019). In addition, an assessment of the quality of the habitats is made.

The models for the higher trophic levels include a model to predict habitat suitability for spawning and larval development of Twaite Shad in the Sea Scheldt (Vanoverbeke et al. 2019a) and a model to predict the numbers of Common Teal on the mudflats in the Upper Sea Scheldt (Vanoverbeke et al. 2019b). These models take input from other models in the modeling train with respect to hydrodynamics, sediment transport, habitat quality and the pelagic ecosystem (Figure 1-1; IMDC et al. 2015).

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2 OVERVIEW OF THE STUDY SYSTEM

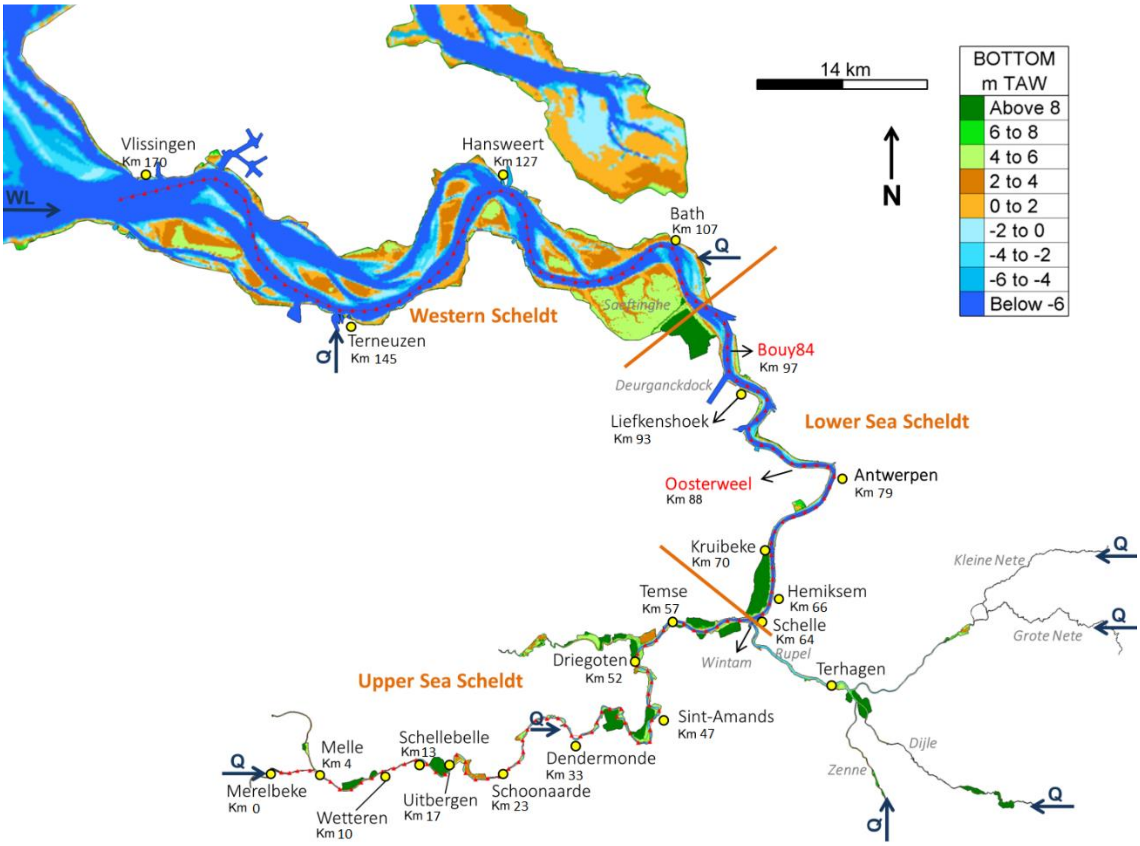

Figure 2-1: Overview of the Scheldt estuary, with indication of the thalweg (red line and dots) and most important locations (yellow dots). Figure taken from Bi et al. (2021b).

3 C-ALTERNATIVES AND CLIMATE SCENARIOS

A number of **alternatives** (specified morphology of the Scheldt river in a specific state and at a specific time) and different **scenarios** (a range of boundary conditions that take into account climate change, sea level rise, increasing or decreasing tidal amplitude, changes in discharge), have been defined.

The **C-alternatives** (C1, C2 and C3) are defined in IMDC (2021). They comprise incremental adaptations (from least in C1 to most in C3) of the bathymetry to improve navigability, flood control and ecosystem functioning and include measures to reduce or mitigate the undesired effects observed in the B-alternatives. Solutions can include depolderings, repositioning of the dikes, the introduction of flood channels, not filling up the old channel at bend cut-offs, the introduction of river training structures, etc.

The C-alternatives are compared against a **reference state** (including the "sustainable management plan for Class IV navigation" and other decided policy measures; IMDC, 2014). The reference state occurs after (autonomous) development of the area by 2050 under the assumption that there is no morphological adaption of the cross-shore profile and that maintenance works are applied to sustain the current state, combined with the execution of policy plans that have been decided as to be realized in 2050. This includes the implementation of flood control areas, controlled reduced tidal areas (CRT- areas) and depolderings within the frame of the SIGMA plan.

An example of the alternative designs is given in Figure 3-1. Examples of deepening and filling of the riverbed in the C-alternatives are given in Figure 3-2.

In 2050, the existence of modified boundary conditions (tide, discharge) is likely. The climate **scenarios** take this into account. The climate scenarios used for the habitats and higher trophic levels are the following:

1. A0CN: the actual tidal range is applied, and no sea level rise, no changes in discharge.
2. AminCL: a decreased tidal range (-40cm in Schelle) is applied to simulate projects downstream that lead to a decreased tidal amplitude. This is combined with a 'low' climate change effect (15 cm sea level rise and changed discharge). This combination of boundary conditions is considered as a 'minimal' scenario.
3. AplusCH: an increased tidal range (+30cm in Schelle) is applied to simulate projects downstream that lead to an increased tidal range. This is combined with a 'high' climate change effect (40 cm sea level rise and changed discharge). This combination of boundary conditions is considered as a 'maximal' scenario.

These climate scenarios provide insight in the range of the effects and the robustness of the findings.

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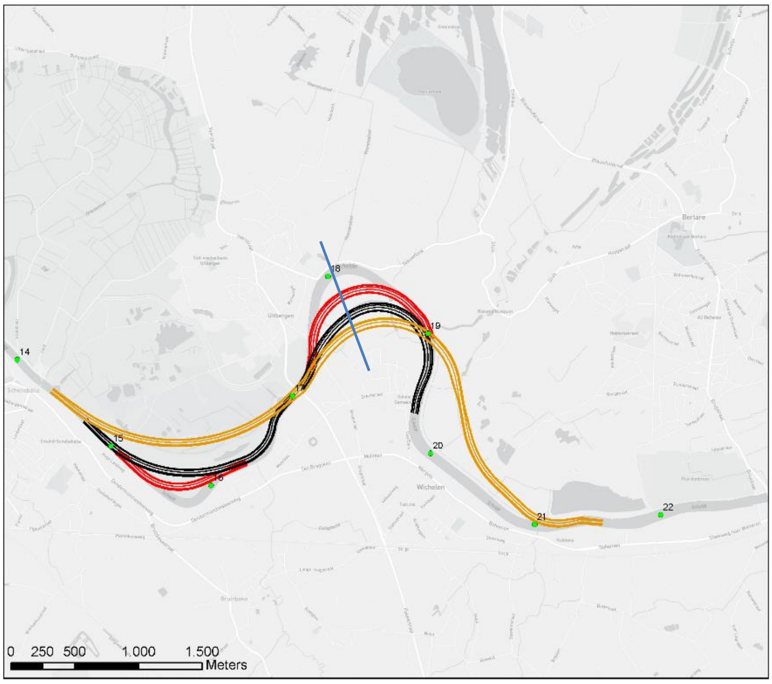
A



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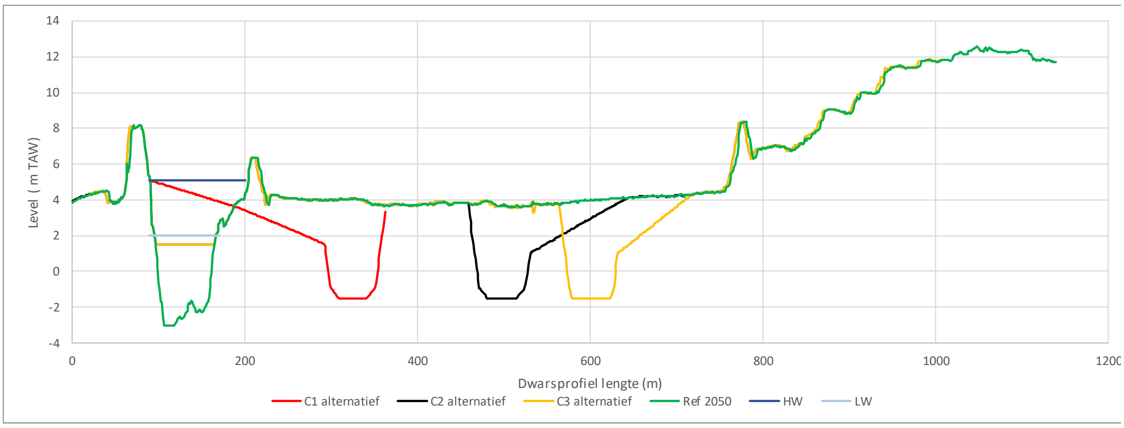
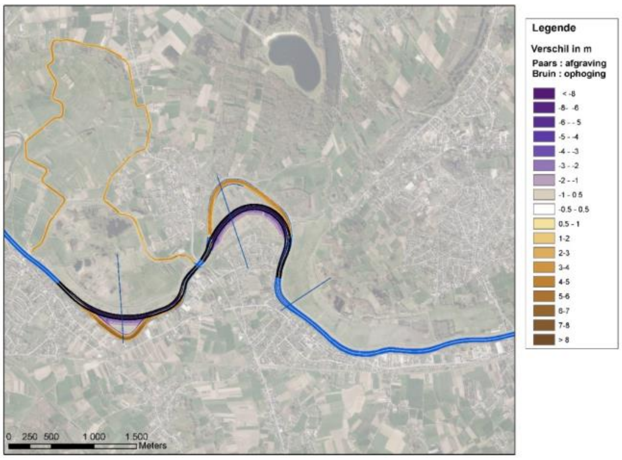
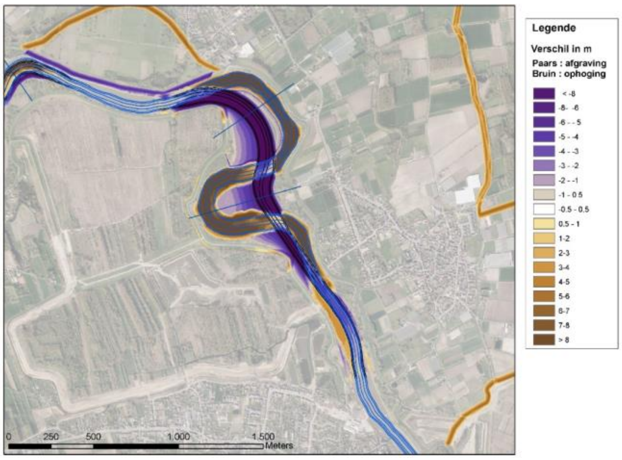


Figure 3-1: (from IMDC 2021). **A**: Example of the effect of the alternatives on the navigational channel at Hoogland-Uitbergen-Paardenweide in C1 (red), C2 (black) and C3 (orange). Straight line indicates the location of the cross-sectional profile in B. **B**: Cross sectional profile at Uitbergen from left bank to right bank.

A) Wijmeers - Bergenmeersen



B) De Kramp



C) Bornem

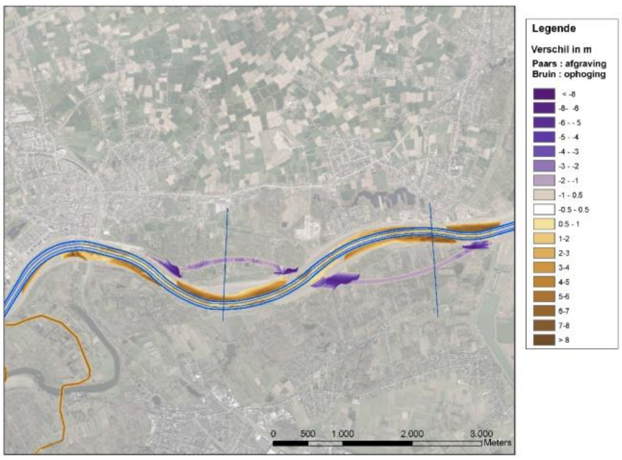


Figure 3-2: Examples of deepening (blue) and filling (brown) to alter the riverbed in the C-alternatives. A) Wijmeers-Uitbergen (14-19 km from Merelbeke); B) De Kramp (39-40 km from Merelbeke); C) Bornem (Temse to mouth Rupel; 57-64 km from Merelbeke).

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4 GENERAL EVALUATION METHODOLOGY

The goal of the evaluation is to assess the impact of the different alternatives and climate scenarios on selected quality indicators of the Upper Sea Scheldt. These indicators are selected to represent key aspects of the functioning of the system and are associated with hydrodynamics, sediment transport, water quality and pelagic ecosystem, habitat quality, fauna and flora. Evaluation can occur at the level of the **state** of the system or the **evolution** of the system (Figure 4-1).

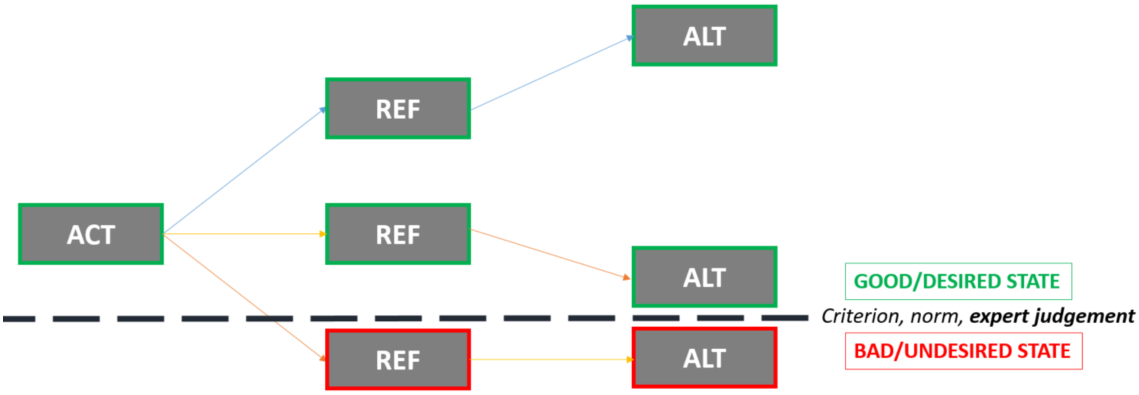

Figure 4-1: Illustration of the evaluation of the **state** and the **evolution** of the system. ACT = current state (2013); REF = reference state (2050); ALT = C-alternatives/scenarios.

- The **state** of the system is evaluated by comparing the model output to a predefined threshold.
- The **evolution** is evaluated by calculating the magnitude of the changes, and can be either a measure of absolute or of relative changes, depending on the quality indicator.

$$\text{magnitude of the change} = \text{Model}_{\text{alternative}} - \text{Model}_{\text{reference}}$$

or

$$\text{magnitude of the change} = \frac{\text{Model}_{\text{alternative}} - \text{Model}_{\text{reference}}}{\text{Model}_{\text{reference}}}$$

The state of the system is only evaluated for certain quality indicators of the habitats and is not evaluated for the higher trophic levels. For the higher trophic levels, the state is discussed but not evaluated as no reference criterion exists to evaluate the state. The magnitude of changes is evaluated for the habitats and the higher trophic levels.

5 EVALUATION OF HABITATS

5.1 INDICATORS

For the habitats, the following indicators are evaluated:

- Tidal regime
    - Since the 19th century, the Scheldt estuary has evolved from a mesotidal system towards a macrotidal system with a tidal amplitude exceeding the 5-meter limit in approximately 1/4 of the stretch. Figure 5-1 shows the historical evolution of the tidal amplitude in the last 150 years. Sea level rise will induce a steady increase in tidal amplitudes (high water rises faster than low water). An additional increase caused by the intended adaptations to the bathymetry is considered undesirable. One of the aims for the future is to reduce the tidal amplitude or at least stop the increase of the tidal amplitude. This goal is driven by morpho-ecological arguments to reduce the tidal wave and water current energy. High(er) amplitude (~energy) reduces habitat stability (more erosion) and without the possibility of lateral expansion slopes of the riverbanks will increase (Adriaensen et al. 2005).
    - Mean tidal amplitude in the different alternatives are derived from the mean low and high water modeled by the SCALDIS model (Smolders et al. 2016).

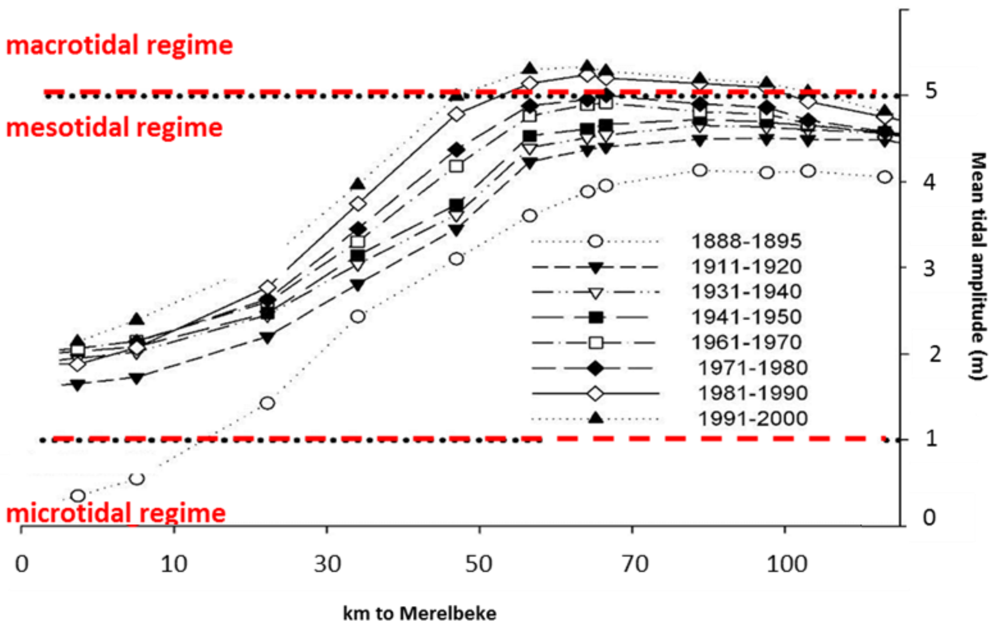

Figure 5-1: Evolution of the mean tidal amplitude (modified after Van Braeckel et al. 2006). Tidal range classifications based on Hayes (1979).

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- <u>Surface area of the habitats</u>
  - The Scheldt estuary is unique in Europe for its extent and diversity of intertidal habitats, especially in the freshwater zone. The habitats not only function as the home for a diversity of specialized fauna and flora, they (and their inhabitants) are also strongly interconnected through nutrient and energy flows (the food web), and therefore dependent on each other. Preserving sufficient surface area of the different habitats is therefore a very important nature conservation goal and a prerequisite for a healthy functioning Scheldt ecosystem.
  - Surface area of the habitats in the different alternatives and scenarios is calculated as described in Van Braeckel et al. (2019).
  - Surface areas are evaluated for the following, ecologically important habitats:
    - Subtidal habitat
    - Tidal mudflat habitat (or littoral or intertidal habitat)
    - Tidal marsh habitat (or supralittoral habitat)
- <u>Habitat quality</u>
  - <u>Hardening of the estuary</u>
    - A further increase in tidal area with hard substrate (rip-rap) reduces potential for geomorphological adaptation and has a low ecological value which is unfavorable. The (proportional) littoral area along the main channel with hard substrate is thus an important (negative) ecological quality indicator.
    - In the present situation shorelines with slopes exceeding 25% are fixed by rip-rap to prevent further erosion (Van Braeckel et al. 2019). We assume a similar management in the future.
  - <u>Propensity for erosion/sedimentation of the mudflats</u>
    - Modeling of morphological adaptation after alterations to the bathymetry is not included in this study. In combination with the initial direct effect of gains/losses in surface area of the mudflats, the propensity for erosion/sedimentation can give an indication of the expected further evolution of changes in surface area. Mudflat area with increased shear stress, which would indicate that further erosion and greater loss of habitat may take place, can be evaluated as more unfavorable.
    - Estimates of erosion on mudflats are based on raster data of the 50 percentile of the velocity shear stress (TAU50 (pascal)) calculated in the 3D-SCALDIS-model (Smolders et al. 2016). The average value of this TAU50 raster is calculated per kilometer stretch of soft bottom tidal mudflat ecotope along the main channel.

- Mudflat with high macrobenthic biomass
    - Biomass of macrobenthos is an important indicator of ecological quality of the mudflats. Macrobenthos is an important food source for benthic fish and epi-/hyperbenthic crustaceans, as well as for birds such as Common teal. Based on the results of Habitatmapping Sea Scheldt partim tidal mudflats (Van Braeckel et al. 2020), the low tidal mudflats (0-25% emersion time) contain significantly lower macrobenthic biomass than the middle and upper tidal mudflats (25%-100% emersion time).
    - The proportion of middle and upper tidal mudflat area is used as a habitat quality indicator for tidal mudflats.

5.2 EVALUATION METHODOLOGY

5.2.1 Tidal regime

The *state* of the tidal regime is examined by comparing the tidal amplitude against predefined thresholds for macrotidal, mesotidal and microtidal regimes (Table 5-1). The criteria are derived from Hayes (1979). A macrotidal system is considered as undesirable.

Table 5-1: thresholds delimiting transitions in tidal regime (based on Hayes (1979)).

threshold	Mean tidal amplitude
Microtidal - mesotidal	1 m
Mesotidal - macrotidal	5 m

5.2.2 Surface area of the habitats

The *state* of the habitats in the different alternatives is evaluated by comparing the surface area of the ecotopes against the desirable state as calculated for each OMES zone (Figure 5-2) based on the methodology described in Maris *et al.* (2013) for the Scheldt in 2005 (

Table 5-2). Surface areas smaller than the desirable state for a given ecotope and OMES zone are evaluated as unfavorable, surface areas equal or larger than the desirable state as favorable. This evaluation is a simplified approximation as the criterion for total surface area required for each ecotope in the entire Sea Scheldt is higher than the sum of the requirements for each OMES zone individually (Table 5-2) (see Maris *et al.*, 2013). This means that realising only the minimum in each OMES zone is not sufficient to reach the goals for the entire Sea

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Scheldt. Thus, the values for the evaluation targets in each OMES zone are indicative for evaluation status of zonal surface area but should not be the goal for future planning.

Table 5-2: Evaluation targets (surface area in ha) for the *state* of the ecotopes in each OMES zone (derived from Maris et al., 2013).

length (km)	**OMES**	**tidal marsh**	**tidal mudflat**	**shallow water**
11	**14**	142	145	82
11	**15**	118	89	68
10	**16**	96	72	55
11	**17**	33	25	19
9	**18**	27	21	16
12	**19***	36	27	21

* : OMES 19 trGM is pooled with OMES 19.

