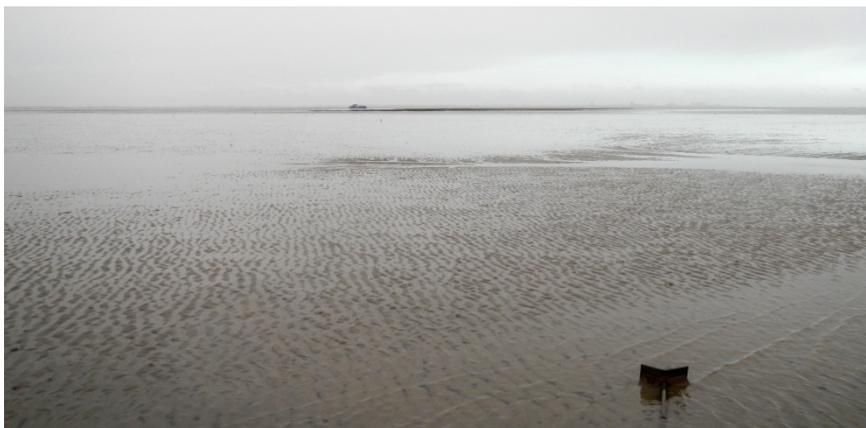


Blueprint for an Ems-Dollard ecosystem model study

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Blueprint for an Ems-Dollard ecosystem model study

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1 Summary

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015.

In the framework of the Ems-Dollard MIRT-study ('Meerjarenprogramma Infrastructuur, Ruimte en Transport'), the present project was commissioned by the Ministry of Economic Affairs leading to the set-up of an ecosystem model study.

Previously, Rijkswaterstaat had commissioned the project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*), carried out by Deltares and IMARES during the years 2012-2013. The aim of that project was to (1) improve the knowledge on the mud dynamics in the Ems Estuary (Figure 1.1), (2) to identify the reasons for the increase in turbidity and (3) to quantify measures to improve the ecological status of the estuary.

Field observations by IMARES on several water quality variables, pelagic and benthic primary production were done, and modelling studies by Deltares on mud dynamics and on the way phytoplankton dynamics were affected by changing dredging regimes were performed.

Since the Deltares model study did not include higher trophic levels, it was suggested to run other models that do include several relevant fauna species/groups. By this, the effect of changing turbidity on higher trophic levels will better be quantified and thus, the effectivity of measures to be taken can better be judged on. The aim of the present report is to describe an ecosystem model application able to include the desired higher trophic levels.

After a short overview of existing (model-)knowledge, an ecosystem model study is proposed. It lays emphasis on secondary producers, such as biomass development, individual growth and mortality and feeding pressure on pelagic algae by shellfish and zooplankton and on benthic algae by sediment browsers. Also pelagic microzooplankton, feeding on pelagic picophytoplankton, are included.

The proposed model is based on the EcoWasp-model, and includes a couple of improvements that are necessary or may be useful enhancing model performance.

2 Introduction

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. The ecological condition of the Ems-Dollard estuary is subject to many discussions, mostly related to an increased turbidity and its ecological implications. These discussions take place in both The Netherlands and Germany. To identify the problem and to quantify the effect of proposed solutions, the research project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*) has been carried out, consisting of a detailed analysis of available data, the collection of new data as well as the improvement and application of numerical models. Results of that project have been published in several reports, and summarized in Taal et al (2015).

Since in the ecological model study as performed in that research phytoplankton and phytobenthos were included, but no higher trophic levels, it was suggested to perform another ecosystem model study that does include higher trophic levels.

In this report, such a model set-up is presented. First, a short overview of existing (model-)knowledge will be presented, including their strengths and shortcomings. Next, the present EcoWasp-model is introduced, and possible improvements or needed extensions are mentioned. Also, the developed WasMo-model (Gerla et al, 2014) will be mentioned.

3 Previous modelling efforts

3.1 Pre-BOEDE modelling

Ecosystem modelling became feasible after computing power became widely available around the mid '70's (DiToro et al, 1971; Kremer & Nixon, 1978; Radford, 1982). The BOEDE-project (Biologisch Onderzoek Eems-Dollard Estuarium, see Baretta & Ruardij, 1988) probably was its time far ahead when it started at the end of the '70's because of the i) implementation of several trophic levels and several functional groups and ii) the application of such a model to a tidal system with a considerable part being tidal flats.

3.2 Boede-model and further developments

Basically, the BOEDE-research in those days was meant to study oxygen dynamics in the Ems-Dollard system, since that area was threatened by possible organic waste water discharges from potato and cardboard industries. One was aware of the complexity of the system, with many processes and organisms affecting oxygen dynamics, and vice versa, many organisms affected by low oxygen concentrations in the water. Consequently, the BOEDE-model thus evolved to a complex model with many variables incorporated, from bacteria and detritus to macrozoobenthos and zooplankton, with silicate, nitrogen components and oxygen as major inorganic substances.

3.3 Post-BOEDE developments, general

Later on, this Boede-model developed to EmoWad (more or less the same model applied to the western Wadden Sea, EON-I, 1988; EON-II, 1988) and to ERSEM¹, result of a large cooperation within an EU-framework project (Baretta et al, 1995; Baretta-Bekker & Baretta, 1997). Newer developments have been described by Vichi et al (2003).

Boede, EmoWad (and later on EcoWasp, see next section) all three used the same underlying physical approximation: an average flow field and dispersive characteristics, thus without a detailed description of hydrodynamics changing with the tides and unaffected by weather conditions nor by tidal variations such as spring and neap tides. Inflowing fresh water is supposed to follow a fixed route to the North Sea.

Such a simple hydrodynamic set-up may be considered as a major shortcoming of these models, especially since nowadays more and more detailed physical models become available (see e.g. Delft-3D (Deltares, 2015)). However, without large computer systems long computing times still are needed to run a combination of hydrological and ecosystem models. This is an important reason for

¹ ERSEM = European Regional Seas Ecosystem Model

many of such applications to run for only one or –in exceptional cases- a few years. For example, EcoWasp as applied to an 18-boxed western Dutch Wadden Sea schematization (Brinkman, 2013) ran about forty minutes for a 30 year simulation on a single core PC, where an application of WasMo, an ERSEM like model for the western Dutch Wadden Sea, took about 18 hours for a 1 year run on an 80-core cluster computer (Gerla et al, 2014).

ERSEM was offered as open source model, and had (and has) several international applications which will not be discussed here. One was the POLCOMS-ERSEM², a 3D-setup running on a very large computer system (see e.g. Moll & Radach, 2001; Moll & Radach, 2003 for an overview, including a number of other models).

Newest developments are not seldomly based on the GETM/GOTM open source physical modelling software (Burchardt & Bolding, 2002; GETM, 2006; GOTM, 2007), that allows for detailed modelling on currents and wave action, including vertical stratification.

3.4 Post-BOEDE developments, Wadden Sea

As a side-route, and after the EmoWad-application work on the Wadden Sea was stopped, the RIN³ at Texel started to go on with Wadden Sea modelling, and the development of the EcoWasp-model started.

A major difference between Boede/EmoWad and EcoWasp concerned the way the microbial food web was modelled (in Boede/EmoWad) or just was parametrized (EcoWasp), and the way fauna dynamics were implemented: simply as biomass (Boede/EmoWad) or as cohorts with individuals growing with time, reproduction (producing large numbers of offspring) with subsequent mortality (reduction of numbers) (EcoWasp).

3.5 EcoTim for the German Wadden Sea area

Necessary to mention here is the development of the EcoTim-ecosystem model at the Carl von Ossietzky-University in Oldenburg (Germany) (Kohlmeier, 2004). The model is based on ERSEM, but coupled to an own Lagrangian transport model description. That is, the water does not flow through compartments (or grid cells), but the grid cells follow the water masses, and thus change their characteristics while flowing from e.g. a tidal area to the gullies and back again. That minimises computer time, and largely eliminates numerical dispersion. The transport model has to be set-up only once, and then the results can be used for the whole simulation period. If needed, one could include several circumstances (spring/neap tides, several wind directions with accompanying water levels, etc). The basic idea for the transport model also is that all the water coming from the tidal

² POL = Proudman Oceanographic Lab (nowadays National Oceanography Centre) in Plymouth.

COMS = Coastal Ocean Modelling System

³ RIN = Research Institute of Nature Management, one of the predecessors of the present IMARES.

flats has to follow the gullies while flowing to the sea and vice versa. Thus, the flow fields are rather fixed.

3.6 GEM and Delft-3D (WED-model)

The Deltares-Wadden Sea Ems Dollard model (called WED) is described briefly in Stolte et al (2014). This description is summarized here.

The Waddensea Ems Dollard (WED) model

The WED model is simulating the effect-chain aiming to relate (changes in) large-scale hydrodynamics to (changes in) turbidity and primary production, including effects of (changing) nutrient input. Limiting factors for primary production are nutrients (determined by nutrient supply and dispersion) and light (determined by turbidity).

Hydrodynamic model. An improvement in the hydrodynamic model is the computation of wave-induced bed shear stresses with the SWAN wave model, instead of the less accurate fetch-length wave approach that was initially applied. The SWAN model generates a stronger along-estuary gradient in wave height and bed shear stress, which promotes up-estuary sediment transport.

Sediment transport model. The WED sediment transport model computes the transport of fine sediment (mud). Dredging and dumping is integrally modelled (sediment depositing in ports is regularly dredged and disposed on dumping locations through a dredging routine). New observations were generated within the sampling programmes performed.

The WED sediment transport model is coupled off-line (in Delft3D-WAQ), which means there is no dynamic feedback between morphology, water density, and the hydrodynamics. A coupling between hydrodynamics and morphology is needed when bed level changes significantly influence the hydrodynamics within the modelled timeframe, which is usually only required for sand and for decadal timescales. However, a fully coupled model is approximately 10 times slower than a non-coupled model, and multi-year simulations are not feasible with a fully coupled model because of the associated computational times.

