



An Integrated Approach to Define Estuarine System Resilience, Applied to the Upper Sea Scheldt, Flanders, Belgium

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Abstract. The Upper Sea Scheldt (Flanders, Belgium) is a part of the Scheldt estuary which extends from the North-Sea in the Netherlands to the shipping locks in Ghent with a total length of 160 km. Challenges on flood protection and nature development in this unique fresh water estuarine system are addressed in the Sigma-plan. Cumulative effects of i) the autonomous morphological development of the estuary, ii) the further evolution as a consequence of past realignments and dredging works, and iii) sea level rise, result in an increase of tidal dynamics and turbidity which affect both habitat and light climate, and finally disrupt the ecosystem functions.

In order to better understand the system functioning and to prepare for counteracting these undesired evolutions De Vlaamse Waterweg, the waterway manager, has launched a study programme to investigate solutions and to prepare a vision for the future management of the river. An extensive modelling instrument was developed coupling different state of the art modules into one model chain. The developed instrument proved to be highly effective to study (i) the interdependencies between the different river functions which allowed for an integrated analysis and evaluation of potential measures, and (ii) the robustness of the measures for climate change, and allowing the selection of a set of measures providing a desired level of system resilience. As such the results of the study form the backbone for the development of a future vision on estuary management, while the model instrument will continue to be used to study design alternatives and finetune measures for implementation.

Keywords: Adaptive river management · Climate resilience · Nature based solutions

1 Introduction

The Upper Sea Scheldt (Flanders, Belgium) is a part of the Scheldt estuary which extends from the North-Sea in the Netherlands to the shipping locks in Ghent, with a total length of 160 km. The upstream part presents a unique fresh water estuarine

system, facing challenges on flood protection and nature development, which are addressed in the Sigma-plan.

Cumulative effects of i) the autonomous morphological development of the estuary, ii) the further evolution as a consequence of past realignments and dredging works, and iii) sea level rise, result in an increase of tidal dynamics and turbidity which affect both habitat and light climate, and finally interfere with the ecosystem functions. Moreover these effects impacts the shipping function.

A study was commissioned by the Vlaamse Waterweg to better understand the functioning of the system, and to define a vision for the management of the river, improving its resilience and ensuring that it can still meet the requirements of the various river functions in the future.

To this end a state of the art modelling instrument was built to learn about the system response to changing boundary conditions and to measures. Measures have been combined into alternatives aiming at improving ecosystem functioning, creating habitat to provide better conditions for birds and fish, safeguarding (or even improving) the safety (against flooding) function, and creating better navigation conditions.

No specific ambition level was defined at the start of study (for example the creation of a specific habitat surface or rate of reduction of the tidal range), as the aim is to investigate what can be achieved when introducing measures, and what measures are required to achieve a certain goal. A reduction of the tidal dynamics, maintaining and improving boundary conditions for estuarine nature, protection against floods and improved navigation can be considered as general goals.

2 Integrated Study

In order to better understand the system functioning and to prepare for counteracting the undesired evolutions De Vlaamse Waterweg, the waterway manager, has launched a study programme to investigate solutions and to prepare a vision for the future management of the river.

An extensive modelling instrument was developed coupling different state of the art modules into one model chain (Fig. 1). This includes hydrodynamic, sediment transport modelling, water quality (ecosystem), habitat and higher trophic level models, and real time navigation simulations.

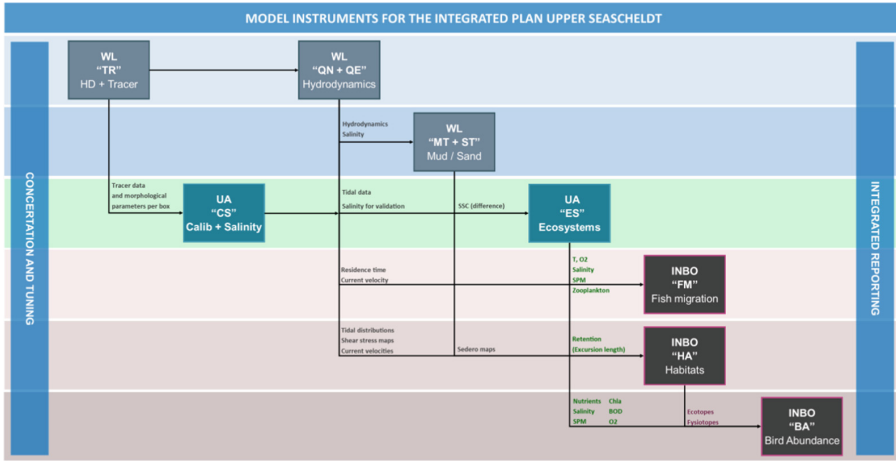


Fig. 1. Sequence and relations between the models of the model chain.