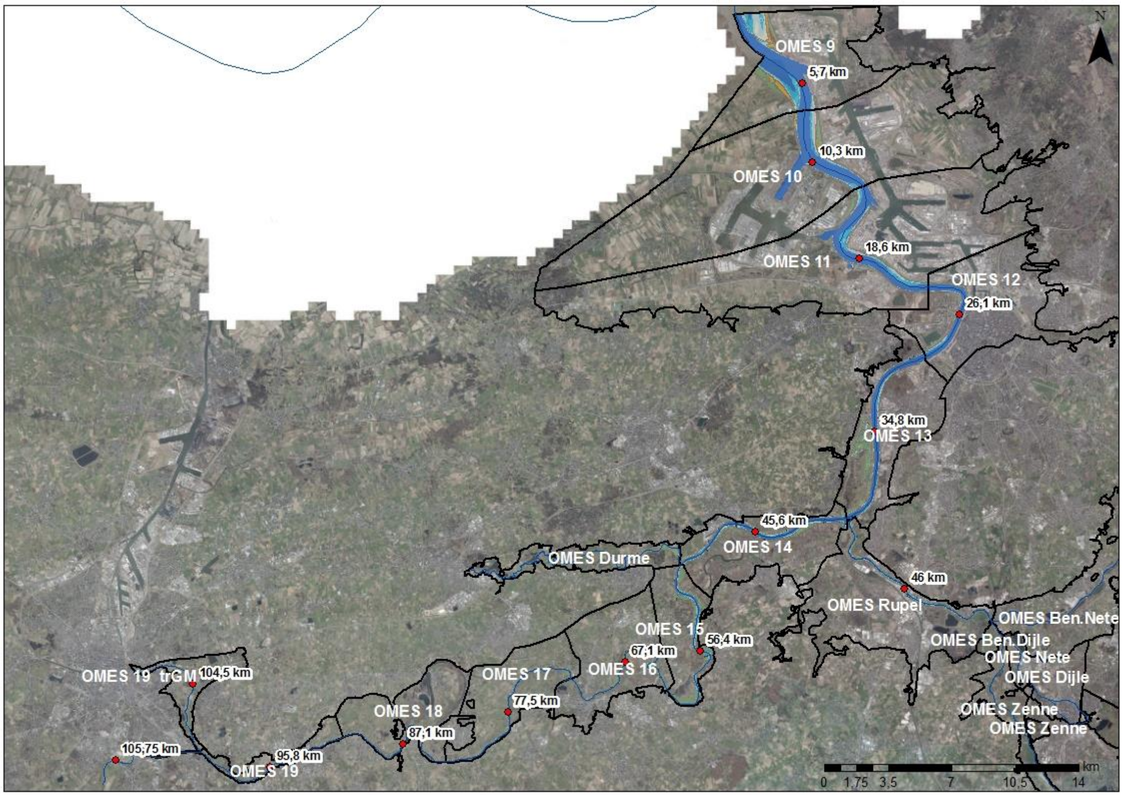

Figure 5-2: Overview of the OMES zones in the Scheldt Estuary. In the current study only the OMES zones in the Upper Sea Scheldt, omitting tributaries, are considered. OMES 19 trGM is pooled with OMES 19.

The *evolution* of the habitats is evaluated according to:

$$\text{magnitude of the change} = \text{Surface area}_{\text{alternative}} - \text{Surface area}_{\text{reference}}$$

A reduction in surface area compared to the 2050 reference is evaluated as unfavorable and *vice versa*.

For the subtidal ecotope, low-dynamic (= slow water currents) habitat is considered ecologically more valuable than high-dynamic (= strong water currents) habitat. There exist, however, no estimates for the desirable state of the subtidal area the OMES zones when taking only into account the low-dynamic habitat. Therefore, at the level of the OMES zones, the *state* and *evolution* of the subtidal ecotope are analysed considering both low-dynamic and high-dynamic areas, but only for the shallow water (< 2m dept). in contrast, for the evaluation of the *evolution* of the subtidal ecotope per kilometer, only the low-dynamic habitat is taken into account but pooled over all depth levels (deep, middle-deep and shallow waters).

5.2.3 Habitat quality

An increased *hardening of the estuary* is an unfavorable evolution for ecology as it redirects the hydromorphological behaviour of the river/estuary often at the cost of existing gradients of soft intertidal habitats with higher ecological value. We focus on the proportion of hard substrate of the total area of tidal flats near the fairway (excl. CRTs and depolderings).

Evolution of the *propensity for erosion/sedimentation* (shear stress) is calculated as:

$$\text{magnitude of the change} = \text{TAU50}_{\text{alternative}} - \text{TAU50}_{\text{reference}}$$

At the riverbanks near the main channel, indications of erosion associated with increased shear stress indicate that the modeled intertidal habitats will not be stable and risk reduction or loss. Therefore, indications of increased erosion and potential loss of tidal mudflats with soft sediment can be evaluated as unfavorable. Erosion of low tidal mudflat near the channel goes hand in hand with increased steepness of the tidal mudflats and the potential need of anthropogenic defence measures such as rip rap (which is undesirable).

Reductions in the proportion of *mudflat with high macrobenthic density and biomass* (middle & upper tidal mudflat) are evaluated as unfavorable.

5.2.4 Tidal regime

Currently the Scheldt estuary has evolved towards a macrotidal system in the downstream area (> 50 km from Merelbeke; Figure 5-1; see also 2013 reference situation in Vanoverbeke et al. 2023 (*in press)*). A further increase to a macrotidal system is undesirable. The tidal amplitude is too large in relation to the lateral space of the river, resulting in steep sloping riverbanks and non-repairable erosion of the marshes (marsh cliffs) leading to non-natural hardening with rip-rap.

Detailed analyses and discussion of the effects of the C-alternatives on hydrodynamics and tidal amplitudes can be found in Bi et al. (2021a).

Effects of the different alternatives and climate scenarios on tidal amplitude are shown in

Figure 5-3. Downstream of Antwerpen (78 km from Merelbeke) differences between the C-alternatives (2050C1, 2050C2, 2050C3) and the C-reference (2050REF_C) are small to non-existing. Upstream of Antwerpen effects of the C1 alternative on tidal amplitudes remain relatively local (between 60-40 km from Merelbeke) but are nevertheless important because they occur in the region with the highest tidal amplitude. There is a maximum decrease of 35-40 cm in tidal amplitude around Tielrode (53 km from Merelbeke) in the A0CN climate scenario, largely ascribed to the local undeepening at Bornem (Km 57-64 from Merelbeke). Also in the upper reaches (< 20 km from Merelbeke) tidal amplitude is reduced by several centimeters, associated with the depoldering of the FCA-CRT at Bergemeersen (18 km from Merelbeke) and extra depoldered area downstream of Wetteren (12 km from Merelbeke).

Upstream of Temse (57 km from Merelbeke), the C2 and especially the C3 alternative show much stronger effects on tidal amplitude. Around Tielrode (53 km from Merelbeke), tidal amplitude is reduced by almost 1 meter in C2 and by more than 2 meters in C3. Near Dendermonde an additional effect of C2 on the tidal amplitude can be observed with a further decrease of tidal amplitude to 1.25 meter. For C3 the reduction in tidal amplitude remains slightly above 2 meters. The strong reductions in tidal amplitude in C2 and C3 are mostly associated with large inclusions of new estuarine area by the introduction of depoldered and/or FCA-CRT areas in the region between Rupel and Tielrode (50-65 km from Merelbeke) and downstream of Dendermonde (35-40 km from Merelbeke). The large depolderings between km 20 and 30 from Merelbeke in C2 and C3, seem to have less effect on the tidal amplitude with no strong indications of a further reduction in tidal amplitude compared to the 2050 reference.

As a result of the reduction in tidal amplitude, alternative C2 and C3 are no longer macrotidal, even in the downstream area (> 50 km from Merelbeke; tidal amplitude in the A0CN climate scenario <= 5 m). In the upstream area (< 30 km from Merelbeke), the C3 alternative even almost becomes microtidal, with a tidal amplitude of less than 1.5 m.

The observed changes in tidal amplitude in the different alternatives are robust against the different climate scenarios (AminCL, AplusCH). Although tidal amplitude can increase (AplusCH) or decrease (AminCL) with about 25-50 cm in the downstream area, the differences between the alternatives are comparable between the different climate scenarios. The increase/decrease in tidal amplitude in the climate scenarios is most likely due to the forced increase/decrease of tidal amplitude at the seaward border of the model area.

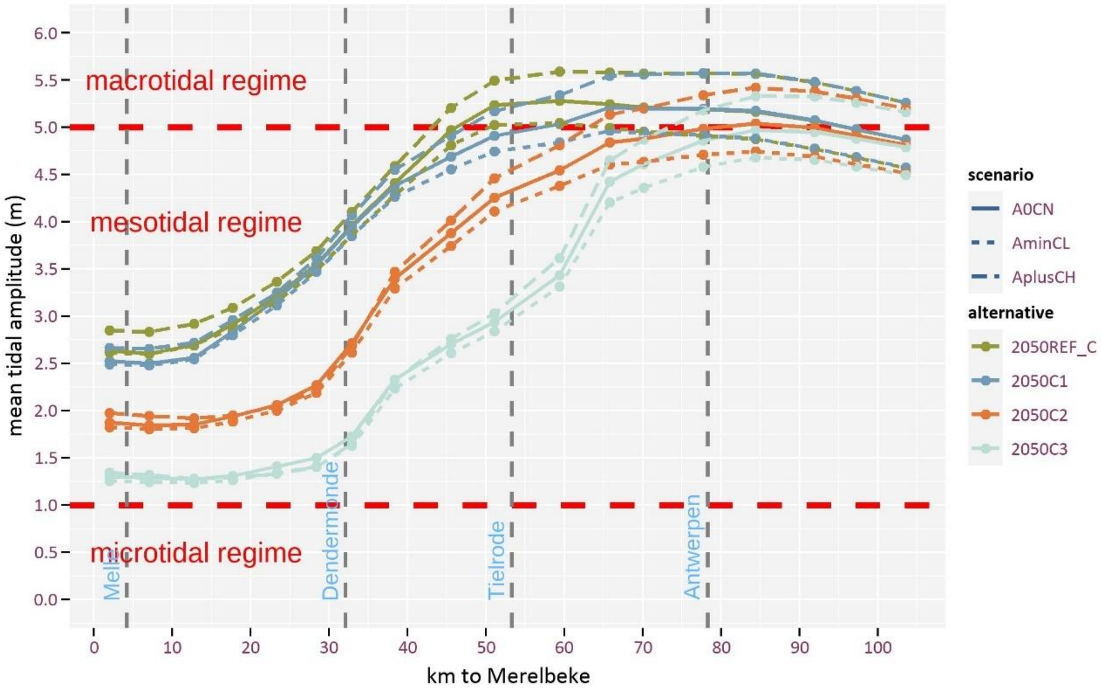

Figure 5-3: mean tidal amplitude in the 2050 C-reference situation and the C-alternatives for the different climate impact scenarios. Tidal range classifications are based on Hayes (1979).

5.2.5 Surface area of the habitats

Before discussing the results, it needs to be remarked that evaluation of the habitats is difficult because the modeling instruments do not fully take into account the autonomous morphological evolution (but see Bi et al. (2021c) for an estimation of long-term siltation processes in new depolderings). The subtidal and intertidal areas are sensitive to changes occurring in the system in response to erosion-sedimentation dynamics after alterations to the bathymetry. In addition, the climate scenarios will add to uncertainty in the future bathymetries. Whereas estimates of expected sedimentation in existing marshes in response to sea level rise are included in the calculation of the habitats, the potential effects on subtidal areas and mudflats (e.g. steepening of the mudflats) have not been accounted for. To have an idea of the expectations without the additional complexity of climate change induced alterations, a scenario is included which omits effects of sea level rise and imposed downstream alteration in tidal amplitude (climate scenario A0CN). Furthermore, to have at least a rudimentary assessment of the expected autonomous evolution on the mudflats, evaluation of the propensity for erosion/sedimentation has been included (see paragraph 5.2.6).

In addition, future realisations of the SIGMA plan and additional depolderings and creation of CRTs in the alternatives create additional estuarine area that is not yet present nowadays. In these newly created estuarine areas, estimation of the final habitat distribution after autonomous evolution is even more uncertain and not accounted for. Despite the uncertain autonomous evolution, the estimates provide some insights in the final achievement of estuarine habitat and the fulfilment of the predefined goals. In the newly depoldered areas the modeled habitats were based on the actual elevation, similar to the methodology for the riverbed and riverbanks. In newly created CRTs, based on estimates from currently realised CRT areas, the proportion of mudflat area in future realised CRT - SIGMA locations is set to 15% of the total area in that location, and marsh area is set to 85% of the total area.

Finally, it needs to be mentioned that some discrepancies exist between the bathymetrical designs used to assess changes in the prevalence of estuarine habitats and the designs used for the hydrodynamic and sediment modeling. Here, Wal-Zwijn in OMES 15 (km 42-48 from Merelbeke) is included as a FCA-CRT in the C-reference, whereas in the hydrodynamic and sediment modeling it is considered as a FCA (without CRT). In addition, Blankaart in OMES 15 (km 48-49 from Merelbeke) is included as a FCA-CRT in alternative C1, whereas in the hydrodynamic and sediment modeling it is considered as a FCA (without CRT).

5.2.5.1 Evaluation of the habitats per OMES zone

The required habitat targets are divided per OMES zone and based on the methodology given in Maris et al. (2013) (Table 5-2). It should be noted that these targets were set for the system as it was in the early 2000s, and that an update is yet not available. The required habitat targets are essentially not a fixed given, but depend on the balance between bathymetry, tidal energy, water discharge, etc. on the one hand and the required space given to the river to cope with these inputs on the other. Required habitat targets for a healthy functioning (eco)system thus depend on the (yet unknown) equilibrium we wish to attain. Therefore, the evaluation of the state against the given habitat targets for a healthy functioning system is mostly indicative. As for the subtidal habitats targets including an evaluation of water dynamics (*low dynamic* habitat) are not yet available, the evaluation of the *state* of the subtidal habitats occurs based on water depth only: the shallow water habitat (area less than 2 water depth to the low water line at LW10%), thus including both low dynamic and high dynamic areas.

For the shallow water (Table 5-3; Figure 5-4), none of the OMES zones are in a favorable state in the 2050 reference in any of the climate scenarios. In the C1 alternative a favorable state is attained only in the most downstream region (OMES 14) in all three climate scenarios. Compared to the reference, the added subtidal area in OMES 14, is mostly located on the newly created groins and the new channel connecting the Durme with the Sea Scheldt. The subtidal area on the groins is largely high dynamic, which is less favorable than low dynamic area. In C2, OMES 14, 17 and 18 attain a favorable state. Next to the added subtidal area on the groins and the new Durme channel, additional subtidal area is created in the added side channels (59-64 km from Merelbeke) in OMES 14. Also here, large part of this area is high dynamic, which is less favorable. Also in OMES zones 17 and 18 additional subtidal area is created in C2 as a result of added side channels. In these side channels the subtidal area is mostly low dynamic, which is positive. Also in the C3 alternative OMES 14, 17 and 18 attain a favorable state in all climate scenarios. Both in OMES 17 and 18 additional low dynamic subtidal area is created in extra (Paardenweide, OMES 18) or extended (OMES 17) side channels.

Besides the creation of side channels, also the differences in tidal amplitude between the different alternatives have an effect on the area of subtidal habitat. Figure 5-5 shows that, when only considering areas in the riverbed and banks where no alterations were made to the bathymetry in any of the alternatives (i.e. excluding newly created side channels), there is still a considerable increase (e.g. 5-25% in A0CN) in subtidal area in alternatives C2 and C3. This can be linked to changes in low water levels, which are up to 0.5 m and 1.2 m higher in C2 and C3, respectively, than in the 2050 reference, resulting in a drowning of the lower mudflats.

For the 2050 reference, C1 and C2, climate scenarios do not affect the resulting subtidal area much. In C3, however, the AminCL and especially the AplusCH climate scenario result in substantial additions of subtidal area, due to drowning of depoldered areas (i.e. gain of subtidal area at the expense of low mudflat area), turning more OMES zones into a favorable state (Table 5-3; Figure 5-4) (e.g. Figure 5-10).

The lowest surface area of shallow water (summed over OMES compartments) and thus the most unfavorable state is found in 2050REF-C A0CN (Table 5-3). The highest surface area of shallow water is found in 2050C3 AplusCH.

For the tidal mudflats only OMES 15[1] and 18 are in a favorable state in the 2050 reference situation (Table 5-4; Figure 5-4). In the C1 alternative, also OMES 19 reaches a favorable state, with a four time increase in area of mudflats. In OMES 18, which is already in a favorable state in the reference situation, there is a doubling of the area of mudflats. In OMES 18 this increase in mudflats compared to the 2050 reference is mainly achieved by the reconversion of the CRT at Bergenmeersen (17-19 km from Merelbeke) to depoldered area. In OMES 19, the increase in mudflat area is linked to the depoldering at Kastermeersen (12 km from Merelbeke) and the creation of additional intertidal nature at Voorde (8 km from Merelbeke). In the C2 alternative, the gains in mudflat area obtained in C1 in OMES 18 are partly lost again at the expense of subtidal area (creation of side channels) and marshes (due to reduction in tidal amplitude). In the A0CN scenario, despite creation of additional intertidal area at 4, 5 and 6 km from Merelbeke (Veerhoek, Melleham and Bommels), also OMES 19 loses some mudflat area. This because of the effects of reduced tidal amplitudes, whereby intertidal area is lost to subtidal area and especially to marshes (Figure 5-8). OMES zones 14-17 also reach a favorable state with respect to intertidal mudflats in alternative C2. In each of these OMES zones, large amounts of additional intertidal area are created by means of depolderings and/or creation of CRTs. In the C3 alternative, mudflat area is further increased in OMES 14, 15 and 17, by further depolderings, strengthening their favorable state. In OMES 16, the loss of mudflat area around the Kramp (40 km from Merelbeke; changed into marshes) is compensated by an additional band of mudflat area in Roggeman (38 km from Merelbeke). Due to depolderings in Wijmeers (16 km from Merelbeke) and Paardenweide (19-21 km from Merelbeke), the loss of mudflats observed in OMES 18 in alternative C2 is compensated. In OMES 19, the negative effect of reduced tidal range on mudflat area is intensified (in climate scenario A0CN) and this zone loses its favorable state in the A0CN climate scenario as most intertidal area is turned into marshes.

Indeed, OMES 19 suffers strongly from the loss of intertidal mudflats due to the strongly reduced tidal amplitude. Whereas this trend can be observed in all OMES zones when only considering areas in the riverbed and banks where no alterations were made to the bathymetry (Figure 5-5), OMES 19 seems to be affected the strongest.

In general, the different climate scenarios do not affect the area of intertidal mudflats much, except for alternative C3, where opposing trends can be observed between OMES zones 14-17,

[1] i.e. including Wal-Zwijn as CRT in OMES 15. Excluding Wal-zwijn as CRT moves the surface area of mudflats in OMES 15 in the C-reference to an unfavorable state (see note with Table 5-4).

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with a decline in area of mudflats with sea level rise, and OMES zones 18-19, with an increase of area of mudflats with sea level rise. In OMES 18-19 the increase can be ascribed to a buffering effect of sea level rise on the conversion of mudflats into marshes in depoldered areas (Figure 5-8). In OMES 14-17, in contrast, large stretches of intertidal mudflats in the depoldered areas are lost with sea level rise due to drowning and conversion into subtidal area (Figure 5-10).

Overall, the lowest area of intertidal mudflats (summed over OMES compartments) and thus the most unfavorable state is found in 2050REF-C A0CN (Table 5-4). The highest surface area of intertidal mudflats is found in 2050C3 A0CN.

Tidal marshes are in a favorable state in the downstream part of the Upper Sea Scheldt (OMES 14, 15 and 16) for the 2050 reference (Table 5-5). The downstream parts remain in a favorable state in the C1, C2 and C3 alternatives, though OMES 16 shows slight reductions in surface area of the marshes. In alternative C1 the loss of marsh area in OMES 16 is due to straightening of the channel at the Kramp (but note that intertidal mudflat area is created instead). In C2 and C3, large parts of the mudflats around the Kramp are turned into marsh area again due to reductions in tidal range, but large parts of the marshes are also lost because high water levels are strongly reduced and the higher areas of the marshes are no longer affected by the tides (becoming non-estuarine, Figure 5-9). Due to this extraction of the higher marshes from tidal influence, despite the introduction of large areas of CRT (with 85% of their area ascribed to tidal marshes) in OMES 14-15 the surface area of the marshes does not increase, but even tends to decrease in alternatives C2 and C3 (albeit remaining well above the minimal requirements for a favorable state). In OMES 15, while remaining in a favorable state, there is a strong augmentation in marsh habitat in alternative C1[2], that is lost again in alternative C2 and C3. The strong increase in C1 is due to the introduction of a new CRT at Blankaart (48 km from Merelbeke). In alternative C2 and C3 this zone is converted into depoldered area. This results in a conversion of marshes into mudflats in Blankaart.

In the upstream part of the Upper Sea Scheldt only OMES 18 is in a favorable state in the C reference. OMES 17 gains a favorable state in all three alternatives, due to creation of additional marsh area through the construction of the CRT at Scheldebroek (27 km from Merelbeke). OMES 18, on the other hand, loses its favorable state in C1 an C2. In OMES 18, the modifications to the bathymetry at Wijmeers and Bergemeersen (15-19 km from Merelbeke), result in a loss of marsh area at the expense of subtidal and mudflat area in C1 and C2, that is only compensated again in C3 by additional depoldering in Wijmeers and Paardenweide and the conversion of mudflats into marshes (due to reduced tidal range). In OMES 19, marsh area steadily increases due to the addition of depoldered areas and CRTs, and this zone reaches a favorable state in alternative C2 and C3 (except for climate scenario AminCL in C3). Note that also in OMES 17-19, however, the observation remains that higher already existing marshes are extracted from tidal influence (and thus lost as estuarine nature) due to the strong reduction in high water levels in alternative C2 and especially C3. Relative losses due to reduced tidal range even seem stronger in OMES 17-19 than in OMES 14-16 (Figure 5-5).

In general, overall losses in marsh area that are observed in climate scenarios A0CN and AminCL due to reduced tidal amplitude in alternative C2 and C3 (Table 5-5), are compensated in climate scenario AplusCH due to sea level rise (and perhaps the forced increase in tidal

[2] i.e. including Blankaart as CRT in OMES 15. When excluding Blankaart as CRT in the C1 alternative, surface area of tidal marshes in OMES 15 in C1 is comparable to C2 and C3 (see note withTable 5-5).

amplitude at the seaward edge of the modeling domain). Even if in most cases total marsh area in AplusCH does not change much compared to the C reference, however, the geographic distribution of the marshes (and mudflats) at local scale can differ strongly compared to other climate scenarios due to relocations of habitat types associated with sea level rise (lower elevation marshes become mudflats, higher elevation marshes remain and do not become non-estuarine habitat).

Overall, the lowest areas of marsh habitat are found in 2050C3 AminCL. The highest areas of marsh habitat are found in 2050C1 A0CN.

Table 5-3: Habitat targets and *state* of the area (ha) of shallow water (<2m). Results include estimates for newly created CRT areas and depolderings. Values in blue indicate a favorable state. *Δ bathy-REF*: comparison of the surface area in the alternatives with the REF 2050 bathymetry for the respective climate scenarios. Green indicates a favorable evolution, red indicates an unfavorable evolution.

Shallow water (<2m HD&LD)		**2050REF_C**			**2050C1**			**2050C2**			**2050C3**		
OMES	**Minimal area**	**A0CN**	**AminCL**	**AplusCH**	**A0CN**	**AminCL**	**AplusCH**	**A0CN**	**AminCL**	**AplusCH**	**A0CN**	**AminCL**	**AplusCH**
14	82	35	36	36	**85**	**88**	**88**	**113**	**120**	**121**	**131**	**173**	**253**
15	68	32	32	33	32	33	33	33	34	34	63	**103**	**210**
16	55	11	12	12	12	12	13	14	16	20	22	34	**116**
17	19	15	15	15	15	15	15	**37**	**39**	**48**	**57**	**67**	**133**
18	16	10	11	11	10	11	12	**28**	**30**	**33**	**50**	**51**	**55**
19	21	14	14	15	14	15	16	15	15	17	16	17	18
Total	261	118	120	121	169	174	177	241	254	**273**	**338**	**445**	**785**
Δ bathy-REF					52	54	56	123	134	151	220	325	664

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Table 5-4: Habitat targets and *state* of the area (ha) of tidal mudflats. Results include estimates for newly created CRT areas and depolderings. Values in blue indicate a favorable state. *Δ bathy-REF*: comparison of the surface area in the alternatives with the REF 2050 bathymetry for the respective climate scenarios. Green indicates a favorable evolution, red indicates an unfavorable evolution.

