Paper 79 - A future proof design alternative of the Upper Sea Scheldt, combining navigation with sustainable nature development

ADAMS R.[1], DE BEUKELAER-DOSSCHE M.[2], BOSMANS S.[2], VANLEDE J.[3], VAN ENGELAND T.[4], VANOVERBEKE J.[5], VANRIJCKEGEM G.[5], DEPREITER D.[1], VAN HOLLAND G.[1]

[1] International Marine and Dredging Consultants NV (IMDC), Antwerp, Belgium
[2] Waterwegen en Zeekanaal NV, Division Zeeschelde, Antwerp, Belgium
[3] Flanders Hydraulics, Antwerp, Belgium
[4] Ecosystem Management Research Group (Ecobe), University of Antwerp, Antwerp, Belgium
[5] Research Institute for Nature and Forest (INBO), Brussels, Belgium

Email (1st author): roeland.adams@imdc.be

ABSTRACT: The Upper Sea Scheldt is a navigable connection between the Ports of Ghent and Antwerp (Flanders, Belgium) and their respective Hinterlands and further connections. Tide and narrow bends limit both draught and ship length (to CEMT Class IV). Constituting an important fresh water estuarine ecosystem, the Upper Sea Scheldt currently forms the scene of a large scale flood protection and nature development programme: the so-called Sigma plan. A feasibility study showed that the upgrading and the integration of the waterway into the Class Va TEN-T network requires an approach integrating the navigation function with nature and other functions. Waterwegen en Zeekanaal NV launched a study to provide the necessary scientific back-up to design a waterway that fits with these purposes. This paper focuses on the approach of the study, the construction of a state of the art model instrument, and the method to evaluate different design alternatives using the model results.

1 INTRODUCTION

The Upper Sea Scheldt is the upper tidal branch of the Scheldt Estuary (Figure 1) (Flanders, Belgium). Apart from its ecological and recreational functions, the Upper Sea Scheldt is an important inland waterway linking the Port of Antwerp with the Port of Ghent and the Seine-Scheldt network.

Although, geometrical bottlenecks limit navigability in the upper stretch of the Sea Scheldt to CEMT class IV, navigation was not considered in the 2000s when reshaping the Scheldt valley in the so-called Sigma plan. The Sigma plan aims at protecting the Scheldt valley against flooding, and includes ecosystem restoration as a requirement to make investments in flood protection both socially and economically acceptable.

Today, also the improvement of navigability and the integration of the waterway into the CEMT class Va network is taken into account, but the measures required to improve navigability may affect both nature and flood risk.

Other evolutions may however also affect these functions: apart from sea level rise (due to climate change), there is also a growing awareness of morphological effects due to historic measures and maintenance practices that may amplify undesired changes to boundary conditions (tide, sediment concentration, …) for navigation, safety and nature.

Therefore, in its mission to promote navigation and sustainable management of the river Waterwegen en Zeekanaal NV launched an integrated study to investigate the requirements of a design that both accommodates class Va navigation and resists such changes.

The study aims at improving the design of alternatives including measures to improve the hydrodynamic, morphological and ecological functioning of the estuary. The effect evaluation is based on the results of a tailor made, state of the art modeling instrument, consisting of interdependent hydrodynamic, sediment transport, higher trophic level and ecosystem models. Real time navigation simulations are included to evaluate and improve the navigation conditions of the different alternatives.

The models will be used to investigate different design alternatives of the future tidal branch, combining the design requirements of a class Va channel, with measures that tackle both undesired effects of the autonomous and morphological evolution, and including ecological requirements and potentials existing along this tidal river. The modeling, but also effect evaluation, is closely monitored by a group of independent international experts, which criticism on the used methods and assumptions are taken into account to improve the modeling and evaluation methodology.

The modeling and effect evaluation, including a strategic environmental assessment (SEA), should finally lead to the definition of a future proof design alternative for navigation, and nature and safety against flooding. The design will be accompanied by a monitoring programme, allowing for adaptive maintenance and management, as it already is being implemented in the Western Scheldt, and is introduced in the Upper Sea Scheldt for the current class IV navigation in 2015.

As such the project will, apart from improving navigation, serve multiple social objectives:

- to preserve the safety function of the floodplains (Sigma plan),
- to hold off undesired morphological effects,
- to intercept mud from the system, and
- to improve the conditions for fresh water estuarine nature development.

The paper will be focusing on the integrated approach for modeling and the method to evaluate the different alternatives.

2 LEASONS LEARNT FROM THE PRECEDING FEASIBILITY STUDY

2.1 *Introduction: the feasibility study*

The Upper Sea Scheldt is a navigable tidal river in the region of Flanders (Belgium). It currently links the ports of Ghent and Antwerp for CEMT-class IV inland vessels (9.5m beam, 85m length). The connection is identified as a major European bottleneck for inland navigation. Its tidal nature limits the navigation to a narrow time window. TEN-T aims at a performing waterway network at CEMT-class Va level (11.4m beam, 110m length) in North West Europe. Waterwegen en Zeekanaal NV, the Flemish waterway authority, commissioned a study to investigate the conditions for improving navigation on the river and the feasibility for upgrading the river to allow CEMT-class Va ships. This fits in the Flemish government's policy to establish transversal links between the major waterways of Flanders.

The feasibility study (IMDC 2013) showed that such a project is feasible only in a joint effort of the navigation authorities with nature developers, urban and territorial planners, water managers, … .

The nautical feasibility and performance of different alternatives combining solutions for bottlenecks at distinct levels of nautical functionality were investigated in the feasibility study. A real-time simulator was constructed by Flanders Hydraulics, and operated by experimented skippers, to study the navigation conditions of the different alternatives. Swept paths of the ship, return of experience of the skippers, under keel clearance, reserve in propeller and rudder use, reserve in use of bow thruster were used to evaluate the nautical feasibility of the solutions of bottlenecks, in the most difficult nautical conditions (during low tide and the highest flood velocities).

Given the space restrictions in Flanders the design of solutions was based on the results of navigation simulations, rather than on standard design criteria. Simulations show that at the location of bottlenecks enlargement of the river section based on swept paths is sufficient to assure the accessibility of larger units (Eloot et al., 2015). Drift angles derived from simulations were used for the design of more comfortable solutions.

The overall performance of the waterway was determined using travel times calculated with a capacity model, calculating ship movement corresponding to traffic predictions, using Schijf's law for the definition of navigation speed, taking into account the section geometry, (time varying) waterlevels and current velocities (reflecting the tide), and meeting and uprunning ships.

Beside its function as a waterway, the Scheldt is an important European nature area, with a unique fresh water tidal ecosystem. Furthermore the valley plays an important role in the protection of cities against flooding. Today, within the so-called Sigma plan, different areas are being transformed into controlled flood areas, with both a flood protection and nature function assigned. However, the redesigning of the waterway for nautical purposes has an influence on the tidal conditions, which determine the success of nature development and flood protection measures. Numerical hydrodynamic models of the estuary were used to investigate possible solutions to limit the effect on water levels, tidal dynamics and estuarine nature area. Some solutions present advantages for both shipping and tidal nature.

A cost benefit analysis shows that compensating measures heavily weigh on the project cost. As a lot of space is required for these measures, it puts the social feasibility of the project at stake as well. Therefore a solution was searched, combining satisfying nautical benefits with limited environmental effects. The outcome of the feasibility study was that with relatively small measures a balance between cost and benefit can be found, but allowing navigability up to Class Va while increasing safety for ships of class IV and lower.

These alternatives, the so-called B alternatives basically consist of 3 different potential waterway designs (Figure 1):

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

A fourth alternative was investigated in the feasibility study, and is described here for information only, but is not considered in the integrated study: the VaR-alternative: Class Va standard design rules applied with a wider (“R” for “Ruim” or wide) uppermost section for single lane upstream navigation and double lane downward navigation.

Figure 1: Example of the spatial effect of the 4 alternatives on the morphology in the Hoogland Bend. The impact of VaH is smaller than in VaG or VaR because no cutting or axial translations are allowed in VaH. The double lane functionality in VaR requires changes to nearly the complete fairway length. (Legend: Blue = Fill; Brown = Cut). Width of map ca. 2km.