Water quality/primary production model. The water quality/primary production model was further developed using a more detailed process description and using newly available monitoring data by IMARES (Brinkman et al, 2014, 2015). The implementation of a more detailed description of nutrient cycles including layered sediment with early diagenesis of organic material resulted in a major improvement in the calculation of phosphate compounds. The phosphate compounds show a strong sediment outflux in summer in the inner parts of the estuary. Secondly, the monitoring programme carried out by IMARES provided a better approximation of phytoplankton growth process parameters, and validation data additional to the national monitoring programme.

Overall. The water quality model thus is fed with results from the hydrodynamics and sediment transport models, operates at a fine-scaled grid and needs considerable computing time. Phytoplankton and phytobenthos dynamics are the main targets of the model, and it contains an

implicit grazing term, but no fauna species or groups. A drawback of the computations (not the model) is that silicate data for inflowing water are lacking; this is repaired by assuming a fixed value. This will lead to too high Si-values in the summer period. Phytobenthos is assigned to the lowest water column layer, and not the sediment proper. Although quantitatively unknown, this must have consequences for the results.

The largest drawback, and main reason for writing the present report, is that fauna groups are lacking. It is well-known that not only algae are important as food for animals, but that grazing by animals will affect phytoplankton and –benthos concentrations, and by that, primary production.

The fine-scaled set-up must be considered a big advantage over box-models (like EcoWasp is) regarding the resolution of the model, whilst the run-time needed is a major draw-back compared to fast running box-models.

3.7 The WasMO Wadden Sea model

Between 2008 and 2013, the ZKO-project “Wadden Sea ecosystem data assimilation and integrated modelling” was performed by IMARES and NIOZ, leading to the set-up of a Wadden Sea model, based on the GETM/GOTM physical model software (Burchard & Bolding, 2002). The simulation area is illustrated in Figure 1, results for suspension feeders are shown in Figure 2 and for benthic diatoms in Figure 3.

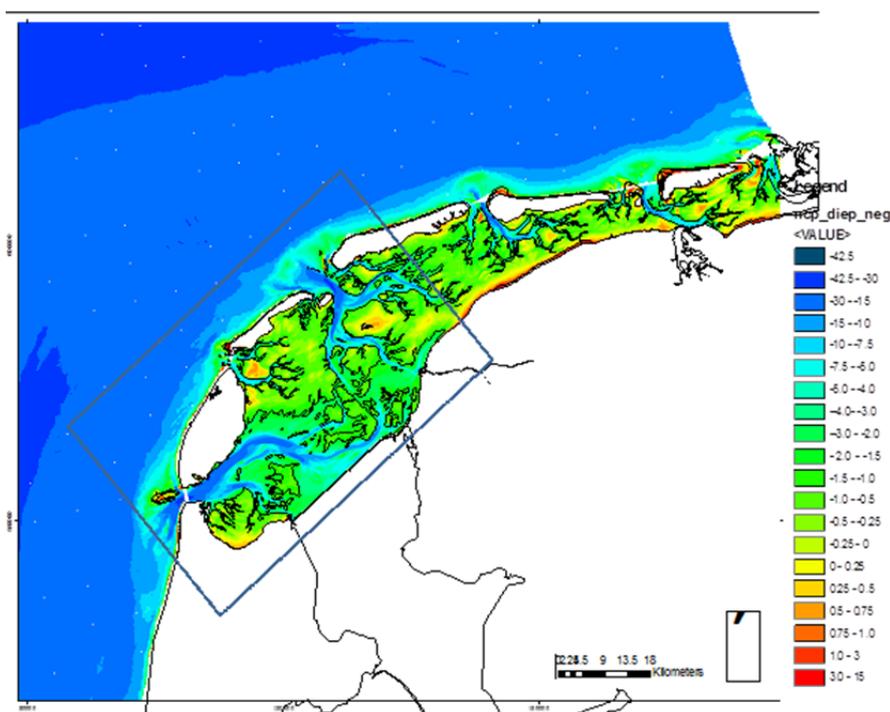


Figure 1 WasMO modelling area: Wadden Sea and adjacent Dutch Continental Shelf. The rectangle shows the -41° rotated model domain covered by the present model set-up (Gerla et al, 2014).

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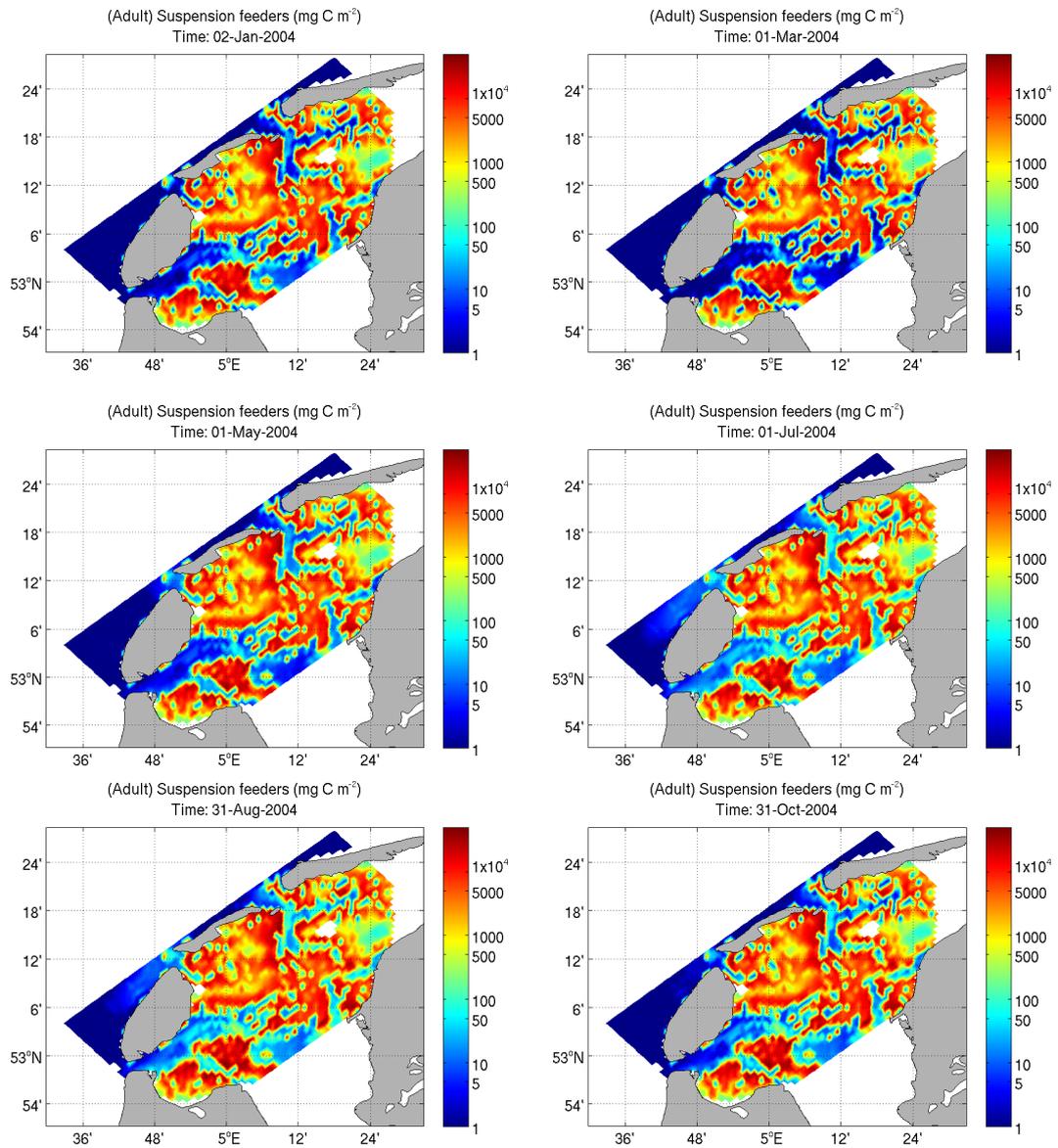


Figure 2 Computed distribution of suspension feeders by WasMO (Gerla et al, 2014).

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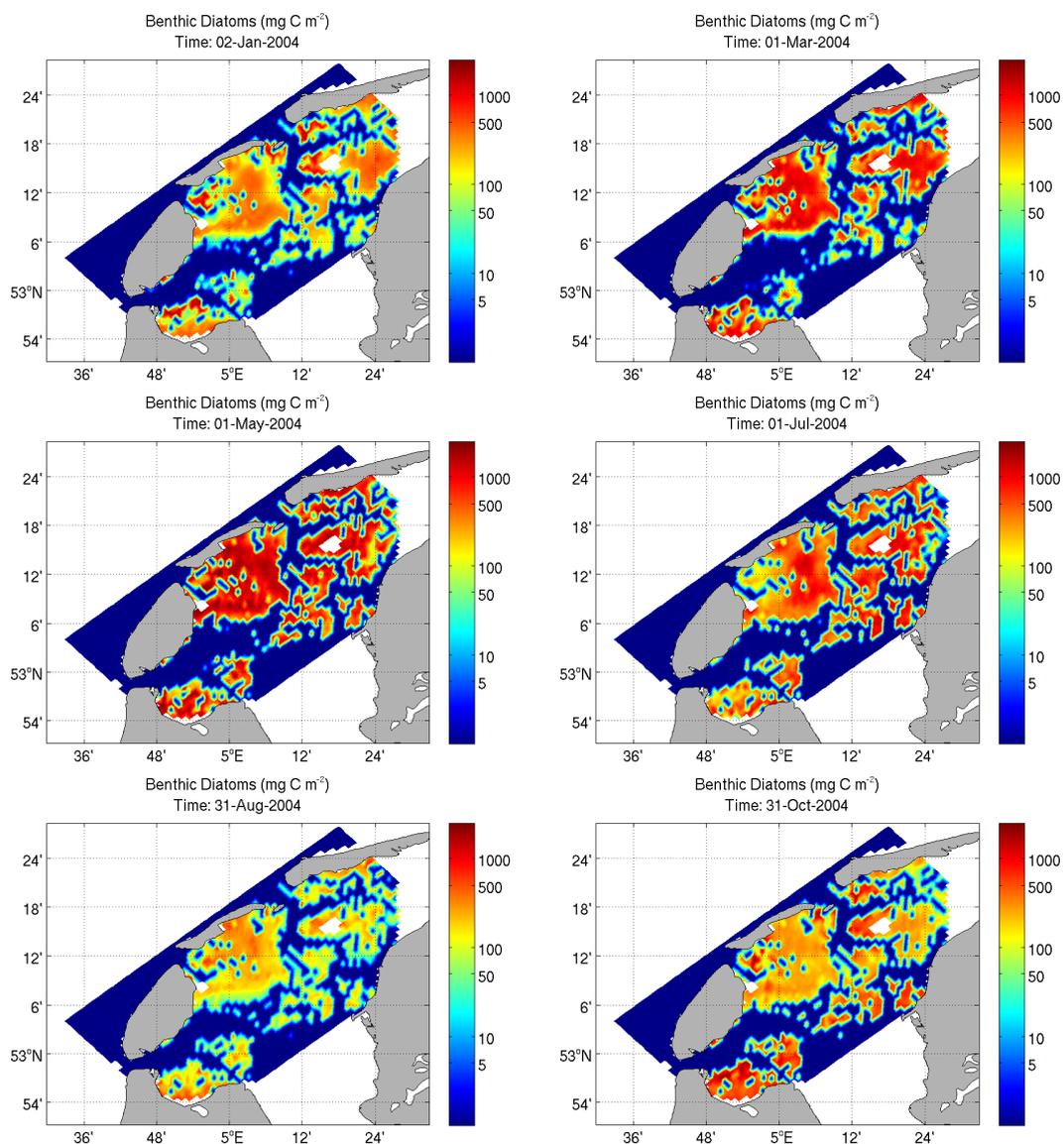