Tidal mudflat		2050REF_C			2050C1			2050C2			2050C3		
OMES	Minimal area	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH
14	145	128	124	126	139	135	138	427	419	423	657	615	540
15	89	93*	95*	98*	107**	109**	113**	187	188	204	635	594	486
16	72	30	33	34	43	42	42	178	184	181	206	194	132
17	25	12	12	12	16	16	17	203	201	194	355	349	288
18	21	30	30	30	60	63	66	30	35	35	58	75	102
19	27	9	9	10	36	39	46	28	32	41	10	36	49
Total	379	303	302	311	402	405	422	1053	1059	1078	1921	1861	1596
Δ bathy-REF					100	103	111	751	757	767	1618	1559	1285

* Surface area excluding Wal-Zwijn in 2050REF_C in OMES 15 is 71, 73 and 76 ha for the different climate scenarios, respectively.
** Surface area excluding Blankaart in 2050C1 in OMES 15 is 88, 90 and 94 ha for the different climate scenarios, respectively.

Table 5-5: Habitat targets and *state* of the area (ha) of tidal marsh. Results include estimates for newly created CRT areas and depolderings. Values in blue indicate a favorable state. *Δ bathy-REF*: comparison of the surface area in the alternatives with the REF 2050 bathymetry for the respective climate scenarios. Green indicates a favorable evolution, red indicates an unfavorable evolution.

Tidal marsh		2050REF_C			2050C1			2050C2			2050C3		
OMES	Minimal area	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH
14	142	285	286	287	268	268	269	284	292	297	254	259	301
15	118	317*	315*	314*	425**	424**	419**	271	298	320	224	232	301
16	96	125	122	120	116	116	115	103	99	115	108	110	100
17	33	31	29	26	57	56	55	39	40	59	45	45	45
18	27	43	42	41	15	11	7	23	18	18	72	65	44
19	36	20	21	21	29	29	22	38	41	39	48	33	37
Total	452	820	814	810	911	904	886	758	789	847	750	744	829
Δ bathy-REF					91	89	77	-63	-26	38	-70	-70	20

* Surface area excluding Wal-Zwijn in 2050REF_C in OMES 15 is 193, 191 and 390 ha for the different climate scenarios, respectively.
** Surface area excluding Blankaart in 2050C1 in OMES 15 is 318, 317 and 312 ha for the different climate scenarios, respectively.

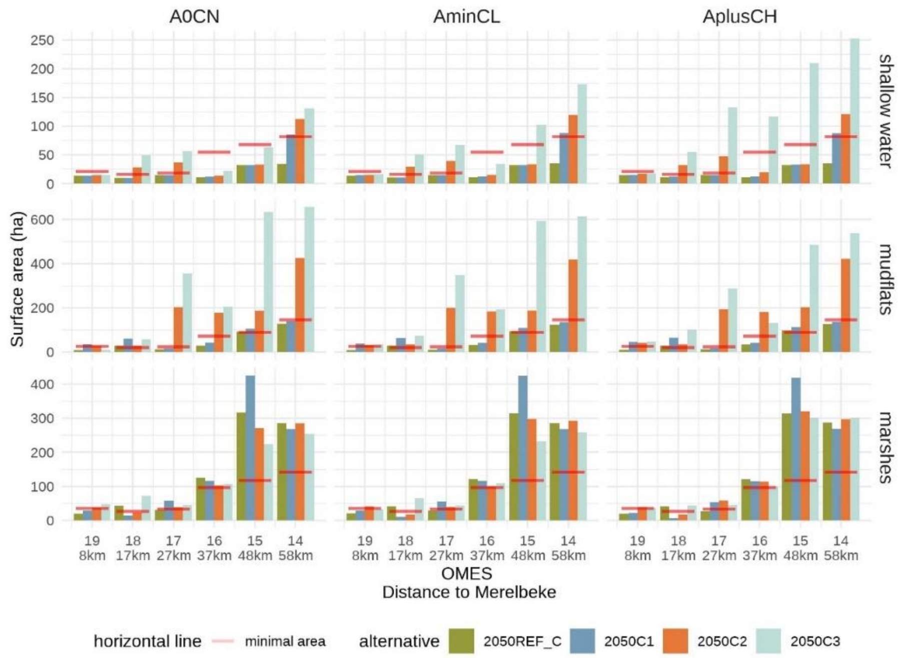

Figure 5-4: S*tate* of the area (ha) of shallow water (<2m), mudflats and marshes per OMES zone, alternative and climate scenario. Results include estimates for newly created CRT areas and depolderings. Horizontal red lines indicate the required habitat targets (see 5.2.2).

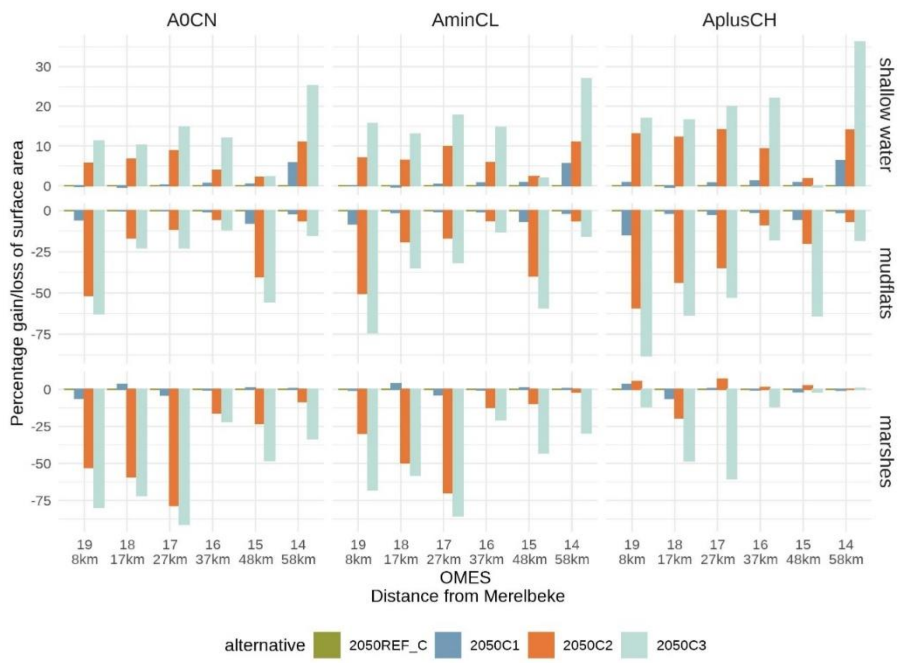

Figure 5-5: Percentage gain/loss of surface area (ha) when only considering areas in the riverbed and banks where no alterations were made to the bathymetry in any of the alternatives. Results for shallow water (<2m), mudflats and marshes per OMES zone, alternative and climate scenario.

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5.2.5.2 Evolution of the habitats per kilometer

The evaluation of *state* and *evolution* of the ecotopes per OMES zone (paragraph 5.2.5.1) gives an estimate of the differences between the C-reference and the C-alternatives at a broader spatial scale (approximately per 10 km). to also have an idea of the differences at a finer geographic scale, we additionally looked at the *evolution* of the ecotopes per kilometer (note that at this scale the *state* is not evaluated, as there exists no external criterion to compare the results with). At this scale, it is, for example, possible to evaluate in more detail the direct, local effects of the implemented measures on changes in habitat composition and water dynamicity. As mentioned in paragraph 5.2.2, for the subtidal habitats, the evaluated habitat per kilometer is partly different than for the evaluation per OMES zone, as only the low dynamic area is considered. In addition, not only the shallow subtidal habitat is included here, but also deep subtidal and subtidal of intermediate depth. For the mudflats and marshes, habitats under consideration are identical to the evaluation at the level of OMES zones.

Alternative C1 has no strong impact on the low dynamic subtidal area (Figure 5-6). At 18 km from Merelbeke, the bend cut-off results in some loss of low dynamic habitat. At the straightening of the channel around the Kramp (40 km from Merelbeke), the results are mixed with local losses and gains. Only in the downstream region (48-55 km from Merelbeke), there is some more extensive increase in low dynamic area compared to the reference. In general, alternative C2 and even more C3 have a positive effect on the availability of low dynamic subtidal area. Upstream of 15 km from Merelbeke, subtidal habitat is already largely low dynamic, and not many improvements can be made. Between 15 and 30 km from Merelbeke, however, inclusion of low dynamic side channels and the conversion from high dynamic to low dynamic habitat in the main channel results in increased availability of low dynamic habitat. Also between km 50 and 60 from Merelbeke in C2, substantial portions of the main channel are converted into low dynamic habitat and some additional low dynamic habitat is created in the side channels (though they also contains large areas of high dynamic area). In C3 increases in low dynamic habitat are also observed between km 30-50 from Merelbeke. Importantly, due to the inclusion of side channels, and large areas of depolderings and CRTs in C2 and C3, low dynamic area is not only created in these side channels but also in the main channel where high dynamic area is converted into low dynamic area, indicating that on average water velocities are reduced in C2 and C3. Only between 30 and 50 km from Merelbeke (OMES 15, 16) in C2, effects are neutral to negative (AminCL). This is even more visible when only focusing on the areas where no alterations were made to the bathymetry in any of the alternatives (Figure 5-7).

In general, climate scenario AminCL tends to have a negative effect on the area of low dynamic subtidal habitat (see Figure 5-7), whereas scenario AplusCH tends to have a positive effect on the availability of low dynamic subtidal habitat in alternative C3. As mentioned for the results per OMES zone (see paragraph 5.2.5.1), sea level rise results in drowning of the mudflats and the creation of additional subtidal (low dynamic) habitat in the more downstream areas (> 20 km from Merelbeke; Figure 5-10).

For the tidal mudflats, in places where additional intertidal area is created through the implemented measures, positive increases in surface area are observed when comparing alternative C1 with the C reference (Figure 5-6). In the upstream area between 8-20 km from Merelbeke this results in relatively consistent improvements in the availability of mudflats. In alternative C2, overall, there are strong increases in mudflat area compared to the reference, especially in regions where large depolderings are implemented (24-29 km, 35-38 km and 58-64 km from Merelbeke). Between 49-52 km from Merelbeke, however, mudflat area is lost to subtidal area. In alternative C3 increases in mudflat area are even stronger, as more areas are depoldered.

As mentioned earlier, both in C2 and C3, even though large gains in mudflat area are achieved through depoldering (and construction of CRTs - only 15% of the area is assigned to mudflats in CRTs), when only looking at areas where no alterations were made to the bathymetry (Figure 5-7), a clear loss of mudflat area is observed due to the strongly reduced tidal amplitude in C2 and C3. Depending on the location, this area is lost due to the conversion of originally high mudflats into tidal marshes (44-45 from Merelbeke) or to the conversion of low mudflats into subtidal area (most other locations). Even in alternative C1 between 40-50 km from Merelbeke, where a reduction in the tidal amplitude is also observed (Figure 5-3), mudflat area is converted into subtidal area (Figure 5-7).

Similar to the low dynamic water and the mudflats, the effects of alternative C1 on the <u>tidal marshes</u> are relatively minor. Some marsh area is lost at Bergenmeersen, the Kramp and the mouth of the Durme. Additional marsh area is gained with the creation of CRTs (> 20 km from Merelbeke) and depolderings (< 20 km from Merelbeke). In alternative C2 mostly negative evolutions of marsh area are observed in the downstream region (> 20 km from Merelbeke), whereas further gains are observed less than 20 km from Merelbeke. In the downstream area, despite the construction of several CRTs with a strong positive effect on marsh area, large parts of the already existing marshes are lost to non-estuarine habitat due to the reduction in tidal amplitude (Figure 5-9). These losses are not fully compensated by the creation of CRTs. Although also large areas of depoldered area are created in alternative C2, the large majority of habitat in these depolderings is tidal mudflat, and they contribute little to the tidal marsh area. In contrast, in the upstream area (< 20 km from Merelbeke) depolderings as well as CRTs do contribute to the creation of additional marsh area. In this region, this is more important than the loss of marsh area due to the reduction in tidal range, resulting in a positive evolution of the tidal marshes. In alternative C3, the same but intensified evolutions as in C2 can be observed. Between 19-21 km from Merelbeke, substantial additional area of tidal marsh is created with the depoldering of Paardenweide. Due to the strongly reduced tidal amplitude in C3, with the loss of already existing marshes to non-estuarine habitat, most of the marshes in this alternative are located in (newly created) CRTs. So, even if the total balance in this alternative is only mildly negative, strong evolutions occur in the location of the marshes.

As mentioned earlier, the loss of marsh area due to reduced tidal amplitude in C2 and C3 is (partly) compensated in climate scenarios AminCL and AplusCH, because sea level rise prevents the already existing marshes from turning into non-estuarine habitat (Figure 5-10).

Special notice may be given to the <u>most upstream section between Melle and Heusden</u> (km 0-4). In this part the same evolutions occur as in other regions in response to changes in the tidal amplitude, with drowning of the lower mudflats, conversion of the higher mudflats into marshes and conversions of the originally existing marshes into non-estuarine habitat (the latter even in alternative C1). In this area, however this results in drastic changes with, as mentioned, large shifts in the locations of the marshes and an almost complete loss of the tidal mudflats in alternative C2 and C3 (Figure 5-11). Whereas the loss of marshes is incrementally reduced in climate scenarios AminCL and AplusCH, this is much less the case for the tidal mudflats, which remain quasi absent in scenario AplusCH in the most upstream section.

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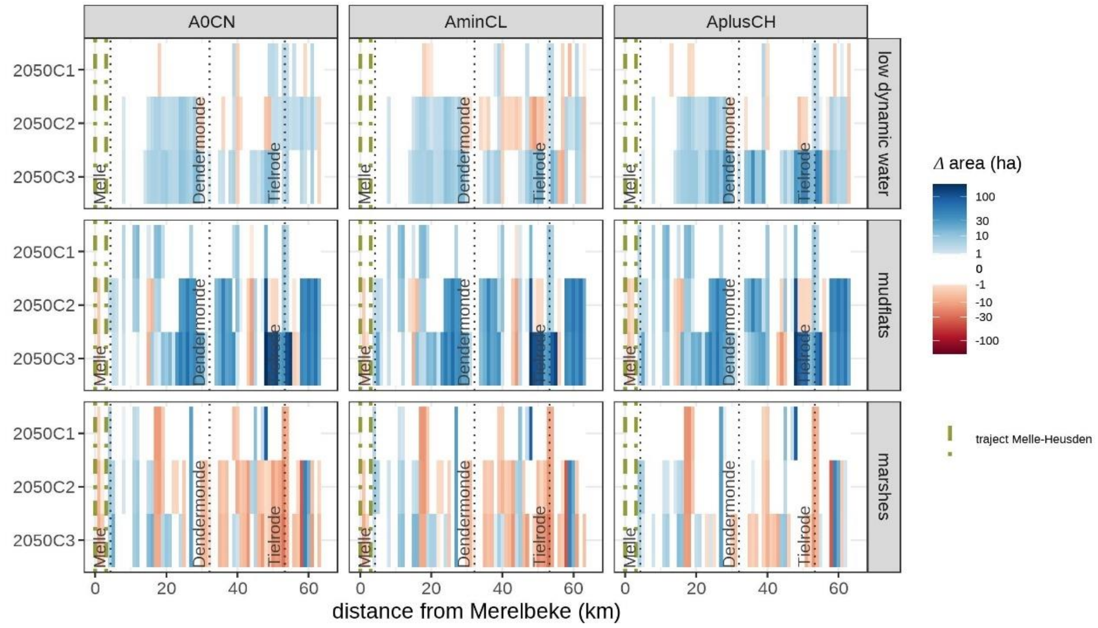

Figure 5-6: Changes in surface area of ecologically important ecotopes. Blue indicates favorable evolution; red indicates unfavorable evolution. Only differences of ≥ 1 ha per km are considered.

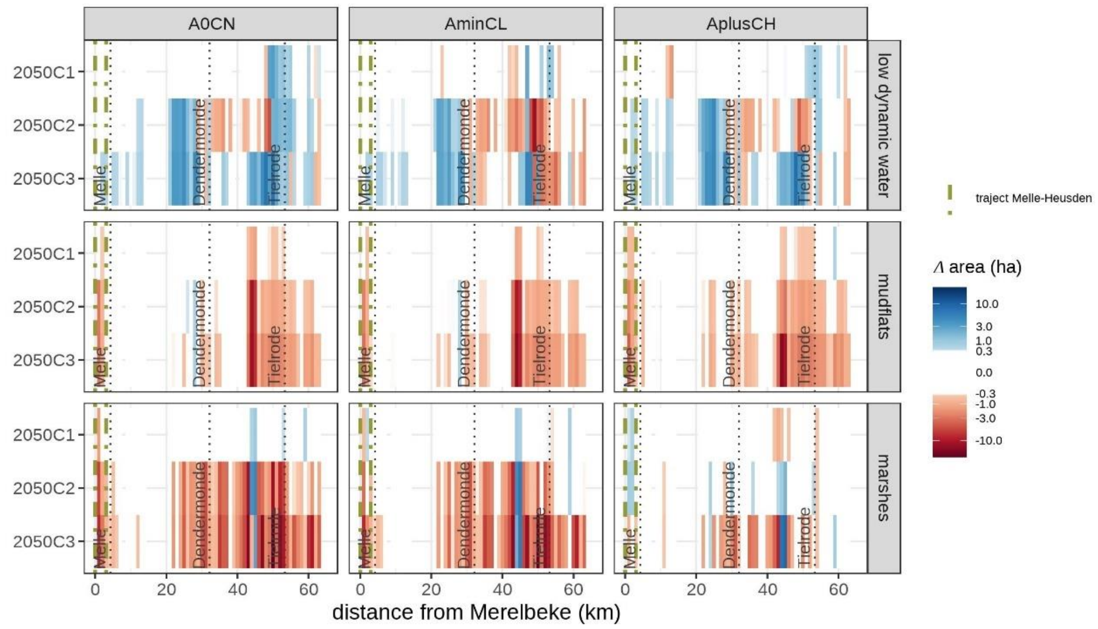

Figure 5-7: Changes in surface area of ecologically important ecotopes, when only considering areas in the riverbed and banks where no alterations were made to the bathymetry in any of the alternatives. Blue indicates favorable evolution; red indicates unfavorable evolution. Only differences of ≥ 0.3 ha per km are considered.

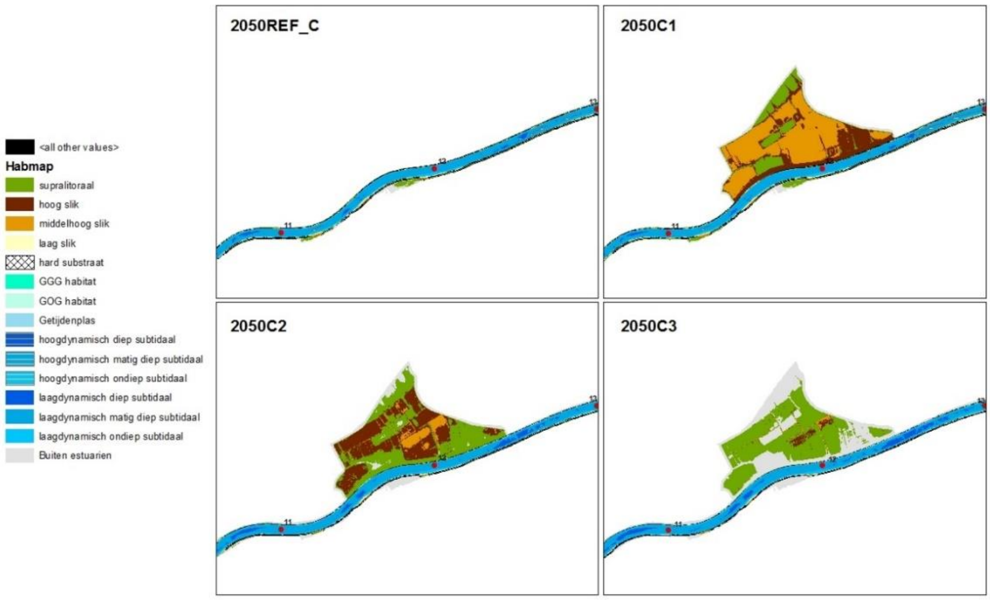

Figure 5-8: Illustration in Kastermeersen of the turnover between types of habitats with decreasing tidal amplitude in the C-alternatives. Mudflat area turns into marshes in C2 and C3. Marshes turn into non-estuarine habitat.

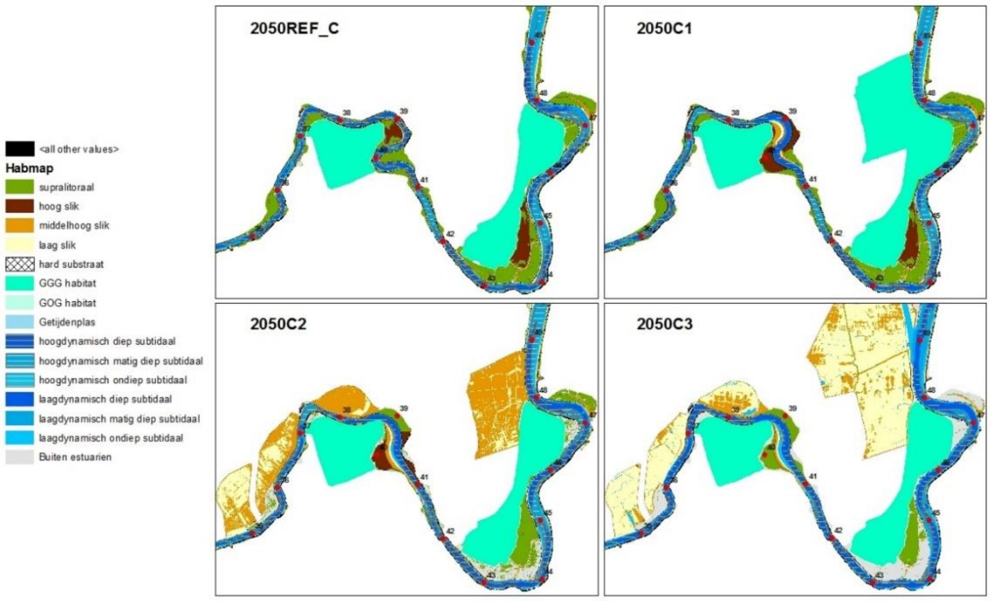

Figure 5-9: Illustration at the Kramp and Blankaart-Akkershoofd of the turnover between types of habitats with decreasing tidal amplitude in the C-alternatives. High mudflats areas turn into marshes in C2 and C3. Higher existing marshes turn into non-estuarine habitat.

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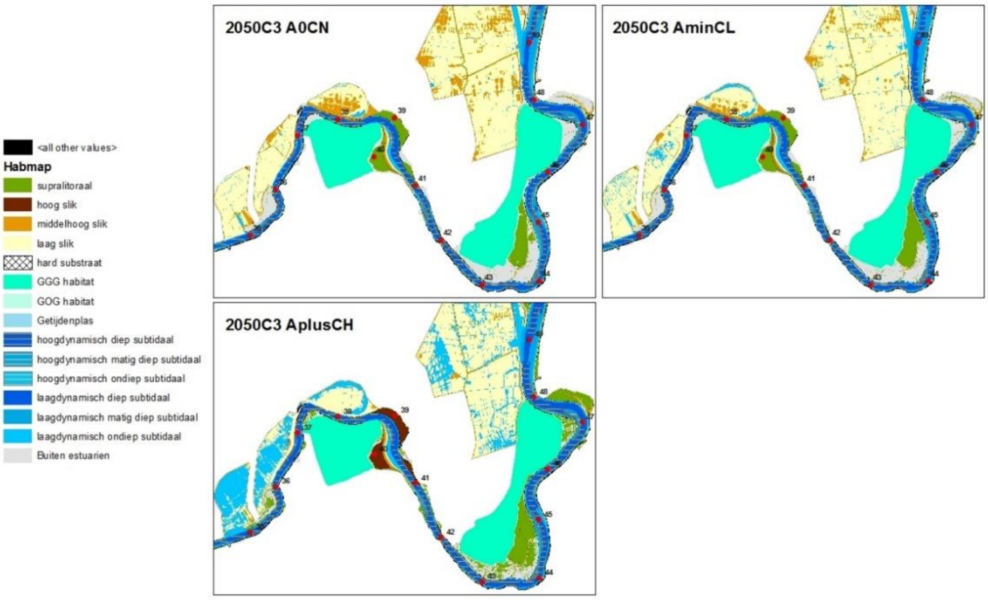

Figure 5-10: Illustration at the Kramp and Blankaart-Akkershoofd of the effects of climate scenarios on the marshes and on the mudflats in depolderings. Desiccation of marshes is reduced with increasing sea level rise. Mudflats in depolderings get drowned with sea level rise in the AminCL and especially the AplusCH climate scenarios.