2.2 *Sustainable maintenance*

A first step in improving navigation conditions and at the same time providing a better cohabitation of navigation and nature functions is the drafting of a durable maintenance scheme.

Today, maintenance in the Sea Scheldt is performed at an ad hoc basis. Maintenance mainly concerns dredging to secure navigation conditions, and bank protection to protect dikes and wetland nature against the effects of wave load. Apart from the dredging of a few known shoals critical to navigation, today dredging often is triggered by needs of sand for construction purposes, and is barely used to maintain a channel for navigation. Today, dredging often occurs on shoals without taking nature into account, leading to conflicts with the nature sector. Bank protection consists of experience based placement of rock after the finding of damage by bank inspection teams, without any knowledge of the need for protection.

A maintenance scheme has been drafted, defining a navigation channel, including a yearly monitoring allowing for adaptive management, and defining areas where dredging can take place without further affecting nature. Dredging will only be allowed for channel maintenance. Moreover, an erosion index was defined, indicating areas in need of bank protection, and defining the possible types of bank protection. A decision tree is devised to preferentially decide on environmental friendly bank protection where possible, before deciding on rock placement.

The maintenance scheme was devised in collaboration with the Flemish Nature Agency, and will receive their acclaim through an appropriate assessment and a construction permit.

2.3 *Integrated plan*

The need of integration of navigation with other functions within the Scheldt valley, the unknown morphological effects due to autonomous evolutions and human activities in the Sea Scheldt, the unknown risk of evolution towards hyperturbid conditions, in analogy with other estuaries in Europe, prompted Waterwegen en Zeekanaal NV to start investigations in this field, realizing that no action can result in the risk of the extinction of the Upper Sea Scheldt as a waterway, and that a project only stands a change if based on thorough scientific research, and in a context in which potential opponents are well informed about results and possible evolutions, and finally get the opportunity to participate to the project, and contribute to its success.

The Belgian-Dutch VNSC (Vlaams Nederlandse Schelde Commissie – Flemish Dutch Scheldt Commission) a joint body monitoring activities in the Western Scheldt en Scheldt Estuary, tries to answer critical questions to the impact of port development and navigation in the Scheldt estuary on nature and safety (against flooding). Up to now studies concentrated on the Western Scheldt and the Lower Sea Scheldt. Within VNSC's "Agenda for the Future" research programme Waterwegen en Zeekanaal NV will through their investigations contribute to a more extensive knowledge of the system functioning of the Upper Sea Scheldt.

A research programme was devised to investigate the long term tidal evolution, the sediment balance, and the hydrodynamic behavior, the reaction of sediment transport, ecosystem behavior, effects on habitat and potential effect on higher trophic levels due to measures to improve navigation as studied in the feasibility study (the so-called B-alternatives). The study of a reference situation will be the baseline for evaluating the autonomous evolution (morphological reaction of the system, climate change). The study of C-alternatives aims at investigating possibilities to either cope with the undesirable effects of the autonomous evolution and the B-alternatives.

The study started in 2014 with the construction of the modeling instrument. The latter should be in place to investigate the B-alternatives in 2015, and to decide on possible C-alternatives in 2016, and to draft an integrated plan for development of the Upper Sea Scheldt (2017).

3 APPROACH OF THE INTEGRATED STUDY

3.1 *Scientific approach*

A scientific study is conducted using state of the art models developed by Flanders Hydraulics, Research Institute for Nature and Forest (INBO), Ecosystem Management Research Group (Ecobe, University of Antwerp), and coordinated by IMDC.

3.2 *Independent expert judgment*

Several international experts were contacted and invited to participate to an independent expert panel.

Although keen to participate, the experts strongly insisted on their independent statute throughout the project.

During the project they will gather 4 to 5 times to critically discuss the approach, the used methods and the results.

The input from the first two expert meetings was used to revise the approach and the use of models.

3.3 *Effect evaluation*

Model results will be exploited to evaluate the effect of measures. The final plan will be subject to a strategic environmental assessment (SEA). Therefore evaluation will be strongly based on the EIA evaluation framework.

On the other hand a specific evaluation framework has been developed by VNSC and is being used for the Scheldt Estuary: Evaluation Method Scheldt Estuary (EMSE; Holzhauer et al., 2011; Maris et al., 2014).

For the project a specific evaluation framework is proposed, making maximum use of the available model results, and complying with the EIA requirements, but also respecting the topics (communication indicators) of the EMSE framework.

3.4 *Communication*

Knowing of the often strong opposition in other navigation projects, but also of the need for improvement of the waterway network, Waterwegen en Zeekanaal NV invests in a very open communication about its navigation projects. The communication includes dissemination of information, but also involvement of stakeholders.

In this early stage of the project, still dealing with the construction of the modeling instrument, the need of stakeholder involvement is of course still limited. But it will gradually increase as potential measures will be discussed. Today already the Flemish Nature Agency, and Division of Maritime Access participate in the daily follow-up of the project.

The Steering Committee also includes the Flemish Territorial Planning Agency, the Basin Management Committee, the Ports of Antwerp and Ghent, … A separate sounding board also includes nature associations, provinces and municipalities, agricultural associations, associations of skippers and other waterway users. Both bodies have been installed recently in a constructive atmosphere.

4 MODELING INSTRUMENT

A state of the art modeling instrument is being set-up, and will serve as a basis to investigate both autonomous developments and effects of measures. In this chapter the different models will be briefly introduced.

4.1 *Hydrodynamic model: SCALDIS*

For the assessment of hydrodynamic effects, an integrated model for the Scheldt Estuary is required. The existing models lacks a high resolution in the Upper Sea Scheldt, and Durme, Rupel and Nete tributaries in the estuary. For this reason, a new reference model is developed for the entire estuary, but with special attention to the upstream parts. The model is developed in TELEMAC.

TELEMAC is a finite element, hydro-informatic system with several modules developed by the National Hydraulics and Environment Laboratory of Electricité de France (EDF).Hydrodynamic and sediment transport processes are calculated by the modules TELEMAC-2D, and -3D, SISYPHE and TOMAWAC (waves). Tracer transport or water quality modeling is possible as well with other modules of the system (SUBIEF-2D and -3D) (Decrop, 2005).

The Finite Element technique is used to solve the equations and to produce the water depth and horizontal velocity components in every node. In case the user judges constant viscosity not appropriate, turbulent quantities can be incorporated using different models (Hervouet, 2007):

- Elder model: Different viscosity values can be specified along and across the flow direction.
- Nezu and Nakagawa
- Standard Mixing Length Model
- Smagorinski model
- k-epsilon model (3D): Turbulent viscosity is determined by simulation of turbulent kinetic energy (k) and turbulent dissipation (epsilon).

TELEMAC-3D solves the Reynolds-Averaged Navier-Stokes(RANS) equations in unstructured meshes obtained by a super-imposition of 2D meshes of triangles. The movement of the mesh is taken into account in the advection step by a sigma transformation. The super-imposed layers may not be evenly spaced. This allows a more accurate representation of the flow field by a refinement near the bed, enabling better accuracy of the turbulence models (mixing-length model, k–epsilon model) and leading to a better estimate of the bed shear stress. The 3D model can be applied to capture the effect of vertical recirculation cells as well as stratification effects, assuming a hydrostatic or non-hydrostatic pressure distribution. (Villaret et al, 2013).

The model domain (Figure 2) covers the entire tidal Scheldt estuary, including the mouth area and the Belgian Coastal Zone from Dunkerque (France), until Goeree (The Netherlands), including the Eastern Scheldt. Upstream, the model extends to the limits of the tidal intrusion. All tributaries of the Scheldt are included.