The models were used to study changing boundary conditions and modifications to the bathymetry as a part the measures. The changes in boundary conditions represent the results of climate change and cumulative effects including anthropogenic influences. For climate change, a time horizon of 2050 situation was considered. Besides a climate neutral scenario (CN), two climate change scenarios have been considered: a climate low (CL) and a climate high (CH) scenario, respectively assuming sea level rise of 15 and 40 cm with respect to 2013. Cumulative development concerns the unknown changes in hydrodynamic boundary conditions as a consequence from the further morphological development of past or yet undefined future dredging and sediment disposal activities in the Wester Scheldt and Lower Seascheldt, which may either lead to a reduction (Amin-) or an increase (Aplus) in tidal range. The reduction relates to a range of 500 cm in Schelle (corresponding to the 1960 situation). The increase implies a tidal range of 570 cm in Schelle, while in 2013 the tidal range is 550 cm. For changes in upstream discharge only one scenario was considered.

A detailed hydrodynamic model was constructed of the Scheldt estuary by Flanders Hydraulics Research (Smolders et al. 2016), from the North Sea to the upstream estuarine channels of the Scheldt and its tributaries using Telemac-3D. The model was calibrated for the 2013 situation using water levels from the existing tidal stations, velocity profiles across the river at several locations sampled during 13h measurement campaigns and a couple of permanent measurements at fixed locations. This was complimentend with salinity data over the entire length of the estuary. Measured wind data and measured upstream discharges were used as input.

The model is nested to the regional ZUNO model of the Southern North Sea (Maximova et al. 2016) from which downstream conditions can be taken for scenario analysis.

A mud transport model was constructed using SEDI3D (Smolders et al. 2020), the sediment transport module of Telemac-3D. The model was calibrated to available SSC measurements. For scenario analysis a delta-approach was used: the change of concentration obtained in the scenario models was transferred to the subsequent ecosystem and higher trophic level models rather than the absolute values and applied to the measurements to define the concentrations for the scenario models.

The existing quasi-2D Sigma model was modified to study the effect on safety against flooding (Coen et al. 2020).

The next model in the chain is the ecosystem model. It can be considered as a reduction of the original MOSES model (Soetaert et al. 1994), but extends further upstream and has a higher spatial resolution. It is developed by the Ecosystem Management Research Group of the University of Antwerp (Van Engeland et al. 2018). It is 1D tide-averaged model that resolves downstream volumetric transport of water and dissolved substances. The volumetric transport consists of a unidirectional advective component and a dispersive component. It simulates primary production, nutrient uptake by phytoplankton, phytoplankton loss, silica dissolution, zooplankton growth and loss, oxic remineralization, nitrification, denitrification.

For scenario analysis the temperature forcing is changed based upon literature study, while delta SSC and hydrodynamics are taken from the hydrodynamic model results. Hypsometric data are changed to study the measures. Dispersion is calibrated for these bathymetries using tracer tests results from the hydrodynamic models.

For the Habitat model (Van Braeckel et al. 2019) the MONEOS approach which is generally used in the estuary (Van Braeckel, 2013) was transformed to be able to work with model results and design bathymetry rather than observations. Boundary conditions are derived from the hydrodynamic model results, and geometric data from the design bathymetry. A major challenge proved to be the disequilibrium between the sea level rise and the bathymetry, as the alternative bathymetry was constructed from the existing bathymetry, and hence does not take into account the gradual adaptation of tidal marshes and mudflat geometry to the rising sea level. For this reason also a situation of the alternative bathymetry was simulated without sea level rise and without tidal amplification.

To study the higher trophic levels models were made to study habitat suitability for fish (using Twaite shad as research species¹) (Vanoverbeke et al. 2019a) and bird abundance (referring to common teal) (Vanoverbeke et al. 2019b). The fish model uses temperature, salinity, oxygen, waterdepth and current velocity to determine a suitability index. The habitat suitability model uses the results of both the hydrodynamic and water quality models for the alternative bathymetries to study scenarios. As, therefore the model cannot be calibrated. The bird abundance model is a regression model comparing bird abundance to habitat: width, slope, dry up duration of mudflats. It uses the results of the hydrodynamic models for the different geometric alternatives to study scenarios.

The navigation simulations will not be discussed in this paper.