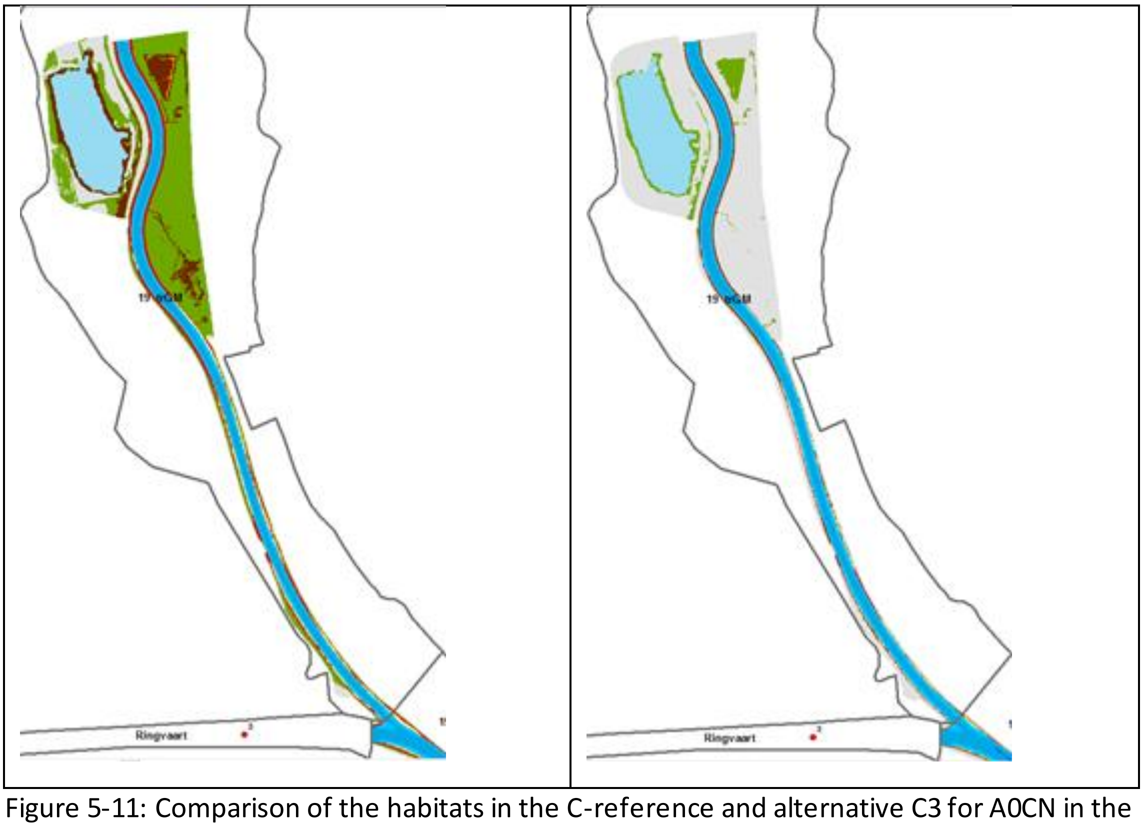

Figure 5-11: Comparison of the habitats in the C-reference and alternative C3 for A0CN in the stretch between Melle and Heusden.

5.2.6 Habitat quality

5.2.6.1 Hardening of the estuary

The overall (all OMES zones together) percentage of hard substrate on steep tidal flats near the fairway (excl. CRTs and depolderings) ranges between 26% and 36% of the intertidal area (Table 5-6). Depending on the OMES zone, alternative and scenario this can range from 14% to 75%. When comparing the alternatives with the reference, strong changes (> 10%) in the percentage of hard substrate are observed in OMES 16-19. In OMES 14-15, changes are non-existing or small. Because OMES 14-15 comprise the bulk of the intertidal area, the locally strong changes in other OMES zones do not affect the overall changes in percentage of hard substrate much. Indeed, though the overall percentage of hard substrate decreases in all C-alternatives compared to the C-reference, the differences are small (≤ 10%). Local changes in OMES 16-19, however, can be strong and are mostly positive, with reductions in the percentage of hard substrate of > 10%. These reductions in percentage of hard substrate are mostly linked to 1) the repositioning of the fairway with the creation of new intertidal areas with more gentle slopes along the new fairway (OMES 16, the Kramp, 38-41 km from Merelbeke; OMES 18, Wijmeers-Uitbergen) or 2) the removal of the dikes along newly depoldered areas (OMES 16, 17, 19) (Figure 5-12). Only in OMES 18 in alternative C3 the changes are generally unfavorable, with an increase in the percentage of hard substrate. This is mainly linked to the repositioning of the main channel at Wijmeers-Uitbergen-Paardenweide (15-21 km from Merelbeke) without redesigning the riverbanks in the C3 bathymetry and with steep slopes along the newly created main channel as a consequence. This is in fact also the case in Uitbergen in C2 (Figure 5-12), but here the unfavorable effects are counterbalanced by the strong favorable effects of the redesigned riverbanks with gentler slopes at Wijmeers.

When looking at the evolutions per km (Figure 5-12) it can be seen that, although evolutions are in general favorable on a larger scale, besides the earlier mentioned negative effects, locally some additional negative effects can occur, mainly downstream of 40 km from Merelbeke and in the most upstream section between Melle and Heusden (< 3 km). These negative evolutions, however, rather arise from strong reductions in the total area of mudflats along the fairway (see 5.2.5) due to reduced tidal amplitudes. Indeed, in these areas the surface area of hard substrate does not increase (and can even decrease) but comprises a larger proportion of the remaining intertidal area along the fairway.

The observed evolutions in the need for hard substrate are fairly consistent within the different climate scenarios, though sea level rise does tend to increase the need for hard substrate along the fairway due to drowning of the mudflats (Figure 5-12).

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Table 5-6: Percentage of hard substrate in the tidal mudflat zone near the fairway per OMES zone and for the different alternatives and climate scenarios. Values for the C-alternatives in green indicate a favorable evolution with respect to the C-reference. Values in red indicate an unfavorable evolution.

Hard substrate (%)	2050REF_C			2050C1			2050C2			2050C3		
OMES	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH
14	15	16	17	15	16	17	15	16	17	14	16	18
15	27	29	30	28	29	31	28	30	33	30	32	37
16	63	64	65	33	33	35	25	21	21	37	37	16
17	51	51	52	52	52	52	40	40	41	39	40	44
18	61	63	67	45	45	46	28	29	30	75	72	70
19	60	60	61	48	48	48	49	49	51	50	52	54
Tot%	34	35	36	30	31	32	26	26	27	28	29	26
Δ Bathy-REF				-4	-5	-5	-8	-10	-10	-6	-6	-10

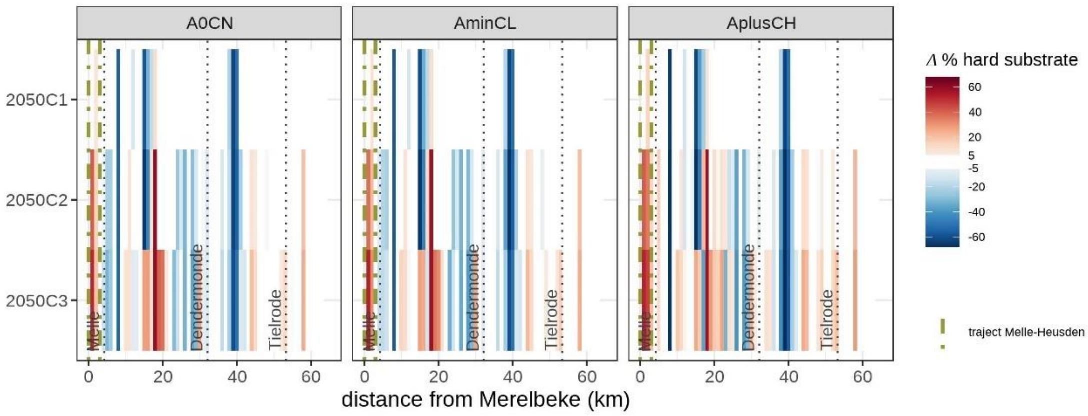

Figure 5-12: Changes in surface area of hard substrate near the fairway. Values are the changes in percentage of hard substrate along the fairway. Only differences of ≥ 5% per km are considered.

5.2.6.2 Propensity for erosion/sedimentation

In Figure 5-13 the *evolution* of the propensity for erosion/sedimentation (Δ TAU50 (pascal)) is shown separately for lower (0-25% emersion time), middle (25-75% emersion time) and upper (>75% emersion time) tidal mudflats averaged over both riverbanks. Results are similar for the three subareas of the mudflats, but with decreasing magnitude of the effects going from the lower to the upper mudflats. This means that an increase in propensity for erosion (positive Δ TAU50) will likely result in an unfavorable steepening of the mudflats as erosion is strongest on the lower mudflats. Likewise, lower propensity for erosion (negative Δ TAU50) will likely result in a favorable unsteepening of the mudflats. We further focus on the observations in the lower mudflats to discuss favorable and unfavorable evolutions. In alternative C1 there are unfavorable evolutions between 14 km and 17 km from Merelbeke and between 57 km and 63 km from Merelbeke. Between 14-17 km from Merelbeke, the unfavorable evolution is associated with redesigning the river bends to improve the navigational channel, resulting in higher water dynamics. In C2 and C3, even though alterations to the riverbed are amplified in this region, water dynamics do not deteriorate, likely through the creation of side channels, and these unfavorable evolutions are no longer observed. The unfavorable evolutions between 57 km and 63 km from Merelbeke are also observed in C2 and C3 and are associated with the installation of groins (local undeepening) in the main channel. In C3 the unfavorable effects are further strengthened between 55-63 km from Merelbeke due to the local undeepening of the main channel, resulting in higher water dynamics in this area in the main channel. Creation of side channels in this area does not seem to dampen the water dynamics substantially (as mentioned earlier, also the newly created side channels are largely high dynamic in this area). Upstream of 30 km (C2) and of 55 km (C3) from Merelbeke the evolution of TAU50 is mostly favorable due to overall reduced flow velocities (Bi et al. 2021a), but locally some unfavorable evolutions can be observed near alterations to the riverbed to improve navigability (Kasteeltje (km 30) and Dender (km 32); Kramp (km 40)). Besides effects of reduced flow velocities, favorable evolutions of shear stress between 40 and 55 km from Merelbeke in C2 and C3 are also linked to increased average water depth.

Even if favorable or unfavorable evolutions can be observed in large stretches of the Upper Sea Scheldt in the C-alternatives, only in the lower reaches (≥ 55 km from Merelbeke; creation of groins and undeepening of the main channel) unfavorable evolutions of TAU50 are larger than 0.1 pascal, which is indicative of clear changes in erosion/sedimentation behavior. Also strong positive evolutions (Δ TAU50 > 0.1) are limited to the lower reaches (≥ 48 km from Merelbeke) and only in alternative C3. Indeed, the introduction of the side channel between 48-52 km from Merelbeke in C3 seems to have a strongly favorable effect (= lower values) on TAU50 in the main river channel.

The effects on TAU50 on the mudflats are robust against the different climate scenarios (Figure 5-13).

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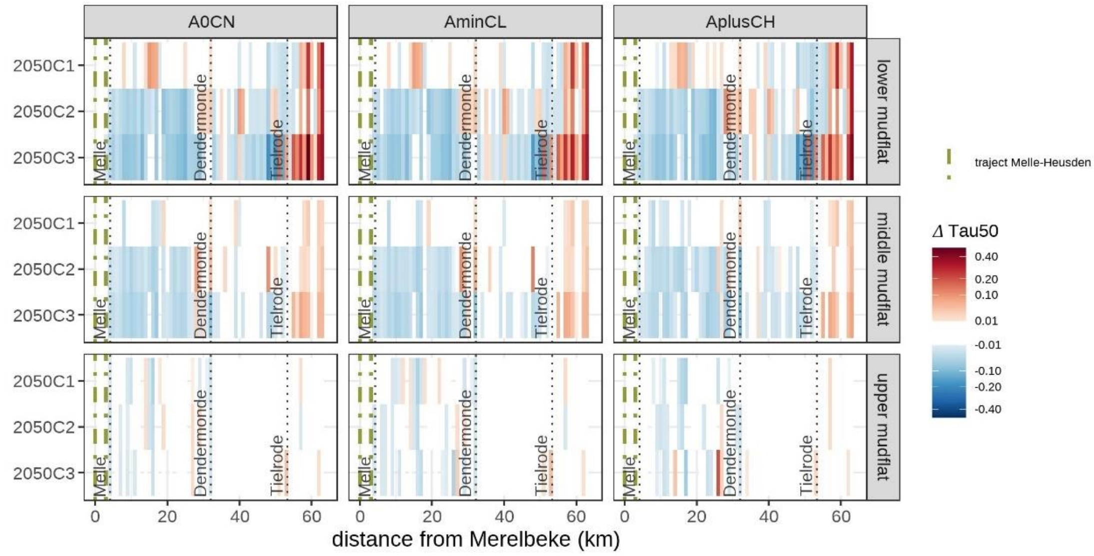

Figure 5-13: Changes in velocity shear stress (TAU50 (pascal)) conditions on the lower, middle and upper tidal mudflats (mean per km-zone of the *Δ* TAU50).

5.2.6.3 Mudflats with high macrobenthic biomass

Intertidal habitat in newly created CRTs and depolderings is included in these calculations. For the CRTs, it is assumed that the entire mudflats are of high quality and the area of high-quality mudflats is thus set to the total area of mudflats (= 15% of the total CRT area).

As with most evaluated aspects of the estuarine habitats, without an unambiguous view of the autonomous morphological evolution of the mudflats, changes in the proportion of macrobenthos rich mudflats must interpreted with care. In alternative C1 strong positive changes (> 10%) in the percentage of high-quality mudflats are observed in OMES 17 (CRT at Scheldebroek) and 19 (new intertidal nature at Voorde and in the depoldering at Kastermeersen with a high proportion of higher mudflats) (Table 5-7). Despite this relatively strong positive evolution in OMES 17 and 19, the overall effect of C1 on the percentage of high-quality mudflats is very limited (< 5% increase), as these OMES zones have low areas of mudflats and do not contribute much to the total. In other OMES zones, C1 has only minor effects on the percentage of high-quality mudflats. In alternatives C2 and C3 evolutions of the percentage of high-quality mudflats are mixed to (strongly) negative, depending on the elevation distribution of the mudflats in new depolderings and the creation (gains in high quality mudflats)/conversion (loss of high-quality mudflats) of CRTs. In climate scenario A0CN particularly strong losses are observed in alternative C3, whereas in C2 the overall losses are moderate. These tendencies are linked to the observation that in newly created depolderings in C2 and C3, large parts of the surface area will be mudflats of lower elevation and thus less valuable. This effect is already present in C2 but is further strengthened in C3 with the additional reduction in tidal amplitude. When looking at climate scenarios AminCL and AplusCH, these negative evolutions are amplified with up to 50% loss of high-quality mudflats. These losses with climate change are mostly driven by the dynamics in OMES 14-17 (with the largest area of mudflats in C2 and C3) where due to sea level rise higher mudflats are turned into lower, less qualitative mudflats. In contrast, like the observations for total area of the mudflats, negative effects of climate change in C2 and C3 are less severe or reversed to positive evolutions in OMES 18-19, where due to sea level rise less of the higher mudflats are turned into marshes.

Table 5-7 Percentage of high macrobenthic density habitat in the tidal mudflat zone per OMESzone. Values for the C-alternatives in green indicate a favorable evolution with respect to the C-reference. Values in red indicate an unfavorable evolution.

High quality mudflat (%)	2050REF_C			2050C1			2050C2			2050C3		
OMES	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH	A0CN	AminCL	AplusCH
14	78	78	77	79	80	78	47	42	39	27	25	24
15	80	82	82	84	85	86	81	66	41	25	20	15
16	91	91	89	89	89	87	66	55	34	28	23	34
17	63	59	57	74	72	68	83	68	24	66	50	28
18	91	90	88	91	90	88	74	79	81	88	91	94
19	69	65	68	91	91	92	86	87	91	66	91	94
Tot%	80	81	80	84	84	84	65	56	39	36	32	29
***Δ* Bathy-REF**				4	4	4	-15	-25	-41	-45	-49	-50

5.3 DISCUSSION AND CONCLUSIONS

5.3.1 Tidal regime

The creation of depolderings, CRTs and bathymetrical adjustments in the C-alternatives has clear favorable effects on the tidal amplitude (

Figure 5-3). Reductions in tidal amplitude compared to the C-reference are observed in all C-alternatives but depend on the extent of the area of introduced measures. In alternative C1 local reductions of about 0.4 meters are observed in the zone of tidal amplitude maximum between 40-50 km from Merelbeke and in the most upstream area (< 20 km from Merelbeke). In C2 and C3 large effects on tidal amplitude are observed (C3 > C2) which have effect in the entire region upstream of Antwerpen (< 80 km from Merelbeke). In C2 tidal amplitude is reduced with up to 1.25 meters and in C3 with even up to 2 meters. With only 1.25 m tidal amplitude, the upstream region (< 30 km from Merelbeke) in C3 becomes close to microtidal (< 1 m tidal amplitude). Given that an evolution of further increases in tidal amplitude is considered unfavorable, all three C-alternatives represent a favorable evolution of reduced tidal amplitudes and preventing the further unfavorable development towards a macrotidal system.

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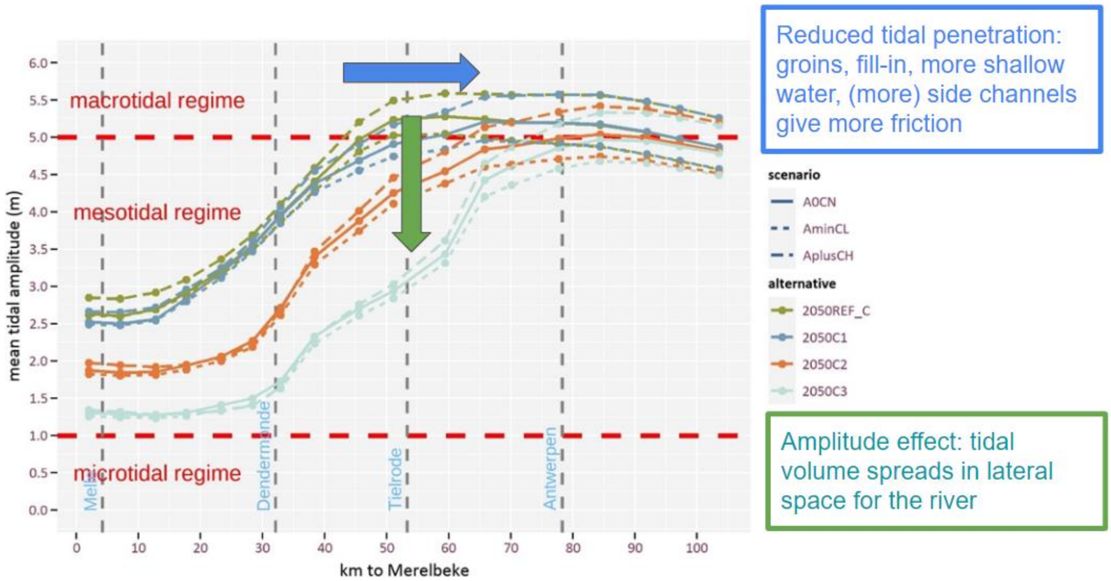

Figure 5-14: Measures can affect tidal dynamics in two ways: 1) by reducing tidal penetration and 2) by reducing tidal amplitude.

Measures studied in the C-alternatives to affect tidal dynamics include two types that work differently on the water dynamics (Figure 5-14). On the one hand, the measures that are concentrated in the subtidal area of the main channel cause friction to the currents and hence reduce the tidal penetration. Measures that enlarge the lateral space for the river, on the other hand, spread out the tidal energy and water volumes in the lateral areas and hence reduce the tidal amplitude. It should hydrodynamically be studied how these effects interact with each other and on which scale they are affective to reduce tidal amplitude.

Given that strong reductions in tidal amplitude also strongly affect the availability and distribution of estuarine habitat (e.g. with a microtidal system the surface area of tidal mudflats and marshes along the river fairway can be strongly negatively affected) it needs to be considered what level of tidal amplitude is desirable to maintain a balance between safety, navigability, and the preservation of unique (freshwater) estuarine nature in the upper reaches of the Sea Scheldt. Upstream of Dendermonde (< 30 km from Merelbeke) tidal amplitude strongly reduces, especially in C3, with a loss of freshwater mudflats and marshes, especially between Melle and Heusden (see 5.2.5.2). The current results do not consider long term evolutions and partial recovery of these habitats due to siltation (because of reduced water dynamics in this area). However, due the canalisation of the river, narrow lateral space and steep banks (rip-rap), possibilities for development and recovery of estuarine nature are limited in the upstream section. Yet, historically, tidal influence in this area used to be low as well (Van Braeckel et al. 2006), and a microtidal system thus might be a more “natural” situation in the upper reaches of the Sea Scheldt. Moreover, loss of marsh area in the most upstream section is not necessarily unfavorable as it may change into valuable non-estuarine river habitat, that is only flooded under extreme circumstances and develops into riparian mixed forests. from a Natura-2000 perspective, however, it should be noted that truly riparian forest (tidal Salicion – Natura 2000 code 91E0) is a priority habitat while mixed forests (Natura 2000 code 91F0) are not. Another important advantage of reduced tidal influence in the upstream parts is reduced water dynamics. This may result in higher primary production

(Maris et al. 2022) and better (more sheltered) conditions for (juvenile) fish, that have no escape in the narrow, canalised riverbed.

5.3.2 Surface area of the habitats (habitat quantity)

State

As mentioned in section (5.2.5.1), the state of the habitats is evaluated against the desirable habitat configuration determined for the Scheldt-estuary in the early 2000s. These goals are not intended to describe a habitat configuration of a totally altered Scheldt system. In fact, when reducing the tides substantially by measures, the system's state of equilibrium will shift as tidal energy reduces and minimal required lateral width for habitat processes and biodiversity reduce. The minimal required habitat surface for a healthy functioning ecosystem will hence decrease following C1 > C2 > C3 and increase with climate change. Indeed, one should balance out the area needed to control tidal energy, optimal bank width (depending on slope between channel depth and spring high water) and residence time. Given that available estuarine habitat surface (mainly mudflats and marshes) is one of the key elements determining tidal energy, a new equilibrium needs to be found where available surface area and tidal energy balance each other in a healthy system. Within this study it was not possible to estimate (calculate) this desirable state for each system configuration. Therefore, we compare the state against the present goals but keep the above general remarks in consideration for future planning. The provided desired surface areas per habitat type, are not a benchmark to be used as a literal criterion for the creation of tidal nature in more concrete realisations of planned measurements, but merely a guidance as to what a healthy system could look like.

In general, the shallow water in the Upper Sea Scheldt is in an unfavorable state in the C reference. In OMES 14 a systematic improvement to a favorable state can be observed in all C-alternatives. However, this improvement in OMES 14 is mainly due to the introduction of high dynamic waters, which is in itself less favorable. In alternative C2 and C3 additional OMES zones are in a favorable state (OMES 17, 18), but in general, reaching the minimal targets or acquiring an overshoot occurs less than for mudflats and marshes. Hence, we should clearly pay attention to this habitat ((low dynamic) shallow water) in future planning to improve the state. Low dynamic shallow water areas can be created, for example, by making the riverbanks less steep and prevent coastal squeezing (= sufficient shallow subtidal and intertidal area flanking the fareway).

