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

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

Joost Vanoverbeke, Alexander Van Braeckel, Erika Van den Bergh and Gunther Van Ryckegem

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

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

Vanoverbeke Joost, Van Braeckel Alexander, Van den Bergh Erika 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, ecosystem functioning, flood control, shipping and maintenance efforts. Within this context several alternative morphological adjustments have been proposed with different degrees of impact on the current morphology (the B-alternatives). In order to evaluate the expected impact of alternative morphological adjustments a series of modelling tools have been developed to predict the effects of the alternatives on each of these components. In addition, different climate scenarios were designed to assess the effects under different magnitudes of future climatic changes. Here we compare the predictions for habitats and higher trophic levels for the different B-alternatives (Chafing, VaH and VaG) against predictions for the current situation and the reference situation in 2050.

Shallow subtidal area in general (including high dynamic and low dynamic area) does not change much towards 2050 and in the B-alternatives. Low dynamic subtidal area (including low dynamic area in the deeper parts), however, increases due to reduced water velocities towards 2050. Yet, the B-alternatives mostly have a negative effect on low dynamic subtidal area, because water velocities increase again. Mudflats and marshes show a clear increase in surface area towards 2050, due to the realisation of additional CRTs and new managed realignment sites. Omitting CRTs and managed realignments, the effects of the B-alternatives on mudflats and marshes near the fairway depend on the local modifications to the bathymetry and can be either favorable or unvaforable.

With respect to suitability for growth and reproduction of Twaite shad, oxygen depletion in some of the river stretches, which can occur already in the current situation, risks to deteriorate towards 2050 and in some of the B-alternatives. From the re-analysis of the 2050 bathymetries with a deepened Ringvaart the Sea Scheldt is only in a favorable state for larval development in the upper 20 km from Merelbeke, with suboptimal state more downstream due too low oxygen levels and too high suspended matter. Although the effect size is unsure due to uncertainty of the modeling results, the deterioration towards 2050 and by the hypothetical alternatives should not be neglected. There is a favourable evolution of reduced maximum water velocities towards 2050 under mild climatic changes, which is counteracted, however, in the VaG bathymetric alternative. VaG may nevertheless locally lead to reduced levels of suspended matter, improving growth conditions for larval Twaite shad in the upper parts of the Sea Scheldt.

Due to sea level rise and the resulting drowning of the mudflats, there is a predominant decline in abundance of Common teal near the fairway towards 2050. This is compensated by the creation of new mudflats in newly created CRTs and managed realignment sites. Abundance of Common teal may further decrease in VaH but improve in the VaG bathymetric alternative. The latter can be ascribed to displacement of the riverbed and increased tidal amplitudes (which in itself could be an unfavourable evolution).

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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 several alternative morphological adjustments have been proposed with different degrees of impact on the current morphology (the B-alternatives). To evaluate the expected impact of alternative morphological adjustments on hydrodynamics, sediment transport, water quality and pelagic ecosystem, habitat quality, fauna and flora, a series of modelling tools have been developed to predict the effects of the alternatives on each of these components (the modelling train; Figure 1-1) (see also 'Model instruments for the Integrated Plan Upper Seascheldt' (IMDC et al. 2015)). In addition, for each alternative different climate scenarios were designed to assess the effects under different magnitudes of future climatic changes.

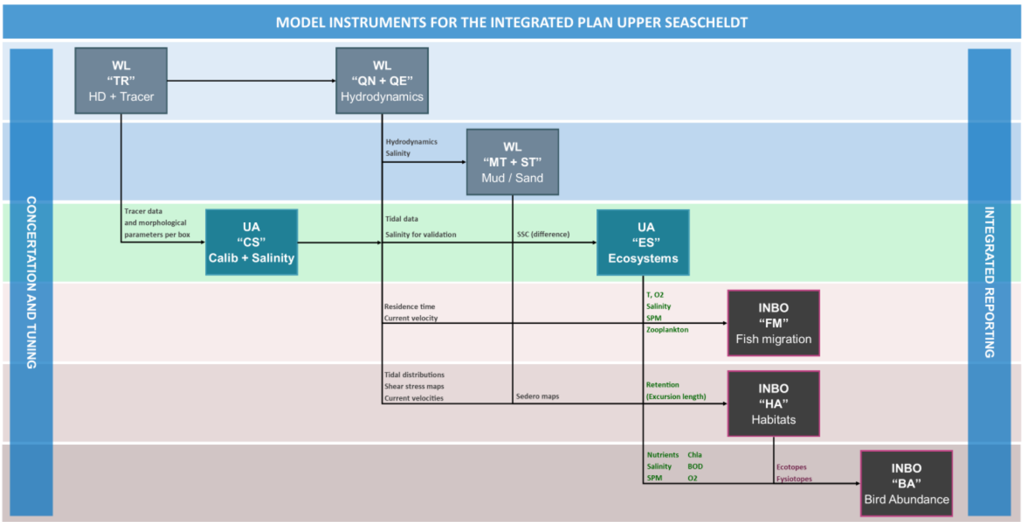

Figure 1-1: Sequences of calculations and data stream through the modelling train for the evaluation of the Integrated plan of the Upper Sea Scheldt.

Here we compare the predictions for habitats and higher trophic levels for the different B-alternatives (including the forks for different climate scenarios) against predictions for the current situation and 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 design mitigating measures to improve the quality of the system.

Based on bathymetrical input and results from modelling 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.

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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 modelling train with respect to hydrodynamics, sediment transport, habitat quality and the pelagic ecosystem (Figure 1-1; IMDC et al. 2015).

2 B-ALTERNATIVES AND CLIMATE SCENARIOS

The text below is based on the information given in IMDC et al. (2015).

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 the climate change, sea level rise, increasing or decreasing tidal amplitude, high or low discharge), have been defined.

The **alternatives** include the current state (2013-2014), a reference state (including the sustainable management plan for Class IV navigation and decided policy) and states including the future accommodation and maintenance of the fairway (the so-called B-alternatives). The B-alternatives have been defined in a preceding study (Navigability study Upper Sea Scheldt; IMDC 2013). They comprise incremental adaptations of the bathymetry and the alternative with the most severe adaptations (VaG) shortens the total length of the estuary.

The **current state** is a representation of the situation in 2013-2014 including the operational controlled reduced tide areas and flood control areas built in the framework of the SIGMA plan.

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 managed retreat areas within the frame of the SIGMA plan.

The **B-alternatives** consist of 3 different potential designs:

1. Chafing (Schaaf): accessibility for ships of 110 m long and 11.4 m wide but not following standard design rules but using fairway envelopes based on real time shipping simulations.

2. VaG: Class Va standard design rules applied, mostly in the current channel ("G" for "Geul" or channel) leading to a single lane Va functionality upwards Wichelen (between Ghent and Dendermonde, uppermost part of Upper Seascheldt).

3. VaH: Class Va standard design rules applied with Hybrid ("H") properties, specifically the "Chafing" alternative downstream Wichelen, and "VaG" upstream Wichelen.

An example of the alternative designs is given in Figure 2-1.

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Figure 2-1: Example of the effect of the alternatives on the morphology in the Hoogland Bend. (Legend: Blue = Fill; Brown = Cut).

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 (5.4 m in Schelle), and no sea level rise.
2. A-CL: a decreased tidal range (-40 cm in Schelle) is applied to simulate projects downstream that lead to a decreased tidal range. This is combined with a 'low' climate change effect (15 cm sea level rise). This combination of boundary conditions is considered as a 'minimal' scenario.
3. A+CH: an increased tidal range (+30 cm 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). This combination of boundary conditions is considered as an 'extreme' scenario.

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

An overview of the combinations of alternatives and scenarios that are evaluated for habitats and higher trophic levels is given in Table 2-1.

Table 2-1: Scenario model runs (per alternative)

Scenario	Current state	Reference state	Chafing	VaH	VaG
A0CN	Yes	no	no	no	no
A-CL	No	yes	yes*	yes*	yes
A+CH	No	yes	yes	yes	yes

*: only for habitats and predictions for Common teal, not for the habitat suitability for Twaite shad

Based on the modelling results of the B-alternatives and climate scenarios and on expert judgement, C alternatives will be defined, investigated and presented in the Integrated Plan. C-alternatives may typically include measures to reduce or mitigate the effects of the B-alternatives. Solutions can include managed realignments, repositioning of the dikes, the introduction of flood channels, reconnecting cut of bends, not filling up cut of channels, the introduction of river training structures…

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3 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 aspect of the functioning of the system and are associated with hydrodynamics, sediment transport, water quality and pelagic ecosystem, habitat quality, fauna and flora. The impact will be evaluated based on the model output. Evaluation can occur at the level of the **state** of the system or the **evolution** of the system (Figure 3-1).

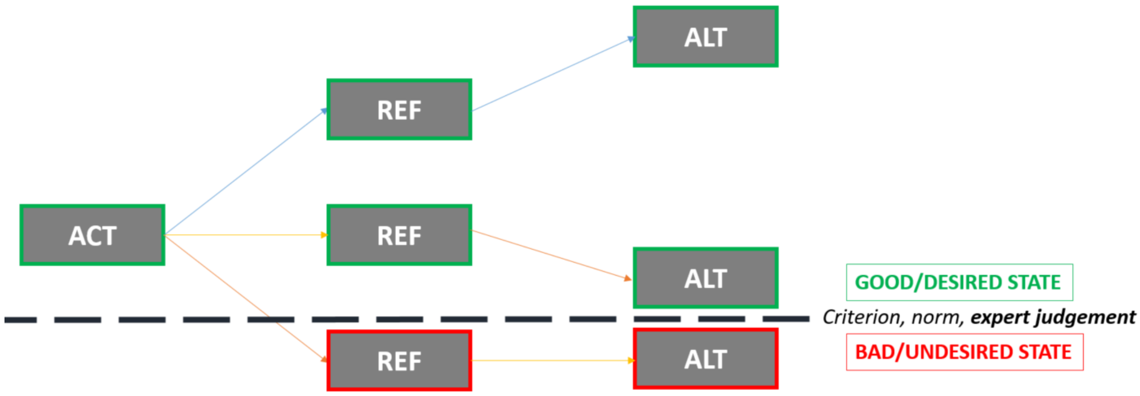

Figure 3-1: Illustration of the evaluation of the **state** and the **evolution** of the system. ACT = current state (2013); REF = reference state (2050); ALT = B-alternatives/scenarios.

- 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.

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

or

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

where *focus* and *reference* for the different alternatives are given in Table 3-1.
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, no reference criterion

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exists to evaluate the state. The magnitude of changes is evaluated for the habitats and the higher trophic levels.

Table 3-1: focus and reference for the different future alternatives

• **focus**	• **Reference**
• **Reference state (2050)**	• Current state (2013)
• **Chafing**	• Reference state (2050)
• **VaH**	• Reference state (2050)
• **VaG**	• Reference state (2050)

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4 EVALUATION OF HABITATS

4.1 QUALITY INDICATORS

For the habitats, the following quality indicators are evaluated:

- Tidal regime
  - 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 4-1 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 the low waters). An additional increase caused by the intended adaptations to the bathymetry is considered undesirable. One of the aims for the future is to reduce or in the best case stop the rise of the tidal amplitude.
  - Tidal amplitude in the different alternatives is derived from the mean low and high water modelled by the SCALDIS model and as used in the habitat modelling.

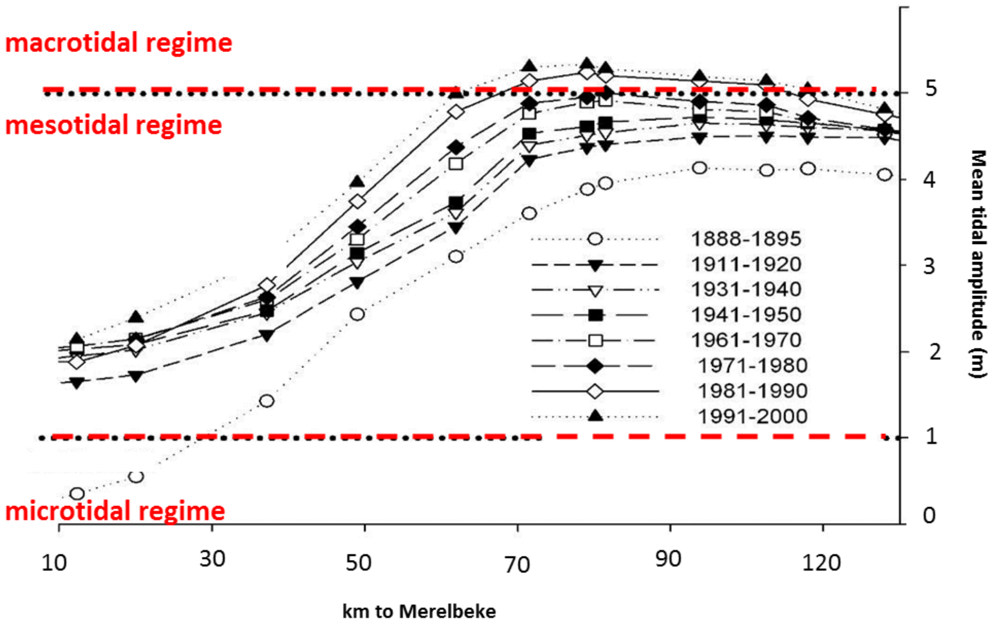

Figure 4-1: Evolution of the mean tidal amplitude (modified after Van Braeckel et al. 2006). Tidal range classifications based on Hayes (1979).

- Surface area of the habitats
    - 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 foodweb), and therefore dependent on each other. Preserving sufficient surface area of the habitats is therefore a very important nature conservation goal and a prerequisite for a healthy functioning Schelde 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:
        - Shallow water habitat for the *state* and all low-dynamic subtidal habitat for the *evolution*
        - tidal mudflat habitat (or littoral or intertidal habitat)
        - tidal marsh habitat (or supralittoral habitat)
- Habitat quality
    - Hardening of the estuary
        - A further increase in tidal mudflat area with hard substrate (rip-rap) reduces geomorphological adaptation and has a low ecological value which is unfavourable. The (proportional) littoral area with hard substrate is thus an important (negative) ecological quality indicator.
        - The littoral area with hard substrate is derived from the surface area of mudflat with slopes exceeding 25% as described in Van Braeckel et al. (2019).
    - Propensity for erosion/sedimentation of the mudflats
        - Modelling 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 unfavourable.
        - Estimates of erosion on mudflats are based on rasterdata of the 50 percentile of the velocity shear stress (TAU50) calculated in the 3D-SCALDIS-model (Smolders et al. 2016). The average value of this TAU50 raster is calculated per patch of soft bottom tidal mudflat ecotope per kilometre.

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            - The selection of TAU50 as variable is based on a comparison between field data and modelled shear stresses in a A0CN-scenario of 2050. Field data were based on high resolution cross shore altimetric profiles. As an increase of more than 0.015 TAU50 in that scenario was associated with the remarkable erosion of the low tidal mudflats in 2016 after the implementation of the measures taken in the sustainable bathymetry (Van Braeckel 2013).

    - <u>Mudflat with high macrobenthic biomass</u>
        - 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 preliminary results of Habitatmapping Sea Scheldt partim tidal mudflats, 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.

- <u>Salinity zones</u>
    - Salinity is an important element determining the occurrence of fauna and flora along the Sea Scheldt.
    - Salt intrusion is not only important for Twaite shad but also for many other species that are part of specific brackish and freshwater communities
        - Vegetation types and plant species composition of tidal marshes are specific for the mesohaline and fresh water reaches with on the one hand, for example, salt meadows (habitat type 1330) and on the other hand alluvial forests (habitat type 91E0). Intrusion of salt further upstream can diminish the rare European alluvial forest habitat that occurs in fresh water tidal areas.
        - Communities of macrobenthos and of water birds show clear differences in species composition in the brackish and freshwater part of the Sea Scheldt.
    - Salinity along the river is obtained from the results of the pelagic ecosystem model (UA; Van engeland et al. 2018).

4.2 EVALUATION METHODOLOGY

4.2.1 Tidal regime

The *state* of the tidal regime is evaluated by comparing the tidal amplitude against predefined thresholds for macrotidal, mesotidal and microtidal regimes. The criteria are derived from Hayes (1979).

4.2.2 Surface area of the habitats

The *state* of the habitats in the different alternatives is evaluated by comparing the surface area of the ecotopes used in the present monitoring against the desirable state as defined in Maris et al. (2013). Surface areas smaller than the desirable state for a given ecotope in each OMES zone are evaluated as unfavourable, surface areas equal or larger than the desirable state as favourable. For the evaluation of the *state of the habitats* in reference bathymetries and B-alternatives the total project area is used inclusive all CRT areas and managed realignments.

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

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

A reduction in surface area compared to the reference (see Table 3-1) is evaluated as unfavourable and *vice versa*.

The *evolution* of the habitats is evaluated excluding the newly created CRT areas and managed realignments (actualised SIGMA plan) (i.e. only the riverbed and adjacent riverbanks). This enables an estimation of the direct effects of bathymetric alterations in the B-alternatives on changes in surface area of the habitats within the confines of the riverbanks. In addition, for the subtidal habitats, only the low dynamic area (see Van Braeckel et al., 2019) is considered (including deep (0-0.95 m/s), middle deep (0-1.06 m/s) to shallow (0-1.18 m/s) subtidal habitats). Water velocity data as calculated from the Scaldis hydrodynamic model.