3 Measures Combined into Alternative Bathymetries

3.1 Alternative Development

Bathymetric alternatives have been composed after prior analysis of the hydrodynamic response of single measures, combinations of measures and previously studied alternatives aiming at improving the navigability of the river (IMDC, 2017). These

¹ Twaite shad reappeared recently in the Scheldt as a result of improved water quality.

alternatives range from slightly widening the bends to creating a realigned waterway, however either respecting the current channel position or preserving the current channel as a side channel next to the new shipping channel. The latter alternatives have also been tested with the described model chain. The results of this analysis showed that although the interventions are beneficial to navigation, they do not create suitable environmental conditions when the valley is not included in the flow.

As it is not known how many measures are actually required to create a sufficiently resilient estuary a gradual approach in building up the alternatives was followed, in order to fully understand the extent to which measures of a certain scale respond. This allows to deduce from what kind of level of inserting singles measures on, one starts to have visible effects, and what is required additionally to achieve good conditions, whether the corresponding investment is reasonable, and what can be achieved with reasonable investments. From this level on one can start building up to arrive at what is either good or reasonable.

As such each of the investigated alternatives in this approach must be considered as part of a further system exploration, and not as a final desired definition of the system.

3.2 Alternative Design Principles and Building Blocks

From the analysis of the measures and the so-called navigation alternatives, it was deduced that following design principles are considered favorable for the sustainable development of the estuary, they have been used as a guiding principle in designing the alternatives and identifying their building blocks:

- **Limiting flow velocity:** Limiting the flow velocity prevents (semi) planktonic organisms (e.g. the eggs / larvae of fish – in this case Twait shad) from being flushed out of the system. In addition, there is also a beneficial effect for the migration of adult fish and potentially for benthic density and feeding grounds for higher trophic levels. This can possibly be achieved by realizing additional room for the river through depoldering (pulling existing dikes land inwards or, creating additional depoldered areas by creating breaches in the existing Scheldt dikes, and/or connecting polders with the Scheldt through flood channels).
- **Limiting tidal dynamics:** By limiting tidal dynamics, beneficial effects are achieved for safety, navigability and sediment transport. This can be achieved both by (i) creating low-dynamic subtidal systems outside the fairway, (ii) depoldering and creating wide tidal flats with mild slopes, (iii) avoiding system shortening (cutting off bends).
- **Stimulating primary production:** Additional extra shallow zones (low-dynamic shallow water zones along the fairway, Flood Control Areas (FCA)/ with Controlled Reduced Tide function (CRT), depoldering) are considered to have a beneficial effect on primary production and the ecosystem.
- **Limiting turbidity:** By limiting turbidity, favorable effects are achieved for primary production and the development/viability of other organisms (e.g. Twait shad). Besides lowering the turbidity in the water by limiting dredging and dumping volumes in the estuary, extra depoldering is a measure that can limit turbidity by trapping sediment and lowering sediment transport.

- **Extra tidal flats, marshes and FCA/CRT:** An extension of tidal flat area is directly related to additional habitat for macrobenthos and resting and foraging avifauna (such as the common teal, research species for the study). Marshes and FCA/CRT are directly related to extra habitat for Natura 2000 habitat types habitat types (tidal willow shrubs and forest H91E0, and salt marsh meadows 1330) and reed beds with breeding avifauna (e.g. marsh harrier). This can be achieved by (i) depoldering - extra tidal flat area and (ii) creation of estuarine nature by FCA/CRT.
- **Improved water quality:** An additional connection with the valley and the creation of estuarine nature can result in improved water quality in the estuary. This can be achieved by creating connections to old meanders and other water bodies along the Scheldt. Note that even despite the decrease of water quality in these water bodies, this may have a positive effect on the water quality in the Scheldt.
- **Buffering** of peak flows. Due to climate change, more extreme events (longer dry periods in summer, more rainfall in winter) can be expected. The planned actions should contribute to the buffering of the expected peak discharges (additional FCA) and mitigate drought stress in the surrounding areas (FCA-CRT, depoldering).

3.3 Alternatives

Three different alternatives consisting of a combination of measures such as bend cut offs, depoldering with or without the introduction of flood or ebb channels, flood control areas with or without reduced tidal action, section widening and narrowing (by sediment disposal or groyne fields) have been composed and investigated (IMDC, 2021). The reference year 2050 was considered for a range of climate change and downstream tidal range scenarios in order to improve the understanding of the reaction of the estuarine system to such measures.

The investigated alternatives range from mild (only interventions in and along the navigation channel), over moderate (the latter complemented with a selection of measures in the valley) to extreme (the previous set with a maximum of measures in the valley).