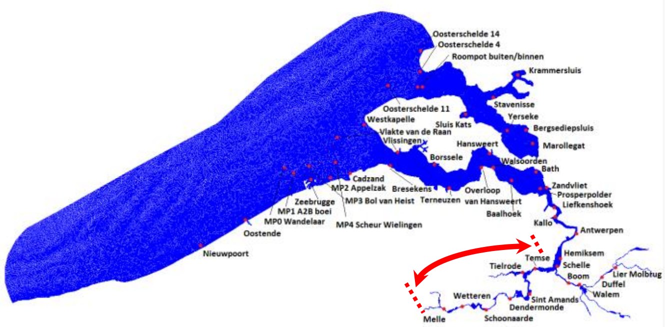

Figure 2: Model domain and output points: North Sea and Scheldt estuary. Upper Sea Scheldt indicated with arrow. Width of map ca. 200km.

Using an unstructured grid allows to combine a large model extent with a high resolution upstream. The grid resolution varies from 7-9m in the Upper Sea Scheldt to 500m at the offshore boundaries.

The model grid consists of +460 000 nodes in the horizontal. The model is 3D with 5 sigma planes over the vertical, which gives a total of +2 300 000 of nodes. The resolution in the coastal area varies from 200 to 500 m depending on water depth. The resolution in the Eastern Scheldt is 200 m. In the Western Scheldt the resolution is 120 m. In the Sea Scheldt the resolution increases slowly to 30m near Antwerp and 10m in the Upper Sea Scheldt. Upstream the tributaries the resolution can reach 4m.

In the actualized Sigma Plan for the Sea Scheldt, different restoration techniques are elaborated which combine safety with estuarine restoration (http://www.sigmaplan.be/). One example is flood control areas (FCA's) with our without a controlled reduced tide.

In order to include the FCA's in the SCALDIS model, the existing culvert functionality in TELEMAC was extended to better represent the hydrodynamics of water exchange between the Scheldt estuary and these flood control areas (Smolders, 2014). Discharge coefficients for in- and outlet structures are calibrated against measurement data in Lippenbroek and Bergenmeersen. Using this new schematization, all planned FCA's that are foreseen in the Sigma Plan are included in the model.

Tracer experiments will be carried out in the 3D hydrodynamic model in order to provide tracer concentration time series for calibration of the dispersion coefficient in the 1D model. For this purpose, the 3D model will be spiked with passive tracers, initialized in polygons that correspond to the boxes in the 1D OMES ecosystem model (see further). This is a similar method as used by Soetaert & Herman (1995a) when they calibrate their 1D MOSES model to the SAWES water quality model for the Western Scheldt.

The 1D model in turn will be used to calculate initial longitudinal salinity distributions for the 3D model calculations.

A 3D run with salinity as an active tracer runs with a speed-up of 8,5 on 60 cores (Intel Xeon Westmere X5650 - 2.66GHz Six Core). Including the flood control areas activates the culvert functionality that was added to the code. This slows down the calculation to a speed-up of 3,5. This is linked to the way sources and sinks are implemented in the TELEMAC code. The implementation of the new culvert code makes extensive use of the existing sources and sinks subroutine in TELEMAC. Optimizing the sources and sinks sub function will greatly reduce the cost of using the newly developed culvert functionality. This has been reported as a feature request to the developers in the TELEMAC consortium.

4.2 *3D Sediment transport*

Two models are used: one for sand transport (SISYPHE), one for transport of cohesive sediments (DELWAQ).

Sand transport is solved online using SISYPHE. SISYPHE is a sediment transport and morphodynamic model, open source that makes part of the TELEMAC-MASCARET numerical platform. It uses the BIEF finite element library, which is the library used by the overall TELEMAC system.

The model can be applied to non-cohesive and cohesive sediments and sand-mud mixtures. The sand composition is defined by different classes characterized by its mean diameter, settling velocity and grain density. In SISYPHE, the sediment transport also takes into account the effect of bottom slope, rigid beds, secondary currents, sliding beds. For the cohesive sediments or sand-mud mixtures the effect of bed consolidation is incorporated.

The total bed shear stress can be either calculated imposing a friction coefficient or predicted by a bed roughness predictor.

The total sediment load is split into the bed load and suspended load. While the bed load is modelled by using classical formulas, the suspended load is obtained through a transport equation for the depth-averaged suspended sediment concentration (in 2D) and the 3D equation for the suspended sediment concentration. The resulting bed changes are calculated by solving the Exner equation - bed evolution equation, using either the finite element or finite volume formulation.

When the current induced bed shear stress is higher than the critical threshold value, coarse particles move as bed load and finer particles as suspended load. The interface between bed load and suspended load is limited by a reference level (Zref). Above this level the sediment grains can be seen as a passive scalar that follows the flow velocity with and additional settling velocity term. Below the reference level there is a thin highly concentrated bed load layer in which the interactions between particles and flow and turbulence strongly affect the structure of the flow. Here, equilibrium conditions are assumed to relate the bed load to the current induced bed shear stress.

SISYPHE has a large range of domain applications, for instance rivers, estuaries and coastal areas. To take into account the effects of currents and waves, the different hydrodynamic variables can be either prescribed through external files (chaining method) or by internal coupling with other existent modules in the TELEMAC system, such as TELEMAC-3D (three-dimensional circulation model), TELEMAC-2D (two-dimensional circulation model) and TOMAWAC (spectral wave model).

Suspended sediment transport is computed with a conventional advection–diffusion solver implemented in DELWAQ. However, with regard to water-bed exchange of sediment, default formulations (such as PK—Partheniades-Krone) have been modified. The bed of the Scheldt estuary is represented by two layers. Conceptually, the first and uppermost layer is the thin fluffy fine sediment layer deposited during slack water. At high current velocity, most or nearly all of this layer is resuspended into the water column. The critical shear stress for resuspension of this layer is low and its erosion constant is high. Conceptually, the second (lower) bed layer with user-defined thickness (d) represents the sand bed which prevails in the Scheldt estuary. Typically, d is in the order of the mixing depth of the bed, about 0,1 m. The mixing depth is defined as the vertical distance over which the bed is more or less homogeneous because of mixing, e.g. by bioturbation (van Kessel et al., 2011).

DELWAQ is chosen as a platform to model cohesive sediment transport, because it has a proven track record in modeling cohesive sediment transport in the Scheldt estuary. Development and application have been published (van Kessel et al., 2011; van der Wal et al., 2010 and Eleveld et al., 2014). Recently, the same modeling approach has been applied to the Ems estuary bordering The Netherlands and Germany (van Maren et al., 2015).

Modeling of cohesive sediment transport will also be tested in SISYPHE (the module that will be used for sand transport). This is done to make sure that the SCALDIS model system can be used in the future for sand-mud interaction (not included in this project)

4.3 *Ecosystem-model*

Primary production in the Scheldt estuary is largely limited by light availability. The actual amount of available light to the phytoplankton depends on the ratio of the light penetration depth (euphotic depth) and the mixing depth, which determines the fraction of their time that can be spent on photosynthesis. Light penetration in the water column is in a turbid estuary largely determined by the suspended matter concentration and its mud content, and depending on the intensity of primary production, also by the phytoplankton (pigment) concentration. Mixing depth is largely determined by the hydrodynamic properties of the system. Considering the complete mixing over a large part of the Scheldt estuary, this mixing depth corresponds largely with the water column depth. It is therefore expected that changes in bathymetry, particularly changes in the relative contribution of shallow regions, could have a strong impact on the attained primary production.

The ecosystem model was devised to investigate the impact of modifications in the Upper Sea Scheldt on potential primary production, biogeochemical cycling, and resource availability to higher trophic levels, via changed hydrodynamics. It receives data from the 3-dimensional hydrodynamic model (SCALDIS), and resolves the impact of changes in hydrodynamics and light climate on the phytoplankton and zooplankton communities and on biogeochemical cycling of nutrients. The generated output from this model is made available for habitat suitability models for the higher trophic levels.