4.2.3 Habitat quality

Three different habitat quality indicators are calculated:

An increased *hardening of the estuary* is an unfavourable 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 (inclusive all new estuarine areas).

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

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

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At the riverbanks near the main channel indications of erosion associated with increased shear stress indicate that the modelled 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 unfavourable. Erosion of low tidal mudflat near the channel goes hand in hand with increased slopes 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 unfavourable.

4.2.4 Salinity zones

For salinity, only the current situation (ACT_2013) and the future reference under the high climate scenario (REF_2050, AplusCH) are compared. Preliminary exploration of the results indicates that the B-alternatives do not affect salt intrusion substantially, but that the main driver is tidal amplitude and climate change.

As an indicator we discuss the shift of the maximum salinity boundary (P90 salinity) in the summer as important stressor for vegetation and biota.

4.3 RESULTS

4.3.1 Tidal regime

Presently (REF2013) the Scheldt estuary has evolved towards a macrotidal system in the downstream area (near St. Amands > 48km to Merelbeke, REF2013, Figure 4-1). Further increase to a macrotidal system is undesirable.

Downstream Temse (57km to Merelbeke) an amplitude rise (A+) or lowering (A-) has the biggest influence on the tidal amplitude. Between Temse and the confluence of Durme (Tielrode, 50 km to Merelbeke) an amplification of the tidal range occurred in *REF2050* that propagates through the upstream part, which is an unfavourable evolution compared to *REF2013*. This amplification is caused mainly by the implementation of the sustainable bathymetry (dredging/sand extraction of sand bares in the channel) and could not be dissipated by the implemented CRTs and managed realigments in REF2050. As a result, the tidal amplitude increases in the upstream area and the macrotidal threshold shifts from km 47 near St. Amands to km 43 (near Baasrode), which is unfavourable. Even the A-scenarios, which have a forced reduced tidal amplitude at Schelle (-30cm; 105km), produce higher tidal amplitudes than REF_2013 upstream Tielrode (50km).

For the *2050 reference scenarios* amplitudes steadily increase between scenarios according to the sequence A-CL, A0CL, A0CH, A+CH, especially in the reach Merelbeke- Schoonaarde (0-22.5km) indicating that not only the imposed tidal amplitude at Schelle but also, to a lesser degree, sea level rise influences tidal amplitude in the upstream area (0-25km; difference between REF_ A0CL and REF_A0CH scenarios).

When comparing the different *alternatives* in the upstream part, the Chafing and the VaH alternative do not differ a lot from the 2050 reference, except for a slight increase in amplitude in VaH in the upper 10km stretch. Amplitudes for the VaG alternative, however, are a lot higher than the 2050 reference in both scenarios in this area, which is highly unfavourable. The biggest change between VaG and REF2050 occurs in the section between Dendermonde and St.Amands including the straitening of the Kramp (km 40).

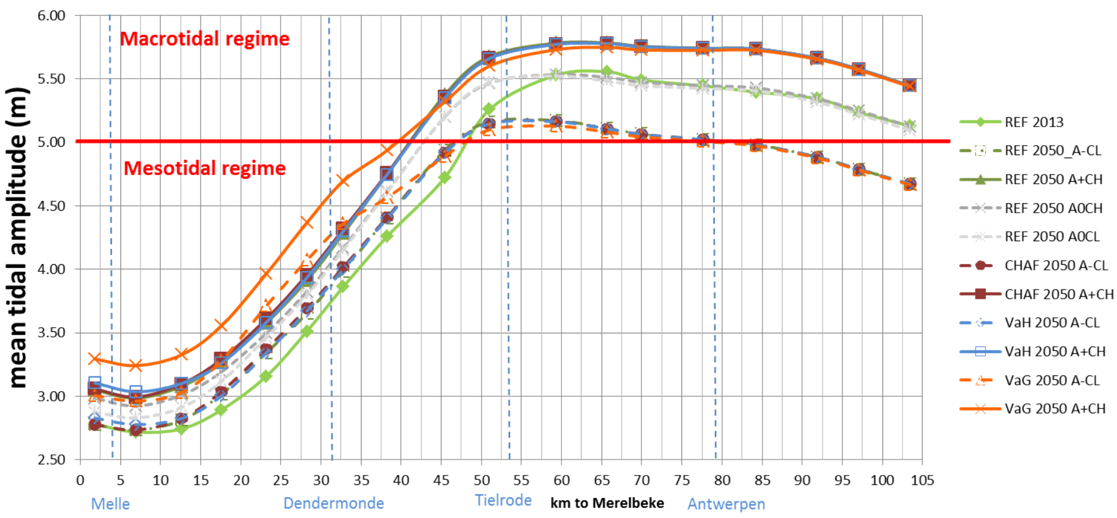

Figure 4-2: mean tidal amplitude in the 2013 and 2050 reference situation and the B-alternatives for the different climate impact scenarios. Tidal range classifications are based on Hayes (1979).

4.3.2 Surface area of the habitats

Before discussing the results, it needs to be remarked that evaluation of the habitats is difficult because the modelling instruments do not fully take into account the autonomous morphological evolution. The subtidal and intertidal areas are sensitive to changes occurring in the system in response to erosion-sedimentation dynamics after alterations to the bathymetry have been made. Therefore, the bathymetry in the future alternatives used for evaluation is unbalanced. Also, the climate scenarios add to the imbalance in the future bathymetries. Whereas estimates of expected sedimentation in marshes, depoldered areas and controlled reduced tidal areas in response to sea level rise are included in the modelling train, the potential effects on subtidal areas and mudflats (e.g. steepening of the mudflats) have not been accounted for. 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 4.3.3).

In addition, future realizations of the SIGMA plan and deepening, filling and displacement of dikes (VaG alternative, Figure 4-3) create extra 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.

For the evaluation of the *state of the habitats* in reference bathymetries and B-alternatives the total project area is used inclusive all CRT areas and managed realignments. Despite the uncertain autonomous evolution, the estimates provide some insights in the final achievement of estuarine habitat and the fulfilment of the predefined goals. Based on estimates from

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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. In the new managed realignments, surface area of the habitats was calculated based on the elevation model and tidal data, similar to the calculation of habitats near the main channel.

In contrast to the *state*, the evaluation of the *habitat evolution* in the B-alternatives only considers evolutions within the riverbed, without taking into account new estuarine area created by realizations of the SIGMA plan. Comparisons between B-alternatives and 2050 reference are best studied in the area where they are implemented and have their largest impact. Including the CRT areas and managed realignments does not add much information about the changes in surface area of the habitats resulting from the specific bathymetric changes for each B-alternative. As the riverbed is displaced in certain locations in the VaG alternative, even then it is difficult to compare VaG with the other alternatives.

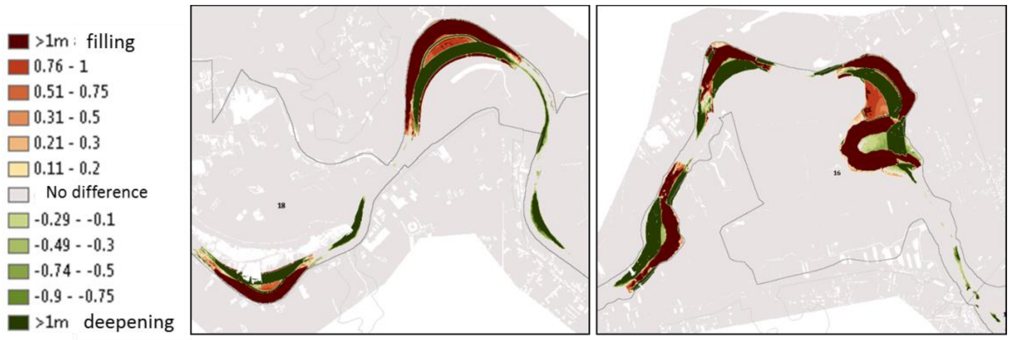

Figure 4-3: Example of deepening and filling to alter the riverbed in the VaG alternative.

4.3.2.1 State of the habitats

The required habitat targets are divided per OMES zone and based on the methodology given in Maris et al. (2013). The desired surface areas can be found in Table 4-1. As targets for *low dynamic* water habitat areas are not yet available, the evaluation of the *state* occurs on water habitat division based on water depth only: the shallow water habitat (less than 2 water depth –LW10).

For the shallow water (Table 4-2), none of the bathymetries and climate scenarios are in a favourable state (they do not reach the minimal target area).

Overall differences between alternatives in surface area of shallow water are minimal. Only in the VaG alternative, there is a small reduction of 8-9 ha.

The tidal mudflats (Table 4-3) show a favourable state in the 2050 alternatives only for OMES 15 and 18. Overall, however, there is a strong improvement in the amount of tidal mudflats in the 2050 reference and alternatives compared to the current state (ACT 2013). This strong improvement of the state of the mudflats in the 2050 reference and alternatives is mainly the result of the realisation of new CRTs and managed realignment sites. In general, the surface area of mudflats is higher in the AplusCH scenario than in the AminCL scenario. This improvement in the state of the mudflats in the high climate scenario is mainly due to the increased tidal amplitude in the high climate scenario (see 4.3.1) and the consequential drowning of tidal marsh along the riverbanks. Despite the strong increases in surface area of the mudflats in some OMES compartments, all future bathymetries and scenarios remain overall in an unfavourable state when looking at total mudflat area.

Tidal marshes are in a favourable state in the downstream part of the Upper Sea Scheldt (OMES 14, 15 and 16) for the 2050 reference and B-alternatives (Table 4-4). In the upstream part of the Upper Sea Scheldt (OMES 17, 18 and 19), only OMES 18 is in a favourable state (in all bathymetries and scenarios). The strong increase in surface area of the marshes in the downstream part of the Upper Sea Scheldt in 2050 is due to the newly created CRT areas and managed realignments.

Table 4-1: Evaluation targets (surface area in ha) for the *state* of the ecotopes in each OMES zone.

length (km)/ omes	**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

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Table 4-2: Habitat targets and *state* of the area (ha) of shallow water (<2m). Results include estimates for newly created CRT areas and managed realignments according to the actualised SIGMA plan. Values in blue indicate a favourable state. *Δ bathy-ACT*: comparison of surface area with the ACT 2013 bathymetry (scenario A0CN for the ACT 2013 bathymetry). *Δ bathy-REF*: comparison of surface area with the REF 2050 bathymetry for the respective climate scenarios.

Shallow water (<2m HD&LD)		**ACT 2013**	**REF 2050**		**Chaf 2050**		**VaH 2050**		**VaG 2050**	
OMES	**Minimal Area**		**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**
14	82	34	36	36	36	36	36	36	36	36
15	68	32	32	32	32	32	32	32	29	29
16	55	12	12	12	12	12	12	12	11	11
17	19	15	15	15	15	15	15	15	14	14
18	16	11	11	11	10	11	10	11	9	10
19	21	17	14	15	14	15	14	14	13	13
Tot	**261**	121	120	121	119	121	119	120	112	113
Δ bathy-ACT			-1	0	-2	0	-2	-1	-9	-8
Δ bathy-REF					-1	0	-1	-1	-8	-8

Table 4-3: Habitat targets and *state* of the area (ha) of tidal mudflats. Results include estimates for newly created CRT areas and managed realignments according to the actualised SIGMA plan. Values in blue indicate a favourable state. *Δ bathy-ACT*: comparison of surface area with the ACT 2013 bathymetry (scenario A0CN for the ACT 2013 bathymetry). *Δ bathy-REF*: comparison of surface area with the REF 2050 bathymetry for the respective climate scenarios.

Tidal mudflat		**ACT 2013**	**REF 2050**		**Chaf 2050**		**VaH 2050**		**VaG 2050**	
OMES	**Minimal Area**		**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**
14	145	74	114	120	114	119	114	119	114	120
15	89	47	**96**	**100**	**96**	**99**	**96**	**99**	**95**	**100**
16	72	12	35	36	34	36	34	36	22	42
17	25	13	11	12	11	12	11	12	12	17
18	21	13	**29**	**30**	**29**	**29**	**29**	**29**	**24**	**33**
19	27	12	13	21	13	21	13	20	15	21
Tot	**379**	171	298	319	297	316	297	315	282	333
Δ bathy-ACT			127	148	126	145	126	144	111	162
Δ bathy-REF					-1	-3	-1	-4	-16	14

Table 4-4: Habitat targets and *state* of the area (ha) of tidal marsh. Results include estimates for newly created CRT areas and managed realignments according to the SIGMA plan. Values in blue indicate a favourable state. *Δ bathy-ACT*: comparison of surface area with the ACT 2013 bathymetry (scenario A0CN for the ACT 2013 bathymetry). *Δ bathy-REF*: comparison of surface area with the REF 2050 bathymetry for the respective climate scenarios.

Tidal marsh		**ACT 2013**	**REF 2050**		**Chaf 2050**		**VaH 2050**		**VaG 2050**	
OMES	**Minimal Area**		**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**
14	142	69	**244**	**247**	**244**	**248**	**244**	**248**	**244**	**246**
15	118	**137**	**302**	**313**	**302**	**314**	**302**	**314**	**301**	**311**
16	96	42	**121**	**121**	**120**	**120**	**120**	**120**	**143**	**124**
17	33	31	29	28	29	27	29	27	26	20
18	27	**42**	**43**	**42**	**43**	**42**	**43**	**42**	**50**	**40**
19	36	21	20	12	20	12	20	11	18	11
Tot	**452**	342	**759**	**763**	**758**	**763**	**758**	**762**	**782**	**752**
Δ bathy-ACT			417	421	416	421	416	420	440	410
Δ bathy-REF					-1	0	-1	-1	23	-11

4.3.2.2 Evolution of the habitats in the riverbed and adjacent riverbanks

As mentioned, evolution of the habitats is evaluated excluding the newly created CRT areas and managed realignments (actualised SIGMA plan). This enables an estimation of the direct effects of bathymetric alterations in the B-alternatives on changes in surface area of the habitats within the confines of the riverbanks. In addition, for the subtidal habitats, only the low dynamic area is considered (including deep to shallow subtidal habitats).

Comparison of the 2050 reference situation with the current state

A decrease in tidal amplitude combined with a low sea level rise (AminCL) results in a favourable evolution of the low dynamic subtidal area in REF2050 compared to the current situation (ACT2013) (Figure 4-4). This favourable evolution in REF 2050 occurs over the entire stretch of the Upper Sea Scheldt, mainly at the expense of the tidal mudflats due to higher low waters in the downstream part and at the expense of high dynamic subtidal area due to a reduction in water velocities in the upstream parts of the Sea Scheldt. In the AplusCH scenario, a favourable evolution of low dynamic subtidal habitat in REF2050 compared to ACT2013 is only observed in the upstream area (< 40km from Merelbeke) and a strong decrease of low dynamic subtidal area occurs in the downstream area (> 40km from Merelbeke). The decrease in low dynamic subtidal area in the downstream part (40-60 km from Merelbeke) is linked to a strong increase in tidal amplitude (Figure 4-2) with higher water velocities in the downstream part. In the upstream part the water velocities are slightly lowered.

The tidal mudflats and marshes show an overall unfavourable evolution along the fairway when comparing REF2050 to ACT2013, with substantial losses of both habitat types in the entire Upper Sea Scheldt, in both climate scenarios. In AminCL the reduced tidal amplitude results in reduced surface area of intertidal, while in AplusCH the riverbank is squeezed towards the steep dikes by an increased water area (sea level rise) resulting in lower intertidal area despite the higher amplitude. The general loss of marshes in the AminCL climate scenario is mainly due to the reduced tidal amplitude with a desiccation of the higher marshes as a result. In the AplusCH scenario marshes are lost due to sea level rise and drowning of the lower marshes (which become intertidal area).

Comparison of the B-alternatives with the 2050 reference

Due to a slight increase in water velocities the Chafing alternative in the low climate scenario (AminCL), suffers some unfavourable losses of low dynamic subtidal area between km 20 and 50 from Merelbeke compared to REF2050 (Figure 4-4). In the high climate scenario, these losses are absent. Due to higher water velocities in the high climate scenario, there is less low dynamic subtidal habitat present in the 2050 reference which is unaffected by the Chafing alternative. In the VaH and especially the VaG alternative substantial amounts of low dynamic subtidal habitat are lost in both climate scenarios (Figure 4-4) due to increased water velocities. Yet some (temporary) gains in low dynamic subtidal habitat could also be observed more upstream (15 km or less from Merelbeke; both VaH and VaG) and between 30 and 35 km from Merelbeke (VaG) due to addition of low dynamic subtidal area in bend cut-offs.

The tidal mudflat area is not affected much in the Chafing and VaH alternatives. Between km 45-60 from Merelbeke, both in Chafing and VaH there is some conversion of high elevation mudflats to marshes in the high climate scenario (AplusCH), but this may be an artefact of bathymetric elevations lying close to the threshold between mudflats and marshes. In the AminCL climate scenario the VaG alternative shows variability in the evolution of mudflats with favourable and unfavourable changes in the tidal mudflat area compared to the 2050 reference, depending on the local measures. In the high climate scenario the VaG alternative shows mainly a favourable evolution of the mudflats, because marshes are converted into intertidal area due to increased tidal range and sea level rise (e.g. locations with relocation of the dikes, elevated outer banks at cut bends; Figure 4-5, Figure 4-6).