The three alternatives have been developed with the following mindset:

- C1 alternative: Looking for opportunities in the river and redefining the Sigma-plan to improve habitat and to reduce the increase in tidal amplitude, and in the meantime to tackle the most prominent nautical bottlenecks;
- C2 alternative: Additional opportunities in the valley (depoldering, side channel) to improve habitat and to reduce increase in tidal amplitude are also included. Additionally also less prominent nautical bottlenecks are tackled, and additional measures for the most prominent ones have been defined. The additional nautical measures include a more extreme smoothening of the bends.
- C3-alternative: Additional measures (larger depolderings, additional depoldering at Weert, undeepening at Temse) aiming at providing added (climate) resilience while also improving habitat conditions, combined with further nautical measures (compared to C2) for a limited number of locations.

4 Effects

4.1 Tidal Range

The simulation results demonstrate that depoldering is a very effective measure to control the increase in tidal range (as a consequence of climate change and bend cut-offs). In addition, depoldering also has a very positive effect on the water quality and development of estuarine nature.

The effect of the alternatives on the hydrodynamics of the system increases from C1 to C3 (Bi et al. 2021a). The mean water level increases roughly from km 20–60 (from the upstream boundary (0 km) at Merelbeke, near the city of Ghent) in C2 and C3, and from km 40–60 in C1. Upstream of km 20, the mean water level decreases in C2 and C3. From km 0–40, the changes of mean water level in C1 is less than 2 cm, which is much smaller than the changes seen in C2 and C3. Further examination shows that the mean high water (HW) decreases and the mean low water (LW) increases in all the C-alternatives. As a result the tidal range decreases (Fig. 2), especially in the zones where the measures are implemented.

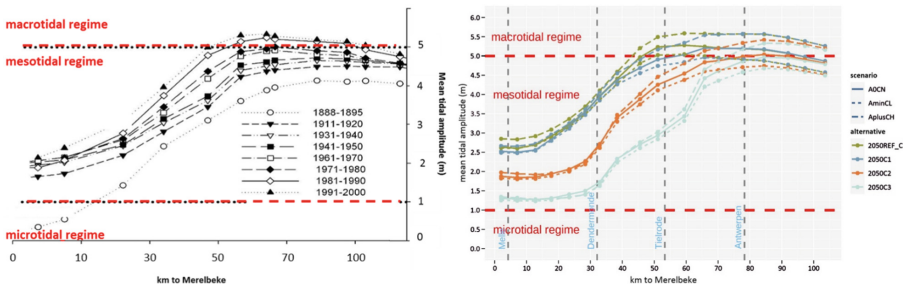


Fig. 2. Development of tidal range over the past century (left), resulting tidal ranges for the investigated alternatives (right). Source: Vanoverbeke et al. (2022).

The reduction is such that a historic mesotidal regime (based on the classification of Hayes, 1979) is restored over a large portion of the estuary. This is an interesting observation as tidal range increased significantly over the past century (Fig. 2). Given that an evolution of further increases in tidal amplitude is considered unfavorable, all three C-alternatives represent a favorable evolution of reduced tidal range. Given that reductions in tidal range also 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. 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. However, mind that in the upstream reaches the regime tends to microtidal in the C3.

4.2 Habitat (Vanoverbeke et al. 2022)

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 (Fig. 3). As a result, in C2 and C3 the mudflats tend to undergo a positive evolution in surface area in almost the entire Upper 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, km 0), with overall losses in habitat area. Even if changes in marsh area might be relatively small, strong changes in the location of the marshes may occur with a shift of marsh area from the originally existing marshes to newly created CRT areas. Indeed, due to the strong effects of measures (depolderings, CRT areas and channel adaptation) on the tidal range, evolutions in habitat area are often a combination of the creation of new habitat (depolderings and CRT areas) 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.

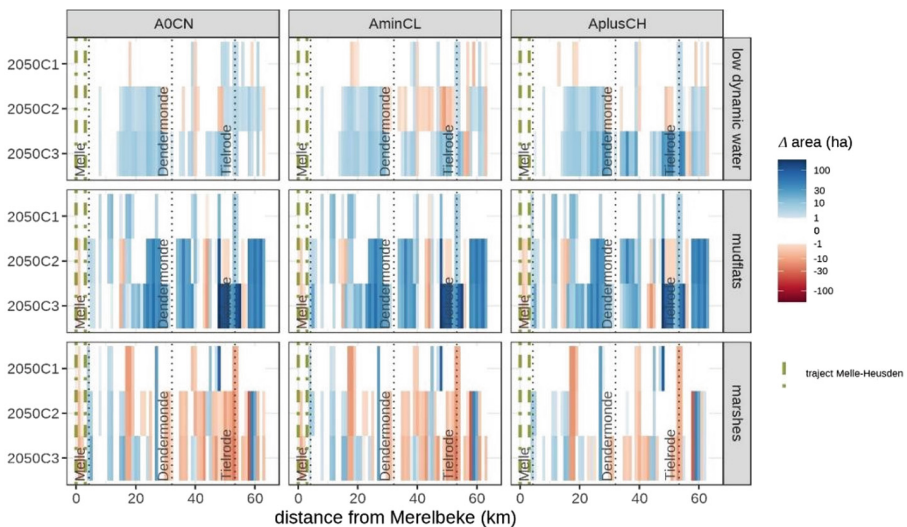


Fig. 3. Changes in surface area of ecologically important ecotopes. Blue indicates favorable evolution; red indicates unfavorable evolution. Source: Vanoverbeke et al. (2022).