Figure 3 Computed distribution of benthic diatoms by WasMO (Gerla et al, 2014).

WasMO is a very promising model, although it needs further tuning for a couple of critical processes (such as resuspension). Since it belongs to the ‘family’ of fine-scaled physical models coupled to ecosystem processes, it needs a long run-time (about 18 hours for a one-year simulation on an 80-core cluster computer).

3.8 The EcoWasp model

3.8.1 Basic set-up

The basic ecosystem model EcoWasp (see Brinkman (1993^{a,b}), Brinkman & Smit (1993) and Brinkman & Smaal (2003) for a detailed overview, and Smit et al (2011) for a short overview) contains descriptions of key processes in the Wadden Sea ecosystem.

The key processes include biological processes (such as growth of algae and fauna), biochemical processes (e.g. breakdown of dead organic matter and bacterial oxidation of ammonium), chemical processes (mainly adsorption onto and desorption from solid particles) and physical processes (horizontal advective and dispersive transport and vertical dispersive transport across the sediment-water interface and the atmosphere-water interface).

Figure 4 gives a schematic overview of the model used in this study. Included are four phytoplankton groups: diatoms, non-diatoms ('flagellates') and pico-phytoplankton in the water column, and benthic diatoms at the water/sediment interface. If needed, this can relatively easily be extended to other algae groups with specific characteristics (e.g. high/low affinity for P, N, Si or light).

Pelagic diatoms and non-diatoms are grazed by filter feeding organisms, of which mussels are the model organisms. In reality, this group mainly consists of Blue mussels (*Mytilus edulis*), Cockles (*Cerasteroderma edule*), Sand gapers (*Mya arenaria*), and recently also American razor clams (*Ensis directus*) and Pacific oysters (*Crassostrea gigas*). Picophytoplankton is the group of <2 µm algae that cannot be filtered by larger shellfish. In the model, picophytoplankton can only be grazed by microzooplankton (typical size assumed in this study 35 µm), by mussel larvae (80-230µm) and partly (== less efficiently) by mussel seed. The PhD-study by Jacobs (2015) has revealed to what extend seed mussels are capable of filtering picophytoplankton. Benthic diatoms are subject to grazing by sediment browsers.

In the model it is assumed that larger shellfish are also capable to feed on microzooplankton and mussel larvae. As such, they are not only primary, but also secondary consumers.

Appendices I-IX give more detailed information on a couple of key processes for this study.

it respire (also: water column), where it puts its faeces (the sediment top-layer for benthic mussel classes, the water column for larvae), etc. In fact, animals are followed during their lives (*cohorts* are followed, from egg to adult), and the model set-up is some version of a simplified structured population model.

However, during their live, cohorts 'jump' from one class to a next one. When a cohort changes from class i to $i+1$, its properties also change. E.g., mussel larvae are born (in the water column) each year

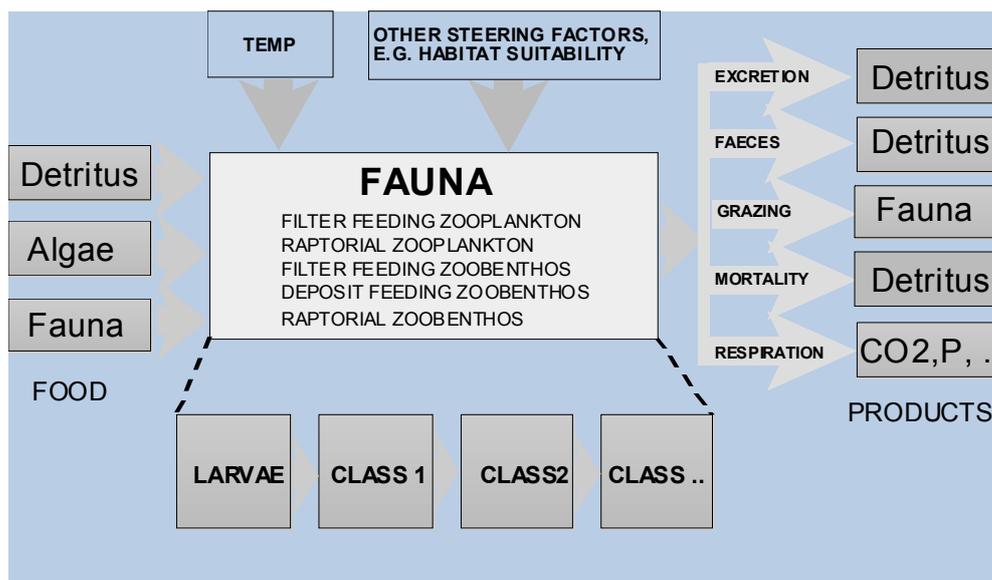


Figure 5 Representation of generic fauna in EcoWasp. Each fauna group consists of one or more classes. In case of more than one, the first contains larvae. Upon reproduction, classes shift to the next class. Fauna feeds on detritus, phytoplankton, other fauna. It produces faeces, adds to detritus when dying, and may serve as food for other fauna. Respiration produces carbon dioxide, but also phosphate, ammonium, etc, according to the stoichiometric ratios. The fauna description is generic.

in a certain period with an initial size of about 80 μm , and grow until they reach a 230 μm size (Bayne et al, 1977). Then they settle and shift to the next class (as illustrated in Figure 6), and change their characteristics. Similar processes occur for other animals. The losses during reproduction and (if appropriate) settlement are estimated: these processes may be far from 100% efficient.

For small, fast reproducing animals it may be decided to consider only one class. In that case, animals keep their (fixed size), and the model description for those animals turns into the classical biomass model.

The description of the fauna processes is generic, and follows the processes illustrated in Figure 18 (appendix A). All the mentioned processes are size-related.

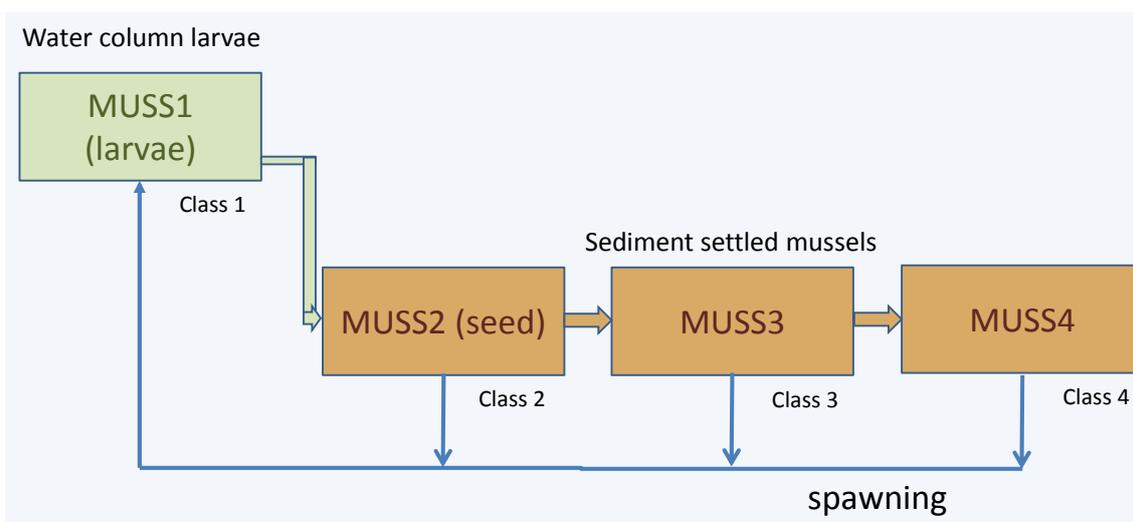


Figure 6 Life history of mussels: larvae are pelagic, and settle to the sediment when large enough. Cohorts shift from class1 > class2 >..> class4. Each time shifting occurs, class3 and class4 are mixed.

3.8.3 Pelagic primary production

Pelagic primary production is computed straightforward in the model: it depends on the water column light climate, temperature and nutrient concentrations and, of course, phytoplankton biomass. Phytoplankton species (groups) have –at the moment- a fixed stoichiometry.

Data on primary production –as measured in the laboratory and those computed for the field situations- can be used to compare the model results with. The data as presented by Colijn (1983) and in Brinkman et al (2014, 2015) concern productivity values expressed as $\text{mg C (mg chl a)}^{-1} \text{ h}^{-1}$. These can be used to tune the algae growth parameters, since the relationship between gross productivity and light intensity is a fixed one.

The production data (this is including weather and water column light climate) can be compared with the model results for each compartment.