The tidal marshes are not affected much in the Chafing and VaH alternative compared to the 2050 reference. Yet, in some places between 30-45 km from Merelbeke some losses are observed due to chafing of bends. Like the tidal mudflats in VaG AminCL, the marshes in some locations VaG undergo strong favourable or unfavourable changes that can be linked to bathymetric alterations at cut bends and channelizations. In the AplusCH scenario the losses of marshes are higher due to conversion of the lower marshes into mudflats as a result of increased tidal range and sea level rise (Figure 4-5, Figure 4-6).

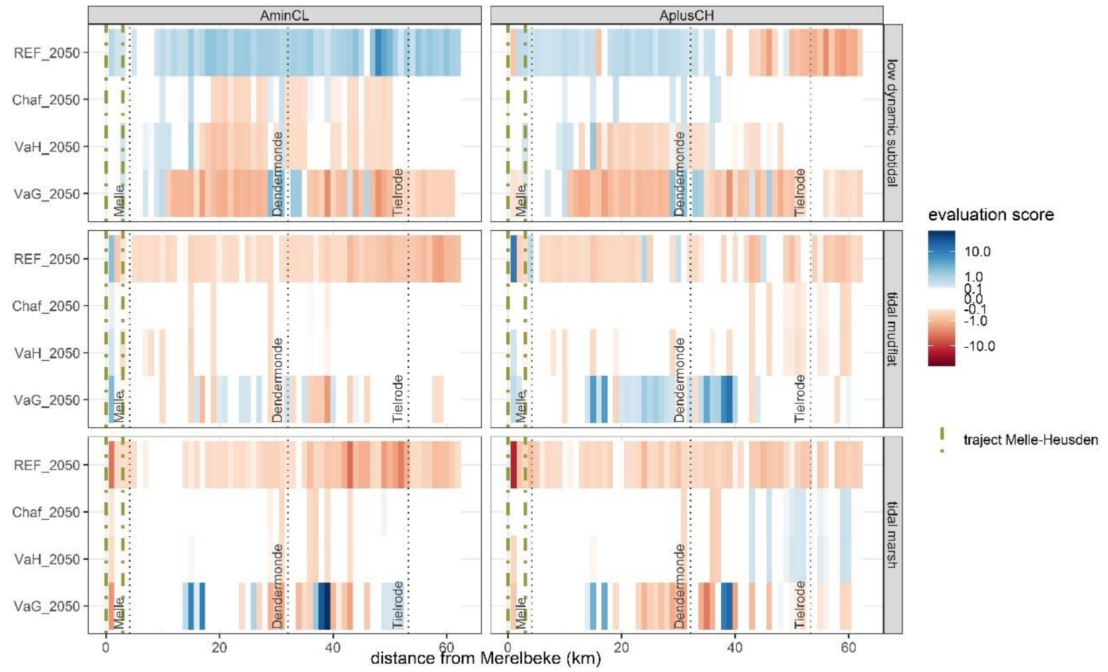

Figure 4-4: Changes in surface area (ha) of ecologically important ecotopes. Only changes > 0.1 ha are shown. Blue indicates favourable evolution; red indicates unfavourable evolution. REF_2050 compared to ACT 2013 and alternatives compared to REF_2050.

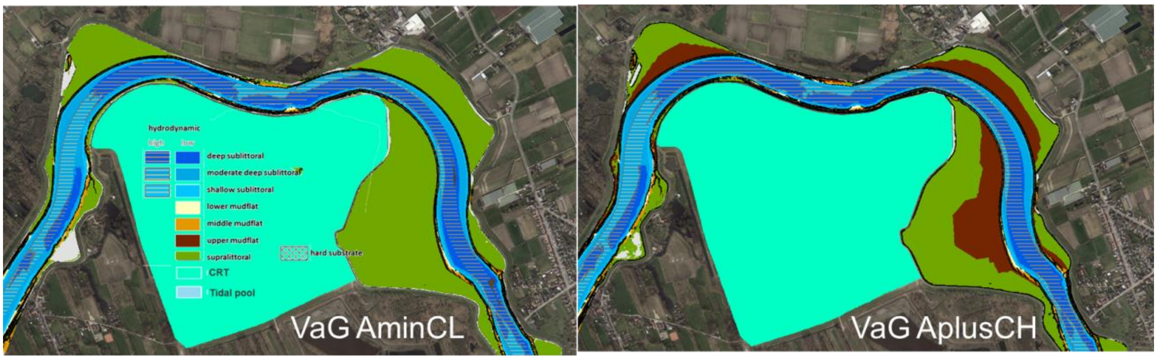

Figure 4-5: Example with elevated outer banks at cut bends (Kramp) which become tidal mudflat in VaG AplusCH (b) while in VaG AminCL (a) they are less flooded, supralitoral tidal marsh area.

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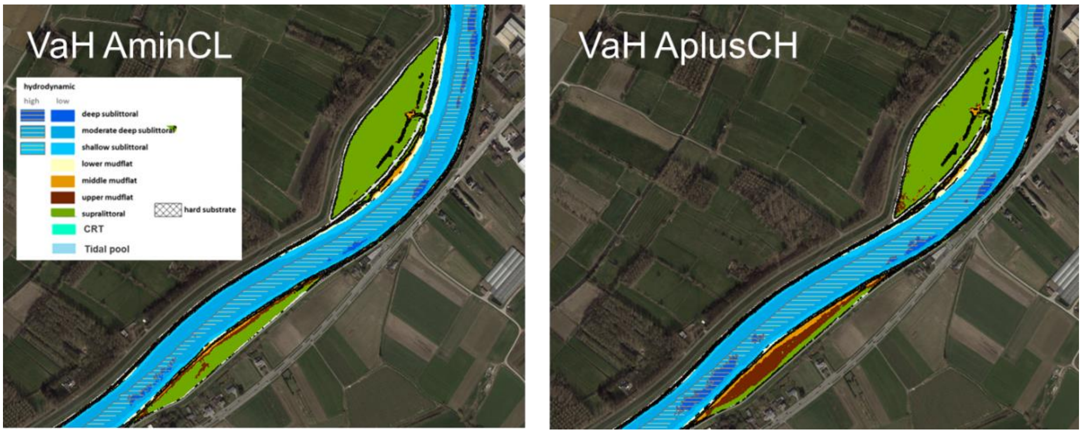

Figure 4-6: Illustration of the drowning of narrow tidal marsh borders as seen in AplusCH scenario (Paddebeek).

4.3.3 Habitat quality

4.3.3.1 Hardening of the estuary

The percentage of hard substrate on steep tidal flats near the fairway (excl. CRT and MR) increases by about 5% in the 2050 reference compared to the current situation (ACT 2013), going from a level of 29% to 34% of hard substrate (Table 4-5). The percentage of hard substrate does not change substantially in the B-alternatives compared to the 2050 reference (≤ 2% difference).

Table 4-5: Percentage of hard substrate in the tidal mudflat zone near the fairway per OMES zone and for the different alternatives and climate scenarios.

Hard substrate (%)	ACT 2013	REF 2050		Chaf 2050		VaH 2050		VaG 2050	
OMES		Amin CL	Aplus CH	Amin CL	Aplus CH	Amin CL	Aplus CH	Amin CL	Aplus CH
14	14	16	17	16	17	16	17	16	17
15	25	29	30	29	30	29	30	30	31
16	53	58	57	59	56	59	58	64	36
17	48	53	52	54	52	54	53	54	47
18	53	61	65	64	66	65	68	71	45
19	38	49	40	49	40	51	42	49	43
Tot%	29	34	34	35	34	35	35	36	32
Δ alter-ACT		5	5	6	5	6	6	7	3
Δ alter-REF				1	0	1	1	2	-2

4.3.3.2 Propensity for erosion/sedimentation on mudflats

In Figure 4-7 the *evolution* of the propensity for erosion/sedimentation 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. The evolution from ACT2013 to REF2050 is mostly favourable in the AminCL scenario, with a reduction of the TAU50 in most locations resulting in sedimentation in response to sea level rise and the evolution of a concave profile (strongest sedimentation in the middle mudflats). However, there are also indications of unfavourable evolutions (increased TAU50) between 0 and 45km from the sluices in Merelbeke with steepening of the lower mudflats. In the AplusCH scenario an expected sedimentation response to sea level rise still occurs in the higher mudflats but the lower mudflats endure clear increases (absolute value > 0.05) in TAU50, with an increased and unfavorable steepening of the mudflats as result, especially near low water.

When comparing the B-alternatives to REF2050, a fairly uniform increase in the propensity for erosion is found, resulting in an unfavourable steepening (strongest erosion in the lower mudflats) of the mudflats in all alternatives and climate scenarios. The strongest unfavourable evolution (steepening) is found in the VaG alternative. The few locations with strong reductions in TAU50 (suggesting sedimentation) in VaG are often located at cut off bents, where tidal mudflat or subtidal area is reversed into marsh area (Figure 4-8).

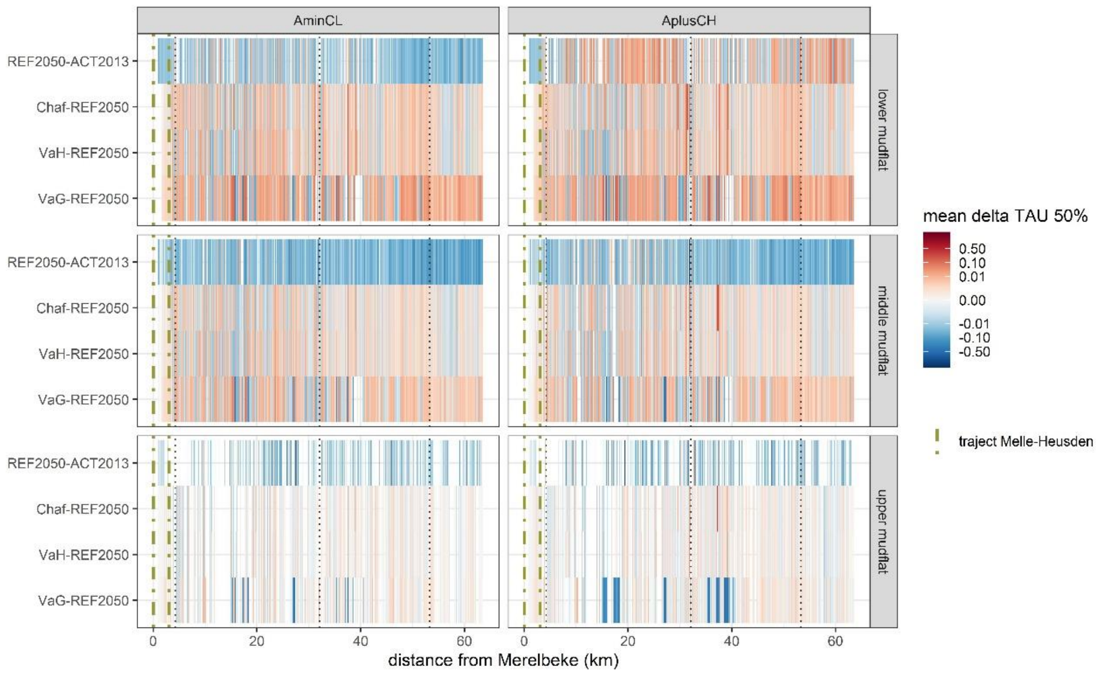

Figure 4-7: Changes in velocity shear stress (TAU50% (pascal)) conditions on the lower, middle and upper tidal mudflats (mean per km-zone of the delta TAU50%).

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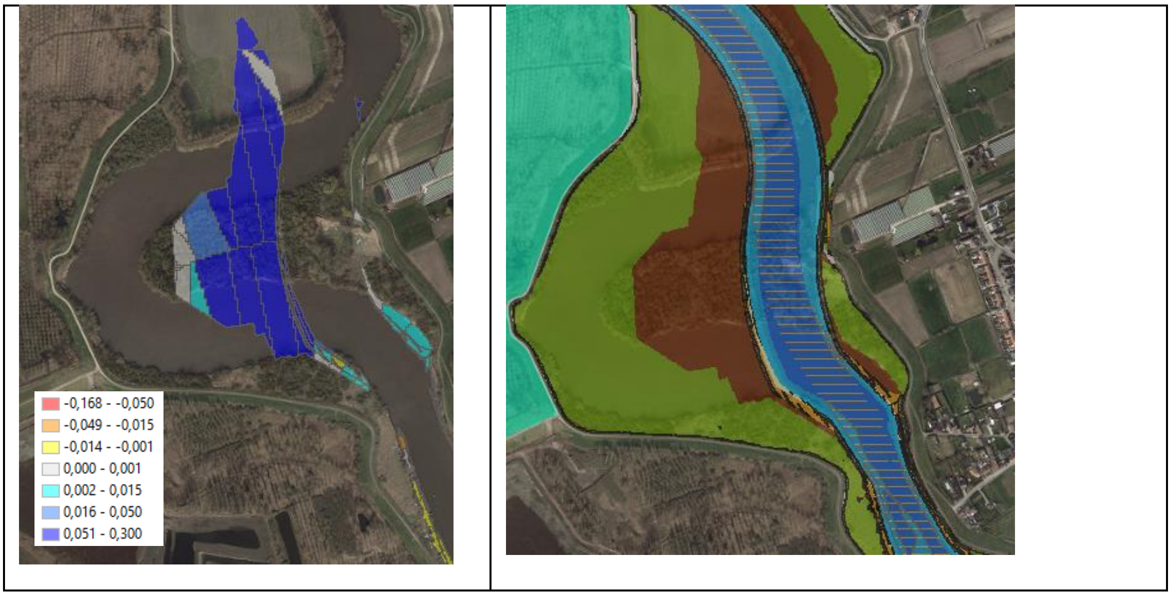

Figure 4-8: Example of extreme reduction in shear stress in VaG AplusCH as a consequence of a cut off bent: decrease of shear stress (TAU 50; blue coloured area in the left panel) in the high tidal mudflat (brown coloured area in the right panel).

4.3.3.3 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).

Without a solid expectation for the autonomous morphological evolution of the mudflats, evaluation of the proportion of macrobenthos rich mudflats has to proceed with caution. The overall percentage of macrobenthos rich mudflats increases with about 20% to a level of 80% in the 2050 reference and B-alternatives mainly due to the inclusion of new CRTs and managed realignments.

Table 4-6: Proportion of high macrobenthic density habitat in the tidal mudflat zone (%) per OMESzone for the different alternatives in the AminCL and AplusCH scenario.

High quality mudflat (%)	**ACT 2013**	**REF 2050**		**Chaf 2050**		**VaH 2050**		**VaG 2050**	
OMES		**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**	**Amin CL**	**Aplus CH**
14	60	77	74	77	74	77	74	77	74
15	56	81	80	81	80	81	80	81	80
16	69	91	88	91	88	91	88	90	93
17	59	57	56	58	57	57	56	60	67
18	74	90	88	91	88	91	89	92	93
19	53	74	82	76	82	78	84	82	84
Tot	60	80	79	80	79	80	79	80	81
Δ alter-ACT		20	19	20	19	20	19	20	21
Δ alter-REF				0	0	0	0	0	2

4.3.4 Salinity zones

Salinity is a major determinant of both faunal and floral species composition along the Sea Scheldt. The reference state in the most extreme scenario AplusCH increased salt intrusion results in a 6km upstream shift of the limit between the fresh water and oligohaline salinity zone. Also the salinity tolerance limit of Salix (Willow) species shifts 6km upstream. This means that the occurrence of rare alluvial forests (Natura2000 habitat type 91E0) is threatened under climate change. On the other hand, as the lower limit of the mesohaline zone moves 3km upstream under climate change, the potential for salt meadows under grazing management (Natura2000 habitat type 1330) increases.