The C-alternatives also affect the (mean cross-sectionally averaged) velocity. This also contributes to the habitat conditions. The effects are much stronger in C2 and C3 compared to those in C1. In all three C-alternatives, the effects on the ebb velocity are similar to the effects on the flood velocity. Based on the changes in the mean velocity, three zones can be distinguished in the Upper Sea-Scheldt: i) from 0 to about 28 km: the mean velocity in general becomes smaller, hence more favorable, as a consequence of depoldering between 24 and 28 km, the development of intertidal areas combined with alternative navigation channel development between 16 and 22 km and further smaller scale depoldering between km 5 and 12; ii) up to 55 km depolderings with side channels, and introducing CRT function in FCA areas, together with a major bend cut-off around 40 km result in variable velocity signals, either more favorable or unfavorable, but with sufficient lateral areas with low velocities; iii) the narrowing (and in C3 also undeeptening) of the channel downstream of 55 km results in an (unfavorable) increase of the velocity in the main channel.

4.3 Safety Against Flooding

Another effect of the alternatives is the drop of waterlevels from C2 on, during flood events, particularly during storms. Despite the reduction of FCA at the cost of depoldering. This shows that depoldering can also have a significant contribution to safety against flooding. Differences may go up to 50 cm in some areas during storm events with return periods of 1000 years, hence even compensating the assumed level of sea level rise (Coen et al. 2021)).

4.4 Suspended Sediment

The suspended sediment concentration is barely affected in the C1 alternative as is shown by the results of the cohesive sediment transport model (Fig. 4). But is very prominent in the C2 and C3 alternatives (Bi et al. 2021b). The results show, as for most of the parameters, that the climate scenario only has a limited effect on the results compared to the effect of the alternatives (Fig. 4). Therefore, in general, conclusions will not be affected by the climate scenarios. In C2 and C3 the depoldered areas operate as sinks. Calculations based on observed settling velocities and suspended sediment concentrations indicate a long longevity (decades) of the measures, as the source of the mud is limited. The sand transport capacity aligns with the velocity hinting at the requirement of dredging in some areas upstream of 55 km to maintain the navigation channel, but definitely requiring protection to prevent erosion between 55 and 64 km where the channel is narrowed (and undeeptened).

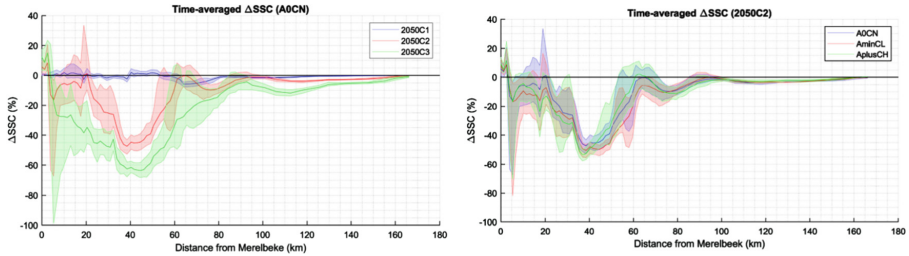


Fig. 4. Effect of alternative on SSC (left), effect of climate scenario on the result of one alternative, here showing C2). Source: Bi et al. 2021b.

4.5 Water Quality and Primary Production

The ecosystem model shows that the increase in shallow areas due to the addition of CRT areas in 2050 (Sigma-plan) positively influences primary production and oxygen concentration as a results of the generally lower water depths (Cox et al. 2021).

The measures taken in the C1, C2 and C3 alternatives and the reduction of suspended matter (better light penetration) lead to additional increase in primary production and oxygen concentrations (Cox et al., 2021). The increase in primary production and biomass are most clear in the C2 and C3 alternatives, as expected by the increasing scale and extent of the implemented measures, however with only relatively small changes between the C1 alternative and 2050 reference simulation (Fig. 5). The sharpest increases are detected in section 2 and section 3 (km 10 to 35 in Fig. 5). Primary production over Biomass (P:B) shows similar trends. The C1 alternatives only shows a clear difference with the reference in the depoldered areas in the upstream part (more primary production in C1).