Through the inclusion of depolderings and CRTs, tidal mudflats can attain a minimal favorable state, but this depends on the location and alternative. The clearest shifts to a favorable state of the mudflats are observed in the more downstream region (OMES 14-17) in alternatives C2 and C3. In the upstream region of the Sea Scheldt (OMES 18, 19), a favorable state is already present or attained in the C1 alternative, but the state deteriorates again towards the C3 alternative. Indeed, the dynamics governing the availability and distribution of tidal mudflats (and marshes) are differently affected by the C-alternatives in the downstream (OMES 14-17) and upstream (OMES 18, 19) region (see further under evolution).

In the downstream area of the Sea Scheldt (OMES 14-16), the C-alternatives do not affect the state of tidal marshes much compared to the C-reference. In these OMES zones the tidal marshes are in a favorable state. In OMES 16, however, while remaining in a favorable state, considerable area of marshes is lost in the C-alternatives because of rearrangements of the

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river channel at the Kramp (C1) and of reduction in tidal amplitude (C2 and C3). In the upstream area (OMES 17-19), whether an OMES zone is in a favorable or unfavorable state depends on the specific zone and alternative. In OMES 17 a systematic change to a favorable state can be observed in all C-alternatives. Over the entire upstream region, the clearest improvements in the state of the marshes are observed in the C3 alternative.

The state of the estuarine habitats is relatively robust to the different climate scenarios, except for the subtidal area where a general improvement in the state can be observed in C3 because of sea level rise. However, when considering the gradual process of autonomous evolution, this will probably not happen as severely as predicted here, because new areas will silt up (assuming enough sediment is available) following sea level rise, preserving the intertidal area.

Evolution

Overall, the evolution of the habitats in C1 is minor and mostly local (except for positive evolution of mudflat area in the upper reaches (< 20 km from Merelbeke)). In C2 and C3 subtidal area tends to undergo overall positive evolutions, due to the reduction in tidal amplitude and the conversion of mudflat area into subtidal area. In general, newly created depolderings have different effects in the upstream region (< 20 km from Merelbeke) than in the more downstream regions. Whereas in the downstream regions, depolderings largely create additional mudflat area (which partly drowns with sea level rise (but which in turn might be buffered by further autonomous evolution)), depolderings in the upstream area both create additional mudflat and marsh habitat. As a result, in C2 and C3 the mudflats tend to undergo a positive evolution in surface area in almost the entire Sea Scheldt, whereas, in contrast, the marshes only undergo a positive evolution in the upstream area but undergo a negative evolution in the mid and downstream region (> 20 km from Merelbeke), with overall losses in habitat area. Over time part of the mudflats will transform in marshes. In absolute numbers, these initial losses can be substantial, but in relative terms the losses are often relatively small. Even if changes in marsh area might be relatively small, however, strong changes in the location of the marshes may occur with a shift of marsh area from the originally existing marshes to the newly created areas. Indeed, due to the strong effects of measures (depolderings, CRTs and channel adaptation) on the tidal range, evolutions in habitat area are often a combination of the creation of new habitat (depolderings and CRTs) and the shift of one habitat type into another due to reduced tidal range. Due to these reductions in tidal amplitude, high mudflats will turn into marshes, low mudflats will turn into subtidal area, and higher marshes will turn into non-estuarine habitat. Furthermore, sea level rise will amplify the drowning of lower mudflats but will temper the desiccation of the higher marshes.

Special attention should be given to the most upstream stretch (between Melle and Heusden) where consistent negative evolutions are observed for the mudflat and marsh habitat. Especially the mudflats in this stretch risk to be entirely lost with the observed developments in the C-alternatives (omitting the effects of autonomous evolution, which may buffer against the loss of mudflats due to siltation), due to the strong reductions in tidal range in this area and the steep slopes of the bathymetry.

5.3.3 Habitat quality

- Hardening of the estuary

In general, there is a tendency for a favorable evolution with a lower need for hard substrate along the fairway. Locally, however, effects of the C-alternatives can differ strongly and have opposing tendencies. In places where the riverbanks have been redesigned or where dikes have been removed, evolutions will be strongly favorable. In other places however, where, for example, the main channel has been repositioned (bend cut-offs) but the riverbanks are not modified in the altered bathymetry, the evolutions can be strongly negative, as the riverbanks are too steep. In addition, when losing intertidal area near the fairway because of reduced tidal amplitude and the conversion to subtidal area, gentle sloping, soft sediment mudflats are lost relatively more than steep (hardened) areas.

- Propensity for sedimentation/erosion

Negative evolutions in TAU50 (steepening of the slopes) are generally observed near alterations to the riverbed to improve navigability (e.g. bend cut-offs) and near the groins (57-63 km) in the C-alternatives. These negative evolutions, however, can be mitigated by creating side channels, which often have a positive effect on water velocities (reducing water currents). Undeepening of the main channel between 57-63 km in C3, induces a further negative evolution (in this case not mitigated by the side channels, which are in this area also largely high dynamic). In the more upstream reaches in C2 and C3, broad stretches can show positive evolutions in shear stress that are associated with overall reductions in flow velocities in these areas. Most of the observed positive and negative evolutions, however, are only moderate in strength and strong (positive and negative) evolutions (Δ TAU50 > 0.1) are only observed in the lower parts of the Upper Sea Scheldt between 48-63 km from Merelbeke.

- Mudflats with high macrobenthic biomass

Gains and losses in the proportion of high-quality mudflats strongly depend on the elevation distribution in newly created intertidal nature. In C1 positive evolutions occur in the upstream region due to creation of intertidal nature with high elevation. In C2 and C3 negative evolutions are often observed in the proportion of high-quality mudflats due to the creation of intertidal nature with predominantly low elevation and the conversion of high-quality mudflats into marshes (due to reduced tidal range). Also the conversion of CRTs into depolderings can result in reductions in the proportion of high quality mudflats. In the downstream area (OMES 14-17) negative evolutions in the proportion of high-quality mudflats are strengthened by climate change, as the intertidal area will be even more dominated by low elevation mudflats. In the upper reaches (OMES 18-19) however, losses of high-quality mudflats trough conversion into marshes will be prevented with sea level rise.

- Salinity zones

The expected change in salinity is discussed in Maris et al. 2022) and was discussed for the B-alternatives in Vanoverbeke et al. (2023 (*in press*)). As an indicator we discuss the shift of the maximum salinity boundary (P90 salinity) in the summer as an important stressor for vegetation and biota (Figure 5-15). The main conclusion, which also stands for the C-alternatives, is that alternatives do not affect salt intrusion substantially compared to the effects of tidal amplitude and climate change. The high climate scenario (AplusCH) causes the major shift (about 6 km) between the present and reference state. The C3 alternative causes an extra salt intrusion compared to the other alternatives.

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Figure 5-15: Modelled maximum (P90) salinity (period 5 years) for the actual situation (ACT_2013), reference situation (REF_2050) and de C- alternatives for three climate scenarios. The vertical lines show the salinity limits in the actual situation (0.5 PSU, Oligohaline-freshwater limit (oligo-fresh), 5 PSU mesohaline-oligohaline limit (meso-oligo)) and the tolerance limit for growth of willow (Salix) species (2 PSU). The salinity limits with shift upwards mainly because of the AplusCH scenario and show less effect for the alternatives.

5.3.4 Expectations for long term evolution of the habitats

The obtained results and conclusions do not consider effects of autonomous evolution. In particular, due to sedimentation in the newly created depolderings, elevations will increase and there will be less tidal storage capacity. As a result, effects on tidal amplitude will be less pronounced than estimated and a redistribution of habitats will occur. There will be less subtidal area because low water levels will increase less and siltation will occur in the side channels. Sedimentation on the mudflats will increase the elevation and thus the quality as benthos habitat of the lower mudflats. But sedimentation will also convert the higher mudflats into tidal marshes. Moreover, tidal marshes will shift to a lower vertical position because the high water levels will increase. As a result of autonomous evolution, side channels might disappear due to sedimentation, especially more upstream (see, for example, section 6.3.1 with indications that the side channels are already too shallow by design). Given that these side channels provide valuable contributions to low dynamic subtidal habitat, it should be considered in future implementations how such sedimentation can be avoided. Also near the fairway sediment sinks and sources will change in response to the altered bathymetries (Bi et al. 2021a), adding to altered dynamics and autonomous adaptations to the bathymetry. Care should thus be taken to avoid loss of connectivity between large depoldered areas, due to altered or deteriorated conditions near the fairway in between.

6 EVALUATION OF HABITAT SUITABILITY FOR TWAITE SHAD

6.1 QUALITY INDICATORS

Migratory fish such as Twaite shad (*Alosa fallax*) are important indicators of ecosystem functioning. Because of their migratory behaviour they depend on a good quality of the entire habitat stretch (sea to freshwater spawning area). The **suitability index (SI)** quantifies the degree to which the Sea Scheldt is suited to allow for growth and reproduction of Twaite shad. A suitability index is calculated both for the **spawning of adult fish (SI_{adult})** migrating into the Upper Sea Scheldt and for the **development of larvae (SI_{larval})** hatching from the eggs. Calculation of the suitability index based on water quality variables and habitat characteristics is described in Vanoverbeke et al. (2019a).

6.2 EVALUATION METHODOLOGY

The *state* of the suitability for spawning (SI_{adult}) and for larval development (SI_{larval}) is given in the results. Since 10-15 years and due to strong improvements in the water quality, Twait shad has reappeared in the Sea Scheldt after decades of absence. Because of this recent and ongoing recolonisation of the Scheldt by Twaite shad, however, an evaluation of the state by comparing to a predefined desirable state is not possible. Values of the state are merely indicative of the suitability in comparison with other alternatives and scenarios.

The *evolution* of the suitability for both spawning and larval development is evaluated according to:

$$\text{magnitude of the change } \Delta\text{SI} = \text{SI}_{\text{alternative}} - \text{SI}_{\text{reference}}$$

A reduction in $SI_{alternative}$ compared to the reference is evaluated as unfavorable and *vice versa*.

The values of the suitability index range from zero to one. Both the *state* and *evolution* are calculated per kilometer. Only changes with a value larger than 0.05 (5% of the possible range) are taken into account. Changes smaller than 0.05 are considered not to be different from the reference.

For predictor variables derived from the pelagic ecosystem model (oxygen, salinity, SPM zooplankton, Van Engeland et al. 2018), modeling results for 5 consecutive years are available, equivalent to measured environmental conditions in 2009-2013 plus predicted changes toward 2046-2050 for the 2050 alternatives and scenarios. For water depth and water velocity, only a single estimate per kilometer is available for each alternative and scenario. Both for the overall SI based on all variables and for estimates of SI dependent on a single predictor variable (except for water depth and velocity), an estimate is produced for each year. For the *state* of the suitability index, both the mean over years and the minimum between years (worst case) are presented. For the *evolution* of the suitability, ΔSI is calculated for the mean state and for the minimum (worst case) in the reference and each alternative. We chose to include the

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worst-case calculations as a warning flag indicating a potential risk of deterioration of the habitat of Twaite shad in the Sea Scheldt.

Based on model evaluation using modeling results and field data for the period for of 2009-2013 (Vanoverbeke et al. 2023), it was decided to exclude temperature from the predictions and the evaluation. Temperature is a forcing variable in the modeling train that does not change between the alternative bathymetries and is not very informative within the context of comparing alternatives. Therefore, it was decided to exclude temperature from the predictions and the evaluation.

6.3 RESULTS

In contrast to the results for the habitats (section 5) and Common Teal (section 7), which only comprise the Upper Sea Scheldt (≤ 63 km from Merelbeke), the results for Twaite Shad also include the area between the confluence with the Rupel and the Dutch-Belgian border (km 64-100 from Merelbeke).

6.3.1 Suitability for larval development

In the C-reference, the state of the Sea Scheldt is on average suitable for larval development upstream 50 km from Merelbeke (Figure 6-1A). Between Antwerp and Tielrode, low levels of oxygen and high levels of SPM are the most important factors reducing the suitability for larval development (Figure 6-2, Figure 6-5). Downstream Antwerp the river is mostly unsuitable because of high salinity and suspended matter (SPM) levels (Figure 6-2, Figure 6-5). On average suitability is reasonably high in km 0-50 from Merelbeke. Yet, in some years (low discharge and high dredging intensity, e.g. 2048 [= 2011]) suspended matter (SPM) can be too high and oxygen levels too low for survival of larval Twaite shad downstream of 25 km from Merelbeke (Figure 6-5) and reduce the overall estimate of SI severely (Figure 6-1B), also in the area between Dendermonde and Tielrode where spawning is most intense and thus most larvae hatch from the eggs.

When comparing the C-alternatives with the C-reference, the most obvious differences in the state of habitat suitability for larval development occur in C2 and C3 near and upstream of the Rupel confluence (km 25 - 63 from Merelbeke) (Figure 6-1, Figure 6-2). In this area clear improvements in SI can be observed in C2 and C3 due to increased levels of oxygen and strongly reduced levels of SPM (Figure 5 2, Figure 5 4).

Evolution of the suitability for larval development between 60 and 90 km from Merelbeke is also clearly influenced by the oxygen levels (C2, C3 > C1; Figure 6-4). The oxygen levels in spring and summer are invariably low in this area and frequently below the threshold for viability of Twaite shad larvae and fish in general (< 4-5 mg/l; Figure 6-5). In the recent past, oxygen depletion in this area acted as a strict barrier for migration of Twaite shad from (adult migration) and to (juvenile migration) the more downstream parts of the Scheldt estuary and the sea. Results suggest that the anoxic zone shifts downstream but also that it becomes larger in C2 and C3, which is an unfavorable evolution (Figure 6-2, Figure 6-4).

Even though evolution in the suitability for larval development is dominated by changes in SPM and oxygen levels, when looking at the separate effects of predictor variables, changes in water velocity between the C-reference and the C-alternatives can also have marked effects on the larval suitability index (Figure 6-4). Clear negative effects of increased water velocities on SI can be observed in C1 compared to the 2050 reference in the region where groins are installed between 55-63 km from Merelbeke. These effects are strongly mitigated by the installation of side channels in C2 but reappear and worsen in C3 due to the additional undeepening of the fairway in this section. Effects of water velocity on SI can also be seen around the Kramp, between 37-42 km from Merelbeke. These effects are unfavorable in C2 but favorable in C3. In C2 at km 29-30 from Merelbeke unfavorable effects are also observed near the straightening of the bend. But these unfavorable effects are also mitigated in C3 by the extended depolderings and side channels in this region. Introduction of side channels and depolderings between 20 and 30 km from Merelbeke in C2 and C3 seems to have a favorable effect on SI by allowing sheltered areas with lower water velocity.

Unfavorable effects associated with increased water velocity are mainly observed in the region between Dendermonde and the inflow of the Rupel where spawning predominantly occurs. High water velocities in the subtidal area in this region are undesirable, as the freshly produced eggs drift passively in the water until they hatch three to four days after release. As water discharge can be high during this period, they risk being carried too far downstream where salinities are too high for survival of the larvae. In addition, after hatching, larvae need sheltered areas near the riverbanks to avoid being flushed by strong currents. Heavy and/or prolonged rainfall may further increase the risk of flushing due to temporary high discharges. Areas with low water dynamics in depoldered areas and CRTs do not help here, as they are drained during low water periods and the larvae (and eggs) are forced into the river channel(s).

Also with respect to water depth, some negative effects can be observed between 15-20 km from Merelbeke in C2 and C3, at locations where side channels are installed. In general, these side channels provide low dynamic sheltered areas, which is a favorable evolution, but the results suggest that in the current implementation they may be designed to be too shallow. Especially when considering that following autonomous evolution sedimentation will occur in these channels.

Results for the different climate scenarios are largely comparable, but in AminCl and AplusCH a deteriotation of the state can be observed between Tielrode and Antwerpen in REF-C and C1 (Figure 6-1) due to reduced oxygen levels (Figure 6-5).

In the AminCL and AplusCH climate scenarios there are also visible negative evolutions associated with oxygen levels in C1 between 30-40 km from Merelbeke (AminCL, unfavorable evolutions) and between 25-35 km from Merelbeke (AplusCH). On the other hand, in AplusCH there are positive evolutions associated with oxygen between 20-25 km from Merelbeke in all three alternatives. These results should be interpreted with care, however, because in the region between 20-40 km from Merelbeke the oxygen levels in bad years (low oxygen) flirt with the critical level of 5 mg/l below which the suitability rapidly declines (Figure 6-5B). Considering uncertainty of the modeling tools and the fact that oxygen levels might sometimes be underestimated (Maris et al. 2022), chances are that oxygen levels stay above 5 mg/l and do not cause unfavorable (or favorable) evolutions in suitabilty.

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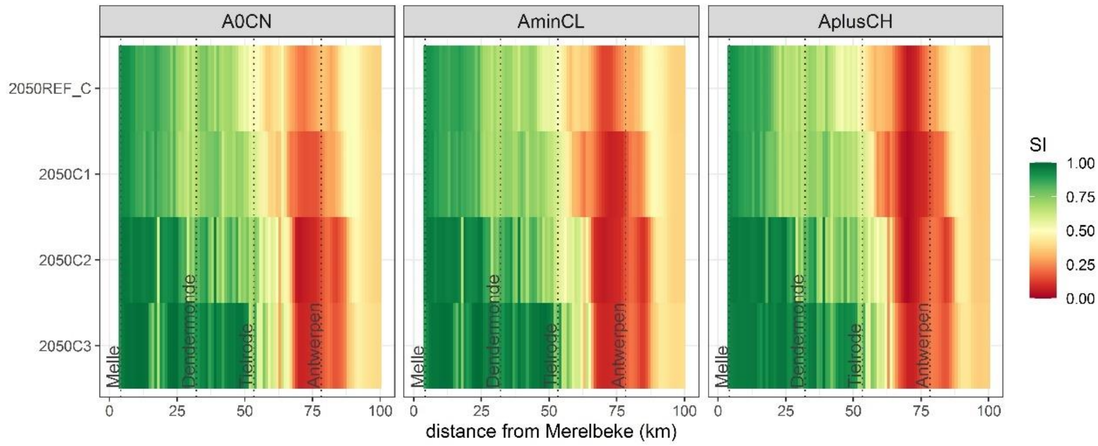

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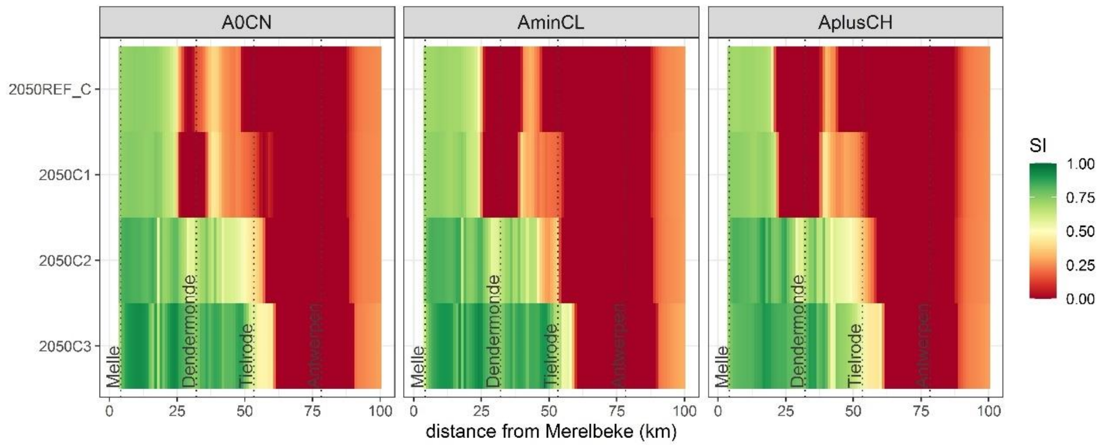
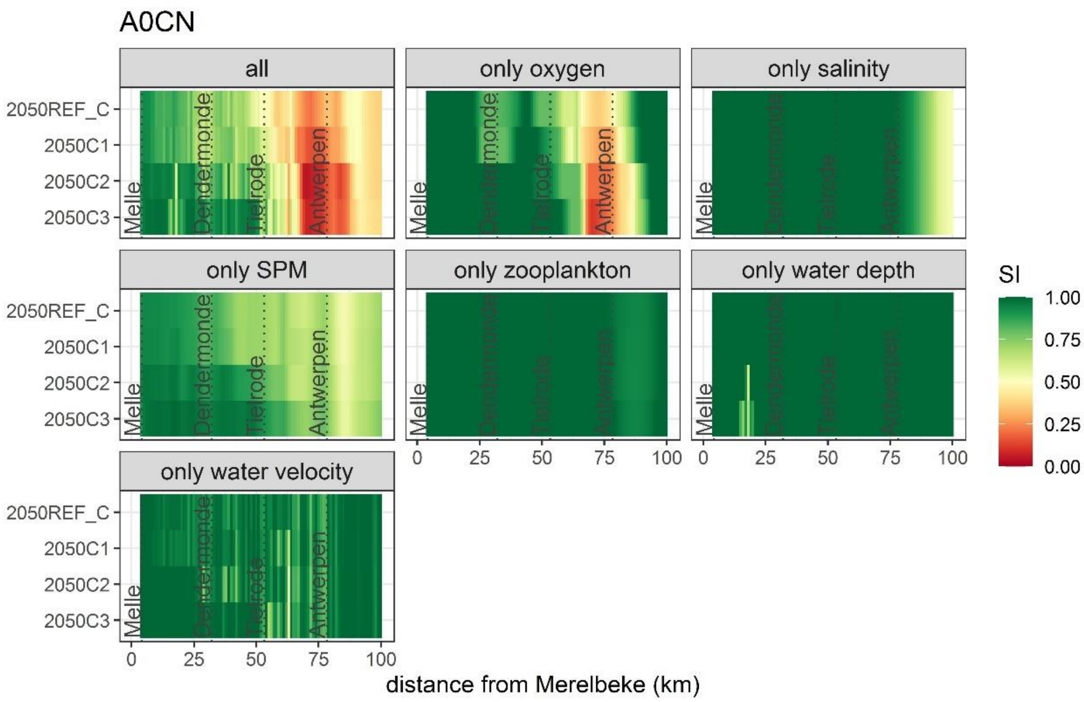


Figure 6-1: Suitability index (SI) for larval development. **A)** mean value over modeled years; **B)** minimum value over modeled years.