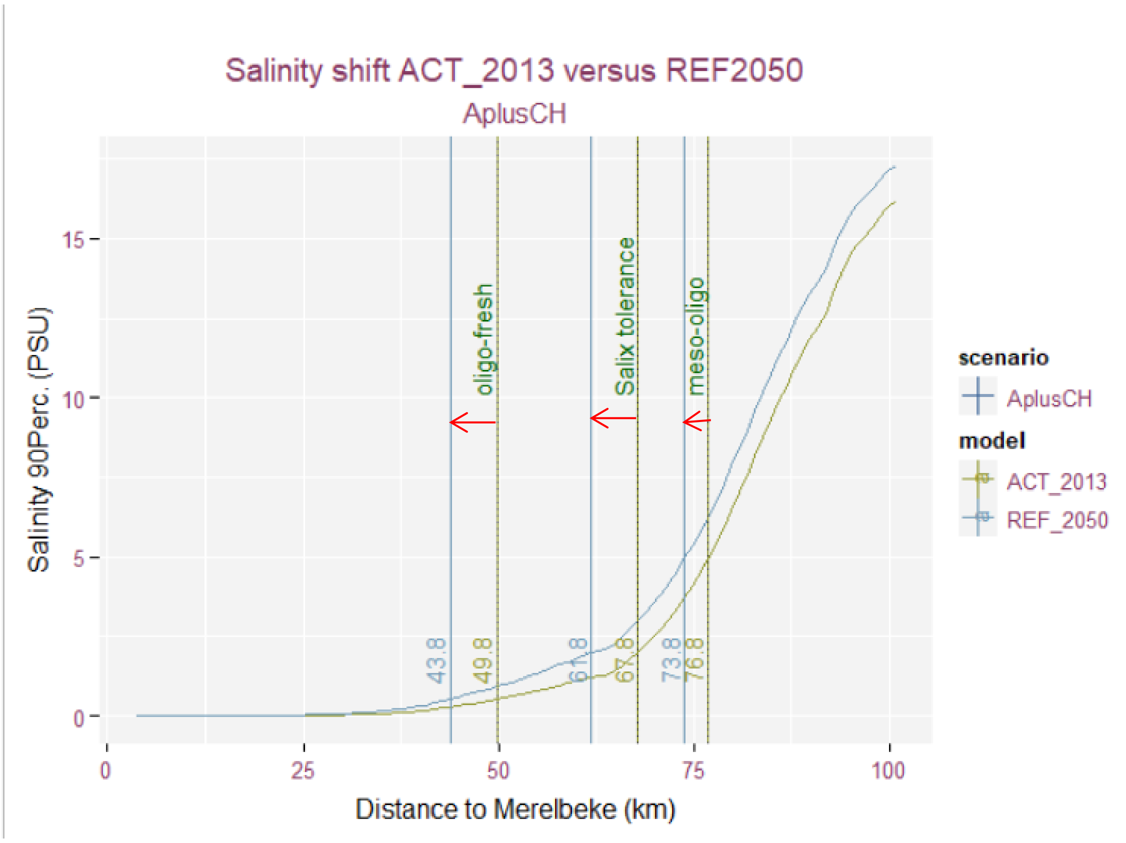

Figure 4-9: modelled maximum (P90) salinity (period 5 years) for the actual situation (ACT_2013, green) and the Reference scenario 2050 (REF_2050, blue) for AplusCH scenario. The vertical lines show the salinity limits (0.5 PSU, Oligohaline-freshwater limit (oligo-fresh), 5 PSU mesohaline-oligohaline limit (meso-oligo)) and the tolerance limit for growth of willow (Salix) species (2 PSU).

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4.3.5 Conclusions

Tidal regime

As could be expected, the forced changes in tidal amplitude in Vlissingen (climate scenarios) have a predominant effect on the tidal regime and are more important than the effect of sea level rise. In the downstream part of the Sea Scheldt, the tidal amplitudes follow the forced tidal amplitude at Vlissingen, with reduced tidal amplitudes for the A- scenario and increased tidal amplitudes for the A+ scenario. Yet, there is an important effect of the implemented sustainable bathymetry towards 2050, with a shift of 5km of the maximum tidal range location in the upstream direction. As a consequence, even for the low climate scenario with reduced tidal amplitude at Vlissingen the tidal amplitudes upstream are larger than for the actual situation (2013 reference). These observed effects of increase in tidal amplitude between REF2013 and REF2050 suggest to re-evaluate the implementation of the sustainable bathymetry.

Indeed, all scenarios and alternatives predict an unfavourable increase of tidal amplitude in the upstream part of the Upper Sea Scheldt (50km or less from Merelbeke). The unfavourable increases in tidal amplitude are further fortified in the VaG alternative due to shortening of the river axis.

Surface area (habitat quantity)

The shallow subtidal areas are in an unfavourable state in the 2013 reference and for all future bathymetries and scenarios. This is mainly due to the deepening of the channel in the past centuries without lateral expansion of the river, leaving only small fringes of shallow water along the main channel. The bathymetric alternatives and climate scenarios have little effect expect for VAG, which slightly decreases the surface area of shallow water. In all future bathymetries, the tidal mudflats are in a favourable state in OMES 15 and 18 only. Despite the inclusion of new CRT areas and managed realignments in 2050 with the creation considerable additional intertidal area, the state of the tidal mudflats remains in an unfavourable state in the other OMES zones. The tidal marshes are in an unfavourable state only in OMES 17 and 19. In OMES 14 and 16 the state of the marshes is unfavourable in the 2013 reference but becomes favourable in the 2050 bathymetries, due to the inclusion of new CRT areas and managed realignments in 2050. The same is observed for the overall state (over all OMES zones) of the marshes.

There is a largely favourable evolution of the low dynamic subtidal area comparing the current situation with the future reference with reduced climate impact (AminCL). With increased climate impact, only the upstream part is predicted to have slightly higher areas of low dynamic area. However, all bathymetric alternatives reduce the area of low dynamic subtidal area, due to increased water velocity. Excluding the positive effects of new CRTs and managed realignments, intertidal mudflats and marshes near the fairway show an unfavourable evolution between the current and the future reference. Chafing and VaH alternatives reveal no to slight unfavourable evolutions compared to the 2050 reference. The strongest evolution in mudflats and marshes is observed for the VaG alternative, with mixed (favorable or unvaforable depending on the location) evolutions. Due to sea level rise and increased tidal range in the high climate scenario a positive evolution of the mudflats is observed at the expense of the lower marshes which are drowning.

Habitat quality

- Hardening of the estuary near the fairway increases in all future alternatives (including the 2050 reference) with about 5% compared to the current situation.
- The evolution of the propensity for erosion of the future reference with reduces climate impact is favourable compared to the 2013 (reduced shear stress on mudflats). But the future reference with high climate impact shows the unfavorable evolution to concave mudflats by increased shear stress on the lower mudflats. Evolution of the B-alternatives is mostly unfavourable with a risk of steepening of the mudflats.
- The percentage of mudflats with high macrobenthic biomass increases in the future bathymetries compared to 2013 and remains stable in the alternatives compared to the 2050 reference. Nevertheless, steepening of the mudflats in the B-alternatives may result in a lowering of the biomass production of macrobenthos.

Salinity zones

Salt intrusion further upstream as a result of climate change entails a risk of losing rare fresh water alluvial forests (habitat type 91E0) and freshwater pioneer vegetation species.

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5 EVALUATION OF HABITAT SUITABILITY FOR TWAITE SHAD

5.1 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 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).

5.2 EVALUATION METHODOLOGY

The *state* of the suitability for spawning (SI_{adult}) and for larval development (SI_{larval}) is given in the results. Because of the 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.

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

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

A reduction in SI_{focus} compared to the reference (see Table 3-1) is evaluated as unfavourable and *vice versa*.

Both the *state* and *evolution* are calculated per kilometre. Only changes with an absolute value larger than 0.05 are taken into account. Changes smaller than 0.05 (absolute value) 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 from 5 consecutive years are available (2009-2013 for the current situation; equivalent to 2046-2050 for 2050 results). For water depth and water velocity only a single estimate per kilometre is available for each alternative and scenario. Both for estimates of SI dependent on a single predictor variable (except for water depth and velocity) and for the overall SI based on all variables, an estimate is produced for each year. For the *state* of the suitability index, both the mean over years and the minimum (worst case) are presented. For the *evolution* of the suitability, we opted for a worst-case approach, in which ΔSI between focus and reference (where ΔSI ranges between -1 and 1) is calculated using in each case the minimum (worst case) value over years. We chose this conservative approach to accommodate for the build-up of uncertainty in the modelling results throughout the modelling train. Any improvement of the worst case is detected in this approach. Moreover, any detected deterioration of the suitability for spawning or larval development functions as a warning flag indicating a potential risk of deterioration of the habitat of Twaite shad in the Sea Scheldt.

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

5.3 RE-ANALYSIS OF RESULTS WITH DEEPENED RINGVAART

To accommodate for the discrepancy in bathymetry of the Ringvaart between REF_2050 and the B-alternatives, the sediment transport of the AplusCH scenario was rerun (Bi et al. 2018) for the 2050 reference, taking into account a deepened Ringvaart. Based on these results and a rerun of the ecosystem model (Maris et al., 2022) for REF_2050 and the B-alternatives (climate scenario AplusCH), a new analysis of SI was made for the AplusCH climate scenario. Because of a recalibration of the ecosystem model prior to rerunning the 2050 reference and B-alternatives in the AplusCH scenario, a comparison of the new results with the 2013 reference (ACT_2013) and the original AminCL results is not possible.

5.4 RESULTS

For the A-CL scenario, results are only available for ACT_2013, REF_2050 and the VaG alternative. For the A+CH scenario results have been calculated for all alternative bathymetries.

5.4.1 Suitability for larval development

On average the *state* of the Sea Scheldt is suitable for larval development upstream of 60 km from Merelbeke (Figure 5-1A). Downstream of Antwerp the river is unsuitable because of high salinity levels (Figure 5-4A, Appendices Figure A 1). Between Antwerp and Tielrode, low levels of oxygen are the most important factor lowering the suitability for larval development (Figure 5-4B, Appendices Figure A 1). Although on average suitability is reasonably high in the Upper Sea Scheldt, in some years (low discharge and high dredging intensity, e.g. 2048 [= 2011]) suspended matter (SPM) can be too high (especially between Dendermonde and Antwerpen) for survival of larval Twaite shad (Figure 5-4C, Appendices Figure A 1), severely reducing the overall estimate of SI (Figure 5-1B).

5.4.1.1 Comparison of the future reference with the current state

Changes in SI (*evolution* of SI) between the current state (ACT_2013) and the 2050 reference (REF_2050) are mainly visible between 40 and 60 km from Merelbeke and between 65 and 75 km from Merelbeke and are mostly favorable. Favorable evolutions between 40 and 60 km from Merelbeke are associated with reduced levels of SPM (Figure 5-2, Figure 5-3, Figure

5-4C). Favorable evolutions between 65 and 75 km from Merelbeke are associated with increased levels of oxygen (Figure 5-2, Figure 5-3, Figure 5-4B).

When zooming in on the response of the suitability index to variation in the individual input variables, improvements in SI associated with reduced maximum water velocities can be observed for the AminCL scenario in REF_2050 compared to ACT_2013 along the entire stretch of the Upper Sea Scheldt (Figure 5-3, Figure 5-4D). For the AplusCH scenario, however, these positive effects are largely canceled due to unfavourable effects of climate change, resulting even in deteriorations of SI between the inflow of Durme and Rupel and near Antwerpen as a result of increased maximum water velocity in these areas.

Focusing on salinity, an unfavorable evolution can be observed towards 2050 near and downstream of Antwerpen (> 75 km from Merelbeke) due to intrusion of salt (see also Figure 4-9). As the (early) development of larval Twaite shad occurs in freshwater, intrusion of salt further upstream will reduce the available area where development is possible. Both climate scenarios indeed predict an increased salt intrusion towards 2050 as a result of sea level rise and possibly increased tidal amplitides (only AplusCH) (see also 4.3.4). If more frequent and longer periods of low discharge are to be expected as a result of climate change, this could further increase the risk of salt intrusion with a reduction of freshwater habitat in the Sea Scheldt.

In a short stretch between 50 and 60 km from Merelbeke a strong reduction in SI is observed in scenario AminCL, due to reduced oxygen levels in the future reference compared to the current situation (Figure 5-2, Figure 5-3, Figure 5-4B). In this zone oxygen levels drop below 5 mg/l in the future scenarios and lower the viability for fish due to an oxygen deficit. There is, however, a considerable uncertainty in the predicted levels of oxygen of the ecosystem model (Maris et al., 2022), and expert expectations are that oxygen levels will not drop as severely as predicted by the ecosystem model. It is thus not clear if the calculated oxygen deficit in this short stretch compared to ACT_2013 is a reliable outcome of the modelling train and therefore relevant.

5.4.1.2 Comparison of alternative bathymetries with the future reference

When comparing the alternative bathymetries with the reference 2050, the most obvious (and favorable) changes in habitat suitability for larval development are situated less than 60 km from Merelbeke (Figure 5-2). These changes, however, are associated with reduced levels of SPM in the B-alternatives compared to the 2050 reference situation. As explained higher (see 5.3), a comparison of the *evolution* of SI between REF_2050 and the B-alternatives in function of SPM is unfortunately not possible in the standard analysis of the B-alternatives because in the alternatives, a deepening of the Ringvaart was implemented in the bathymetry, which is not present in REF_2050. This deepening of the Ringvaart acts as a sediment trap and masks changes in SPM concentrations that could occur due to more downstream changes to the bathymetry in the B-alternatives. Results for the AplusCH climate scenario with deepened Ringvaart in the 2050 reference are discussed in paragraph 5.4.1.3.

In the Chafing and VaG alternative, unfavourable effects on SI between Rupel and Antwerpen can also be observed, which are associated with reduced oxygen levels in these alternatives compared to REF_2050 (Figure 5-3). The changes in oxygen levels are very subtle (Figure 5-4), and the model is very sensitive for changes in oxygen levels in the range between 4 and 5 mg/l (cf. In VaH the oxygen levels are slightly higher than in Chafing and VaG and do not drop below the 5 mg/l threshold). In addition, as mentioned, there is considerable uncertainty in the predicted levels of oxygen from the pelagic ecosystem model (Maris et al., 2022). Therefore, these results should be interpreted with care. Nevertheless, the oxygen levels in spring and summer are invariantly low in this area and in the past frequently dropped below the threshold for viability of Twaite shad and fish in general (< 4-5 mg/l). 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. Any indications that the oxygen levels could drop again should be taken into account.

Upstream of Dendermonde, increased maximum water velocities in VaG result in an unfavourable deterioration of the suitability index (Figure 5-3, Figure 5-4). Larvae need sheltered areas near the riverbanks to avoid being flushed by strong currents. In recent years, larval and juvenile Twaite shad are detected up to Merelbeke, and a reduction of sheltered pockets in the VaG alternative, might thus negatively impact suitability in this area. Also downstream of Dendermonde water velocities should be monitored. Heavy and/or prolonged rainfall may also in this zone entail a risk of flushing due to temporary high discharges. Results for REF_2050 (see above) indeed suggest that this might occur in the future due to climate change. Particularly during spawning, which predominantly occurs in the zone between Dendermonde and the inflow of the Rupel, high discharges might be undesirable, as the freshly produced eggs drift passively in the water until they hatch three to four days after release. During that period, they risk being carried too far downstream where salinities are too high for survival of the larvae. In all three alternatives the effect of changes in maximum water velocity between 60 and 80 km from Merelbeke are strongly dependent on the local conditions. Near Antwerp there is a severe deterioration of SI because of a peak in maximum water velocity. Upstream and downstream of Antwerp water currents evolve mostly favourable (lower velocities).

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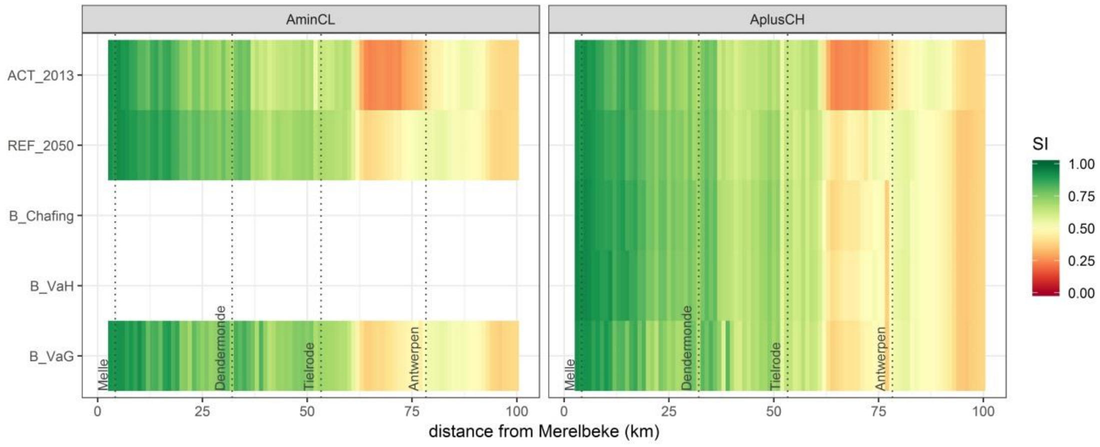

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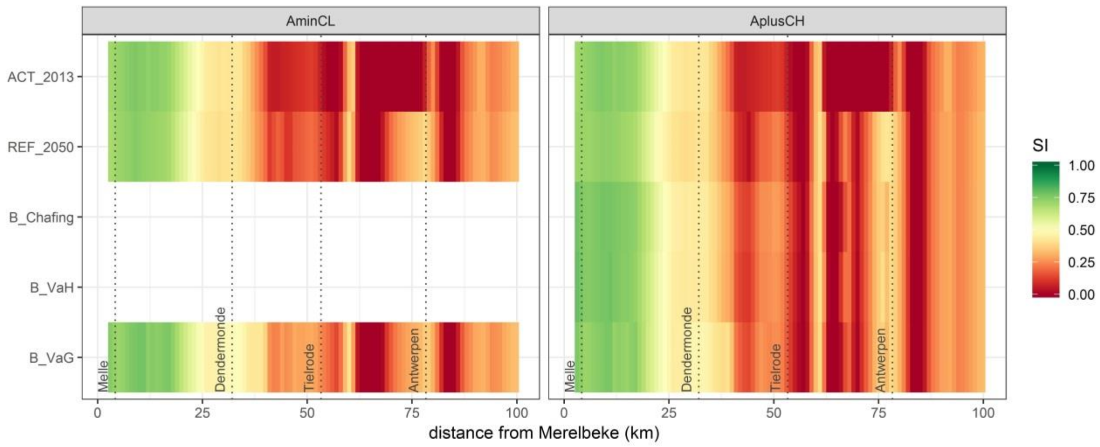

Figure 5-1: Suitability index for larval development (SI_{larval}). **A)** mean value over modeled years; **B)** minimum value over modeled years.