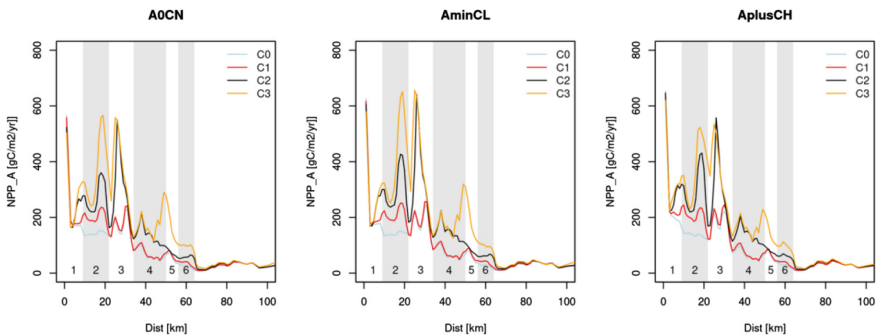


Fig. 5. Annual area-normalized net primary production (NPP) (gc/m²/yr). (Cox et al. 2021).

Patterns of increased primary production and oxygen upstream are followed by decay of organic material and lower oxygen concentrations downstream. This effect is strong downstream of the Rupel tributary, resulting in an “oxygen-dip” (which

currently also occurs). Note that the impact of the current and future water quality of the Rupel tributary on the Scheldt is not modelled but may also be an important driver, as the discharge of the Rupel is relatively high compared to the one of the Scheldt. Generally oxygen concentrations show an increase in the direction of the 2050 reference situation (C0), C1, C2, C3 (Fig. 6). The C2 and C3 generally lead to improved oxygen conditions in the study area (zones 1–6 in Fig. 6), with the same patterns shown for the 3 climate scenarios. In the zone downstream from the Rupel the oxygen-dip effect for the C3 alternative is strong under the A0CN and AminCL scenario's, while the dip is smallest for the C2 alternative.

It is expected that improved water quality can further improve the situation. Also consider that large areas of mudflats and tidal marshes in the alternatives replace agricultural land. This probably will also lead to a reduction of nutrient input to the system, and will also influence the primary production. This effect is not modelled.

The impacts of measures installed for the different alternatives are generally robust under different climate scenarios, showing the same patterns among alternatives, with relatively small differences. However the AplusCH scenario (increase of tidal range and sea level rise of 40 cm) shows for some zones smaller Chlorofyll concentrations and primary production rates than the AminCL scenario.

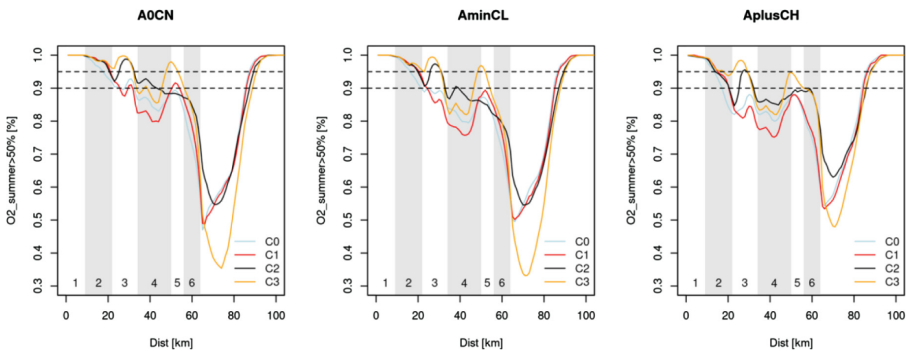


Fig. 6. % of time (Y-axis) summer oxygen concentrations are above 50% (Cox et al. 2021)

The predicted decrease in silica must be carefully assessed, suggesting an impact on diatoms, as the model is not designed for the simulation of population dynamics. The impact of silica release from implemented lateral areas in the different C alternatives is not modelled, and therefore the simulated silica depletion is probably overestimated.

4.6 Suitability for Twait Shad and Abundance of Common Teal

The reduced tidal influence in the upstream parts leads to reduced water dynamics and increased residence time. This not only results in higher primary production (as discussed before), but also leads to better (more sheltered) conditions for (juvenile) fish, that have no escape in the narrow, canalized riverbed.

Conditions are in general favorable for larval development upstream of Dendermonde (km 28) in the C-reference and alternative C1. In years with high suspended particle matter (SPM), however, suitability can strongly reduce in the region between Dendermonde and Tielrode (km 28 to km 50), 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.