The goals of this modeling research are to assess:

1. the impact of potential changes in river morphology, residence time, and average mixing depth (through changes in bathymetry) on potential primary production, oxygen balance and the system's trophic state
2. the impact of changes in turbidity and by extension euphotic depth on potential primary production, oxygen balance and trophic state of the system

The present 1-dimensional model is tide averaged. It resolves downstream volumetric transport of water and dissolved substances, but no tidal variability. Its spatial configuration is based on MOSES model by Soetaert et al. (1994), but extends further upstream and has a higher spatial resolution (ca. 82 serial segments or boxes of variable length (ca. 5 km in the Western Scheldt, ca. 1.5 km in the Sea Scheldt) along the longitudinal axis (Vlissingen – Merelbeke; 155 km). At the boundaries it receives inputs from the Bovenschelde, and the tributaries Rupel, Dender and Durme. The bathymetry of the Durme and tidal branch (Gentbrugge) are included in the bathymetry of the most nearby box; the Rupel will be included as a dynamically calculated box on its own. For the flood Control Areas with a Controlled Reduced Tide (FCA/CRT systems) that are already functional or planned in the future, the surface-depth relationship of the FCA/CRT will be added to that of the connected river segment. This results in an implicit inclusion of additional primary production in the shallow areas of the FCA/CRT systems without the computational burden of explicitly adding FCA/CRT compartments with a complicated exchange with the main channel. The FCA/CRT systems, the tidal arm and the bathymetry of the Durme are an extension relative to the original MOSES model.

In many other aspects, the present model is a reduction of the original MOSES model (Soetaert et al. 1994; Soetaert and Herman, 1995a, b). For instance, no benthic-pelagic coupling is foreseen in this version for several reasons. Firstly, to the best of our knowledge, a considerable part of the river bed consists of sands with a certain degree of permeability. In a first approximation, the benthic processes occurring in such sediments could be approximated as part of the water column (assuming that sufficient exchange is present at the sediment-water interface). Outcrops of clay layers represent another significant fraction of the river bed. These sediments could be considered biologically inert because of the virtually zero-permeability. Secondly, no data exists on the processes occurring in the sediments. This implies that if benthic processes would be included in the model, they would not be constrained. Although inclusion of these processes in the model would imply an explicit acknowledgement of the uncertainty, it could also severely complicate interpretation of the results from calibrations, sensitivity analyses and simulations. Therefore, we chose not to include benthic-pelagic coupling, but keep in mind that if the model does not reproduce observations satisfactorily, this lack of functionality could be one possible reason. In that case, we will add extra functionality to further explore the uncertainty.

Other original functionalities that were removed in this version are, among others, phyto- and zoobenthos (cf. benthic-pelagic coupling, previous paragraph), several phytoplankton functional types, and a reduction of the number of detritus pools.

These choices can always be traced back to our general approach towards modeling; the model is primarily used as a tool to integrate quantitative data and qualitative knowledge (i.e. a data-centric approach). Theoretical reflections on the system's functioning (model-centric approach) and hypothesis generation are only secondary. In addition, it is often more efficient to use different simple models, instead of one 'ultimate' ecosystem model (Fulton et al. 2003; Allen and Fulton, 2010) to understand a system. Therefore, we chose to start with a simple model and add functionality as we see a need for it. As a result, the present model should not be considered the endpoint, but rather a phase in an ongoing process of development towards a model of intermediate complexity that is deemed appropriate for this project, in which following processes are included (non limitative):

- Primary production
- Nutrient uptake by phytoplankton
- Phytoplankton losses, exudation, excretion and respiration
- Silica dissolution
- Grazing and zooplankton growth
- Zooplankton losses, excretion and respiration
- Remineralisation
- Nitrification
- Denitrification
- Transport processes

4.4 *Habitats and Higher trophic levels*

In order to predict ecosystem responses, a number of existing scripts and modeling tools will be used to estimate the expected changes in habitat (quality) and abundance/biomass of species:

1. Ecotopes: changes in area of the habitats (ecotope maps).

There is a wide variety of habitats in het Sea Scheldt. This variation is caused by three major gradients: a gradient from completely fresh to mesohaline, a vertical gradient from the deepest point of the channel to the highest part of the marsh, and an internal gradient of a cyclical variation in habitat turn-over. These habitats and their characteristics are the result of morpho- and hydrodynamics (see flowchart Figure 2 27for main variables).

Higher trophic levels, such as macrophytes, benthic invertebrates, fish and birds depend on these habitats as a growth, resting, reproducing or feeding area. To keep the estuary in a good ecological condition the presence of certain habitats (such as low dynamic intertidal), the area and diversity of ecotopes is crucial.

The Scheldt estuary is continually subject to change. Ecotope maps are one of the instruments used in the Scheldt-estuary to follow up the habitat diversity (Van Ryckegem et al. (2014)). In this approach this instrument is proposed to evaluate the different morphological alternatives and scenarios to check for direct effects on the habitat diversity. So the ecotope mapping will give a glance on the state of the system assuming a realization of all measures in a short time span without the establishment of a new morphological equilibrium. Therefore it will be needed to give a post-hoc expert opinion on each scenario.

2. Marsh vegetation: marsh ecotope model (Gyselings et al., 2011).

Tidal marshes in the Sea Scheldt are composed of highly productive vegetation providing habitat for breeding birds and sustaining a high biodiversity of plants and animals within the Scheldt-ecosystem. The different plant species or vegetation types have a specific distribution in the study area. Salinity is the main driver in the zone with a high salinity gradient, but for simplicity and because several variables behave differently in changing salinity conditions separate models were developed for brackish and freshwater parts of the estuary .

The habitat characterizations for vegetation types were modeled with generalized mixed models and logistic regressions in R. A specific mixed model for densities of pioneers, rushes and reeds for the freshwater zone is developed and the calculated parameters will be used in this study. The logistic regression models estimate the probability of presence of a vegetation type at a grid cell. The modeled outcome of the probabilities is illustrated in Figure 3 and Figure 4.

Based on the modeled relationships, changes in potential spatial distribution of focal vegetation types (pioneers, rushes and reeds) will be quantified (surface area).

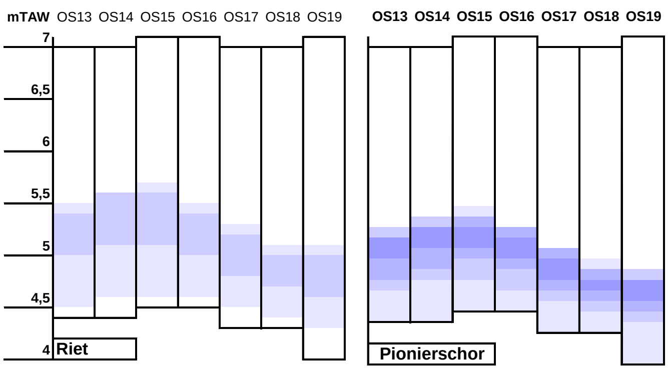

Figure 3: Modeled probability presence given a tidal marsh elevation (m TAW) within different OMES segments in the fresh water part of the Sea Scheldt. Reed and pioneer vegetation (Gyselings et al., 2011). X-axis represents the OMES segment and Y-axis the tidal march elevation. Light blue shades represent low probabilities of occurrence and dark

blue shades represent high probabilities of occurrence.

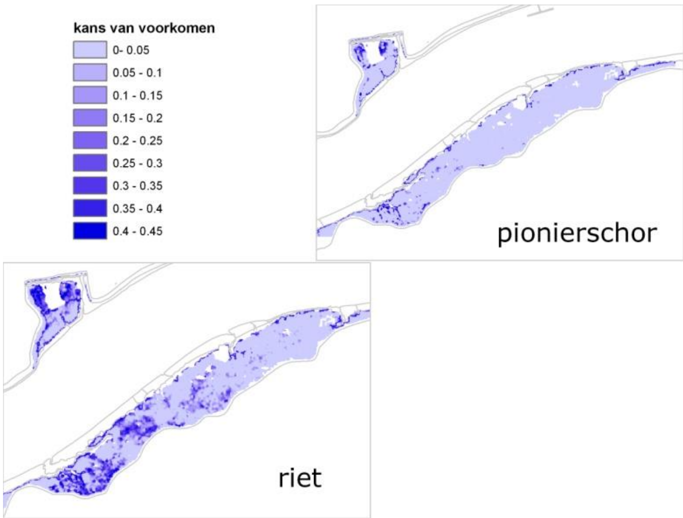

Figure 4: Illustration of the modeled probability of pioneer marsh and reed vegetation (Kijkverdriet and Notelaar marsh) (Gyselings et al., 2011)

3. Response on higher trophic levels: changes in habitat suitability for migratory fish based on modeling tool for twait shad (Alosa fallax) (Stevens et al., 2011).