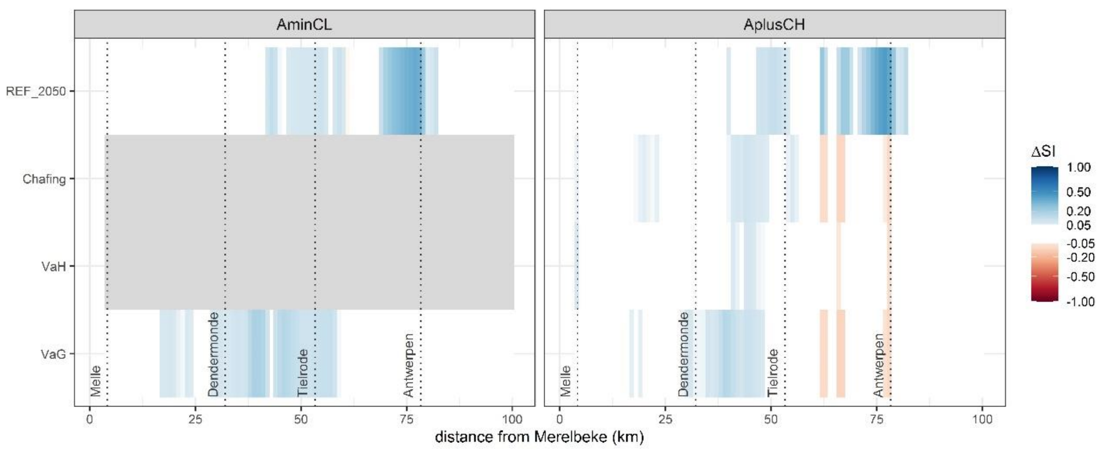

Figure 5-2: evolution of the suitability index for larval development (ΔSI_{larval}; worst case scenario). Blue indicates favourable evolution; red indicates unfavourable evolution.

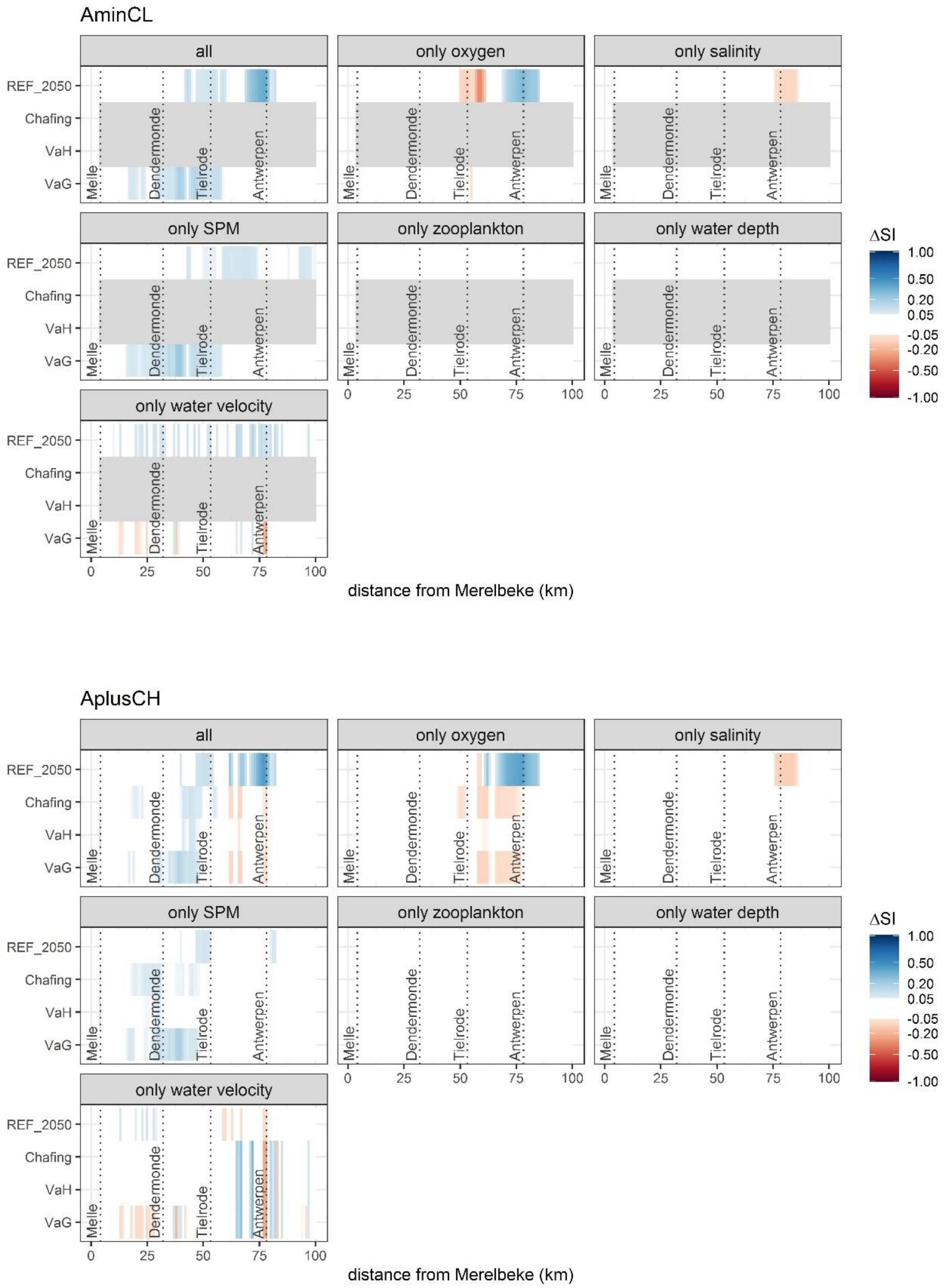

Figure 5-3: evolution of the suitability index (SI_{larval}; worst case scenario) in response to individual predictor variables. Blue indicates favourable evolution; red indicates unfavourable evolution.

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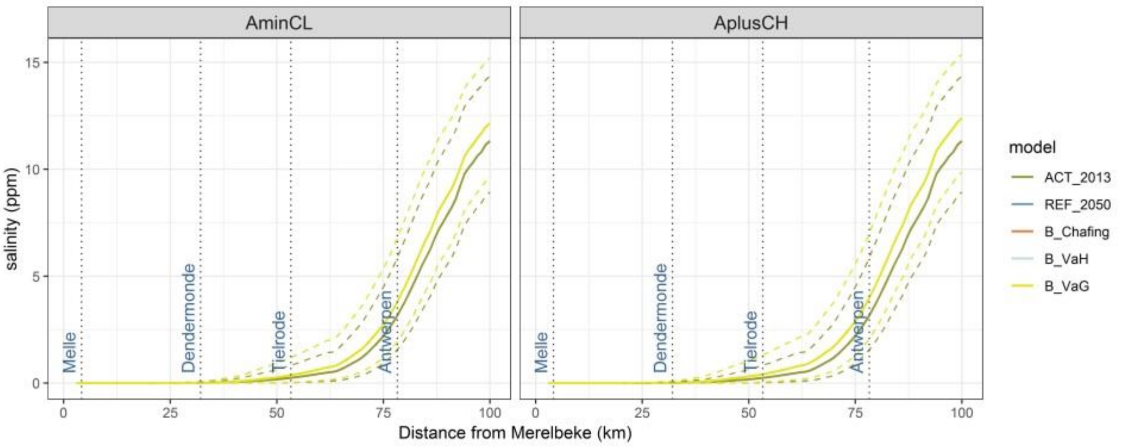
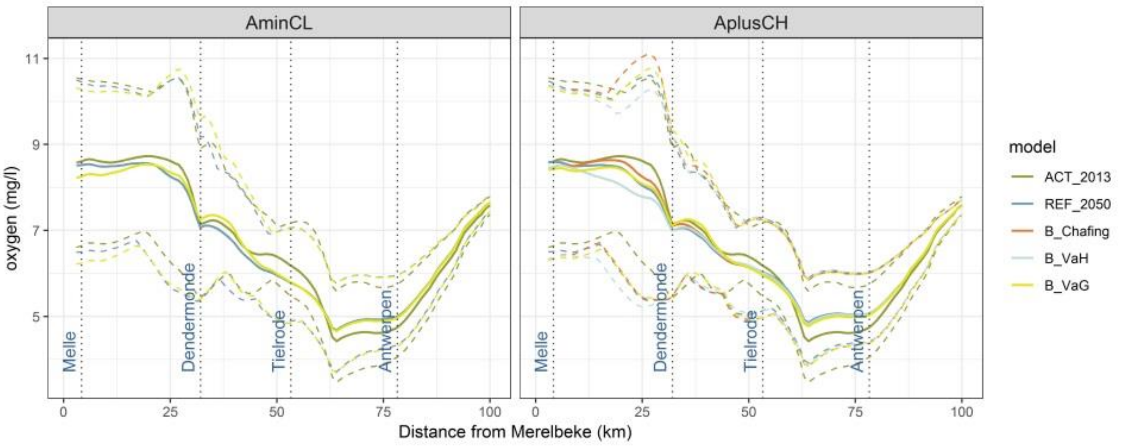
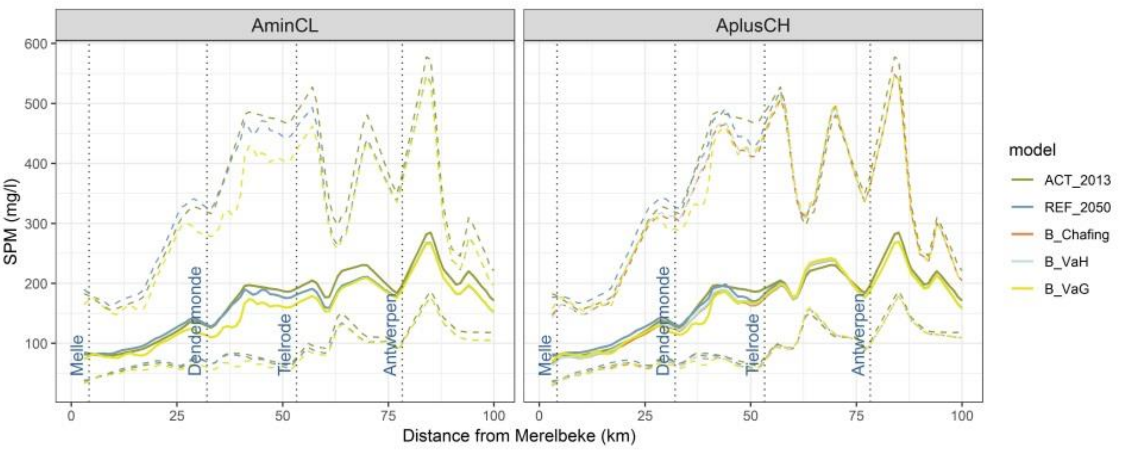

AminCL
AplusCH
salinity (ppm)
Distance from Merelbeke (km)
Melle
Dendermonde
Tielrode
Antwerpen
model
ACT_2013
REF_2050
B_Chafing
B_VaH
B_VaG

B


AminCL
AplusCH
oxygen (mg/l)
Distance from Merelbeke (km)
Melle
Dendermonde
Tielrode
Antwerpen
model
ACT_2013
REF_2050
B_Chafing
B_VaH
B_VaG

C


AminCL
AplusCH
SPM (mg/l)
Distance from Merelbeke (km)
Melle
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Tielrode
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B_VaH
B_VaG

D

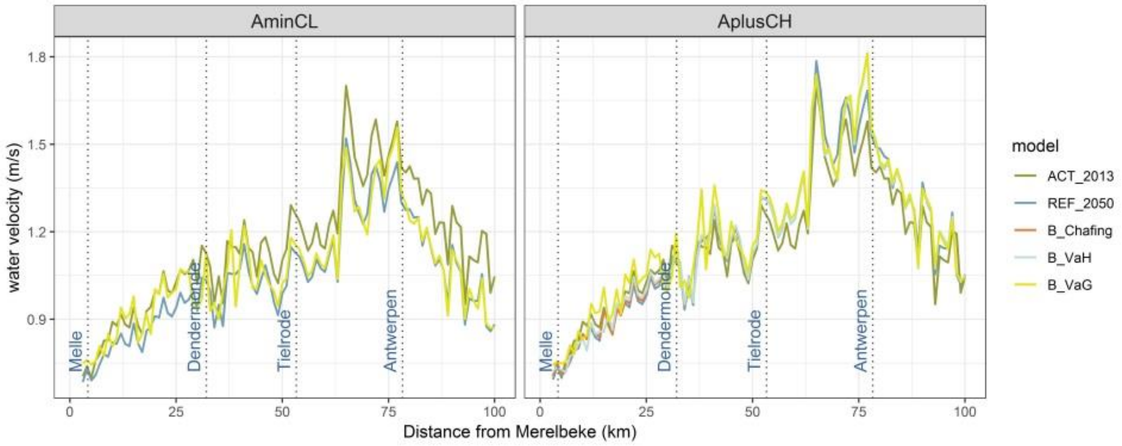

Figure 5-4: Predictor variables affecting the state and/or evolution of the suitability for larval development. Full lines represent the mean over modelled years; dashed lines represent minimum and maximum values among modelled years. (For water velocity, only a mean estimate is available).

5.4.1.3 <u>Re-analysis with deepened Ringvaart</u>

When looking at the *state* of the suitability index for larval development for the re-analysed results of the 2050 reference and B-alternatives (only climate scenario AplusCH), only in the upstream area, less than 20 km from Merelbeke, SI is consistently high (> 0.5; Figure 5-5). Lower values of SI more than 20 km from Merelbeke are associated with severe drops in oxygen levels (< 5 mg/l; 20-30 km & 60-80 km from Merelbeke) and with too high levels of SPM (> 50 mg/l; > 25 km from Merelbeke).

When comparing the alternative bathymetries with the reference 2050 (ΔSI; Figure 5-6), unfavorable evolutions are observed in all three alternatives around 20 km from Merelbeke, associated with deterioration of the levels of oxygen (Figure 5-6, Figure 5-7). In the VaG alternative unfavorable evolutions, associated with deteriorated oxygen conditions, are also observed around km 30 and 60 from Merelbeke. Between km 35 and 40 from Merelbeke SI evolves favorable in VaG due to decreased levels of SPM (Figure 5-6, Figure 5-7).

Looking in more detail at the evolution in SI (ΔSI) based on individual predictor variable input (Figure 5-6B), changes in minimum oxygen levels in VaH and VaG have opposing effects on SI between km 30-35 (VaH +; VaG -) and between km 40-45 (VaH -; VaG +) from Merelbeke. The results with respect to water velocity are identical to the results of the original B runs, with unfavorable evolutions in VaG upstream of Dendermonde and around Antwerpen, due to increased maximum water velocities, and with mostly favorable evolutions in SI in all B-alteratives upstream and downstream of Antwerpen, due to reduced maximum water velocities.