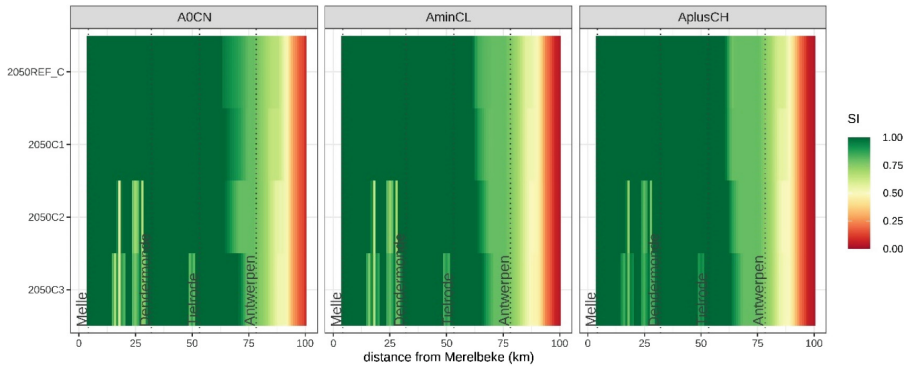


Fig. 7. Twait Shad suitability index for different alternatives (vertical), and different climate scenarios (horizontal). Suitability for spawning (mean value over modeled years), per kilometer from Merelbeke (0 km) to Antwerp (100 km). Source: Vanoverbeke et al. (2022).

Conditions for spawning are generally favorable in the Upper Sea Scheldt (Fig. 7), including the region between Dendermonde and Tielrode, where most of the spawning is observed today. Both for upstream migration (spawning) and downstream migration (developing juveniles) there are indications that between 50–90 km from Merelbeke in some years oxygen levels can be too low as a result of the earlier discussed decay of organic material, creating a barrier for migration. The C-alternatives do improve this, also today present, situation by narrowing the stretch where oxygen levels are unfavorable. There is a general positive evolution from C1 to C3 in the numbers of common teal when comparing the C-alternatives with the reference situation) due to the inclusion of large areas of newly created depolderings and CRTs, with positive evolutions on the area of mudflats.

4.7 Long Term Morphological Stability

The impact of the C-alternatives on the hydrodynamical and morphological stability has been assessed by means of an analysis of the relation between the wet cross-section, the tidal prism and the tidal range (IMDC, 2022). For this analysis it was assumed that the present state is in ‘equilibrium’. This is debatable, as the river is largely impacted by human intervention, such as bank fixations, river straightening, (downstream) deepening, maintenance dredging, etc. The cumulative impact of the measures in the C-alternatives will have a strong global impact on in particular the tidal

prism and the tidal range and a local impact on the wet cross-section. Especially the depolderings are dominant in the initial response, as they tend to dampen the tidal range and affect the tidal prism up- and downstream. Locally the wet cross-section will increase as a result of the added intertidal area. In the C-alternatives, straightening or removal of sharp bends in the river typically is combined with either depoldering, or the creation of intertidal area. While straightening would theoretically lead to a reduction of the convergence length and subsequent amplification, the creation of new intertidal area dominates the hydrodynamic response (damping).

Only as far as the increase in wet cross-section locally contributes to an increased flow capacity one can expect that (short-term) sedimentation may reduce the initial impact of the measures on the hydrodynamics. However, as most of the depolderings involve the lateral connection of large areas of polder land, local sedimentation will not lead to a diminution of the impact on the tidal prism. On the scale of in particular the C3 alternative, and in a lesser extent the C2-alternative, it is unlikely that sedimentation will be the driver in restoring the equilibrium on the longer term. Downstream erosion, as a result of increased tidal prism and reduced water levels, may result in an increase in tidal amplitude. But as a result of the logarithmic shape, it will require quite large modifications in wet cross-section in order to impact the tidal prism.

Another important aspect to consider is that different sediment types, i.e. sand and mud, will respond to the changes in different ways. Sand will respond quickly to the changed conditions, but may be limited to a local scale, because of limited availability. On the other hand, there is an abundance of mud in the system. But it requires large volumes of mud deposition before significant impact on the hydrodynamics will take place.

Deposition of mud is mainly expected in the low-dynamic areas, like the depoldered areas. These depoldered areas will therefore function as a sink, which allows mud transport against the net sediment transport direction that would be derived from the asymmetry of the tidal flow (eb-dominance). Given the large number of depolderings and the strong reduction in tidal dynamics, it may be expected that turbidity in the river will be reduced significantly. This in itself may pose a risk for drowning of the mudflats along the river, as less sediment may be available to adjust to changes in the average water level due to sea level rise. Further downstream, in the Lower Sea Scheldt, impact of the measures on the hydrodynamics are visible in the results. While it will take a long time to experience any impact on the sand transport, the impact on the mud concentrations may be noticeable. It may be expected that the proposed interventions (especially the C2 and C3 alternatives) may lead to a change in the dynamics in the estuarine turbidity maximum (ETM). On the one hand it is expected that the system will become more eb-dominant, but as a result of the tidal pumping a larger exchange of sediment to upstream may be expected.