3.8.4 Benthic primary production

Benthic diatoms occur in the model at the sediment/water interface (Figure 7). They are assumed to be in the 1 cm top layer only. It is possible to compute benthic diatom production after estimation of solar light penetration into the sediment, with light attenuation characteristics based on sediment composition. However, it is not clear whether the sediment top layer has a uniform composition with depth. Most likely, this is not the case. Neither known is how to incorporate diatom mortality: many of or even most of benthic diatoms can migrate towards optimal light conditions. Therefore, in

EcoWasp, light conditions are assumed to be optimal for benthic diatoms. In Brinkman et al. (2014) it was investigated what the effect was of several assumptions and it appeared that in most cases an optimal light intensity came close to a probably realistic case. During model runs this has to be subject to further fine tuning.

If total benthic diatom mass increases a lot, a lot of space is required. Since benthic diatoms in the model don't have a volume, a maximum limit is set to benthic diatom density. At the same time this

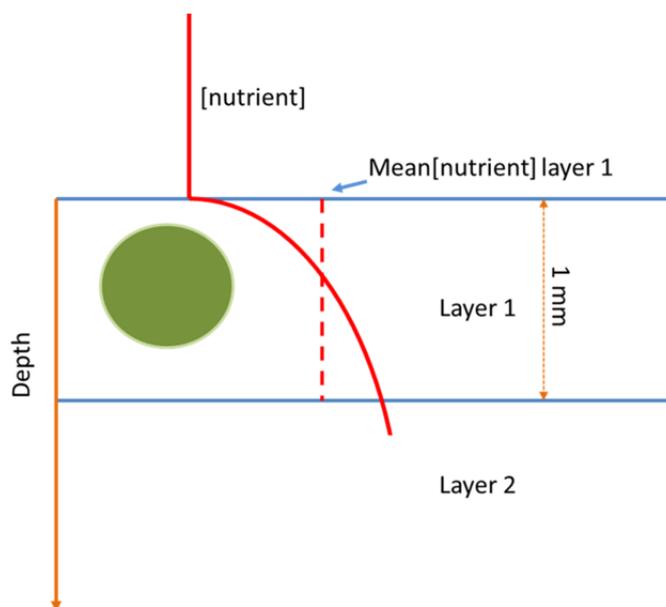


Figure 7 Benthic diatoms: they optimally use light, and ‘see’ the average top layer nutrient concentration.

maximum density parameter can be used to tune benthic primary production and make it come close to measured values.

In the Ems-Dollard, maximum benthic chlorophyll-a values are recorded of about 200 mg chla m⁻² (De Jonge et al, 2012). The IMARES 2013 measurements (Brinkman et al, 2014) gave maximum values of 100-150 mg chla m⁻². These mostly concern 2 - 5 mm thick layers, which means 20-100 g chla m⁻³, and 2000-10000 g DW benthic diatoms m⁻³.

3.8.5 Water column light climate

An important characteristic is the water column light climate, determined by dissolved (humics and fulvics) and suspended components (silt, sand, detritus, algae). They all linearly contribute in the model to the water column light attenuation coefficient (k_d , m⁻¹):

$$k_d = a + \sum_i b_i \cdot phyto_i + \sum_i c_i \cdot detritus_i + \sum_i d_i \cdot solid_i + \sum_i e_i \cdot dissolved_i \quad (m^{-1}) \quad (1)$$

The coefficients a, b_i.. e_i are model parameters; a is the basic attenuation coefficient of pure water.

3.8.6 Picophytoplankton and microzooplankton

In the present application, picophytoplankton ($< 2 \mu\text{m}$) and microzooplankton (between 20 and 200 μm) have been included. For both populations, a new set of parameters was needed. A first guess for microzooplankton parameters was achieved following the description in Brinkman (2013), appendix III, and fine tuning was done using literature data and data from the PhD-work of Pascale Jacobs (IMARES) (Jacobs, 2015).

3.8.7 Temperature dependency

Many processes depend on temperature. A very flexible optimum function is implemented in the EcoWasp-model (see Textbox 1 and Figure 19, appendix B); parameter values completely determine the shape of the relationship.

4 The Ems-Dollard area

4.1 Introduction

In this chapter a number of characteristics of the Ems-Dollard area is given, plus the sites where the pelagic and benthic samples were taken.

4.2 The area

The Ems-Dollard area (Figure 8) is characterised by its large spatial differences from the North Sea side down to the Dollard area. At the North Sea side, water is clear (the light attenuation coefficient is about 1.2 m^{-1}), salinity is high (about 28‰), suspended matter content is low (about 20 mg l^{-1}) and nutrient concentrations are relatively low. In the Dollard area, the water is very turbid (the light attenuation coefficient is up to or even above 10 m^{-1}), suspended matter content is high (up to a few hundred mg l^{-1}), the area is highly influenced by fresh water input from the rivers Ems and, to a lesser extent, the Westerwoldse Aa (salinity is about 5‰), and nutrient contents are relatively high (see for all these data Colijn 1983; De Jonge & Brauer, 2006; Brinkman et al, 2014).



Figure 8 Ems-Dollard area, with meteorological stations Lauwersoog en Nieuw-Beerta mentioned. Source: Google Earth.

The average mean high water depth of the compartments decreases from slightly over 5 m in the outer areas to about 1 m in the Dollard area; low water channel depths decrease from about 10 m in the outer areas to less than 1 m in the Dollard area. In the Dollard, almost the complete area runs dry at low water, with an average emersion period of 43%. Close to the North Sea, the sediment has a low silt (grain size <math><63 \mu\text{m}</math>) content; this is up to 100% in the Dollard (RIKZ, 1998).

4.3 Changes in the last decades

As stated in the introduction, the reason to perform the research is the increased turbidity in the estuary, its supposed consequences for ecosystem functioning and the relationship of these changes with intensified dredging activities which are performed to secure the accessibility of the Meyer shipyard in Papenburg, the Emden harbour and the Groningen Seaport (Eemshaven). All three require dredging shipping channels in the estuary, and the first also requires dredging the Ems river.

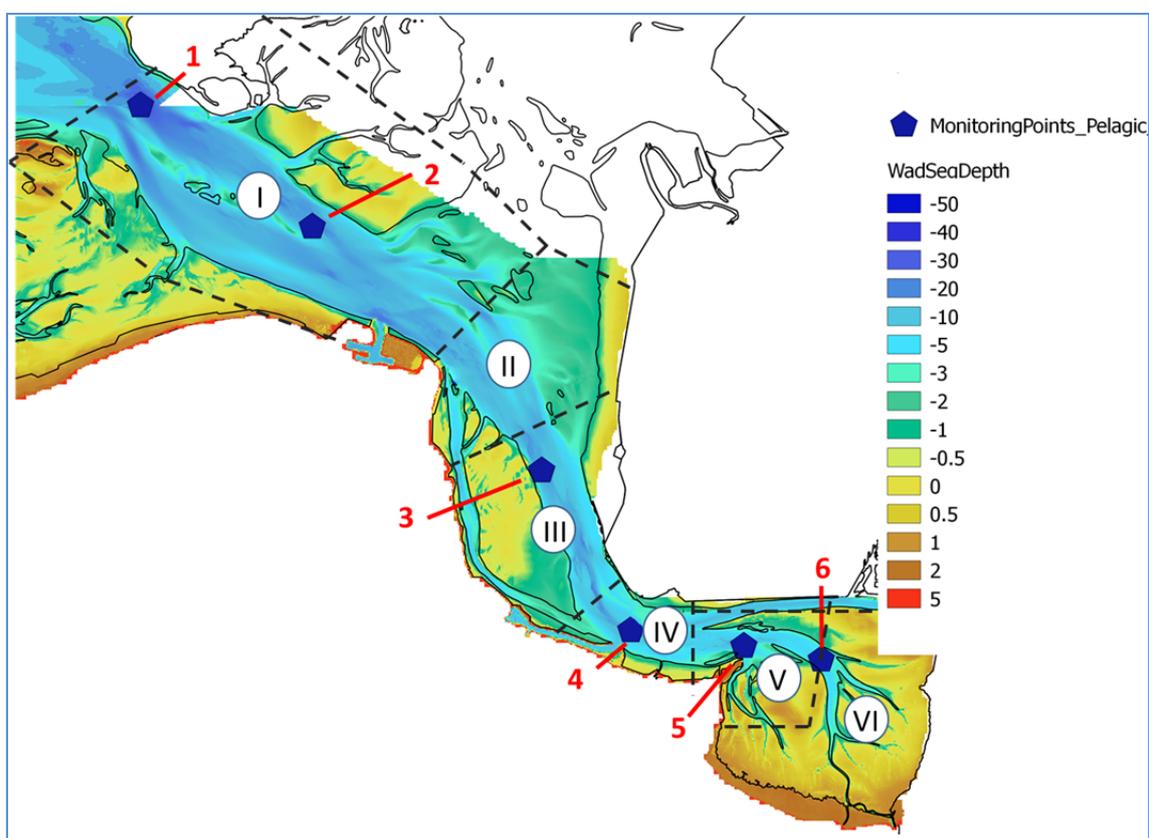


Figure 9 Depth map of the Ems-Dollard area, with pelagic sampling stations (1-6) and compartments (I-VI) as distinguished in the present study.

5 Proposed model set-up for the Ems-Dollard

5.1 Sediment browsers as major model extension

The model, as used so far, did not include sediment browsers: animals that feed upon benthic algae. Considering the large part of tidal flats in the study area, these are to be added to the model runs. It concerns Mudsnaills *Hydrobia ulvae* (about 4 mm size) and Common periwinkles *Littorina litorea* (a few cm size). Worms and similarly acting animals feeding on sediment detritus can be added as well, but this is not foreseen initially.