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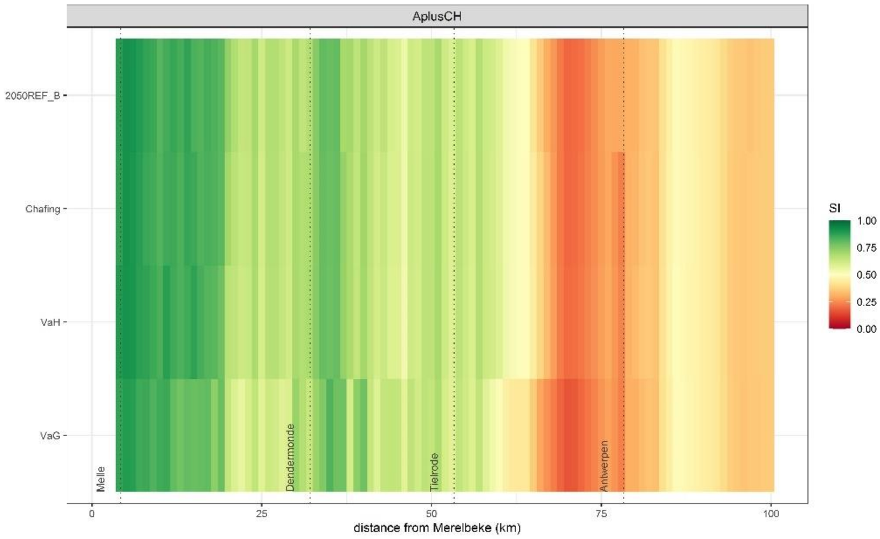

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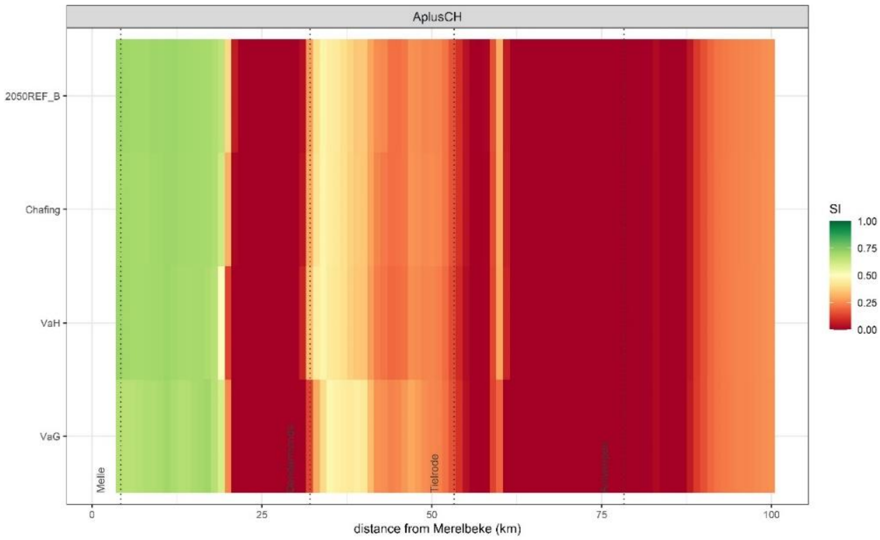

Figure 5-5: Suitability index for larval development (SI_{larval}) (climate scenario ApusCH). Results after rerun with altered bathymetry at the Ringvaart for REF_2050. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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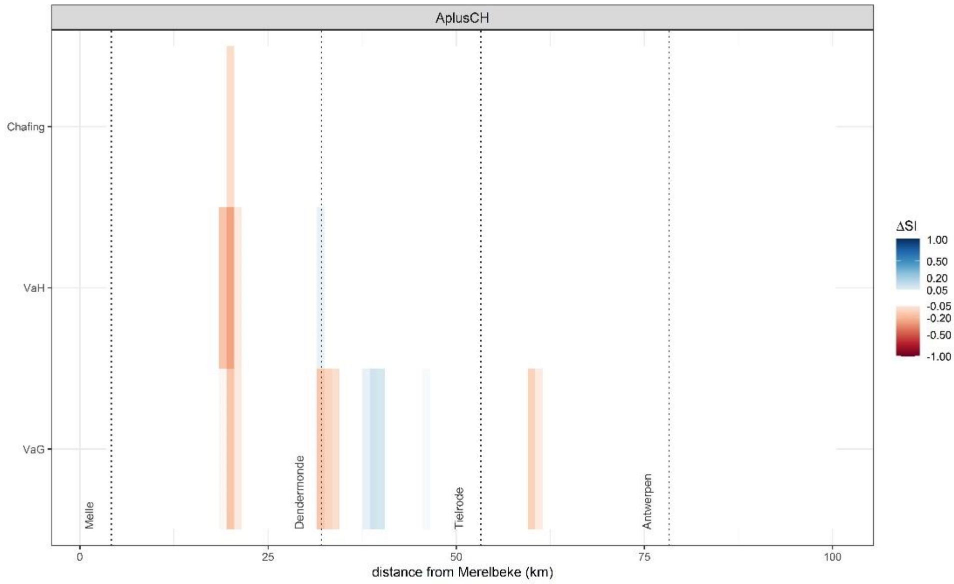

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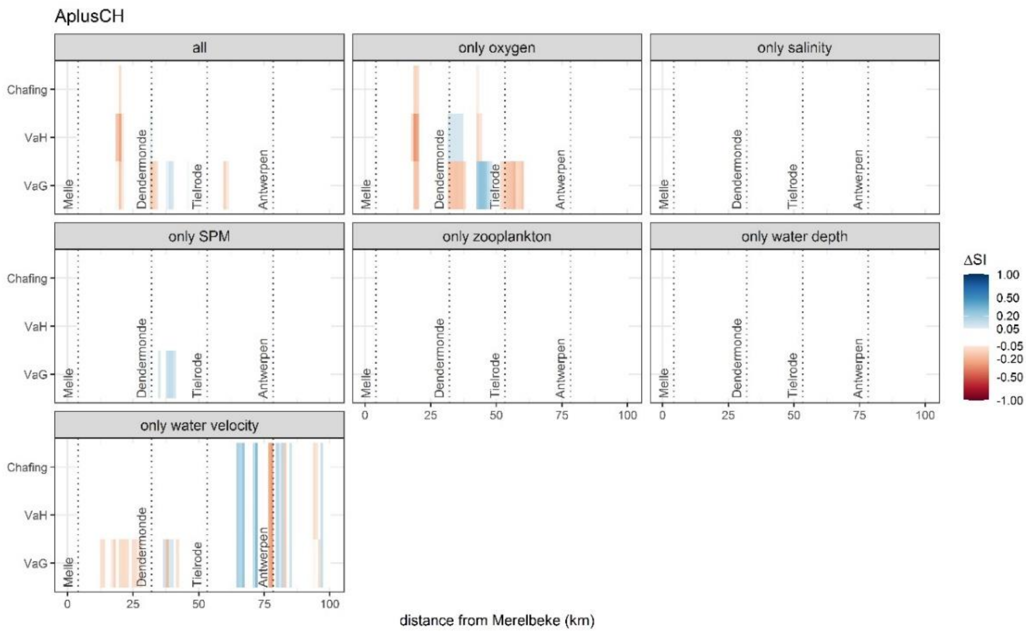

Figure 5-6: Evolution of the suitability index for larval development (ΔSI_{larval}; worst case scenario) in the B-alternatives (climate scenario ApusCH). Results after rerun with altered bathymetry at the Ringvaart for REF_2050. Blue indicates favourable evolution; red indicates unfavourable evolution. **A)** predictions including all predictor variables. **B)** Response to individual predictor variables.

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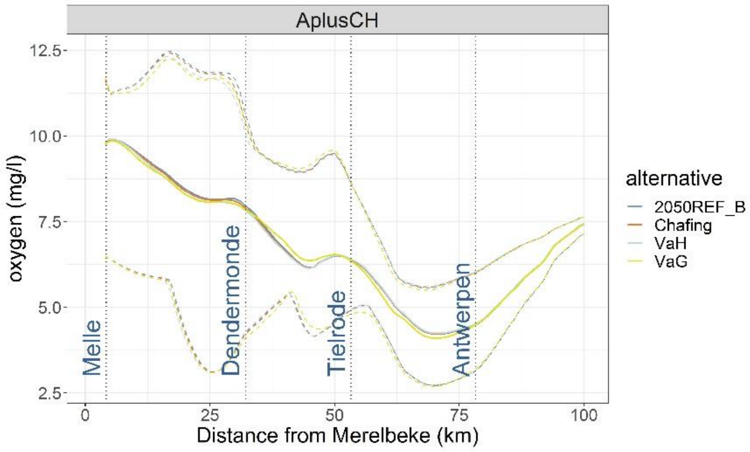

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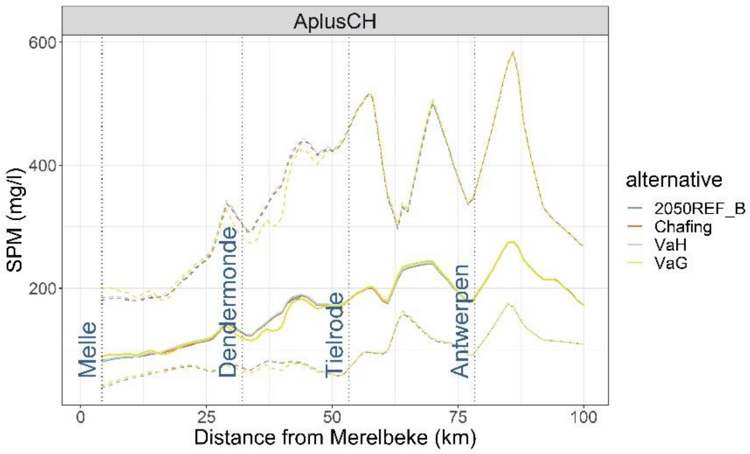

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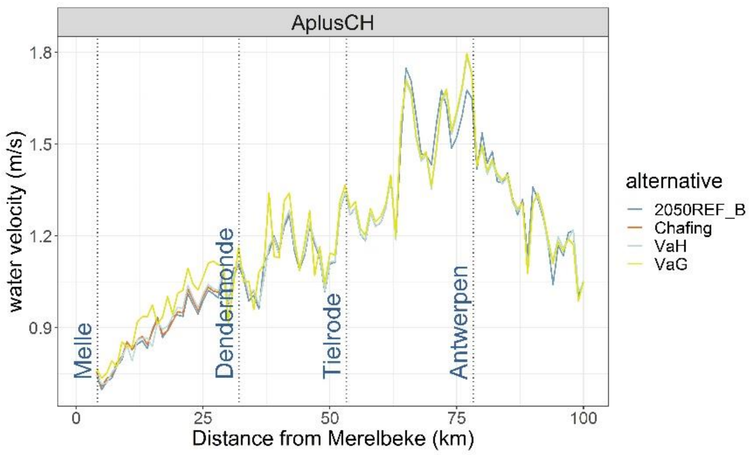

Figure 5-7: Predictor variables affecting the state and/or evolution of the suitability for larval development for the 2050 reference and B-alternatives, after a rerun with altered bathymetry at the Ringvaart for REF_2050 (climate scenario ApusCH). Full lines represent the mean over modelled years; dashed lines represent minimum and maximum values among modelled years. (For water velocity, only a mean estimate is available).

5.4.2 Suitability for spawning

Based on the suitability index (SI_{adult}), conditions for spawning (*state*) are favourable in the Upper Sea Scheldt (Figure 5-8A) both for the current and for future modelled alternatives and scenarios. 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 after considerable improvements in the water quality and the disappearance of the hypoxic zone near the inflow of the Rupel, it can be expected that the zone in which spawning occurs might further expand upstream and to the tributaries of the Scheldt (where historically Twaite shad was also found) in the future.

The suitable area for spawning is mainly delimited by high salinities downstream of Antwerp (75-80 km from Merelbeke) (Figure 5-8, Appendices Figure A 2). Changes in salinity as a consequence of climate change also affect the *evolution* of SI between the current situation (ACT_2013) and the future reference (REF_2050) (Figure 5-9, Figure 5-10). As mentioned earlier (paragraph4.3.4, paragraph 5.4.1), upstream intrusion of salinity as a result of climate change and the following reduction in freshwater tidal area is undesirable.

In analogy to the effects on larval development, reduced oxygen levels might also reduce opportunities for spawning. In particular, there are indications that in some years oxygen levels might still be too low between the inflow of the Rupel and Antwerpen (60 to 75 km from Merelbeke), inhibiting upstream migration of adults to the spawning areas (Figure 5-8B, Figure 5-9). Moreover, comparison between REF_2050 and the B-alternatives suggest that conditions might deteriorate when implementing any of the alternatives in a high climate impact scenario (AplusCH) (Figure 5-10).

For the re-analysed results of the 2050 reference and B-alternatives (only climate scenario AplusCH), conditions for spawning (*state*) are also favourable in the Upper Sea Scheldt (Figure 5-11). In the VAG alternative, a favorable evolution in the suitability for spawning is observed between km 60 and 75 from Merelbeke, associated with improved levels of oxygen (Figure 5-12, Figure 5-13).

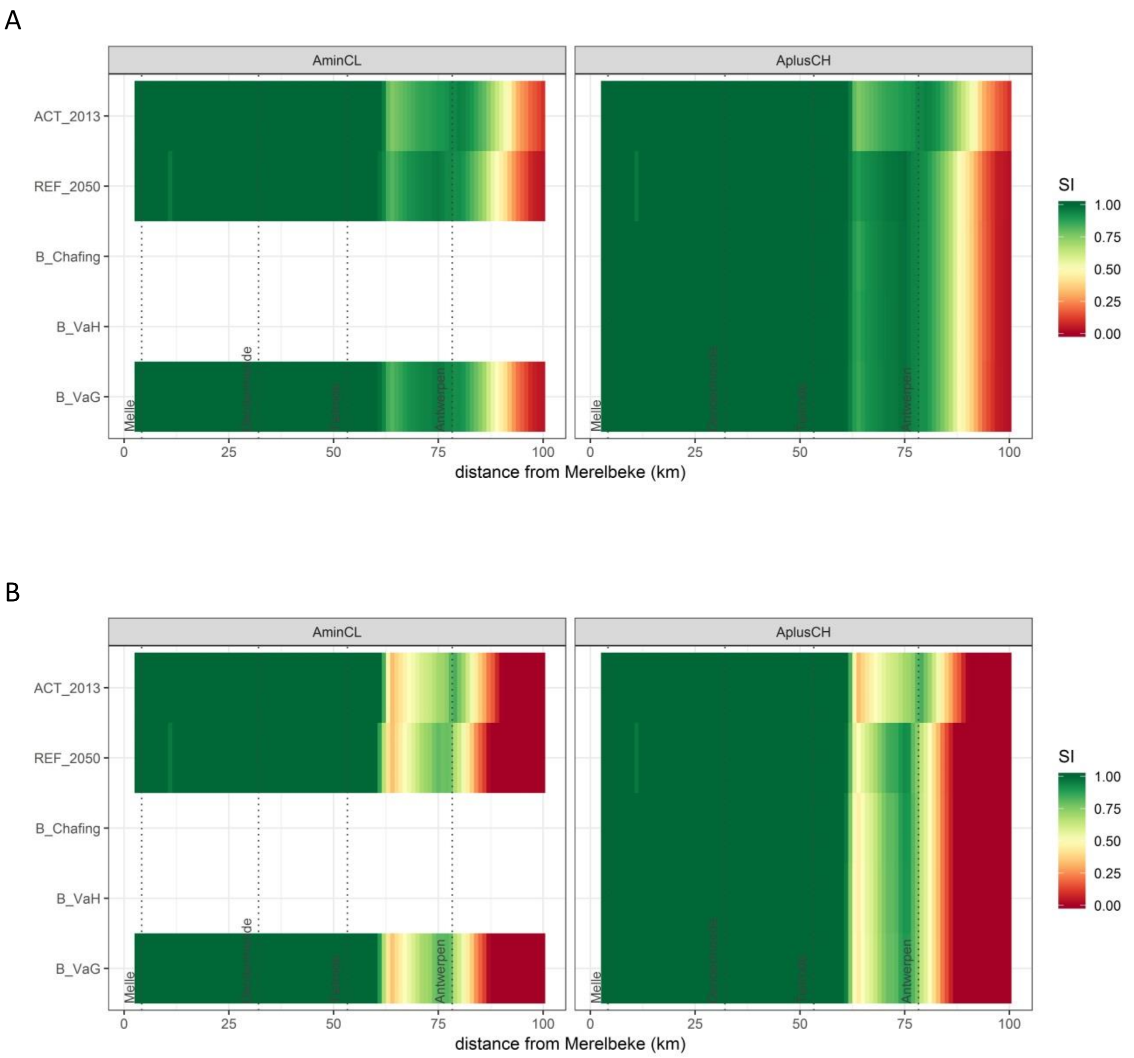

Figure 5-8: Suitability index for adult spawning (SI_{adult}). **A)** mean value over modeled years; **B)** minimum value over modeled years.

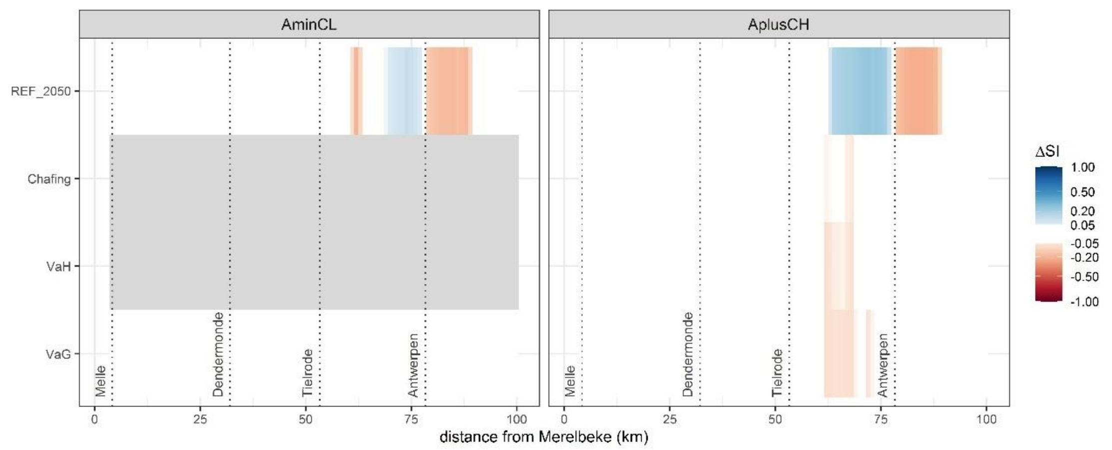

Figure 5-9: evolution of the suitability index for adult spawning (ΔSI_{adult}; worst case scenario). Blue indicates favourable evolution; red indicates unfavourable evolution.