A



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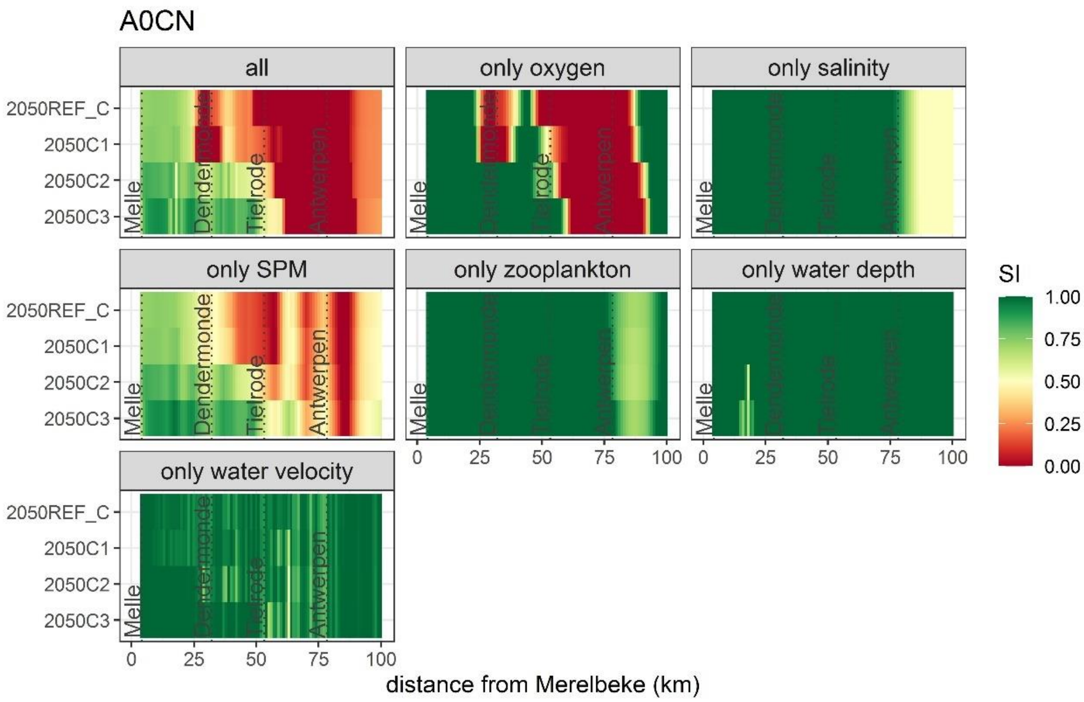

Figure 6-2: Suitability index (SI) for larval development in response to individual predictor variables. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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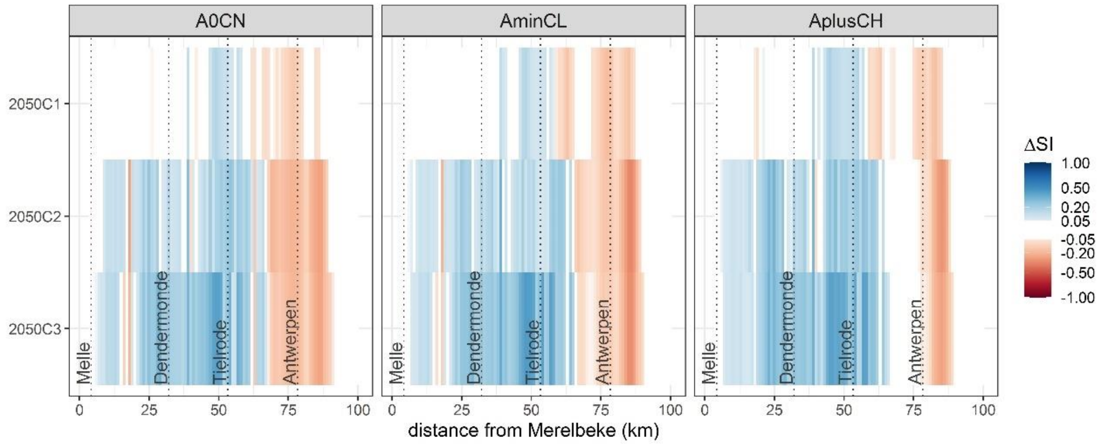

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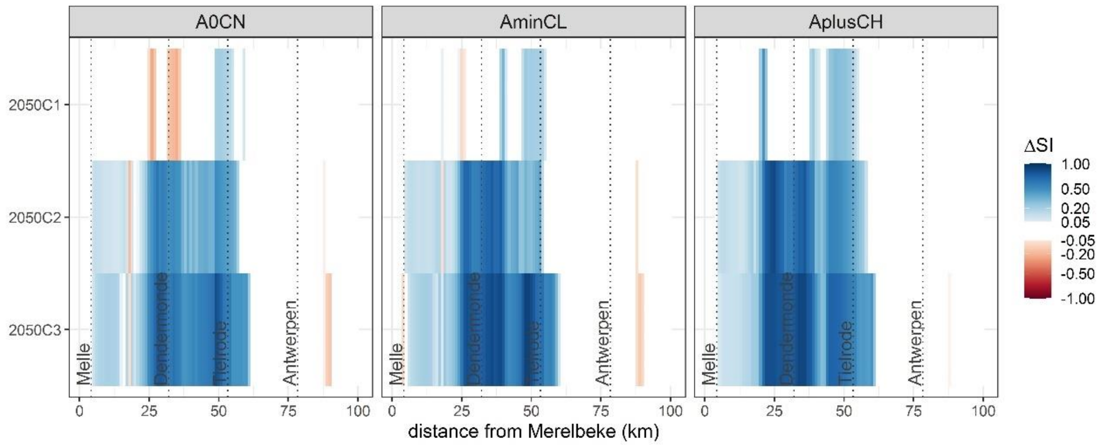

Figure 6-3: evolution of the suitability index (ΔSI) for larval development. Blue indicates favorable evolution; red indicates unfavorable evolution. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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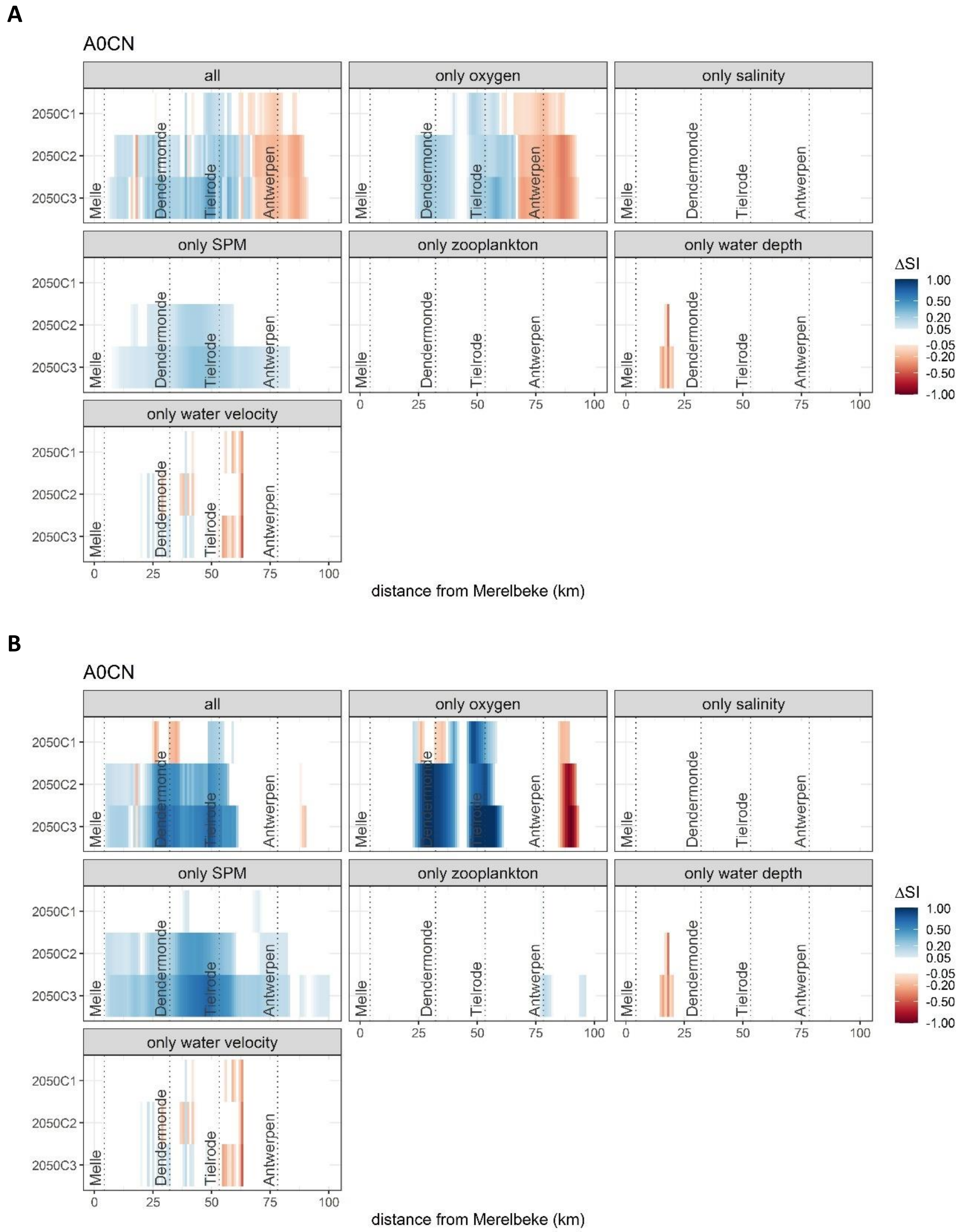

Figure 6-4: evolution of the suitability index (SI) for larval development in response to individual predictor variables. Blue indicates favorable evolution; red indicates unfavorable evolution. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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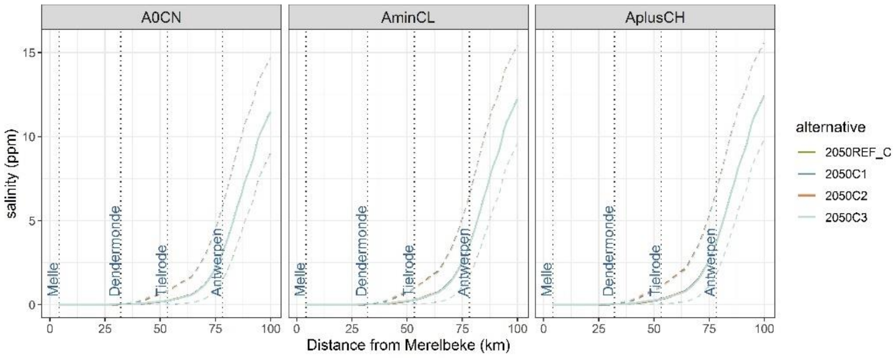
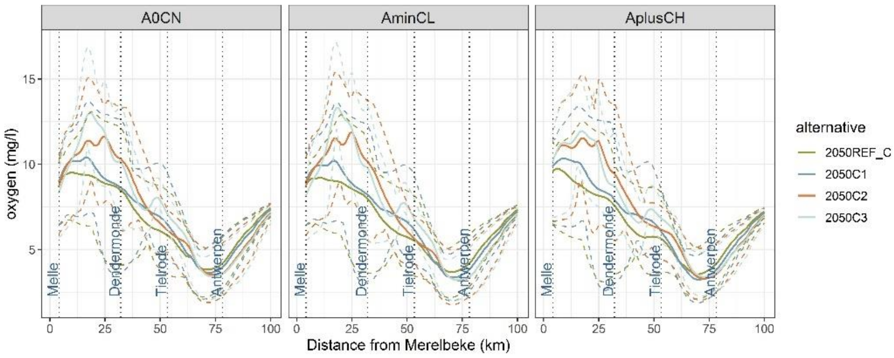
A



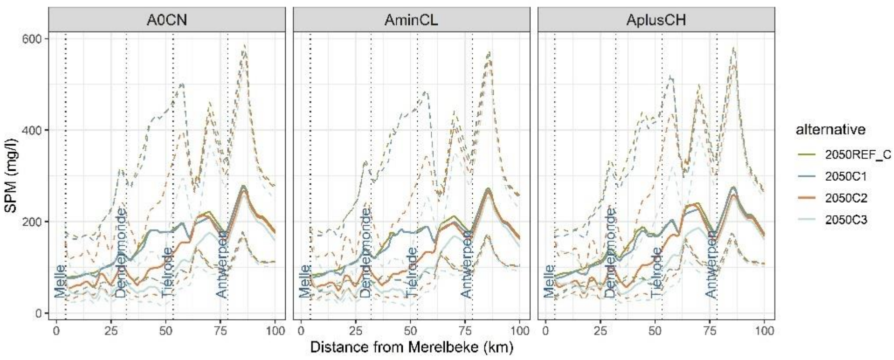
A0CN
AminCL
AplusCH
salinity (ppm)
Melle
Dendermonde
Tielrode
Antwerpen
Distance from Merelbeke (km)
alternative
2050REF_C
2050C1
2050C2
2050C3

B



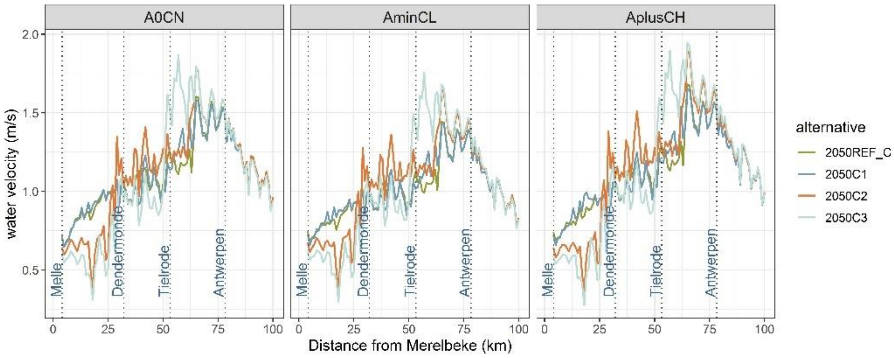
A0CN
AminCL
AplusCH
oxygen (mg/l)
Melle
Dendermonde
Tielrode
Antwerpen
Distance from Merelbeke (km)
alternative
2050REF_C
2050C1
2050C2
2050C3

C



A0CN
AminCL
AplusCH
SPM (mg/l)
Melle
Dendermonde
Tielrode
Antwerpen
Distance from Merelbeke (km)
alternative
2050REF_C
2050C1
2050C2
2050C3

D



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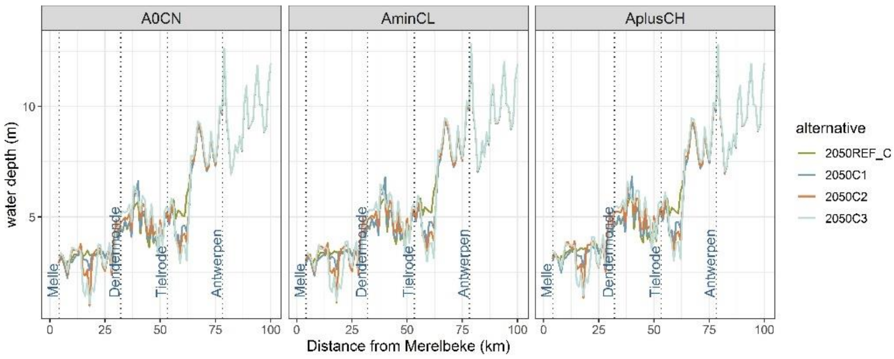

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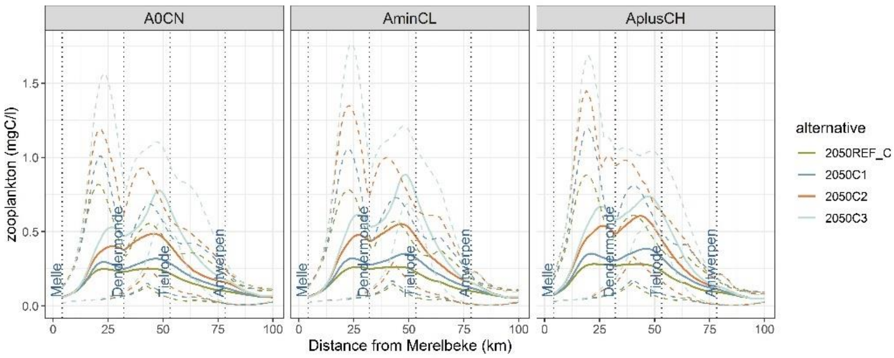


Figure 6-5: Predictor variables affecting the state and/or evolution of the suitability for larval development. Full lines represent the mean over modeled years; dashed lines represent minimum and maximum values among modeled years. (For water velocity and water depth, only a mean estimate is available).

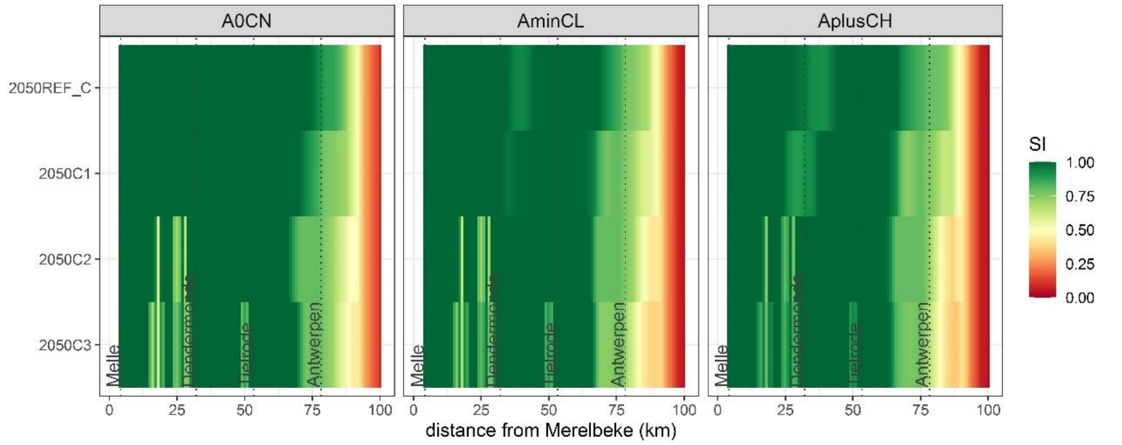
6.3.2 Suitability for spawning

Based on the suitability index (SI), conditions for spawning (state) are mostly favorable in the Upper Sea Scheldt (Figure 6-6A) both for the C-reference and the C-alternatives. In recent years spawning is observed in the zone between Dendermonde and the inflow of the Rupel (35 to 60 km from Merelbeke). Given that the Sea Scheldt has only recently been recolonized by Twaite shad following considerable water quality improvements and reduction of the hypoxic zone near the Rupel confluence, the spawning area is expected to expand upstream and into the tributaries where Twaite shad also spawned historically.

In some years however, as also is the case today, oxygen depletion around Antwerpen (70-90 km from Merelbeke) entails a risk of failed upstream migration as this might create an impenetrable barrier (Figure 6-7B; Figure 6-10B). Conditions of oxygen depletion around Antwerpen deteriorate in all three C-alternatives (C2, C3 > C1; Figure 6-10) resulting in unfavorable evolution of the suitability index in this area (Figure 6-9). Similar to the results for larval development, some (un)favorable evolutions may occur in the C-alternatives between 25-40 km from Merelbeke in the AminCL and AplusCH climate scenarios, associated with changes in oxygen levels around the threshold level of 5 mg/l. As mentioned, these results should be interpreted with care due to uncertainty on the obtained oxygen levels (Maris et al. 2022) and the sensitivity of the suitability index around this threshold.

As for larval development, the suitability index for spawning also shows some unfavorable evolutions at locations where side channels are installed, due to reduced water depth (Figure 6-7; Figure 6-9). As the spawning model averages water depths over main and side channels, this may in truth not be a problem, as this is mainly caused by the low water depth in the side channels.

A



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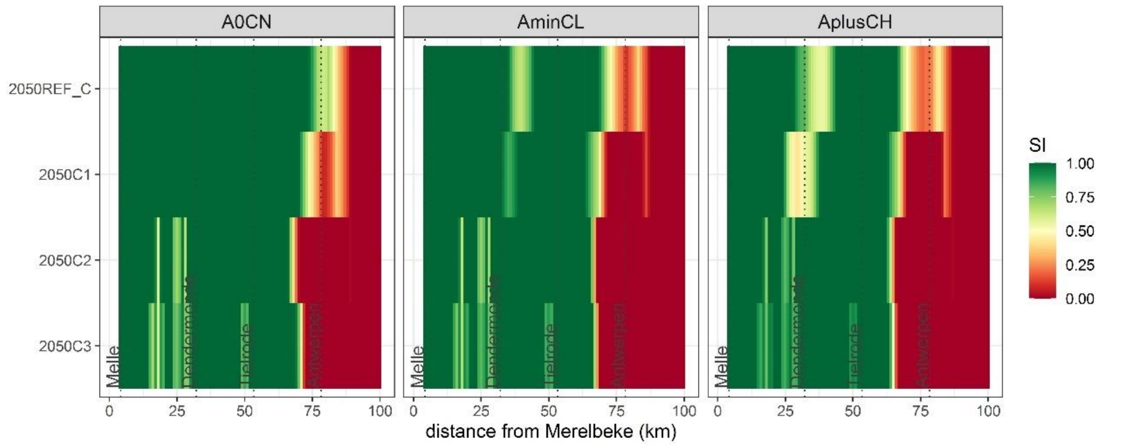

Figure 6-6: Suitability index (SI) for spawning. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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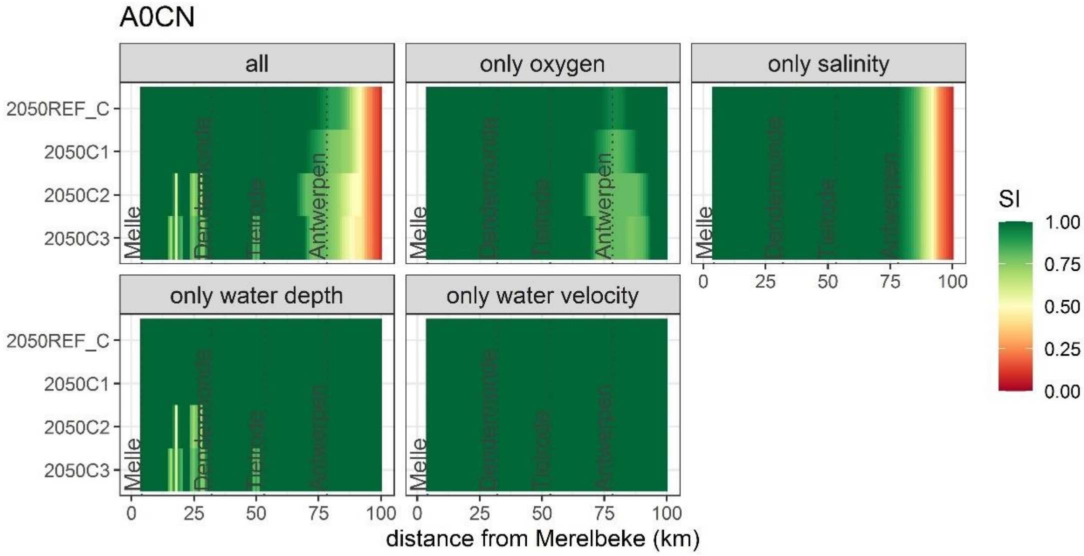
A



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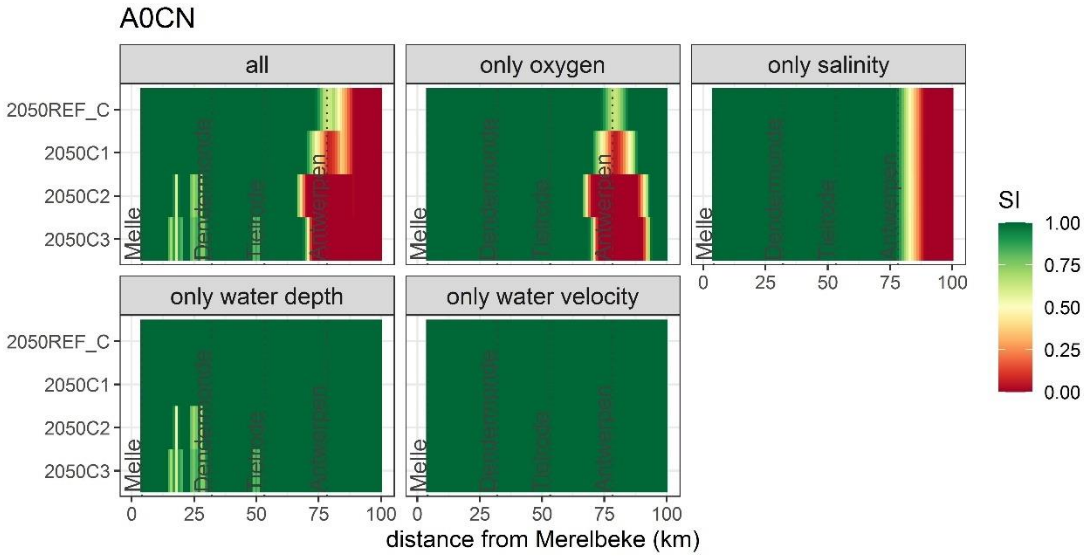

Figure 6-7: Suitability index (SI) for spawning in response to individual predictor variables. **A)** mean value over modeled years; **B)** minimum value over modeled years.