Migratory fish such as twait shad are important indicators of ecosystem functioning. Because of their migratory behavior they depend on a good quality of the entire stretch they use in the system (sea to spawning area). Those requirements, which are incorporated as variables in the models, are mainly good water quality characteristics and specific habitat conditions in order to be able to reproduce successfully. Moreover, policy makers have specific responsibility to restore and to sustain the population in a favorable state as the species is on the annex 2 of the Habitat Directive (92/43/EEG 21 mei 1992).

The used model for the Sea Scheldt is a spatial habitat suitability model based on literature data since the population of twait shad in the Scheldt is too small to identify the critical habitats by sampling in the field. To describe the habitat suitability two submodels were developed one to evaluate the suitability for spawning and one to evaluate the suitability for larvae development. The following variables are considered: temperature, oxygen%, turbidity, water depth, water velocity, retention time and available food – zooplankton. For each variable a tolerance range was determined. The spatial model combines the variables using fuzzy logic in order to determine the degree of suitability of a section in the Scheldt for spawning and larvae development.

4. Benthos: changes in biomass in function of changes in the surface area of the ecotopes.

Benthos is an important intermediate component in the food chain. Benthos consume algae (primary production) and detritus and are consumed by higher trophic levels such as fishes and birds. Because of their central role, changes in densities, species composition and quality of benthos may have important consequences for the ecosystem.

For changes in biomass of benthos a straightforward relation between biomass and surface area of the ecotopes is assumed which can be modeled by simple linear regression.

Two new modeling tools will be developed:

1. To assess (changes in) habitat quality, a GIS-tool will be developed to map changes in bank slopes (steepness): this is an important criterion to determine durability of tidal mudflats and neighboring marshes (marsh edges).

2. Many (water)birds depend on the mud flats and contained benthos for their food acquisition, and large parts of these habitats are therefore incorporated in the habitat- and bird-directives. Any changes in availability of the mud flats (changes in surface area, tidal characteristics,…) or in the quality of the mud flats and water (oxygen, salinity,…) will potentially affect bird abundances, including sensitive bird species that are chosen as indicators of Scheldt ecosystem quality. To assess responses on higher trophic levels, a predictive modeling tool will be developed to provide a quantitative analysis of the impact on bird abundances.

Field data on bird abundances and predictive variables for the period 2000-2013 are available that can be used to develop and validate the model.

Based on a conceptual framework of the food web and the benthic-pelagic coupling, the predictor variables can be linked to three alternative pathways that may influence bird abundances. These pathways assume that there is a link between water quality variables and the productivity in the benthic habitats (phytobenthos and macro-invertebrates) of the mud flats. Phytobenthos and especially benthic macro-invertebrates are known to be an important food source of foraging ducks in the Sea Scheldt (Van Ryckegem et al., 2006). Field data on phytobenthos and macrobenthos, however, are too scarce to be incorporated directly into the model as explanatory variables. The three alternative pathways are suggested as possible hypotheses, as little is known yet about the actual dynamics of the benthic-pelagic coupling in the Sea Scheldt.

A first hypothetical pathway links the productivity of the benthic community to the level of primary production and the available phytoplankton and phytobenthos. Phytoplankton and phytobenthos have been shown to be an important food source of benthic macro-invertebrates in the Westerscheldt (Herman et al, 1999), but the link between primary production and macro-invertebrates in the Sea Scheldt has not been investigated in great detail. Given that, as opposed to the Westerscheldt, the macro-invertebrates in the Sea Scheldt mainly consist of deposit feeders (feeding in and on the mud) instead of suspension feeders (filtering the water column), it is yet unclear to what extent primary production and phytoplankton also determine productivity in the benthic faunal community of the Sea Scheldt. The availability of phytoplankton can be measured by the availability of Chl a in the water column. Data on phytobenthos are very scarcely available, but it is assumed that it correlates with the abundance of phytoplankton.

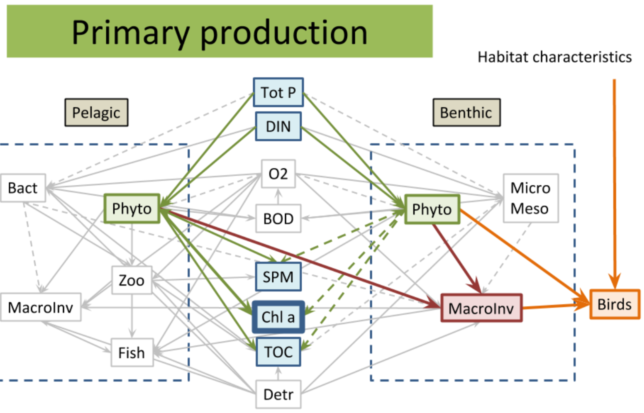

Figure 5: Illustration of the food web in the Sea Scheldt, highlighting the link between the benthic community and primary production

A second pathway links abundance of benthic macro-invertebrates to carbon load and detritus. Stable isotope analyses suggests that detritus derived from terrestrial sources (leaf litter) is a poor food source for estuarine benthic invertebrates (Sakamaki et al. 2010). Before 2007, however, a large proportion of the detritus in the Sea Scheldt (especially in the oligohaline zone) came from waste water inflow, which is much more biodegradable (Abril et al., 2002). It is striking that the activation of the water treatment facilities for the city of Brussels in 2007, coincide with a strong decline in the abundance of both benthic invertebrates and waterfowl (Speybroeck et al., 2014; Van Ryckegem et al., 2014). Detritus is not measured directly but can be calculated as the difference between particulate organic carbon and the carbon biomass of phyto- and zooplankton.

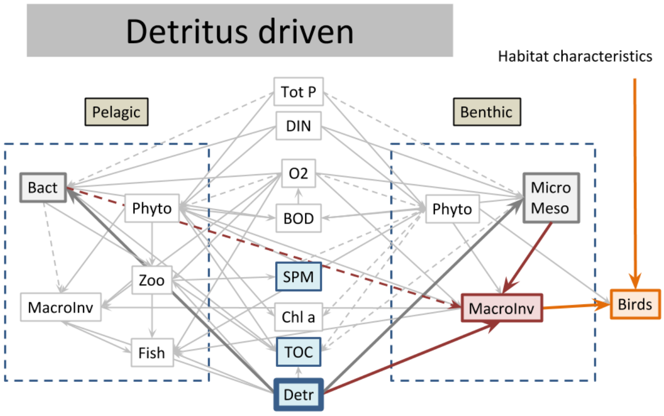

Figure 6: Illustration of the food web in the Sea Scheldt, highlighting the link between the benthic community and detritus

The general water treatment program of the Scheldt indeed coincides with remarkable changes in the ecological functioning of the Sea Scheldt. Whereas the initiation of the water treatment in the nineties and the subsequent recovery from hypereutrophic and anoxic conditions (Cox et al., 2009), resulted in the buildup of a dense benthic invertebrate community, further improvement of the water quality and increased availability of oxygen after the finalization of the program in 2007, coincides with a strong decline of benthic invertebrates and the (re)appearance of fish and hyperbenthic invertebrates (living near the bottom). Therefore, a third hypothetical pathway suggests that changes in abundance of benthic macro-invertebrates in the years 2000 are not caused by depletion of available food sources but by negative interference from competitors (hyperbenthos) and predators (fish) that are more sensitive to oxygen depletion. As indicator variables of the state of the food web, BOD and O_2 will be used.