5.2 Compartment set-up for the Ems-Dollard area

5.2.1 Spatial resolution

A possible (and also proposed) spatial set-up for the Ems-Dollard model is illustrated in Figure 10 (the sub-compartments now look like a level-map). A number of main compartments is assumed, each with a tidal flat area (sub-divided into high, medium and low tidal flats), a subtidal area (down to

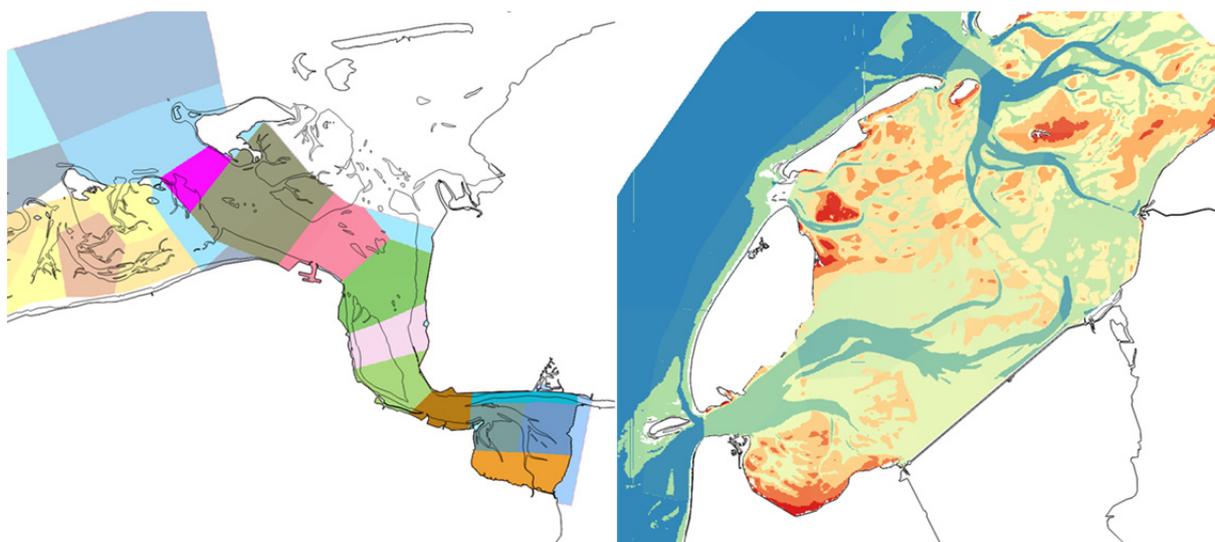


Figure 10 Possible compartment set-up for the Ems-Dollard area (left). A number of fixed area is distinguished; in each of these main-compartments high- medium- and low tidal flats are distinguished and subtidal and channels. Such subcompartments may look like the western Wadden Sea subcompartments (right): the sub-compartments.

NAP-5 m) and a channel area (the deepest parts). There is advective and dispersive transport between the compartments and with the North Sea, and there is freshwater inflow from river Ems and other tributaries. Physical data (flow, effects of waves) are taken from existing data sets (see e.g. Brinkman & Bult, 2003), best taken now from most recent studies by Deltares (Van Maren et al,

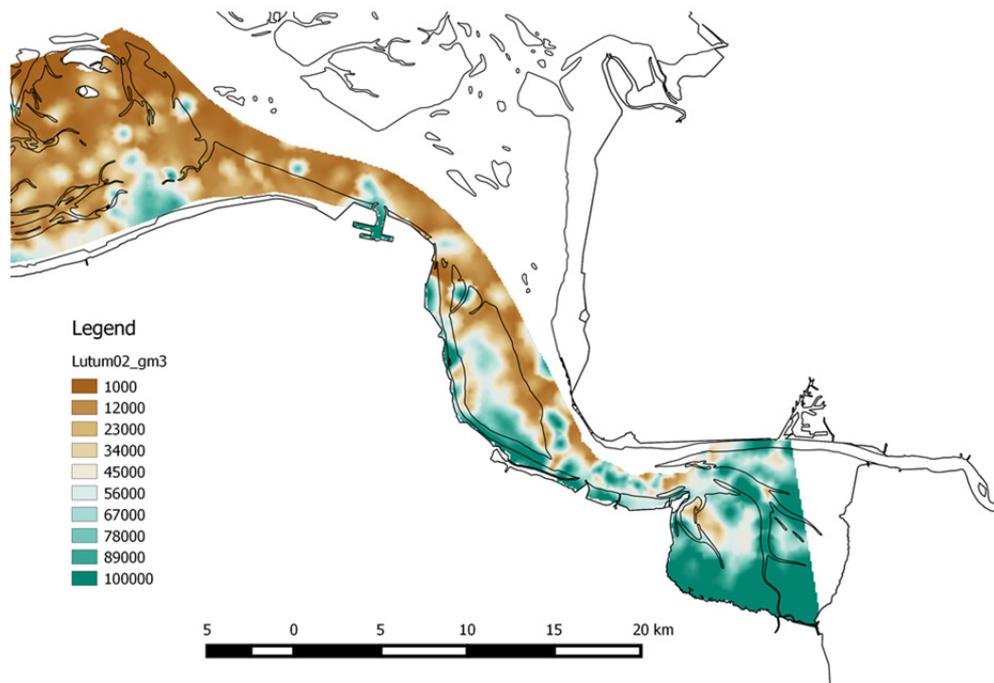


Figure 11 Sediment lutum content (0-2 µm grain size) in Ems-Dollard. Data elaborated from RWS-Sediment atlas (RIKZ, 1998). Data here are only for the Dutch part of the system, and have to be extended to the German part as well (necessary data are available).

2104). Exchange of water between compartments and the exchange between the system and the adjacent North Sea is not a result of the Alkyon computations, and has to be estimated from a comparison between salinity measurements and model results.

5.2.2 Sediment data and morphology

Morphological data (depth, emersion times of tidal flats) are obtained from Rijkswaterstaat. Data on sediment composition are from the Sedimentatlas (RIKZ, 1998). From these data a number of sediment characteristics have been estimated (such as lutum, silt content, porosity, amount of adsorbed phosphate, see Brinkman, 2015). An example is given in Figure 11. This has to be extended to the German part; the RWS-sediment atlas (RIKZ, 1998) contains the necessary data, also for the German part of the system.

6 Water quality and quantity data, meteorological data and necessary data compilations

6.1 Basic data

Running the model needs many boundary condition data (conditions at the edges of the modelled system). And, data for the modelled compartments have to be known (inside the modelled system) for comparison.

Water quality data for North Sea and from inside the system are basically obtained from Rijkswaterstaat (RWS, 2015; inside system sampling sites are shown in Figure 13), and from the own research performed in 2012-2013 (see section 6.3 and 6.4). Data for local tributaries (like the Westerwoldse Aa and others) are to be obtained from local water authorities. Water quality data for the river Ems and other input sites (for the whole period from the mid-seventies if available) have to be obtained from German water authorities. Water quantity data, preferably on a daily basis, are also to be provided by Dutch and German water authorities.

Daily meteorological data are needed and available from the Royal Netherlands Meteorological Institute (KNMI, 2015).

6.2 Data elaboration

Water quality data collected in the 'Waterbase' (RWS, 2015) are primarily collected because of the Dutch 'Wet Verontreiniging Oppervlaktewateren' (WVO) from 1969 and, from December 2009, the 'Waterwet' (Water Act), that replaces the WVO. The data serve as indicators whether water quality targets are achieved or not.

From the available data other quantities were derived that are not directly measured. Especially an estimate for the amounts of algae, diatoms/non-diatoms, refractory organic matter (ROM) and labile organic matter (LOM) may be computed, including an estimation of the phytoplankton content from chlorophyll-a data, the composition of algae (N & P) and the composition of the remaining fractions: detritus (N & P) and inorganic matter (P).

Especially for the boundary conditions it is important that data series do not contain large gaps. Therefore, missing data are estimated based on existing data for the target site plus those for neighbouring sites. Thus, time series for dissolved components, phytoplankton, detritus, e.g. are produced for the whole period relevant for ecosystem simulations. This has, by IMARES, already been done for the Dutch National Waters, but not for the other inflows.

Blueprint for an Ems-Dollard ecosystem model study

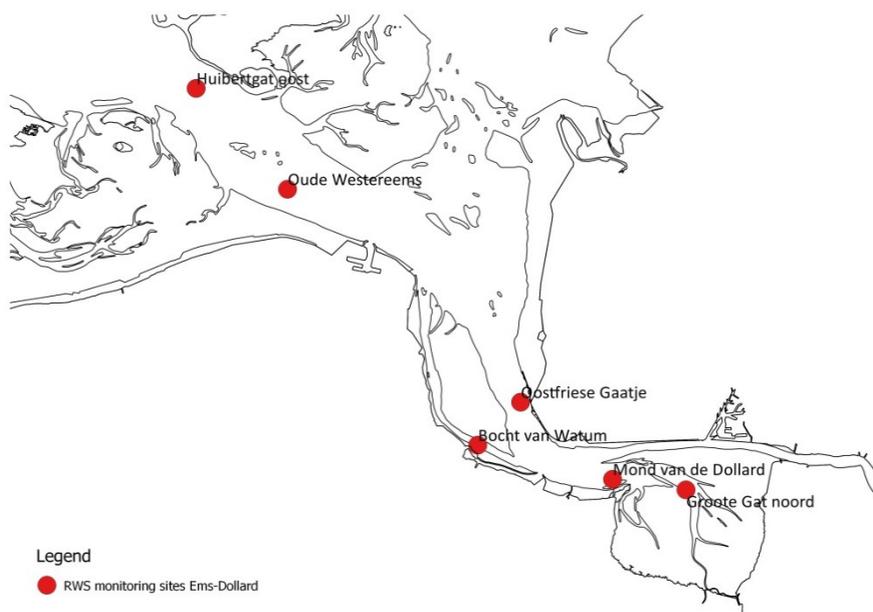


Figure 13 Sampling sites for monthly monitoring by RWS (MWTL-monitoring sites), Waterbase (2014). Sites ‘Oude Westereems’ (finished 1984), ‘Oostfriese Gaatje’ (finished 1995) and ‘Mond van de Dollard’ (finished 1987) are not monitored anymore; ‘Bocht van Watum’ became a monitoring site in 1984. A few other sites (not mentioned) have been sampled during shorter periods.