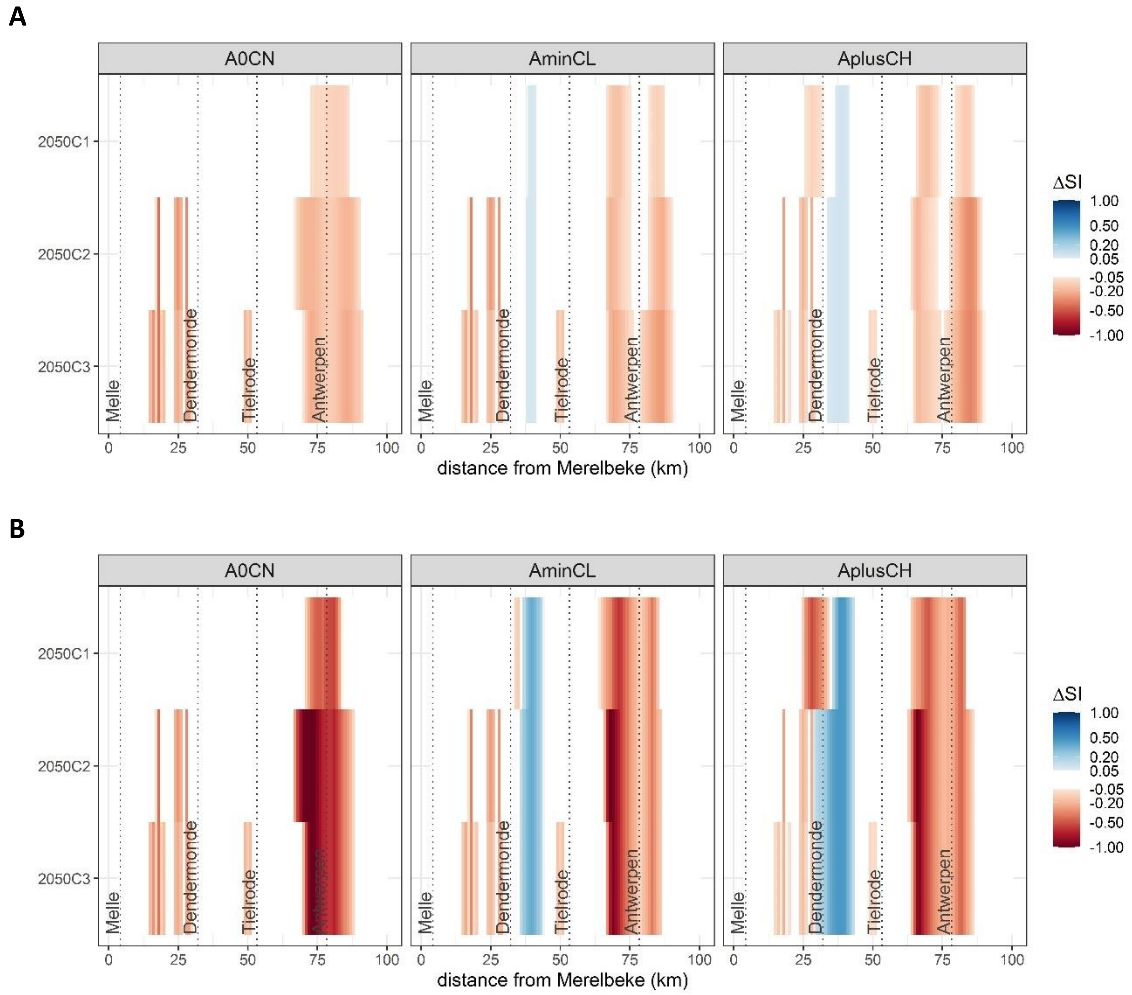

Figure 6-8: evolution of the suitability index (ΔSI) for spawning. Blue indicates favorable evolution; red indicates unfavorable evolution. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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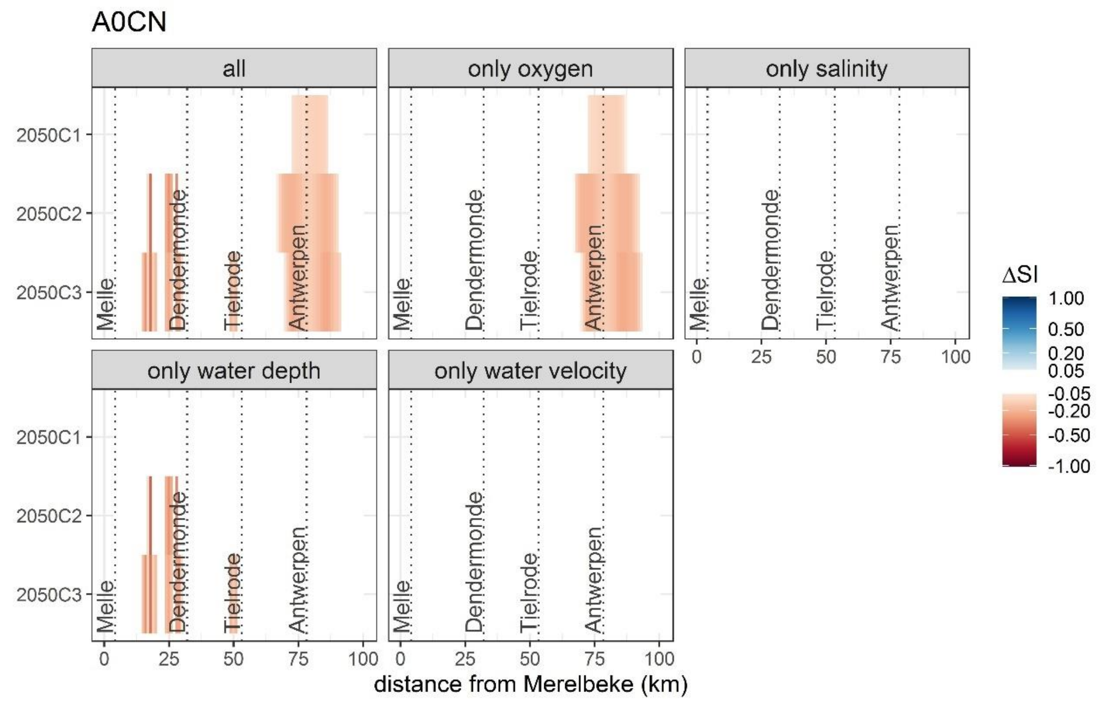
A



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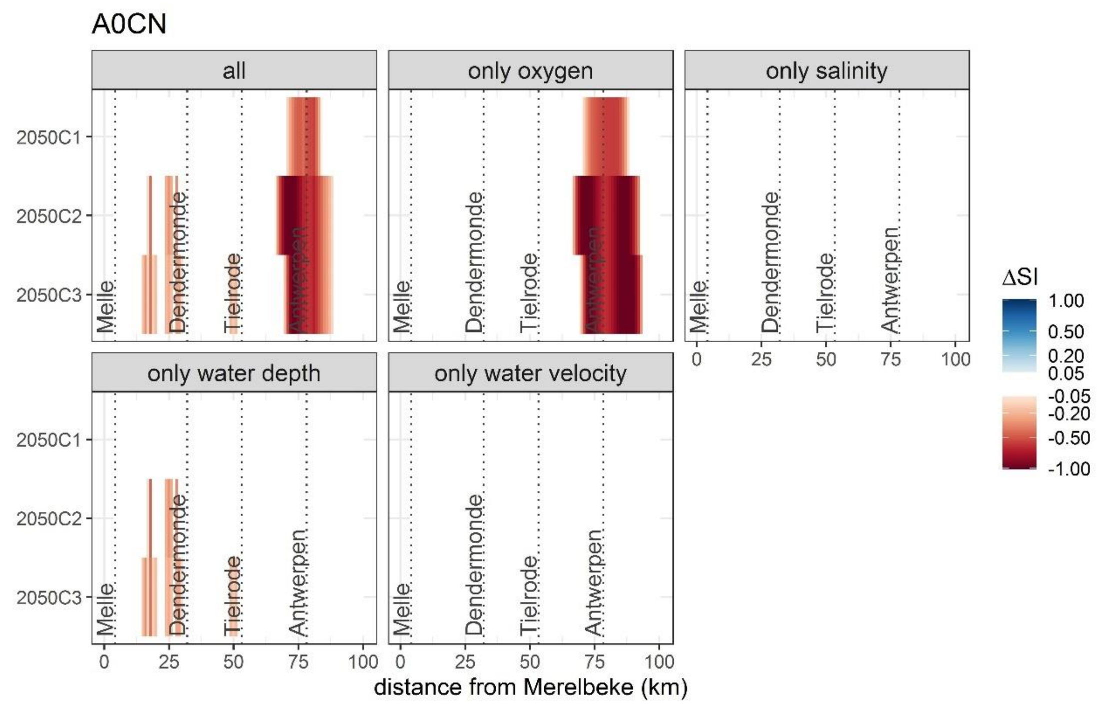
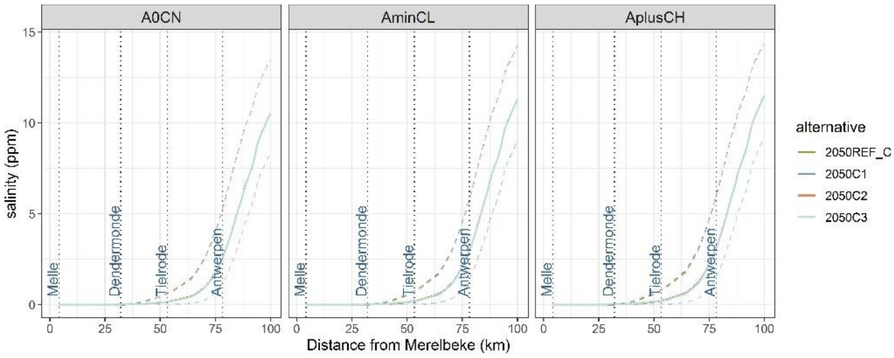


Figure 6-9: evolution of the suitability index (SI) for spawning in response to individual predictor variables. Blue indicates favorable evolution; red indicates unfavorable evolution. **A)** mean value over modeled years; **B)** minimum value over modeled years.

A



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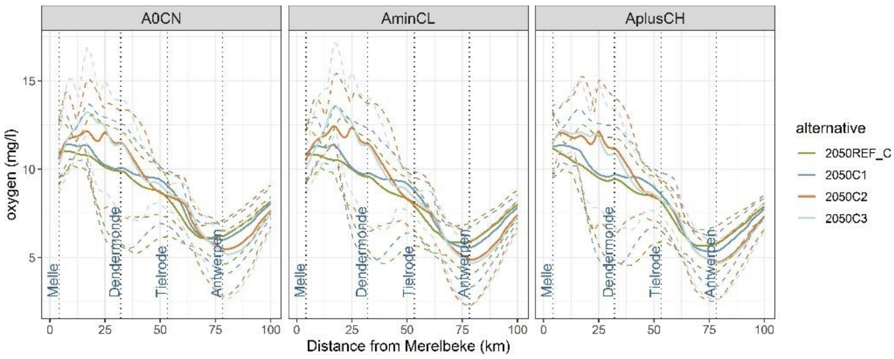

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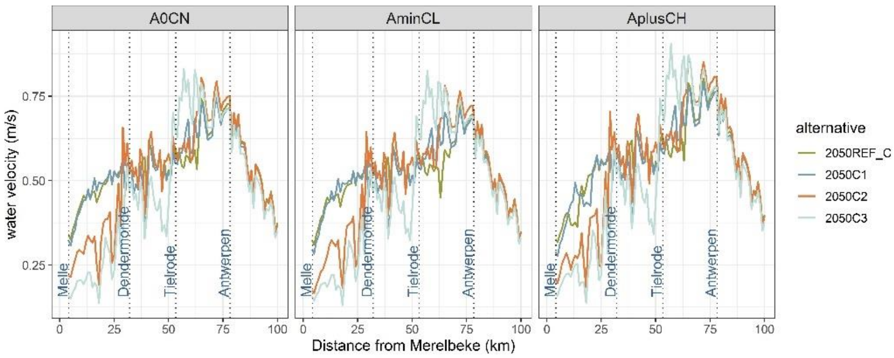

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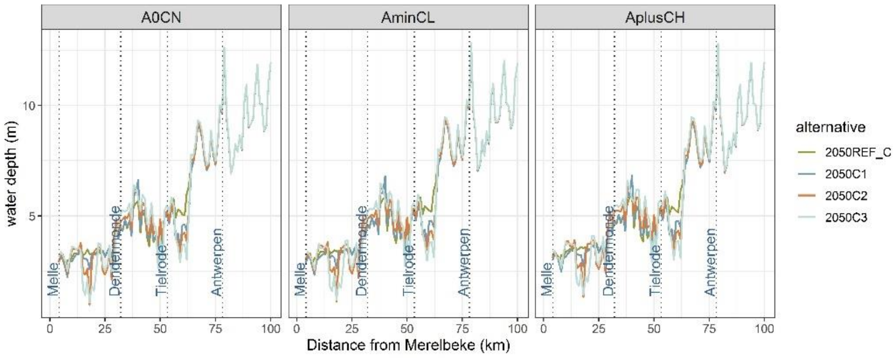

Figure 6-10: Predictor variables affecting the state and/or evolution of the suitability for spawning. Full lines represent the mean over modeled years; dashed lines represent minimum and maximum values among modeled years. (For water velocity and water depth, only a mean estimate is available).

6.4 HABITAT SUITABILITY IN THE MARINE ENVIRONMENT

For diadromous fish like Twaite shad, also the marine environment is an indispensable part of the habitat. In the case of anadromous fish, the adults live in the marine environment and migrate upriver mouths to spawn in the freshwater parts of rivers. Whether the Sea Scheldt could be an important recruitment area for Twaite shad, thus not only depends on the suitability of the river itself, but also on the quality of the marine environment near the river outlet, occupied by the fish during most of their adult life. To investigate the marine habitat suitability for Twaite shad in the vicinities of the Scheldt sea outlet, the research group 'Équipe Fonctionnement et Restauration des Écosystèmes Estuariens et des populations de Migrateurs Amphihalins' (FREEMA, EABX, France) used a Bayesian hierarchical model (i.e. a site occupancy intrinsic conditional autoregressive model (SO iCAR)) developed by Elliott et al. (*under review*[3]). This spatialized model incorporates habitat suitability, dependency to nearest sites and an observational process (the effect of gear capture). The extent of the model prediction is from French Mediterranean Metropolitan, Bay of Biscay, Celtic Sea and the Greater North Sea (depending on the species presence). The model has been developed for eleven diadromous species[4] and gives the probability of suitability of the marine environment using, for *Alosa fallax* (Twaite shad), four environmental variables (i.e. distance to the nearest coast, sediment, salinity, and net primary production). Presences/Absences of the species were extracted from the MigrenMer database (Elliott et al., *under review*). This database contains records of the captures of diadromous species from French fisheries observers and scientific surveys (downloaded from ICES DATRAS and French scientific surveys). The database will be available at varying resolutions depending on the source of the data since it contains sensitive fisheries observer data.

As part of Chloé Dambrine's post-doctorate (H2020 FutureMARES project; www.futuremares.eu), the model has been recalibrated, using presences/absences from MigrenMer (2006-2019), and a different set of environmental variables has been extrapolated into a wider area (from Portugal to southern Scandinavia). For this work, the environmental variables were extracted from the POLCOMS-ERSEM model (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-marine-properties?tab=overview) and EMODnet (https://emodnet.ec.europa.eu/en/geology) and the predictions grid resolution was 0.1°x 0.1°. Considering a buffer[5] of 30 ^{2}km around the Scheldt river mouth, the model gave an average Habitat Suitability Index (HSI; between 0 and 1) of 0.92. Using a larger buffer of 200 km, the average HSI for all the pixels in the zone was 0.82. Thus, the marine environment near the Scheldt sea outlet appeared favourable for the species survival. Twaite shad presences around the Scheldt sea outlet over the period were confirmed from MigrenMer with 20 occurrences recorded in the buffer of 30 km and 186 in the buffer of 200 km. These findings indicate that the surrounding marine environment is well suited for the occurrence of Twaite shad.

Besides investigating the marine suitability for Twaite shad (and other diadromous fish), the research group at FREEMA also looks at the (historical) occurrence of diadromous fish in river

[3] Pôle MIAME "Gestion des Migrateurs AMphihalins dans leur Environnement"

[4] *Alosa alosa*, *Alosa fallax*, *Alosa agone*, *Petromyzon marinus*, *Lampetra fluviatilis*, *Salmo salar, Salmo trutta*, *Osmerus eperlanus*, *Chelon ramada*, *Platichthys flesus*, and *Anguilla anguilla*

[5] *In GIS, a buffer is a zone that is drawn around any point, line, or polygon that encompasses all of the area within a specified distance of the feature*

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basins. The EuroDiad 4.0 database (Barber et al., 2022) classifies the population functionality for 28 diadromous species over 350 catchments in Europe, North Africa and Middle East starting in 1750. Four categories (i.e. abundant, common, rare and absent) were defined in the database. “Rare” means that occasional vagrants were recorded in the basin. “Common” was defined as a functional population present in the catchment and “Abundant” as a functional population present and numerically dominant in the freshwater community. The population functioning of Twaite shad in the Scheldt river for the present time (i.e., in EuroDiad, from 2010 to present) was “Rare”. Its closest catchments, Meuse and Rhine, also presented low categories of population functionality, as recorded in EuroDiad as “Absent” and “Rare”, respectively. Thus, the overall status for the species in the continental waters of that part of Europe could be described as “low” (Figure 6-11). This indicates the urge to create better habitat conditions for spawning and larval/juvenile development and to prevent the deterioration of suitability in the Scheldt and other river basins.

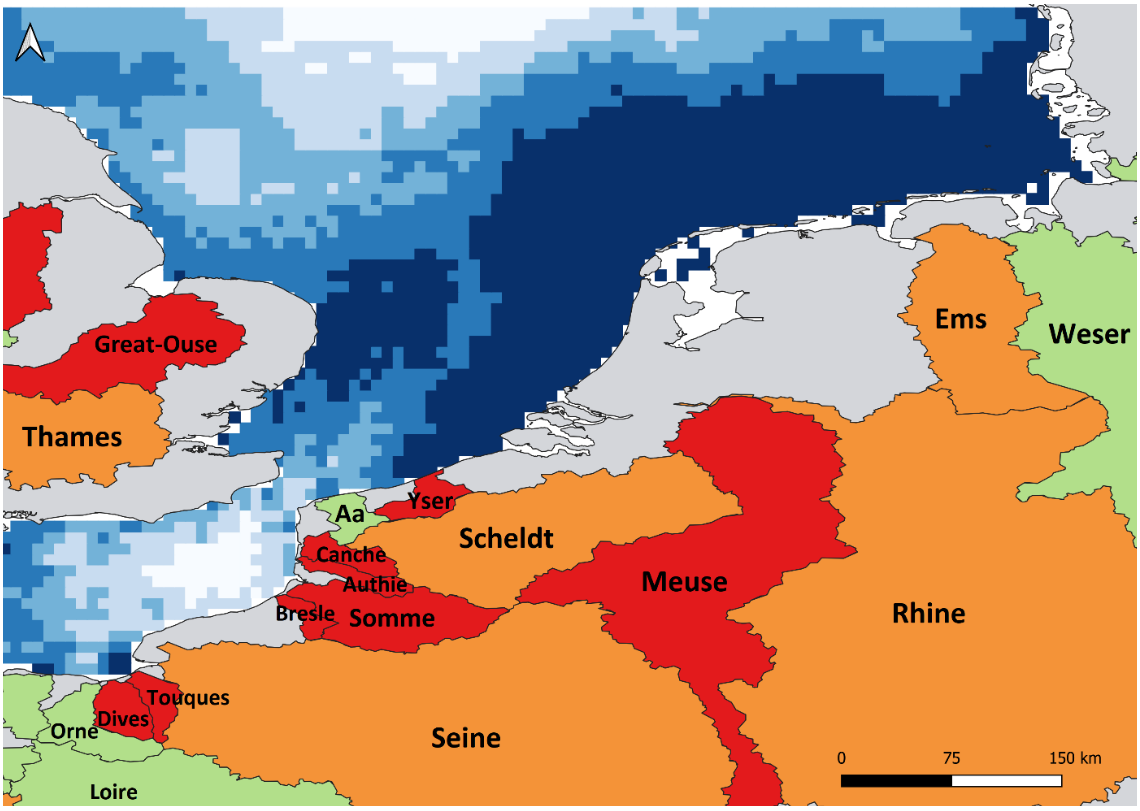

Figure 6-11: Simulated marine habitat suitability over 2006-2019 for Twaite shad (Elliott et al., under review; Navarro et al., in prep) and observed continental population functionality over 2010 to present days (Barber et al., 2022). Marine habitats suitability goes from light blue (0) to dark blue (1). Freshwater population functioning is classified in three categories: red (absent), orange (rare), light green (common). The last category “abundant” does not appear on the map.

6.5 CONCLUSIONS

Conditions are in general favorable for larval development upstream of Dendermonde in the C-reference and alternative C1. In years with high SPM or low oxygen levels, however, suitability can strongly reduce in the region between Dendermonde and Tielrode, which is the most important spawning area nowadays. In the C2 and C3 alternative, conditions between Dendermonde and Tielrode are clearly improved due to higher oxygen levels and reduced levels of SPM compared to the 2050 reference. In contrast, lower oxygen levels have an unfavorable effect on the suitability index around Antwerpen in the C-alternatives (but see below). In some areas (around the Kramp in C2 and between Temse and Rupel in C1 and C3) water currents evolve unfavorably. The lack of sheltered areas is unfavorable and entails an increased risk of flushing developing larvae to more downstream, less suitable areas. To reduce the risk of flushing to downstream unfavorable areas, sheltered (relatively undeep areas with low flow velocities) subtidal areas should be provided at regular intervals. There are also indications that the subtidal parts in created side channels (which are in themselves favorable as they provide low dynamic shelter) are too shallow. Given that, following autonomous evolution, sedimentation will occur in these side channels, they risk becoming even more shallow or disappear.

Conditions for spawning are generally favorable in the Upper Sea Scheldt, including the region between Dendermonde and Tielrode, where most of the spawning is observed.

Results are robust against climate scenarios AminCL and AplusCH.

Both for upstream migration (spawning) and downstream migration (developing juveniles) there are indications that, as is today, oxygen levels can be too low in some years between 50-90 km from Merelbeke, creating a barrier for migration. In general, oxygen levels between 60-90 km from Merelbeke tend to evolve unfavorably in the C-alternatives. Given the uncertainty on the modelled oxygen levels, and especially the drops in oxygen concentrations below the threshold of 5 mg/l (Maris et al. 2022), unfavorable evolutions associated with decreasing oxygen levels should be interpreted with care, as they could be linked to an underestimation of the oxygen levels in the modeling train. Downstream of areas with high primary production, oxygen concentrations tend to reduce because of respiration by the accumulated biomass (Maris et al. 2022). The pelagic model, however, does not take into account that a large part of the accumulated biomass will sediment in the newly created CRTs and depolderings, which will reduce the extra oxygen consumption downstream of the areas with high primary production. Especially in the Lower Sea Scheldt expert judgment states that nowadays (anno 2022), in general, oxygen levels are in a fairly good state and that the evolution of oxygen concentrations in the C-alternatives will rather be neutral to slightly positive. Nevertheless, evolutions towards a more unfavorable state in the C-alternatives because of oxygen depletion should not be totally neglected. The contrasting insights from model output and expert judgment indicate that further study is needed to obtained better supported results.

Given the good status of the marine environment in the vicinity of the Scheldt outlet, and the rather poor occupancy of Twaite shad in nearby river basins (including The Scheldt), the Sea Scheldt is indispensable for sustaining a healthy population of Twaite shad.

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7 EVALUATION OF NUMBERS OF WINTERING COMMON TEAL

7.1 QUALITY INDICATORS

The Scheldt is an important resting and foraging place for waterfowl. Many migratory birds depend on the diversity and richness of its habitats to survive winter. One of the most abundant ducks foraging on the mudflats of the Upper Sea Scheldt during winter is the Common teal (*Anas crecca*). It is dependent on both habitat quantity (area of mudflats) and quality (sufficient food) to survive as a winter guest. The **number of birds** is used as an indicator of the quality of the mudflats and modeled as described in Vanoverbeke et al. (2019b).

7.2 EVALUATION METHODOLOGY

There is no predefined criterion to evaluate the *state* for Common teal. The results are nevertheless presented for clarity.

The *evolution* in the number of birds is evaluated according to:

$$\text{magnitude of the change } = \frac{number_{\text{alternative}} - number_{\text{reference}}}{number_{\text{reference}}}$$

Changes in the number of birds are thus evaluated relative to the number of birds occurring in the reference. A reduction in the $number_{\text{alternative}}$ compared to the reference is evaluated as unfavorable and *vice versa*.