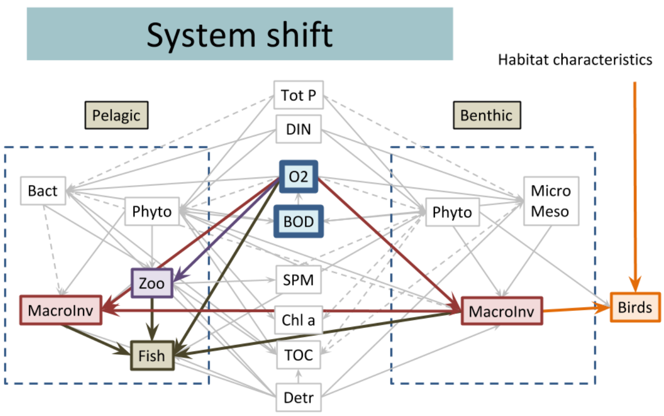

Figure 7: Illustration of the food web in the Sea Scheldt, highlighting the link between the benthic community and oxygen associated changes in the food web

For predicting bird abundances, a number of regression and machine learning methods will be compared in which abundance of individual bird species will be linked to available abiotic and biotic predictive variables. Variance inflation factors and pairwise correlations will be used for selecting independent predictive variables.

Based on the deviance of predicted outcomes from validation data, we will compare the predictive power of generalized linear mixed models, Generalized Additive Mixed Models, N-mixture models and boosted regression trees. Advantages of GLMM and GAMM are that they are less complex and easier to compute, but they may be prone to over-fitting of the training data and therefore lack predictive power when other data are supplied.

GLMM will be first applied on data pertaining to months with highest species abundance. Initially, the model will be applied to recent years only (after the abundance decrease since 2008) as these appear to be the most relevant for predicting future abundance. Initial model selection will be based on the Akaike Information Criterion (AIC). Definitive model selection will be based on k-fold cross-validation (part of the dataset is used for calibration, part for validation; routine is repeated k times to derive a predictive deviance, so the model with lowest deviance can be selected).

GAMM models will not be applied in first instance but only if clearly nonlinear response between important predictive parameters are observed in GLMM.

N-mixture modeling and Boosted Regression Trees will be investigated preliminary for assessing their value in the analysis.

N-mixture modeling is a recent technique that does not only estimate population abundances in relation to predictive variables, but also detection probability of the animals during surveys. This should lead to more precise estimates of bird population sizes when detection probability is less than one.

Boosted regression trees (BRTs) combine elements of regression techniques and machine learning and is a promising recent technique which is expected to have better predictive power than for example, GLMM and GAMM. Similar to GAMM, it is able to incorporate non-linear responses into the model without the need for data transformations. A drawback of BRTs is that it is currently not possible to include spatial and temporal dependency structure (random blocking factors in GLMM) into a model for count data. To be able to take this dependency structure of the data into account, a subsampling scheme for cross-validation needs to be developed in which each spatial and each temporal 'block' is only represented once in the calibration set.

4.5 *Autonomous morphological development*

The independent experts asked particular attention for the long-term autonomous development of the morphology of the Scheldt as a response to measures and human activities up to present.

Initially a morphodynamic model was not included in the research programme. The main reason for this is that detailed morphodynamic modeling is considered a field of research. Such morphodynamic models may produce results with important uncertainties that may be larger than the alternatives foreseen in present study and thus lead to false conclusions.

However, since the long-term morphological evolution between the present and 2050 (reference situation) and the evolution after 2050 is considered important, it was finally decided to include a 1D modeling approach using existing models of the Scheldt.

In long-term morphological modeling, the goal is to reproduce (or forecast) the evolution of the morphological system equilibrium in response to changes (perturbations) of that system. Perturbations may include shortening, widening, deepening etc. The local (detailed) evolution of the bathymetry is not the aim of such modeling, but rather the behavior of the system as a whole.

The procedure includes following steps:

1. Actualization of the model and calibration for the morphological evolution of the period 2000-2015, including widening and deepening of the channel downstream, sand mining, construction of the tidal Deurganckdok in the Port of Antwerp, etc.
2. Validation of the morphological model for the period 1970-2000 (or 2015), departing from the bathymetry of 1970 and keeping the same settings of the model parameters. All known measures related to dredging and disposal and large-scale projects will be included in the model. The goal of the validation is to verify whether the observed erosion of the Upper Sea Scheldt can be reproduced. With a model capable of reproducing the past decades, we are rather confident that future processes can be modeled as well. The uncertainty concerning the dredged volumes in the past will be part of an ensemble modeling approach (see further).

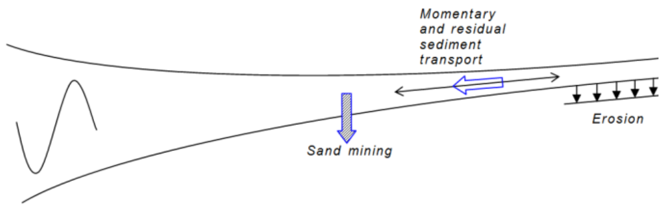

Figure 8: Conceptual long term response of sand winning near Antwerp leading to upstream erosion.

3. Uncertainty analysis will be performed to evaluate the effect of the uncertainty on the hydrodynamic and morphodynamic response in function of system parameters that pertain a certain uncertainty as well (tidal amplitude downstream, sand mining upstream, implementation of measures). The goal is to obtain a range of morphological outcomes at present day based on a set of hindcasts. From this analysis, it will be possible to evaluate hypotheses concerning the amount of sediment extracted from the Upper Sea Scheldt. A low, likely and high sand extraction hypothesis will be tested.

4. For the future projection (present to 2050 and further), an ensemble modeling approach will be set up. This will include the uncertainty of the system parameters (uncertainty analysis mentioned above) and model parameters (from the calibration stage / sensitivity analysis).

5. The ensemble modeling approach will be applied to different periods and alternatives:

a. Analysis of the autonomous development in the period 2013-2050;

b. Analysis of the period 2050 – 2085 with and without the proposed B-alternatives.

c. Investigation of the feasibility of different basic types of measures (lengthening or shortening the channel, cutting bends, deepening, depoldering…) and different management strategies (including upstream and downstream) to mitigate negative (historic) evolutions (tidal amplitude, sediment transport). These measures are 'building blocks' that will supplement the B-alternatives while developing the C-alternatives.

The output of the modeling will give insight in the autonomous evolution of the system by 2050 (starting from the 2013 reference geometry) and by 2085 (starting from the 2050 reference geometry).

6. The output of the models in terms of changing geometry, bathymetry and hydrodynamics will also serve as further input for the analysis towards hyperturbidity risks with the Winterwerp analytical model (see next paragraph).

The results of the 2013-2050 long term run will not be transposed to the 3D model and other parts of the model train due to reasons of uncertainty on the high-resolution bathymetrical changes. The relative magnitude of the autonomous development in comparison to the effects of the measures will be used in further interpretation and judgment.

4.6 *Evaluation of the risk for hyperturbid regime shifts*

The Expert Group asked attention for the risk for a regime shift towards a hyperturbid system, as has been observed in other estuaries in Europe as a consequence of deepening the estuary. This effectively led to increased tidal range and tidal pumping, in turn yielding increased sediment concentrations in the water column to such a point that hydraulic drag was decreased and further tidal amplitude increase was promoted.

It is thus essential to have an integrated view on the coupling of historical measures (deepening, sand mining and tidal characteristics. Further deepening or cutting of meanders could invoke a further degradation of the system. The new 3D hydrodynamic and sediment transport models are too expensive (time-consuming) to model long term evolutions related to this problem. Therefore, a more pragmatic approach is presented to address the problem (Van Holland et al., 2015).

The historical evolution of geometry, bathymetry and hydraulic damping in different European estuaries has been studied by Winterwerp (2013a, 2013b). It was shown that a trend appeared in the relation between geometry (convergence) and damping, or other hydraulic parameters (Figure 9). The Scheldt shows similar behavior, but the main difference with other estuaries is that the Scheldt is not in a state of hyperturbidity, whereas the others are. The question that arises is whether the proposed (and maybe other) measures may further effectuate this trend, with possible similar consequences as observed in other estuaries.