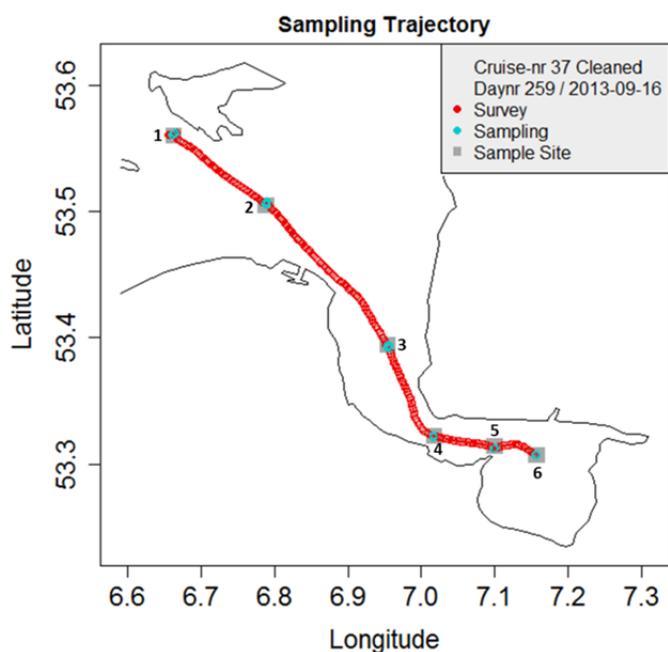


Figure 12 Continuous measurements while sailing from site 1 (most North-western site) up to site 6 (most South-eastern site), sampling trajectory as registered by the PocketBox. Example for day 259 in 2013 (September 19th). Sampling is only assumed to be reliable when sailing speed is $< 8.5 \text{ km h}^{-1}$.

6.3 Available water quality data from the Ems-Dollard 2012-2013 study by IMARES.

In 2012 and 2013, IMARES assessed a lot of water quality data at six sites in the estuary, and also performed continuous sampling along the sailing track from the outer area (near Borkum) to the inside area in the Dollard. Sampling sites are shown in Figure 12, as is the sailing track. A total of 39 sampling trips have been undertaken in those two years, from January to December. Data included nutrient concentrations, water column light climate (extinction coefficients), temperature, oxygen, and dissolved organic matter, chlorophyll-concentrations and, in 2013, also phytoplankton composition (Brinkman et al, 2014). Next to water quality data, also primary productivity of water samples was measured. These resulted in parameter values describing the relationship between light intensity and ^{14}C -uptake rate. Thus, primary production at each sampling station and each sampling moment could be computed. These data are needed to tune phytoplankton primary production computations by the model.

6.4 Available benthic data from the Ems-Dollard 2013 study by IMARES.

In 2013, IMARES (Brinkman et al, 2014; Wanink et al, 2014) performed research on benthic primary production, and assessed chlorophyll-a content of the upper 0.5 cm sediment top layer, and productivity of sediment samples depending on light intensity. A total of 11 sampling trips have been undertaken in that year, from February to December. Sampling sites are shown in Figure 14.

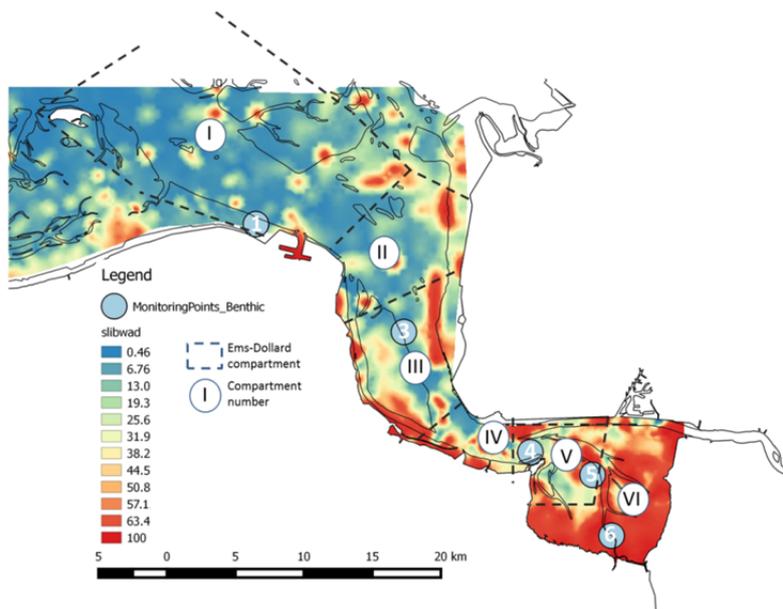


Figure 14 Silt map of the Ems-Dollard area (after the Rijkswaterstaat Wadden Sea sediment map; RIKZ 1998), with benthic sampling stations (1, 3-6) and compartments (I-VI) as distinguished in the IMARES 2012-2013 study. Sampling point 2 is lacking, since it was visited only once.

6.5 Available data for the Ems-Dollard inner area from former research.

Earlier research has mainly been conducted by Colijn (1983), De Jonge and Colijn (1994), Colijn & De Jonge (1984), De Jonge et al (2012), plus the already mentioned BOEDE research (Baretta & Ruardij, 1988). Most importantly, the first two studies included water column light climate, chlorophyll-a content in water column and sediment top layer and primary production in the water column and sediment. BOEDE also included many micro- and macrofauna data, bacteria, phytoplankton, oxygen and nutrient dynamics, and organic dissolved components.

7 Some details and extensions

7.1 Including habitat suitability

The EcoWasp-model is almost entirely based on the production (rates) of food and its consumption: algae growth and grazing by fauna, fauna growth, reproduction and mortality and detritus mineralization. Sediment storage and adsorption of elements onto sediment particles can be considered as supply of 'food' to primary production.

However, it appeared to be useful to incorporate additional knowledge. For example: in the western Wadden Sea study on effects of changing turbidity on primary and secondary production, it appeared that the best environment for shellfish are the subtidal areas (see the western Wadden Sea as example, Figure 15).

However, from several studies (see e.g. Saier, 2000^{a,b}; Smaal et al, 2013) it appeared that in subtidal areas predation on shellfish (from earliest spat to adult animals) is (much larger) than on tidal flats (where food availability starts to be limiting for filter feeding organisms). So, to cope with such cases, two major possible approaches can be followed: (1) one might try to model shellfish predators as well and: (2) a kind of habitat suitability approach may be very helpful. The latter means that a previous analysis of where fauna is observed, related to e.g. depth, flow or wave intensity, sediment composition, etc, can be used to *a priori* set the growth or mortality parameter. This is done in such a way that finally the observed density distribution is reproduced as good as possible. This solution is

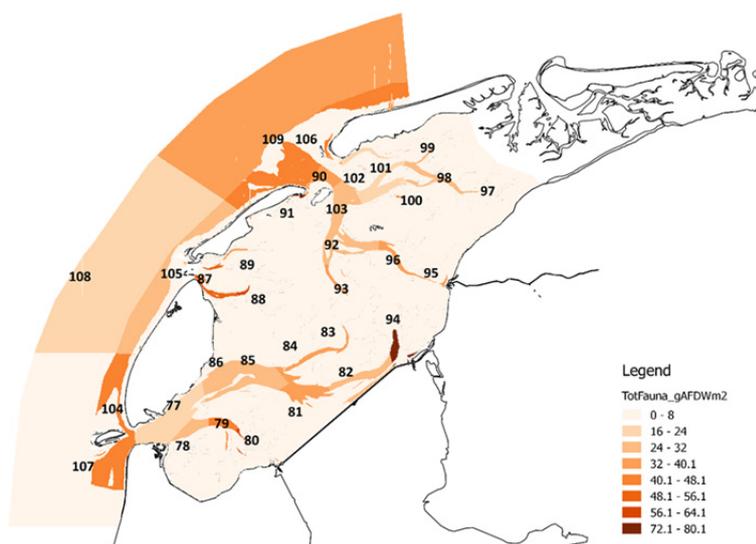


Figure 15 EcoWasp result fauna distribution western Wadden Sea (Brinkman, 2015). Average for period 2001-2011. Note that in subtidal areas densities are highest; a result of full-tidal feeding conditions and) not included habitat suitability characteristics (== predation by starfish etc.)

straightforward and less flexible than the other, simply because one sets certain conditions.

An example of such habitat suitability data is shown in Figure 16 (Troost et al, 2015). Also this picture should be extended to the German part of the system. And, the analyses that was the basis for the map shown in Figure 16 did not include suspended sediment content of the water ; a characteristic that doubtlessly would change the Dollard gullies suitability for shellfish to the lowest classes.

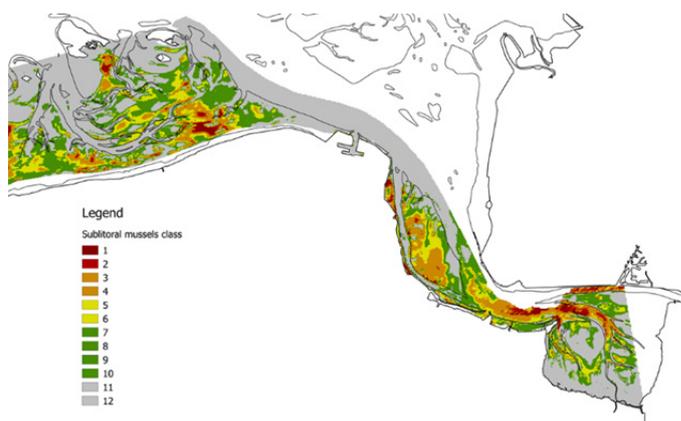


Figure 16 Habitat suitability map for mussels. Based on whole Wadden Sea data (mussel beds on tidal flats, mussel densities in sublittoral areas). Class 1 is the best area, class 12 has the lowest ranking. High ranking in the Dollard area is a result of quiet conditions plus fresh water presence, but not including high silt content of the water column.

7.2 Lagrangian transport description

The present set-up of EcoWasp includes dispersive processes, a fixed distribution of fresh water flowing into the system and a rest flow of flow through the system from the Vlie to the Marsdiep tidal inlet. Such a rest flow does not exist in a one-dimensional system like the Ems-Dollard).