Both the *state* and *evolution* are calculated per OMES zone. Numbers within the riverbed and in depoldered areas are calculated based on surface area of the mudflats (converted to width of the mudflats), slope of the mudflats and spread in exposure time (SpD), with

$$SpD = \frac{1}{\sum {p_i}^2}$$

where p_i equals the proportion of the i-th exposure time class (with classes going from 0% to 100% exposure time in steps of 5%).

For the CRTs, numbers are based on surface area only (set to 15% of the total CRT area), since slope and SpD are not available for the CRTs. For the evolution, only relative changes between alternatives and reference with a value larger than 10% are taken into account. Changes smaller than 10% are considered not to be sufficiently different from the reference.

7.3 RESULTS

As it is difficult to predict the evolution of littoral (mudflats) and supralittoral (marshes) habitat in newly created estuarine area through realizations of the SIGMA plan (see paragraph 5.2.5), the results should be interpreted with care.

The *state* (Figure 7-1) and *evolution* (Figure 7-2) of the numbers of Common teal largely correspond to the results for the surface area of the mudflats (see paragraph 5.2.5). Indeed, surface area of the mudflats (included in the model as mudflat width), has by far the largest impact on the predicted numbers of Common Teal (Figure 7-3 A).

Most Common Teal is in general found in OMES 14 and 15 (40 – 60 km from Merelbeke) (Figure 7-1), where the largest mudflats occur in the Upper Sea Scheldt. Improvements in the numbers of Common Teal occur however in all OMES zones (with the exception of OMES 14 in C1) when comparing the C-alternatives with the C-reference (Figure 7-2) as a result of the creation of (relatively) large additional areas of mudflats through the inclusion of depolderings and CRTs in the C-alternatives. Especially in OMES 19 and 17, strong improvements (up to a 10-fold increase in OMES 17) in the numbers of Common Teal are observed.

The evolution in numbers of Common Teal is fairly robust against the different Climate scenarios, be it that in the upstream area (OMES 18 and 19) the numbers of Common Teal tend to increase with climate change and in the downstream area (OMES 14-17) the numbers of Common Teal tend to decrease with climate change. This is linked to the observations as described in 5.2.5.1, with a buffering effect of sea level rise on the conversion of mudflats into marshes in the upstream area and, in contrast, drowning of the mudflats with sea level rise in the depoldered areas in the downstream area.

Whereas surface area of the mudflats is much more important in determining the numbers of Common Teal than slope and spread in exposure time (SpD) of the mudflats, calculations based on SpD alone (excluding CRTs), indicate some deterioration in the quality of the mudflats in C2 and C3 due to reduced SpD (Figure 7-3 B). This may be linked to the overdominance of lower mudflats in the newly created depolderings (see 5.2.6.3). As the lower mudflats are lower in quality (lower biomass of macrobenthos), these evolutions are even more negative than indicated by the reduced SpD. These results do not take into account the autonomous evolution, however, which may improve the quality of the mudflats over time due to sedimentation and gradual elevation of the mudflats in newly created depolderings.

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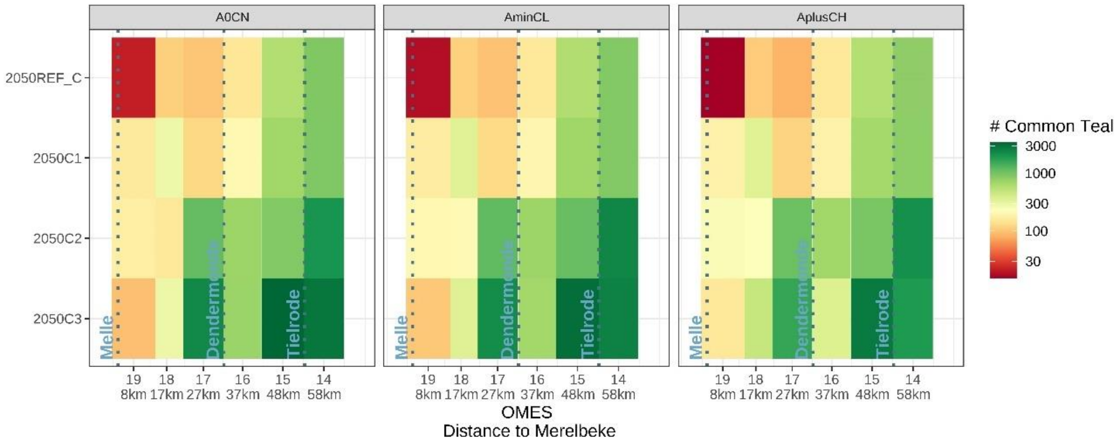


Figure 7-1: predicted numbers of Common teal per OMES zone.

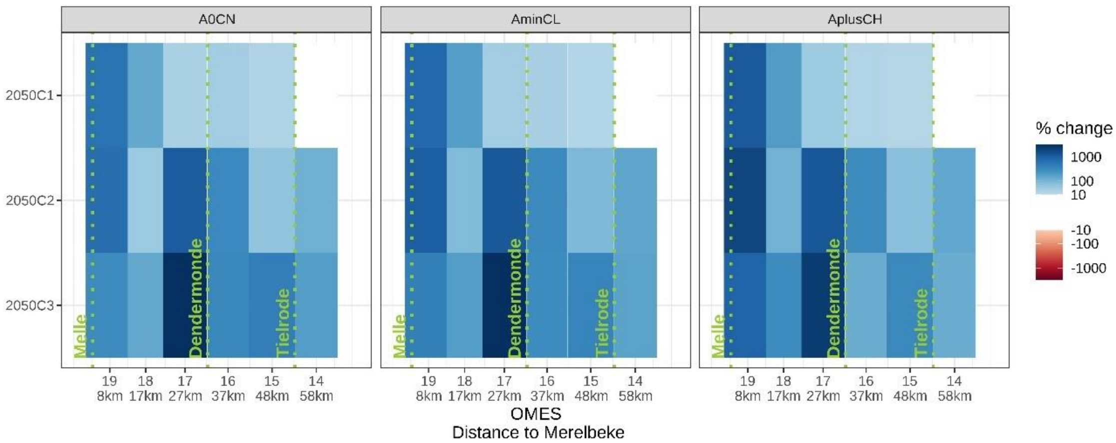
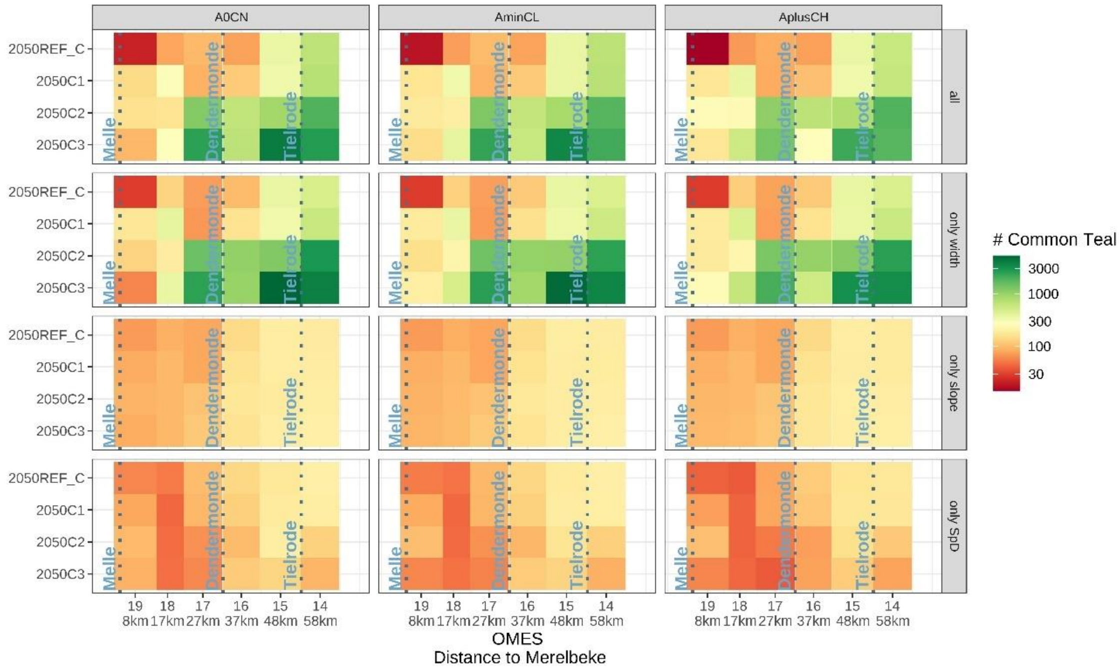


Figure 7-2: evolution of the predicted numbers of Common teal per OMES zone. Only changes of ≥ 10% per OMES zone are considered.

A



B

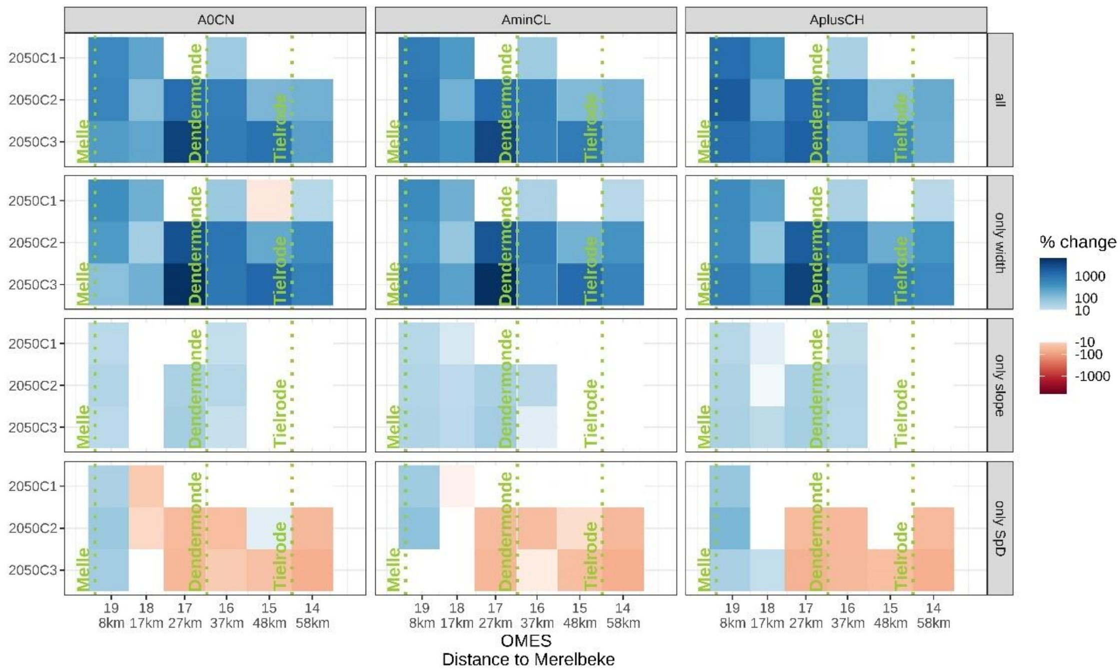


Figure 7-3: sensitivity of predicted numbers (A) and evolution (B) of Common teal to individual predictor variables. FCA-CRTs are omitted from these results because slope and spread in exposure time (SpD) are not calculated in these areas. For the evolution, only changes of ≥ 10% per OMES zone are considered.

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7.4 CONCLUSIONS

There is a general positive evolution in the numbers of Common Teal when comparing the C-alternatives with the C-reference due to the inclusion of large areas of newly created depolderings and CRTs, with positive evolutions on the area of mudflats. Favorable evolutions are relatively largest in the more upstream region (OMES 17 and 19). Care should be taken, however, to the quality of the mudflats. A large proportion of the newly created area will (initially, ignoring autonomous evolution) be mudflat of lower elevation which contains less biomass of macrobenthos (Van Braeckel et al. 2020).

8 GENERAL CONCLUSIONS

8.1 IMMEDIATE AND SHORT-TERM EFFECTS

Tidal regime

The creation of depolderings, CRTs and bathymetrical adjustments in the C-alternatives has clear favorable effects by reducing the tidal amplitude and preventing the further unfavorable development towards a macrotidal system. Reductions in tidal amplitude compared to the C-reference depend on the extent of the area of introduced measures (C1 > C2 < C3). Measures studied in the C-alternatives to affect tidal dynamics include two types that work differently on the water dynamics. On the one hand, the measures that are concentrated in the subtidal area of the main channel cause friction to the currents and hence reduce the tidal penetration. Measures that enlarge the lateral space for the river, on the other hand, spread out the tidal energy and water volumes in the lateral areas and hence reduce the tidal amplitude. It should be studied how these effects interact with each other.

Habitats

In general, the shallow waters in the Upper Sea Scheldt are in an unfavourable state in the C reference and all C-alternatives. There is an overall shortage in shallow water which is relatively larger than for the mudflats and marshes. Thanks to the introduction of side channels and the reduction in tidal amplitude (with the associated conversion of mudflat area into subtidal area) In C2 and C3, subtidal area tends to undergo overall favorable evolutions. Despite these favorable evolutions the Upper Sea Scheldt broadly remains in an unfavourable state for shallow waters even in C2 and C3.

Through the inclusion of realignments and CRTs, tidal mudflats can attain a minimal favorable state, but this depends on the location and the C-alternative. In the upstream region of the Sea Scheldt (OMES 18, 19, <20 km from Merelbeke), a favourable state is mainly attained in the C1 alternative, whereas in the more downstream region (OMES 14-17, >20 km from Merelbeke) a favorable state of the mudflats is mainly achieved in alternatives C2 and C3. Even though a favorable state is not always attained, the mudflats tend to undergo a positive evolution in surface area in alternative C2 and C3 in almost the entire Sea Scheldt. The larger inclusions of tidal flats in the more downstream area, however, will (initially, disregarding autonomous evolution) be of lower quality, as they will mostly consist of lower elevation mudflats which carry less macrobenthos biomass.

The C-alternatives do not affect the state of tidal marshes much compared to the C-reference. The downstream area of the Sea Scheldt (OMES 14, 15, >40 km from Merelbeke) is in a favorable state of marsh area, whereas the upstream area (OMES 17-19, <30 km from Merelbeke) is in an unfavorable state. In OMES 16 the favorable state of the marshes is lost in the C-alternatives because of rearrangements of the river channel at the Kramp (C1, km 40) and of the reduction in tidal amplitude (C2 and C3). In C2 an C3, the marshes only undergo a positive evolution in the upstream area but undergo a negative evolution in the mid and downstream region (> 20 km from Merelbeke), with overall losses in habitat area. Even if changes in the amount of marsh area might be relatively small, however, strong changes in the location of the marshes may occur with a shift of marsh area from the originally existing

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marshes to the newly created CRTs. This will lower connectivity between marshes. Older already existing marches will turn into non-estuarine habitat, which might create opportunities for the development of other valuable non-estuarine types of vegetation. Desiccation of the higher elevation marshes, however, is counteracted by sea level rise.

There is a general favorable tendency towards a lower need for hard substrate along the fairway. Locally, however, when altering the fairway, care should be taken to include the riverbanks in the new design to make them more gentle sloping and avoid the need for hard substrate. Shear stress estimates indicate a risk of an evolution to steeper shores near alterations to the fairway. Especially between Tielrode (km 53) and the Rupel (km 63).

<u>*Twaite shad*</u>

Conditions are in general favorable for larval development upstream of Dendermonde in the C-reference and alternative C1. In some years with high SPM and/or low oxygen levels, however, suitability can strongly reduce in the region between Dendermonde and Tielrode, which is the most important spawning area nowadays. In the C2 and C3 alternative, conditions between Dendermonde and Tielrode are clearly improved due to reduced levels of SPM and higher oxygen levels. In some areas (around km 40 - the Kramp in C2 and between km 57 Temse and km 63 Rupel in C1 and C3) water currents evolve negatively, entailing an increased risk of flushing developing larvae to more downstream, less suitable areas. There are also indications that the subtidal parts in created side channels (which are in themselves favorable as they provide low dynamic shelter) are too shallow. Given that following autonomous evolution sedimentation will occur in these side channels they risk becoming even more shallow or disappear.

Conditions for spawning are generally favorable in the Upper Sea Scheldt, including the region between Dendermonde and Tielrode, where most of the spawning is observed.

Both for upstream migration (spawning) and downstream migration (developing juveniles) there are indications that oxygen levels can be too low in some years between 50-90 km from Merelbeke, creating a barrier for migration. Results suggest that the anoxic zone shifts downstream but also that it becomes larger in C2 and C3, which is an unfavorable evolution. Results associated with oxygen levels should be considered carefully, as they could be linked to an underestimation of the oxygen levels in the modeling train (Maris et al. 2022) (see 6.5). In the Lower Sea Scheldt expert judgment states that the evolutions with respect to oxygen concentrations in the C-alternatives will rather be neutral to slightly favorable. Contrasting insights from model output and expert judgment indicate, however, that further research is needed to obtained better supported results.

<u>*Common teal*</u>

There is a general positive evolution in the numbers of Common Teal when comparing the C-alternatives with the C-reference due to the inclusion of large areas of newly created realignments and CRTs, with positive evolutions of the area of mudflats. Favorable evolutions are relatively largest in the more upstream region (OMES 17 and 19). Care should be taken, however, to the quality of the mudflats. Large amounts of the newly created area will (initially, ignoring autonomous evolution) be mudflats of lower elevation which all will have a similar short exposure window (feeding window is short) and contain less biomass of macrobenthos.

8.2 ROBUSTNESS/IMPACT OF CLIMATE SCENARIO

The favorable/unfavorable state of the estuarine habitats is relatively robust to the different climate scenarios, except for the subtidal area where a general improvement in the state can be observed in C2 and C3 as a result of sea level rise (and a reinforcement of the effects of a reduction in tidal amplitude in C2). Sea level rise will indeed strengthen the evolution of drowning of the lower mudflats but will temper the desiccation of the higher marshes. However, when considering the gradual process of autonomous evolution, this will probably not happen as severely as predicted here, because new areas will silt up (assuming enough sediment is available) following sea level rise, preserving the intertidal area.

Results with respect to the suitability for growth and reproduction of Twaite shad are largely comparable in the different climate scenarios, but both in AminCl and AplusCH a deterioration of the state can be observed between Tielrode and Antwerpen in REF-C and C1 due to reduced oxygen levels.

The evolution in numbers of Common teal is fairly robust against the different climate scenarios, be it that in the upstream area (OMES 18 and 19, <20 km from Merelbeke) the numbers of Common Teal tend to increase with climate change and in the downstream area (OMES 14-17, >20 km from Merelbeke) the numbers of Common Teal tend to decrease with climate change. This is linked to a buffering effect of sea level rise on the conversion of mudflats into marshes in the upstream area and, in contrast, drowning of the mudflats with sea level rise in the depoldered areas in the downstream area.

8.3 LONG TERM-EVOLUTION

The obtained results and conclusions do not consider effects of autonomous evolution. In particular, due to long-term sedimentation in the newly created realignments, elevations will increase and there will be less tidal storage capacity. As a result, effects on tidal amplitude will over time be less pronounced than the estimated initial effect and a redistribution of habitats will occur. There will be less subtidal area (less increase in low waters and siltation of side channels), less mudflats (conversion into marshes), but of higher quality (higher elevation), more marshes (conversion of mudflats into marshes and less loss of mudflats due to decreased levels of high waters). These predicted long-term evolutions will be much less pronounced in new estuarine area developed near the fairway than in realignments and CRTs.

8.4 CONSIDERATIONS FOR FUTURE IMPLEMENTATIONS

Timing and location of the measures

Due to the size of the measures in C2 and C3, effects on tidal amplitude and suspended matter (SPM) are substantial. To the extent that SPM might be so low that sedimentation in the new depolderings will be slow (decades) and even insufficient to follow the trends of sea level rise (Bi et al. 2021b). In reality, however, implementation of the measures will be phased and the effects of sediment depletion much less pronounced. Phasing of the alterations to fairway and

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inclusion of new depolderings/CRTs, raises the question as to what strategy to use. From the viewpoint of nature conservation, it is advisable to include new areas of nature development prior to altering areas where nature will be destroyed. This ensures a gradual evolution/rejuvenation of estuarine nature and the inclusion of areas in different stages of development towards a new local equilibrium. Estuarine nature is by default dynamic with natural transgressions between mudflats and younger and older marshes (van de Koppel et al. 2005). Due to limited lateral space because of historical embankments and protection of riverbanks with rip-rap in the current situation, this natural evolution has mostly come to a halt, with most marshes evolving to a climax vegetation (riparian tidal willow forest) and a (strong) decline in pioneer and young marsh habitats. A well thought strategy of phased depolderings might facilitate the restoration of the natural dynamics and turnover of estuarine habitats. Given the long development time to the climax vegetation, it might be wise though to preserve as much as possible of the older marshes with riparian tidal willow forest. A phased implementation of measures also ensures that corrections can be made if unexpected and undesirable evolutions of the system arise.

With respect to system functioning, priority should first be given to measures in the downstream to mid region of the Sea Scheldt (> 10-15 km from Merelbeke) as they will have more impact on the entire system. Moreover, larger envisioned depolderings in these sections also have larger impact on nature conservation (conservation of focal habitats and species) and links to higher trophic levels. In the more upstream area (< 20 km from Merelbeke), it is less useful to implement large depoldering areas that reach far inland from the river. Better to work with realignments - relocation of dikes a bit more inland (e.g. km 4 and 6 from Merelbeke in the C-alternatives) to create more space along the fairway with lowered and less steep river banks.

Given the expected increased salt intrusion (see Figure 5-15 and Figure 4-9 in Vanoverbeke et al. 2023 (*in press)*) (due to sea level rise), one should also consider to give priority to locations that can protect vegetation types that grow on the edge of the freshwater zone (km 60-70 from Merelbeke). With future salt intrusion these vegetations entail a risk of extinction if suitable habitat is not created more upstream, anticipating the expected salt intrusion.

Priority of habitat types

The largest deficits with respect to the minimal desired surface area are observed for low dynamic and shallow subtidal habitat. There is an evolution towards substantial improvements in subtidal area in the C-alternatives, but this is mostly linked to strongly reduced tidal amplitude and effects of sea level rise, which are not really structural improvements to this kind of habitat, and will be most likely less pronounced due to long term evolution of the system. Structural improvements that may be more permanent are to design side channels in a way that maximises stability of subtidal area in these channels. This may be achieved by improving in and/or outflow by creating over space at in-/outlets to prevent excessive siltation in the side channels and maximise long term sustainability. Where possible, riverbanks should also be made less steep and gradually grading into subtidal area, creating gentle sloping shallow water near the fairway. This is only feasible, however, if lateral space is sufficient to dampen tidal energy and energy from ship waves. The creation of sheltered subtidal areas (relatively undeep areas with low flow velocities) is important to reduce the risk of flushing of, for example, small fish like Twaite shad larvae to more downstream and unfavorable areas (relatively undeep areas with low flow velocities). i.e. mitigation of coastal squeezing not only by developing depolderings and CRTs but also by providing shallow subtidal and intertidal area near the fairway (= gentle sloping river banks) will promote a dynamic yet healthy estuary.

Alternatives C2 and C3 also suggest large improvements in the availability of unprotected mudflats. Due to autonomous evolution, however, large parts of the newly created mudflats in depoldered areas will attract sediment and evolve into marshes. Measures to assure a healthy balance between mudflats and marshes rely again on facilitating water flow in and out of depolderings and CRTs by designing broad connections with the river, redesigning winter dikes to allow for spacious and gentle connection with the river and facilitating the creation of large in- and outflow creeks.

Autonomous evolution will automatically lead to the creation of additional new marshes as a result of siltation in new depolderings, compensating for the loss of existing marshes due to reduced tidal amplitude. As mentioned, care should be taken that this occurs in a phased manner, such that new marshes can develop before old marshes are destroyed, to create marshes in different phases of vegetational succession. Moreover, loss of marsh area due to reduced tidal amplitude, can still turn into valuable gains for nature preservation. Indeed, if the connection of these areas with the river is not severed, they are flooded occasionally during extreme weather events and can develop into riparian mixed forest.

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