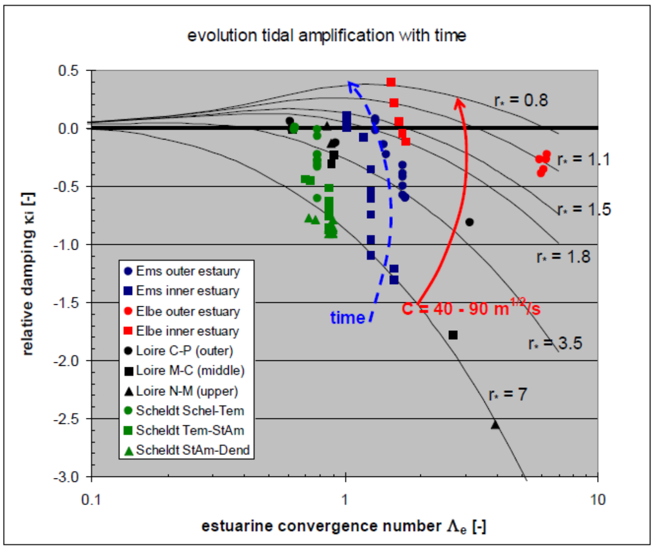

Figure 9: Comparison of tidal evolution in 4 European rivers, a shift of position indicates an increased risk on hyperturbidity (Winterwerp, 2013).

The same 1D hydrodynamic model of the Scheldt estuary as used for the morphological modeling, will be used.

Firstly, the analysis by Winterwerp (2013a and b) will be repeated using the model output from the 1D model (the hindcast) instead of the measurements and observations (as conducted by Winterwerp). This will result in a representation of the past and current state of the system as in the figure above. Secondly, the alternatives and other measures will be analyzed in a similar way to illustrate the hydrodynamic and geometric effect of the measures. Since morphological modeling is carried out, both the instantaneous effects (2050) and long term effects (post 2050) will be evaluated.

Complementary research will be conducted in the VNSC "Agenda of the Future" research programme (2014-2017). In this framework, an idealised 2DV (width averaged) model will be set up by Flanders Hydraulics, which project goals are stated as follows:

1. describe the physical mechanisms that are important for the origin of hyperturbid conditions;
2. find out how critical the passage from one state to another is;
3. identify system-dependent parameters that render some estuaries more susceptible to a regime shift than others;
4. identify potential measures to counter hyperturbidity.

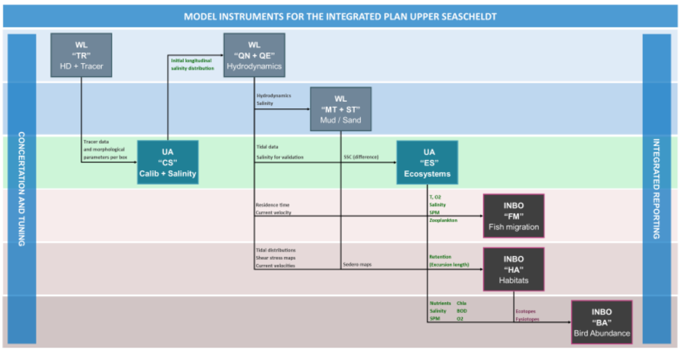

Figure 10: Model Sequence and data flow

5 EVALUATION

An assessment or evaluation framework is required to assess the impact related to the different project alternatives. An overall evaluation framework is being developed by EIA experts as part of the EIA notification conforming to the requirements of the Flemish EIA procedure.

A partial evaluation framework is prepared that addresses the EIA disciplines Water and Fauna & Flora and more specifically the part of these disciplines that can be evaluated on the basis of the output of the model instrument. During the setup of the partial framework, the Evaluation Method for the Scheldt Estuary (EMSE) (Holzhauer et al., 2011; Maris et al., 2014) will be taken into account because it is a tailor-made method that has been designed for the evaluation of the state of the Scheldt estuary (based on monitoring data), starting from a "Long Term Vision" on the estuary and its and the ecosystem functioning, and taking into account the management goals from legal frameworks and management decisions.

5.1 *EIA disciplines and criteria selection*

The EIA service of the Flemish government has published a set of Guidelines per discipline: Air, Water, Sound and vibrations, Soil, Fauna and Flora, Landscape, Built heritage and archaeology, Human – health, Light, heath and electromagnetic waves, Human – spatial aspects, Mobility, Climate

The numerical and statistical models that are being developed and approved in the framework of the Integrated Plan, do not address all of these disciplines. Based on effect groups defined in the Guidelines, the output of the model instruments can be attributed to the EIA disciplines Water and Fauna & Flora.

A list of criteria (for the disciplines Water and Fauna & Flora) that will be evaluated in the EIA (C-alternatives) has been composed. Part of these criteria correspond to parameters that are available as model output. The set of criteria has been expanded with additional criteria that are considered important for the (eco)system functioning, and have been inspired by the Evaluation Method for the Scheldt Estuary (EMSE; Holzhauer et al., 2011; Maris et al., 2014). The final set of parameters form the basis of the partial evaluation framework for the B-alternatives and will also be applied for the evaluation of the C-alternatives as part of the EIA.

5.2 *Evaluation method Scheldt estuary*

The Evaluation Method Scheldt Estuary (EMSE) is a mostly quantitative and multidisciplinary approach to evaluating the state of the estuarine system of the Scheldt. The method is divided in topics but many links and relations between those topics are included in the method.

The fundaments of the Method are the management goals from the Long Term Vision 2030 and the functioning of the ecosystem. The monitoring programme of the Scheldt Estuary (MONEOS) (Meire and Maris, 2008) and the EMSE must offer the possibility to early recognize and evaluate developments of the ecosystem as a support for adaptive management. The EMSE is based on the main functions of the estuary: Navigability, Naturalness and Safety.

The EMSE is deemed a scientifically based, integrated evaluation framework that can be used in the impact assessment of this specific project, in relation to the specific disciplines of Water and Fauna & Flora.

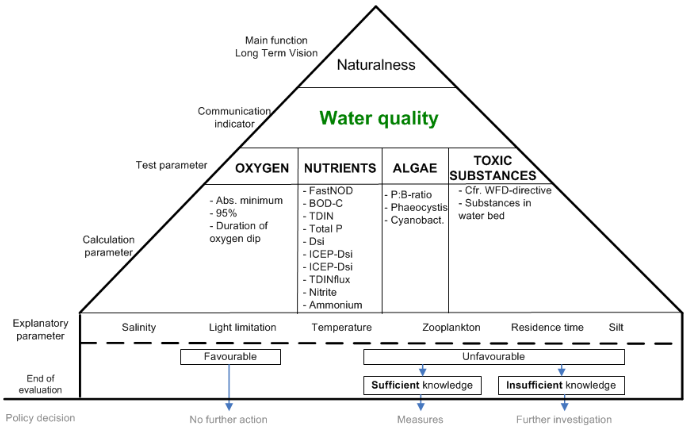

Figure 11: Example of EMSE communication indicator or topic Water Quality (Maris et al., 2014).

6 CONCLUSION

A feasibility study to improve the navigability of the Upper Sea Scheldt showed the necessity to embed a future navigation project of the river in the general functioning of the Scheldt estuary, and of the need to improve the knowledge of the hydromorphological and ecosystem functioning of the estuary. Waterwegen en Zeekanaal NV participates in the "Agenda for the Future" research program with a study dedicated to the upstream part of the Scheldt estuary.

The scientific research based on state of the art models is communicated to the public, and stakeholders will be involved in the devising of alternatives, that may affect their future.

The research of the Flemish research institutes and universities is monitored by an independent international expert group, that effectively impacts the study to improve its validity.

Alternatives will be evaluated using model results, respecting both EIA requirements as specific evaluation methods tuned for the Scheldt estuary.

While the study may still take several years to result in concrete plans, Waterwegen en Zeekanaal NV already changed its philosophy of maintenance (dredging and bank protection) looking for a sustainable way to guarantee navigation and preserve nature.

REFERENCES

Abril, G., Nogueira, M., Etcheber, H., Cabeçadas, G., Lemaire, E., & Brogueira, M. J. (2002). Behaviour of organic carbon in nine contrasting European estuaries. Estuarine, Coastal and Shelf Science, 54(2), 241-262.