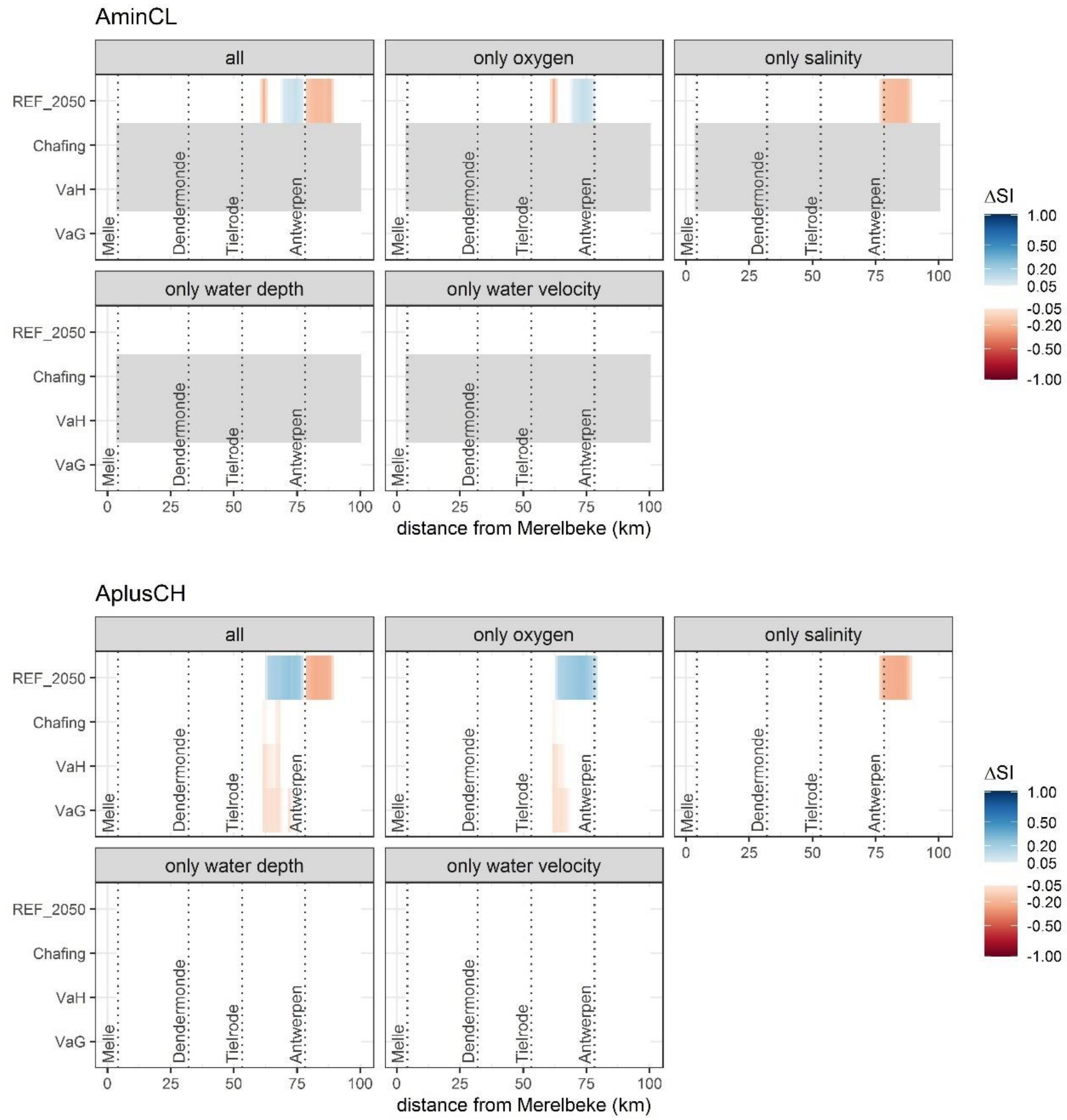

Figure 5-10: evolution of the suitability index (SI_{adult}; worst case approach) in response to individual predictor variables. Blue indicates favourable evolution; red indicates unfavourable evolution.

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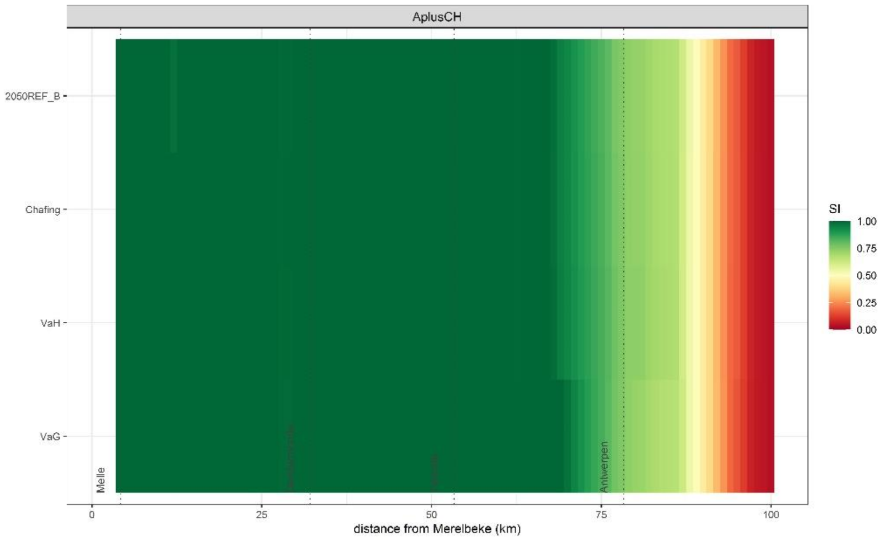

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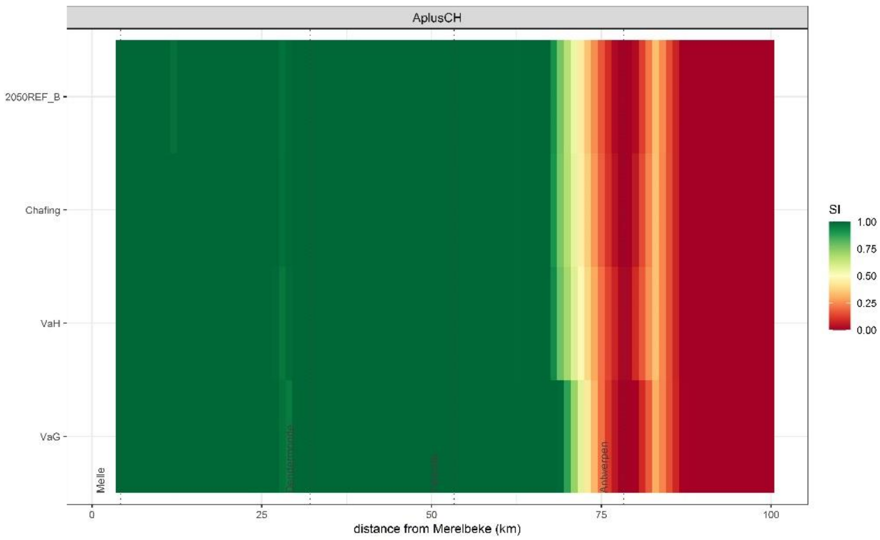

Figure 5-11: Suitability index for spawning (SI_{adult}) (climate scenario ApusCH). Results after rerun with altered bathymetry at the Ringvaart for REF_2050. **A)** mean value over modeled years; **B)** minimum value over modeled years.

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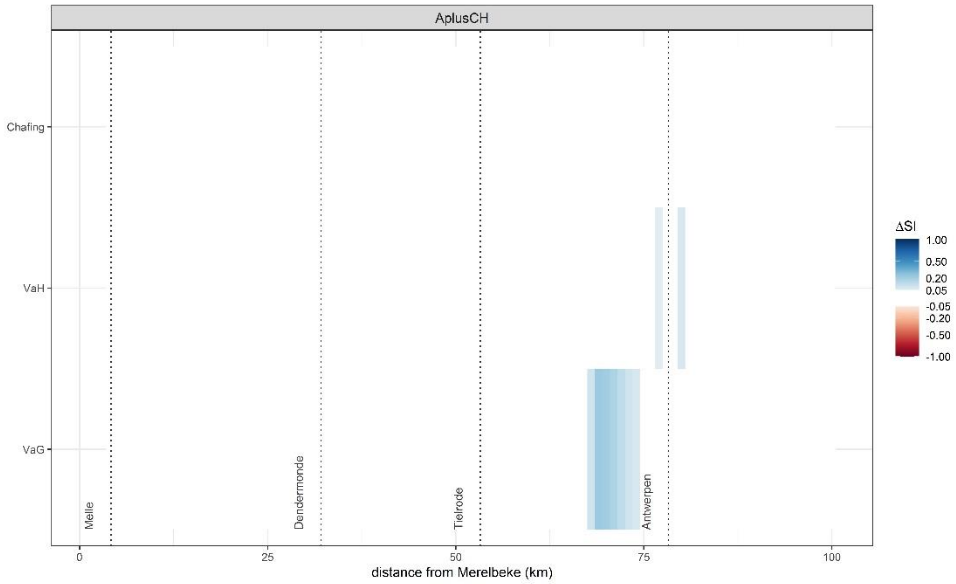

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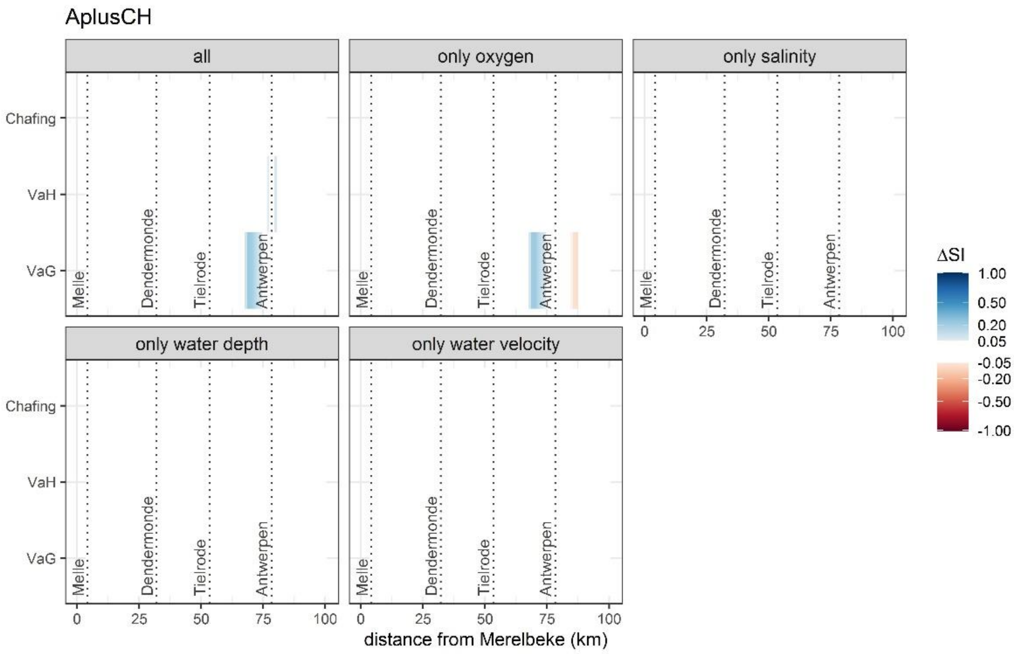

Figure 5-12: Evolution of the suitability index for spawning (ΔSI_{adult}; worst case approach) in the B-alternatives (climate scenario ApusCH). Results after rerun with altered bathymetry at the Ringvaart for REF_2050. Blue indicates favourable evolution; red indicates unfavourable evolution. **A)** predictions including all predictor variables. **B)** Response to individual predictor variables.

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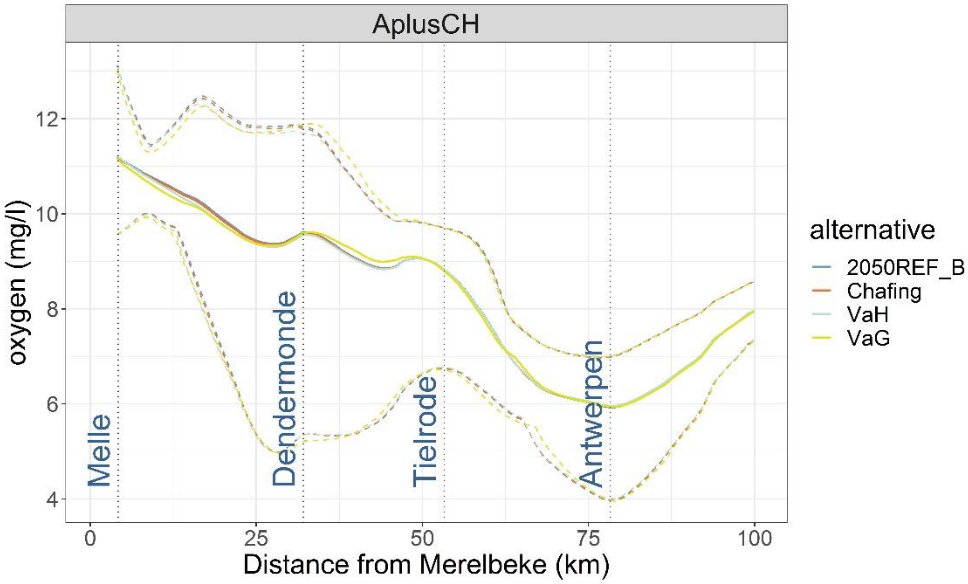

Figure 5-13: Predictor levels of oxygen affecting the state and/or evolution of the suitability for spawning (SI_{adult}). Results for reruns with altered bathymetry at the Ringvaart for REF_2050 (climate scenario ApusCH). Full lines represent the mean over modelled years; dashed lines represent minimum and maximum values among modelled years.

5.5 CONCLUSIONS

Many of the important effects on the suitability index are associated with oxygen levels in the water column. Given that there is considerable uncertainty in the estimated values of oxygen through the modeling train (pelagic ecosystem model, UA, Maris et al., 2022) and that the Twait shad suitability model is very sensitive to changes in oxygen levels below 5 mg/l, interpretation of the changes must be done with an emphasis on direction and less on effect size. From the re-analysis with a deepened Ringvaart a clear detoriation of the state is shown and although the effect size is unsure the deterioration by the hypothetical alternatives should not be neglected.

5.5.1 State of the suitability index

Based on the original runs, the state for larval development of Twait shad is suitable upstream of 60 km from Merelbeke. In some years, however, SPM can be too high for larval development. In the reruns with deepened Ringvaart (only AplusCH), however, the state is only favorable ($SI_{larval} > 0.5$) in the upper 20 km of the Sea Scheldt, due to lower values of oxygen.

5.5.2 Comparison of the future reference with the current state

There is a favourable evolution of the maximum water velocity in the 2050 reference compared to the current situation. This positive effect is only visible, however, in the low climate impact scenario. Presently observed unfavourable effects of SPM are not mitigated in the 2050 reference.

5.5.3 Comparison of alternative bathymetries with the future reference

There is an increased risk of oxygen depletion in the area between the inflow of the Rupel and Antwerp. This is an unfavourable evolution both for the upstream migration of adult fish to the spawning grounds, and the downstream migration of larvae/juveniles back to sea. In the VaG alternative, maximum water velocity risks to be too high for the larvae, with a risk of flushing to downstream and saline areas unsuitable for larval development. The re-analysis with deepened Ringvaart in the 2050 reference indicates that in the VaG alternative a reduction in suspended matter (SPM) will lead to improved conditions for larval development between km 30 and km 40 from Merelbeke.

6 EVALUATION OF OVERWINTERING NUMBERS OF COMMON TEAL

6.1 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 modelled as described in (Vanoverbeke et al., 2019b).

6.2 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:

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

Changes in the number of birds are thus evaluated relative to the number of birds occurring in the reference. A reduction in the $number_{\text{focus}}$ compared to the reference (see Table 3-1) is evaluated as unfavourable and *vice versa*.

Both the *state* and *evolution* are calculated per three kilometres (the resolution at which birds are counted in the field and the resolution of the model). Only relative changes with an absolute value larger than 5% are taken into account. Changes smaller than 5% are considered not to be different from the reference.

6.3 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 4.3.2), evaluation of the *evolution* in numbers of Common teal only takes into account changes that occur within the river bed, and do not include newly created CRT areas and managed realignments (realizations of the SIGMA plan). For the *state*, both results with and without the newly created estuarine area are presented.

The *state* and *evolution* of the numbers of Common teal largely correspond to the results for the surface area of the mudflats (see paragraph 4.3.2, Appendices Figure A 3).

With respect to *state*, the majority of Common teal are in general found between the inflow of Durme and Rupel (50 – 60 km from Merelbeke) (Figure 6-1, without NEA), where the largest mudflats occur in the Upper Sea Scheldt. When new estuarine areas (SIGMA plan) are included in the predictions, they have a strong positive effect on the expected numbers of Common teal (Figure 6-1, with NEA).