However, every tide water flows from the tidal flats into the gullies, seawards, and back. A possible, and proposed hereby, set-up for the Ems-Dollard area is that water volumes are tracked: the high water volume of a tidal flat (or a part of a tidal flat) is followed when it flows towards a gully, and replaces the original gully water volume. Which replaces water volumes that are more seawards, etc. Still, water flows are fixed, but now a water volume gets other water column depths, and has contact with other sediment type. Such a distribution of water has to be computed separately, and read by the model as time series. Stratification is not part of such a description, which quite certainly will not be a major issue in the Ems-Dollard system (see Brinkman et al, 2014, they describe vertical water column profile measurements indicating that these hardly exist).

7.3 Computation of food production for higher trophic levels

Mortality of fauna in the model is nothing else than a parameterization of predation upon that fauna group. The EcoWasp-model computes growth (and thus size) and mortality of animals, and stores the number and size of animals that die. By that, the biomass that was predated in a certain size class during a certain period is computed. If e.g. a bird eats shellfish of size 3-5 cm (like Eider Ducks do), than this value shows the number of that bird species that can feed itself with the food production of the system. Unnecessary to say that this is not a very precise estimate. But, since mortality of fauna groups is tuned with data on year class appearance (what is the amount of 1 year-old animals, and two-year old, etc), the computation as sketched here should certainly give an idea of the food production for higher trophic levels. As an example, computed data for the western Dutch Wadden Sea are presented in Figure 17.

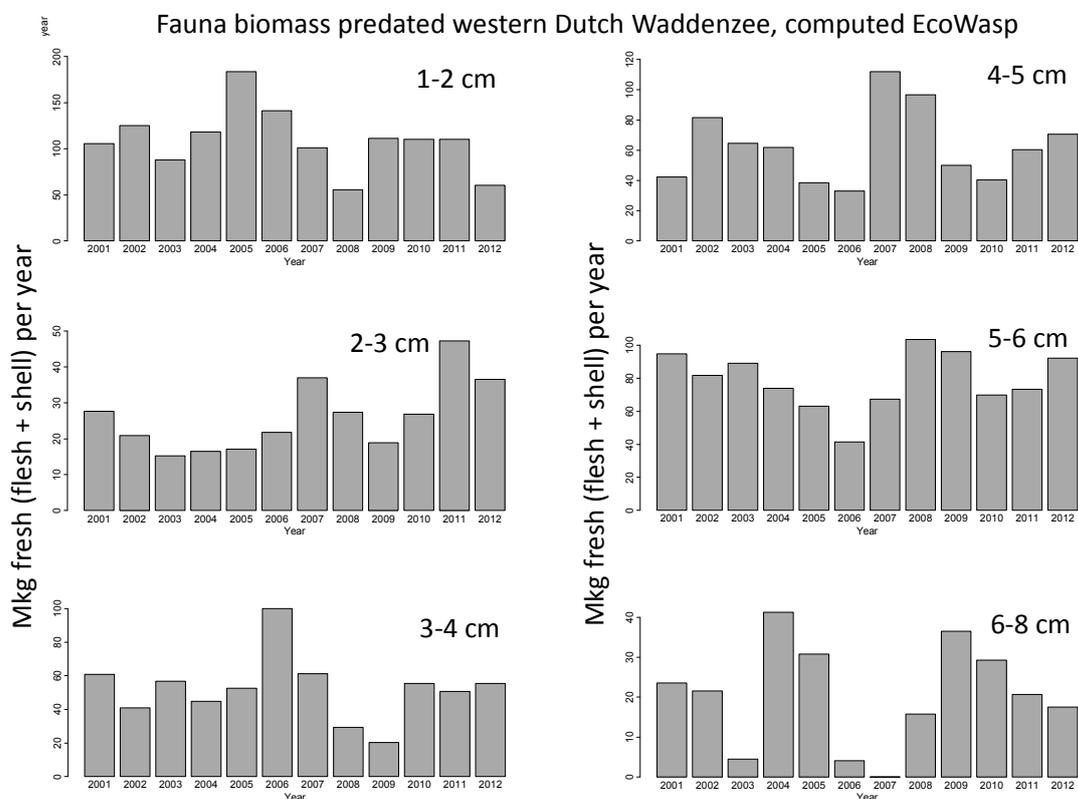


Figure 17 Amount of fauna biomass died yearly in the western Wadden Sea (== predated by other animals), after size classes. Computation with EcoWasp. Data as fresh mass (flesh + shells), this is 20* AFDM. This amount can be regarded as eaten by bird, crabs, starfish (and others), plus the amount fishes by fishermen, plus the amount died as a result of other causes such as starvation, physical processes, etc.

8 Implementation risks of extensions needed or desirable to the EcoWasp model

When applying the ecosystem model to the Ems-Dollard area, some extensions (or improvements) may be needed or wished. It is relevant to know the chances for success or failure when deciding to implement such extensions.

Adding new fauna groups with new feeding and reproduction characteristics demands data on the animals' life cycle: reproduction, feeding behaviour, growth, mortality and habitat preference. Usually, such data are not extensively available. Even for relatively well known animals such as the Blue Mussel, there are many uncertainties. Literature data on abundance, periods of appearance and disappearance, sizes and reproduction characteristics mostly are not enough to fill in the necessary parameter set; but at the other hand usually give enough possibilities to estimate the animals life cycle. It should be stressed, still, that uncertainties will remain. Keeping this in mind, the implementation of new animals in the model is not a major operation, and can be considered as a safe extension. The same goes for adding (if desired) new phytoplankton groups. The model, as it is generic, does not need at all or may be just some small additional software extensions.

Changing the way hydrodynamics is used in the model (e.g. the supposed Lagrangian way of describing the water movement, see 7.2) is a major extension, that needs a) a separate computation of water movements, and b) an adaptation of the way water column and sediment interact. Choosing such an extension includes a risk in that sense that the time needed for this adaptation may become substantially larger than expected in advance.

9 Conclusions

In this report, a model set-up for the Ems-Dollard area is proposed, including a number of possible extensions. The model is to better estimate the effect of changing water column turbidity (as proposed as part of the management measures to improve the Ems-Dollard ecosystem quality) on trophic levels higher than phytoplankton.

Some additions to the existing EcoWasp-model are needed and relatively easily implemented such as the implementation of sediment browsers and more phytoplankton groups. Implementations of a better description of water movement requires an adaptation of the model software.

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Appendix A Individual fauna processes

Gain and losses

All the fauna processes are size-related, and illustrated in Figure 18. Mortality is also size-related: relative mortality decreases with increasing size. All processes also depend on temperature.

Assimilation is the only process that contributes positively to the animal's energy budget; all other processes concern losses. Assimilation is expressed as $\text{g AFDW ind}^{-1} \text{d}^{-1}$, assimilation efficiency is expressed as a fraction of food ingested. This efficiency depends on the type of food.

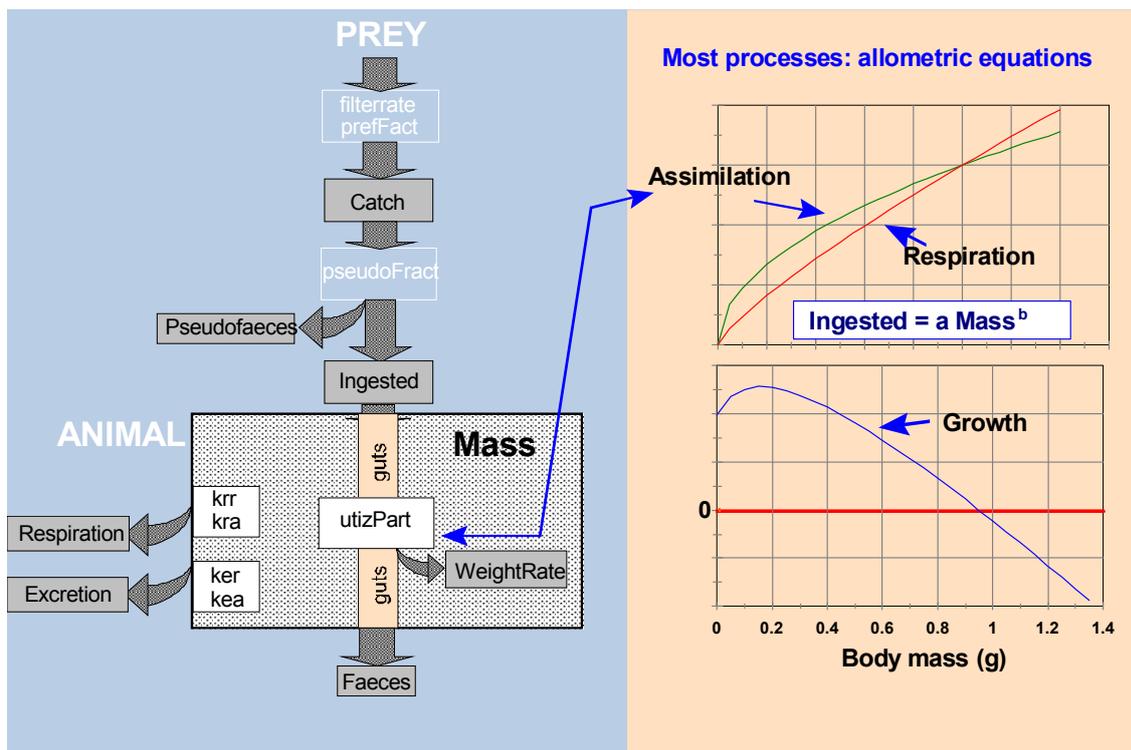


Figure 18 The model animal. Physiological processes are size-related (allometric). E.g., a mussel filters water and catches solid particles (algae, detritus, silt). A preference ($0 \leq \text{preference} \leq 1$) is used first to select particles, and next, the size of the particles may be important. A part of the catch may be laid aside as pseudofaeces. A part of the ingested food is assimilated (assimilation efficiency), the rest is excreted as faeces. The net growth (mass rate) depends on the assimilated food and extra losses as maintenance respiration, activity related respiration and digestion costs.

Maintenance respiration is always needed, expressed as $\text{g AFDW ind}^{-1} \text{d}^{-1}$. Digestion costs are relative to the amount of food ingested, and total costs are expressed as $\text{g AFDW ind}^{-1} \text{d}^{-1}$.

There is a standard excretion possible, similar to the maintenance respiration.