Allen J.I., E.A. Fulton (2010). Top-down, bottom-up or middle-out? Avoiding extraneous detail and over-generality in marine ecosystem models. Progress in Oceanography, 84: 129-133

Blauw A.N., H.F.J. Los, M. Bokhorst, P.L.A. Erftemeijer (2009). GEM: a generic ecological model for estuaries and coastal waters. Hydrobiologia 618:175–198

Decrop, B. (2005) Sand transport modelling in the Ijzer Estuary using TELEMAC-2D and SISYPHE.

Cox, T. J. S., Maris, T., Soetaert, K. E. R., Conley, D. J., Damme, S. V., Meire, P., Middelburg, J. J., Vos, M. & Struyf, E. (2009). A macro-tidal freshwater ecosystem recovering from hypereutrophication: the Schelde case study. Biogeosciences,6.

Eleveld, M.A., van der Wal, D., van Kessel, T., 2014. Estuarine suspended particulate matter concentrations from sun-synchronous satellite remote sensing: Tidal and meteorological effects and biases. Remote Sensing of Environment, 1 (43), 204–215. doi:10.1016/j.rse.2013.12.019.

Eloot, K., Vantorre, M., Adams, R.' Bosmans, S., De Beukelaer-Dossche, M. (2015). Design Guidelines versus Practices for the Upper-Seascheldt, the Inland Waterway Connection between Antwerp and Ghent. Smart Rivers 2015, paper 99.

Fulton E.A., A.D.M. Smith, C.R. Johnson (2003). Effect of complexity on marine ecosystem models. Marine Ecology Progress Series, 253: 1–16

Gyselings, R., Van De Meutter, F., Vandevoorde, B., Milotic, T., Van Braeckel, A., Van den Bergh, E. (2011). Ontwikkeling van één schor ecotopenstelsel voor het Schelde-estuarium (Vervolgstudie). Rapporten van het Instituut voor Natuur- en Bosonderzoek 2011 (31). Instituut voor Natuur- en Bosonderzoek, Brussel. [with English summary] [www.inbo.be/files/ bibliotheek/49/228149.pdf]

Herman, P. M. J., Middelburg, J. J., Van de Koppel, J., & Heip, C. H. R. (1999). Ecology of estuarine macrobenthos. Advances in ecological research,29, 195-240.

Hervouet, Jean-Michel. Hydrodynamics of Free Surface Flows: Modelling with the finite element method. John Wiley & Sons, 2007.

IMDC (2013). Bevordering Binnenvaart - Zeeschelde. Studie bevaarbaarheid van de Boven-Zeeschelde en Zuidelijk vak Ringvaart voor klasse Va-schepen. Maatschappelijke Kosten-Batenanalyse. In opdracht van Waterwegen en Zeekanaal NV

Kessel, T. van, J. Vanlede, J.M. de Kok (2011). Development of a mud transport model for the

Scheldt estuary. Continental Shelf Research, 31 S165–S181 doi: 10.1016/j.csr.2010.12.006.

Maren, D.S. van, T. van Kessel, K. Cronin, L. Sittoni (2015). The impact of channel deepening and dredging on estuarine sediment concentration. Continental Shelf Research, 95, 1-14. doi:10.1016/j.csr.2014.12.010.

Maris, T., Bruens, A., van Duren, L., Vroom, J., Holzhauer, H., De Jonge, M., Van Damme, S., Nolte, A., Kuijper, K., Taal, M., Jeuken, C., Kromkamp J. en van Wesenbeeck, B., Van Ryckegem, G., Van den Bergh, E., Wijnhoven S. en Meire P. - Evaluatiemethodiek Schelde-estuarium – Update 2014, VNSC.

Meire, P. & Maris, T. (2008), MONEOS, Geïntegreerde systeemmonitoring van het schelde-estuarium. Rapport ECOBE 08-R-113. Universiteit Antwerpen, Antwerpen.

Sakamaki, T., Shum, J. Y., & Richardson, J. S. (2010). Watershed effects on chemical properties of sediment and primary consumption in estuarine tidal flats: Importance of watershed size and food selectivity by macrobenthos.Ecosystems, 13(2), 328-337.

Smolders, S.; Maximova, T.; Vanlede, J.; Teles, M.J. (2014). Implementation of controlled reduced tide and flooding areas in the TELEMAC 3D model of the Scheldt Estuary, in: Bertrand, O. et al. (Ed.) (2014). Proceedings of the 21st TELEMAC-MASCARET User Conference,15th-17th October 2014, Grenoble – France. pp. 111-118

Speybroeck J., De Regge N., Soors J., Terrie T., Van Ryckegem G., Van Braeckel A., Van den Bergh E. (2014). Monitoring van het macrobenthos van de Zeeschelde en haar getij-onderhevige zijrivieren (1999-2010). Beschrijvend overzicht van historische gegevens (1999, 2002, 2005) en eerste cyclus van nieuwe strategie (2008, 2009, 2010). Rapporten van het Instituut voor Natuur- en Bosonderzoek 2014 (INBO.R.2014.1717661). Instituut voor Natuur- en Bosonderzoek, Brussel.

Soetaert K., P.M.J. Herman (1995a). Nitrogen dynamics in the Westerschelde estuary (SW Netherlands) estimated by means of the ecosystem model MOSES. Hydrobiologia, 311: 225-246

Soetaert K., P.M.J. Herman (1995b). Carbon flows in the Westerschelde estuary (The Netherlands) evaluated by means of an ecosystem model (MOSES). Hydrobiologia, 311: 247-266

Soetaert K., P.M.J. Herman, H. Scholten (1994). Model of the Scheldt Estuary – Ecosystem model development under SENECA. Concept report.

Stevens, M., Van den Neucker, T., Gelaude, E., Baeyens, R., Jacobs, Y., Mouton, A., Buysse, D. & Coeck, J. (2011). Onderzoek naar de trekvissoorten in het Schelde-estuarium. Voortplantings- en opgroeihabitat van rivierprik en fint. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2011 (14). Instituut voor Natuur- en Bosonderzoek, Brussel. [with English summary] [www.inbo.be/files/bibliotheek/40/224140.pdf]

Van Holland, G., Depreiter, D., Winterwerp H., De Beukelaer-Dossche, M. (2015). Sediment management in the Sea Scheldt - risk of hyper turbidity, INTERCOH 2015

Van Ryckegem G. , De Regge N. & Van den Bergh E. (2006). Voedselecologie en gedrag van overwinterende watervogels langs de Zeeschelde. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2006 (INBO.R.2006.28). Instituut voor Natuur- en Bosonderzoek, Brussel.

Van Ryckegem G. , Van Braeckel A., Elsen R., Speybroeck J., Vandevoorde B., Mertens W., Breine J., De Regge N., Soors J., Dhaluin P., Terrie T., Van Lierop, F., Hessel K. & Van den Bergh E. (2014). MONEOS – Geïntegreerd datarapport INBO: toestand Zeeschelde 2013. Monitoringsoverzicht en 1ste lijnsrapportage Geomorfologie, diversiteit Habitats en diversiteit Soorten. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2014 (2646963). Instituut voor Natuur- en Bosonderzoek, Brussel.

Villaret, C., Hervouet, J.-M., Kopmann, R., Merkel, U., & Davies, A. G. (2013). Morphodynamic modeling using the TELEMAC finite-element system. Computers & Geosciences, 53, 105–113. doi:10.1016/j.cageo.2011.10.004

Wal D. van der, T. van Kessel, M.A. Eleveld, J. Vanlede (2010). Spatial heterogeneity in estuarine mud dynamics. Ocean Dynamics, 60:519–533. doi:10.1007/s10236-010-0271-9.

Winterwerp J.C. and Wang Z-B. (2013a). Man-induced regime shifts in small estuaries – I: theory, Ocean Dynamics, DOI 10.1007/s10236-013-0662-9.

Winterwerp J.C., Wang Z-B., Van Brackel A., Van Holland G., and Kösters F. (2013b). Man-induced regime shifts in small estuaries – II: a comparison of rivers, Ocean Dynamics, DOI 10.1007/s10236-013-0663-8.