Looking at the *evolution* in the numbers of Common teal, there is a predominant decline in abundance when comparing the 2050 reference (REF_2050) with the current state (ACT_2013) (Figure 6-2). This follows from the effects of changes in tidal amplitude and of climate change and the resulting reduction in the quantity of intertidal area along the fairway (see paragraph 4.3.2). In the Chafing and VaH alternatives the numbers of Common teal might even further reduce compared to REF_2050. Especially in the VaH alternative in combination with the AplusCH climate scenario, unfavourable declines in the abundance of Common teal may occur in important winter foraging areas in the stretch between the inflow of Durme and Rupel (50-60 km from Merelbeke). For the VaG alternative the predictions show a predominantly favourable development to higher numbers of Common teal compared to REF_2050, in particular in the climate high scenario (AplusCH). As mentioned earlier, displacement of the riverbed and increased tidal amplitudes in this alternative create additional intertidal area within the riverbed and thus extra habitat for water birds.

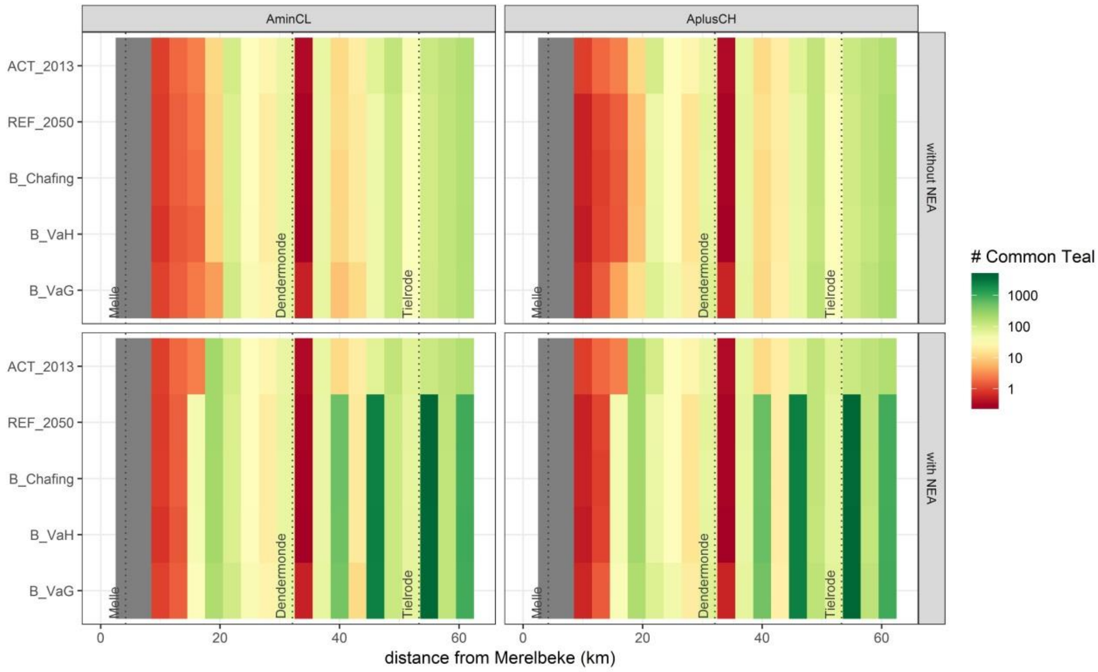

Figure 6-1: predicted numbers of Common teal. Without NEA = omitting new estuarine area as a realization of the SIGMA plan; With NEA = including new estuarine area as a realization of the SIGMA plan.

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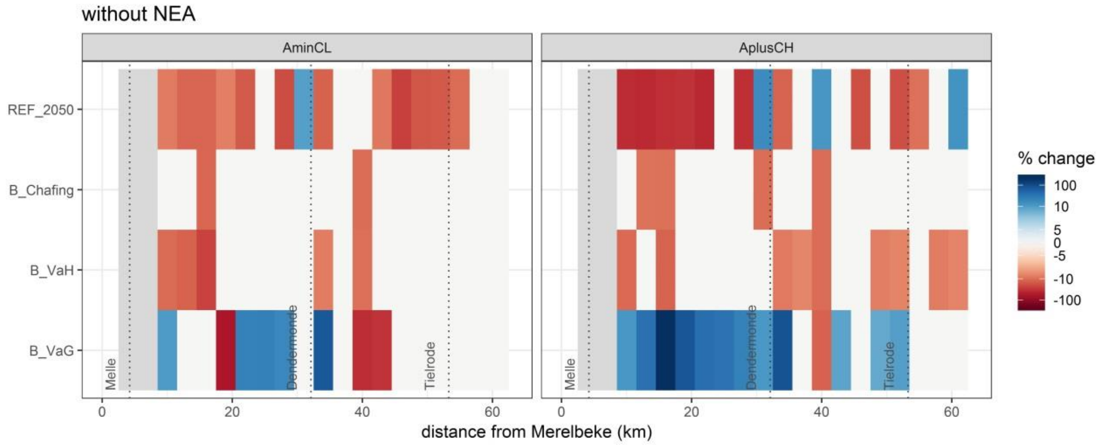

Figure 6-2: evolution of the predicted numbers of Common teal. Results do not take into account new estuarine area as a realization of the SIGMA plan.

6.4 CONCLUSIONS

Due to sea level rise and the resulting drowning of the mudflats, there is a predominant decline in abundance of Common teal when comparing the 2050 reference with the current state. In the high climate impact scenario of VaH, unfavourable declines in the abundance of Common teal may occur in important winter foraging areas between the inflow of Durme and Rupel. Displacement of the riverbed and increased tidal amplitudes in the VaG scenario (locally) create new estuarine habitat resulting in favourable increases in the numbers of Common teal.

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APPENDICES

APPENDIX 1

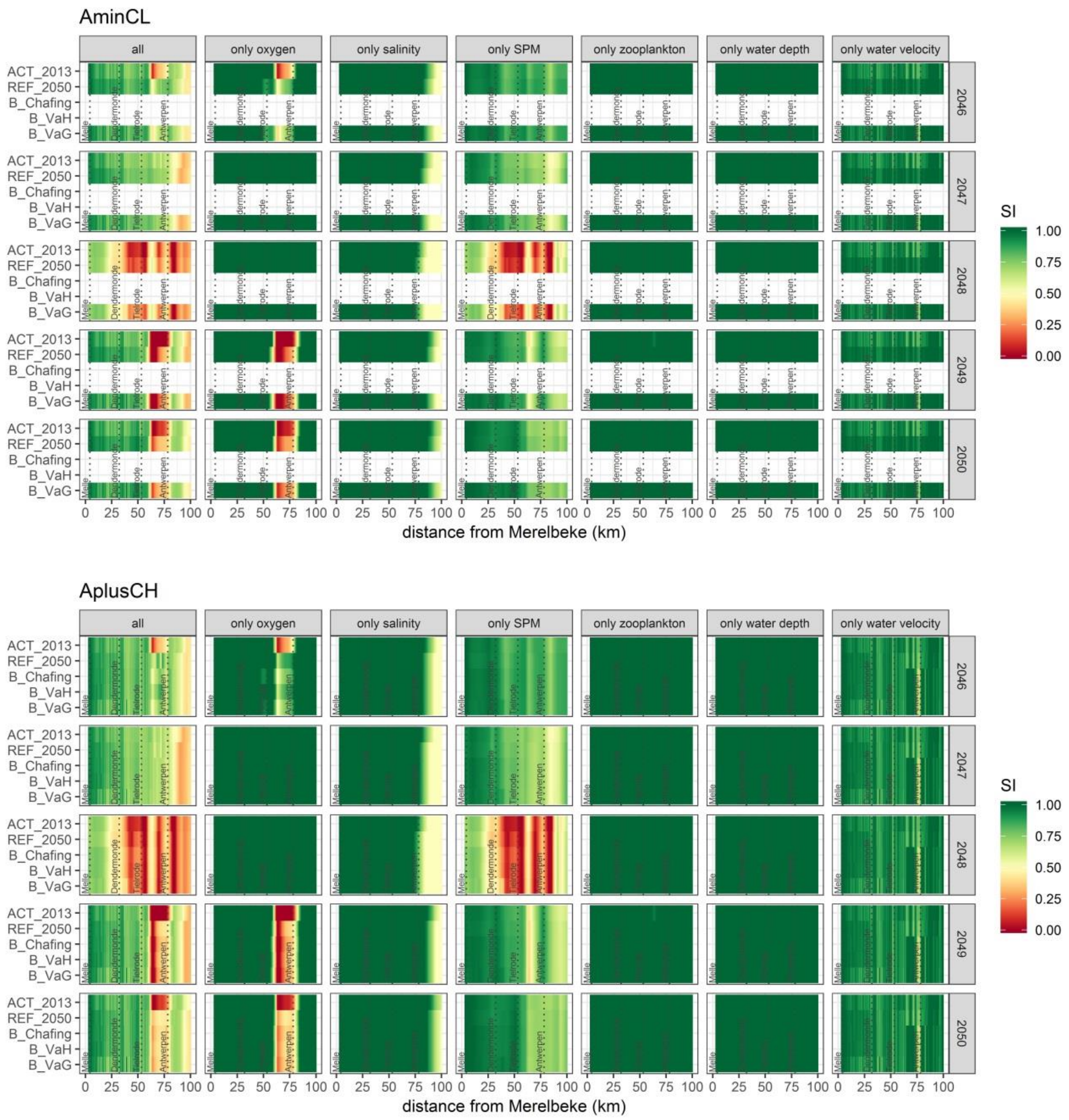
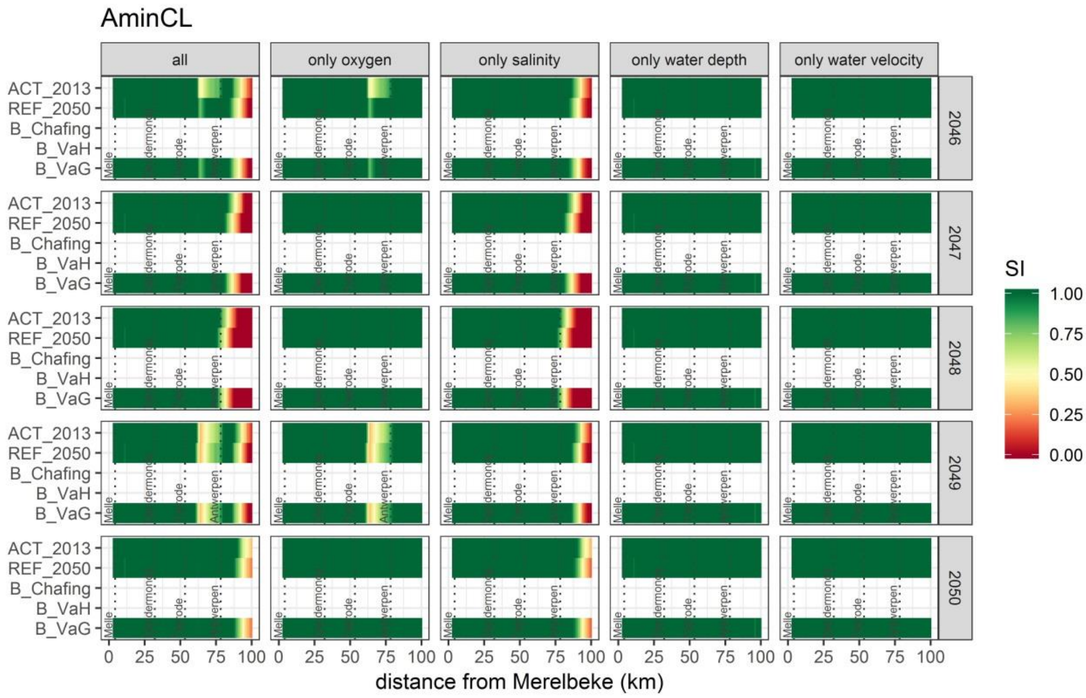


Figure A 1: response of the suitability index for larval development (SI_{larval}) to individual predictor variables in the different modeled years. (For ACT_2013, 2046-2050 = 2009-2013.)

doi.org/10.21436/inbor.92036025



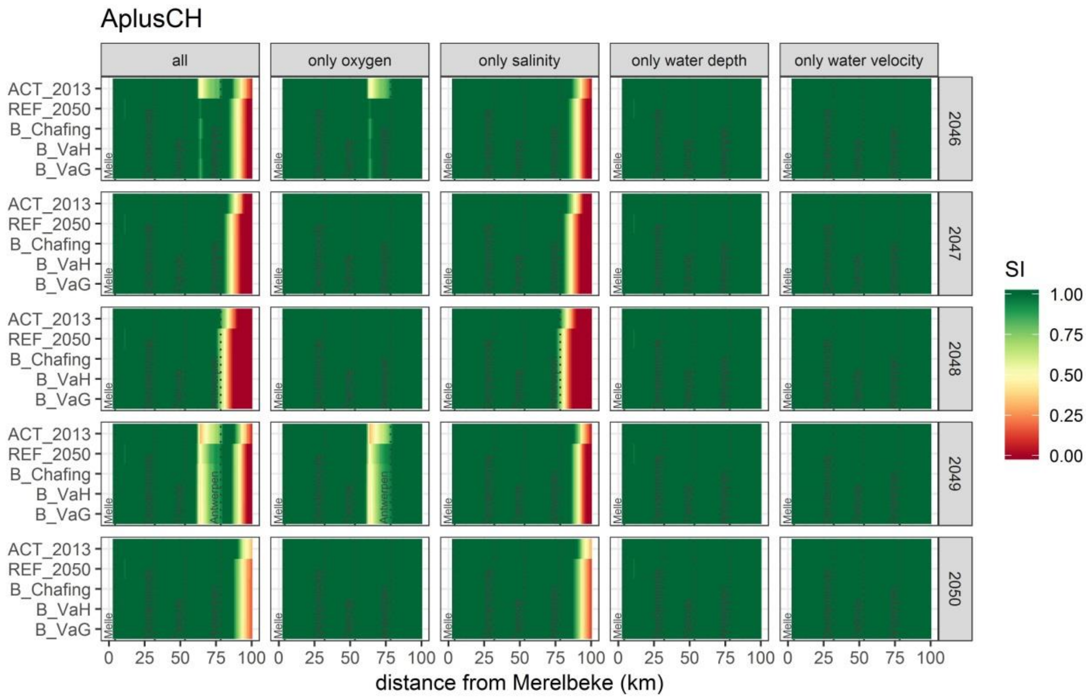


Figure A 2: response of the suitability index for adult spawning (SI_{adult}) to individual predictor variables in the different modeled years. (For ACT_2013, 2046-2050 = 2009-2013.)

APPENDIX 2

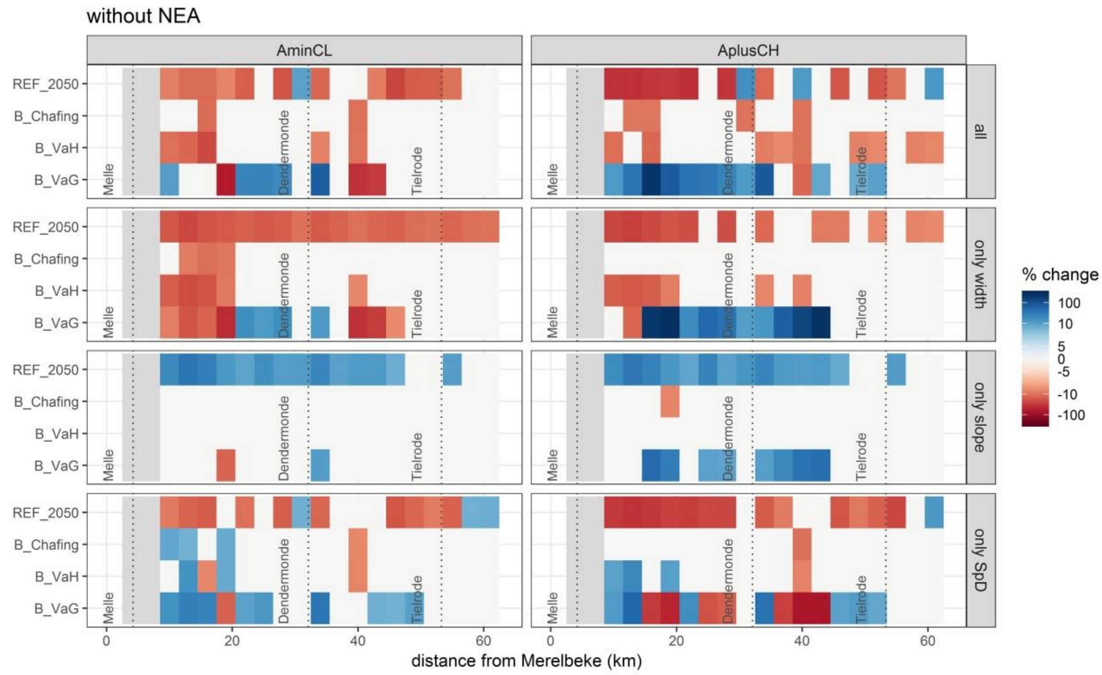


Figure A 3: Changes in the predicted numbers of Common teal in response to changes in individual predictor variables. Width = width of the mudflats; slope = slope of the mudflats; SpD = spread in exposure time of the mudflats.

 doi.org/10.21436/inbor.92036025