The amount of water filtered may be a cost factor (although is generally assumed that these costs are minor); expressed as g AFDW m⁻³ filtered.

The production of pseudofaeces is accompanied by the excretion of mucus, and thus, it is a negative contribution to the energy budget. Expressed in g AFDW g⁻¹ pseudofaeces.

High silt contents in the water column may have negative consequences for the filtration success and supposed to be one of the reasons that mussels in the turbid Dollard-area have little chance to grow to adult sizes. Silt content in the water is modelled as a cost for shellfish.

Numbers

Mortality is the sum of all loss processes such as predation, fishery and physical processes (e.g. ice winters, storms). In some cases these processes are taken into account, in others cases they have to be parameterized. In the latter case, the mortality rate parameter depends of the size of the animal, having a high value when animals are small.

In this application, settlement of shellfish larvae (from a pelagic stage to a benthic one) occurs with a large loss. As a result, also the mortality rate parameters for seed (MUSS2, see Figure 6) and also the adult shellfish (MUSS3 and MUSS4) had to be adjusted. This is mainly based on a) a comparison with existing data on total shellfish content in the western Dutch Wadden Sea, and b) data on the ratio of seed mussel numbers to total mussel numbers on the Balgzand area (the tidal flats in the south-western part of the western Wadden Sea). Data for mussels were kindly supplied by R Dekker (NIOZ).

Appendix B Temperature relationships

Temperature dependencies in the EcoWasp model are described using an optimum curve; by the choice of the parameters $T_1..T_3$ almost any shape can be produced.

Temperature and other possible dependencies

The function used for all the biological processes reads

$$F(T) = \left[\frac{(T - T_1)^2}{(T - T_2)^2 + (T - T_1)^2} \right] \quad (\text{if } T < T_2)$$

$$F(T) = \left[\frac{(T - T_3)^2}{(T - T_2)^2 + (T - T_3)^2} \right] \quad (\text{if } T > T_2)$$

and

$$F(T) = 0 \quad (\text{if } T < T_1 \text{ or } T > T_3)$$

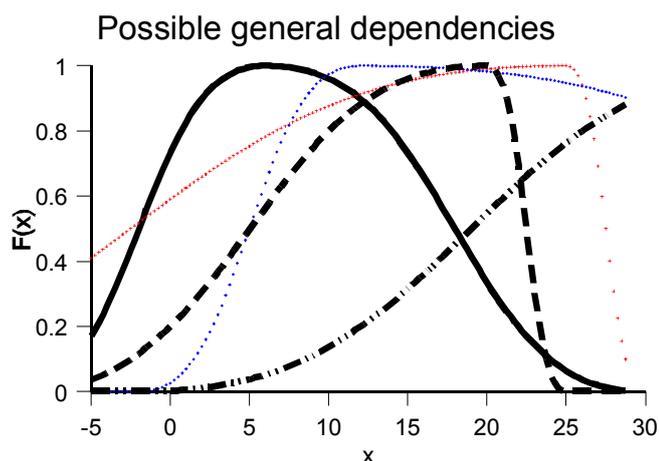
with exceptional cases

$$F(T) = 1 \quad (\text{if } T < T_2 \text{ and } T_1 = T_2) \text{ or } (\text{if } T > T_2 \text{ and } T_3 = T_2)$$

where $F(T=T_2) = 1.0$. For $T < T_1$ and $T > T_3$ $F(T) = 0$. When $(T_2 - T_1) = (T_3 - T_2)$, then the function is symmetric around T_2 . Also, the area under the curve is 1.0, which is useful in a couple of cases. Important is that the shape of this function is very different for different parameter combinations, thus allowing temperature dependent species competition, or optimum temperatures for species occurrence.

Textbox 1 Temperature dependency in EcoWasp. The function has an optimum of 1 at $T=T_2$. The same function may be applied to other dependencies, e.g. the relationship between processes and salinity. A second type of this function includes an intermediate area between (T_{2low} and T_{2high}) where $F(T)=1$. See for an illustration

Figure 19 Several possible temperature dependencies in EcoWasp.



Appendix C Importance of finding correct initial state

Generally, ecosystem models run for a few or even many years. It is crucial that any behaviour of the model is steered by the changing external drivers (weather, nutrient, etc), and not by the difference between the model's present state and its so-called steady state. This is the state when arrived at that, when running the model over and over again with the same external drivers, the model output does not change anymore. Then, and only then, the 'real' simulation can start. If not, it will not be clear what the model results mean: a change as a result of the external conditions, or the ongoing

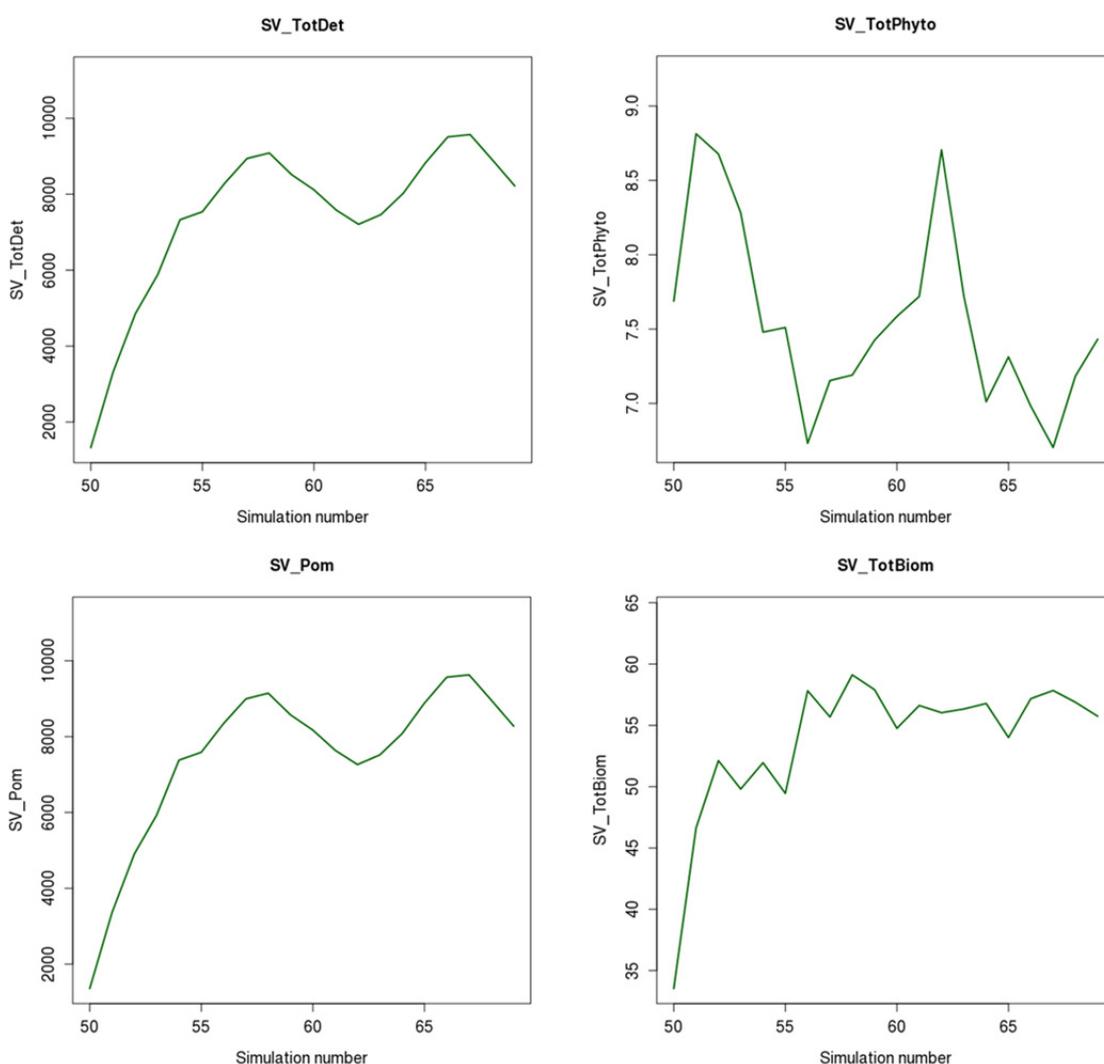


Figure 20 Reaching a steady state for the model (extended model set-up). Some totals for the last 20 simulation runs covering the years 1976 & 1977. Upper left: total detritus, upper right: total phytoplankton, lower left: total organic matter, lower right: total biomass. All data as system average densities (g AFDM m⁻²).

move towards such a steady state.

As an example, the results of the western Wadden Sea project 'KRW-slib'⁴ is used (Brinkman, 2015). The model ran from 1976 to 2010, and the years 1976-1977 were repeated about 70 times. Results for the last 20 runs are used to illustrate that finally some steady state was reached. During these last 20 runs some variations still occurs, but there is no structural change anymore. This implies that further changes will not depend on a wrong initial state, but only on changing external conditions.

⁴ "Silt dynamics in the western Wadden Sea", a Rijkswaterstaat project performed by Deltares and IMARES.

Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation. The scope can be found at the website of the Council for Accreditation (www.rva.nl).

On the basis of this accreditation, the quality characteristic Q is awarded to results of components which are incorporated in the scope, provided they comply with all quality requirements, as described in the applied Internal Standard Working procedure (ISW) of the relevant accredited test method.

The quality of the test methods is ensured in various ways. The accuracy of the analysis is regularly assessed by participation in inter-laboratory performance studies including those organized by QUASIMEME. If no inter-laboratory study is available, a second-level control is performed. In addition, a first-level control is performed for each series of measurements.

In addition to the line controls the following general quality controls are carried out:

- Blank research.
- Recovery.
- Internal standard
- Injection standard.
- Sensitivity.

The above controls are described in IMARES ISW 2.10.2.105.

If the quality cannot be guaranteed, appropriate measures are taken.

Justification

Report number: C158/15

Project number: 4312810004

The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of IMARES.

Approved: Dr. ir Martin Baptist

Researcher

Signature:

Date: 2015-12-15

Approved: Drs Jakob Asjes

Head Ecosystems Department

Signature:

Date: 2015-12-19