5 Discussion

Depolderings appear to be very efficient in reducing the tidal range, and are an important part of the measures. As we move further downstream, the measures must be larger to create the same hydrodynamic effect. On the other hand, large measures

downstream have a major (and desired) impact on the tidal range upwards. A downward narrowing is therefore not considered necessary, and the undeeptening of the access channel is perceived as negative. Not having to consider the latter has the advantage that expensive bank and soil protection costs can be avoided. Depoldering and CRT areas on the other hand, do require a redefinition of the functions of existing Sigma areas, or the development of additional areas, requiring the necessary compensations.

In addition to the system benefits caused by the reduction of the tidal range (better habitat conditions are created, and the reduction of suspended sediment, captured by the depoldered and CRT areas, leads to an improvement of the light climate, the Chlorophyll content and oxygen balance, and increased primary production), there are also significant indirect benefits from the avoided flood risk. In an evaluation of the safety level of the current Sigma-plan, and possible update taking into account the higher sea level rise associated with the current climate change scenarios, the investigated depolderings can occupy a prominent position.

The investigated depolderings compensate for the effects of bend straightening, which offers prospects for improving navigability. The nautical bottlenecks have been identified in the study, and although the measures examined for shipping may incur local but temporary impacts on habitat, but lead foremost to an improvement of navigability, without adverse system effects.

The measures seem to have a long life span. The depolderings capture sediment, but the sedimentation rate is slow, so that there is even a risk of drowning the system (turning mudflats into subtidal area), and the instantaneous loss of tidal marshes as a consequence of the drop of the high water level. A gradual construction (area by area) allows to catch sediment to gradually develop a balanced and diversified morphology, and to limit temporary damage by loss of habitat. The construction of the plan in a short period of time would also be a major challenge from a budgetary point of view, so the risk for such an unbalanced intervention is small.

In addition, it is far from certain what effects occur over the entire estuary. Redistribution of sand is expected soon after construction, however on the long term the morphological changes are difficult to predict, but it seems that the required adjustments of the downstream area are so large that it is unlikely to happen in the near future.

6 Conclusion: Towards a Vision and Bringing It into Practice

The wide range of simulated alternatives and achievable effects for different intervention levels, allow the selection of measures to obtain a desired level of system resilience. As such the results of the study form the backbone for the development of a future vision on estuary management. The vision aims at developing a sustainable and multifunctional estuarine system, compatible with the ambitions of both the waterway manager and its stakeholders.

The creation or restoration to a mesotidal regime should be aimed at. This implies the expansion of the estuarine domain by creating intertidal zones with controlled reduced tide function (CRT), and most notably additional depolderings.

Spreading the measures is considered advisable for fish (several well distributed low dynamic areas along the river axis), birds, but also for the ecosystem functioning (CRT ensures diatom development providing an important food source and building block of the food web). Regularly distributed measures can also be considered as stepping stones between larger habitat patches, each of which are necessary for a better functioning of the estuary.

The measures should be diversified according to location. The discharge dominated upstream section requires focus on the development of a fresh water tidal river landscape (with the preservation of wetlands). This means creating tidal flats to strengthen the pasture area next to the breeding area. This can be achieved by setting up depoldering, FCA (buffer effect), FCA/CRT (raising groundwater level) or side channels (impact on dynamics). Downstream, the estuarine nature can be improved (more qualitative area) by aiming at a well equilibrated tidal flat/marsh surface and more shallow subtidal area (flood channel). Therefore generally, we look for a different focus between the up and downstream section, upstream looking for opportunities to improve riverine and safety functions, and downstream to improve estuarine functions.

It is also considered important to keep the estuarine areas dynamic in order to increase the long term tidal mudflat function and limit sedimentation and vegetation succession by implementing large dike breaches when depoldering, direct connection to the main channel (dike withdrawal) or the introduction of creek dynamics (introducing side channels), in order to involve a larger part of the valley in the flow.

Already today, the gained insights from the modeling tool are put into practice by the installation and follow up of pilot projects, such as the depoldering in Wichelen, where a side channel has been created to improve the tidal dynamics and habitat. On the other hand the experience with such pilot projects will allow to gain insights to improve the design of new areas.

The developed model instrument proved to be highly effective in studying the interdependencies between the different river functions which allowed for an integrated analysis and evaluation of potential measures, and to test the robustness of the measures for climate change, and finally to allowing the selection of a set of measures providing a desired level of system resilience. The model instrument, and further improvements to it, will therefore continue to be used to study design alternatives and finetune measures for implementation.

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