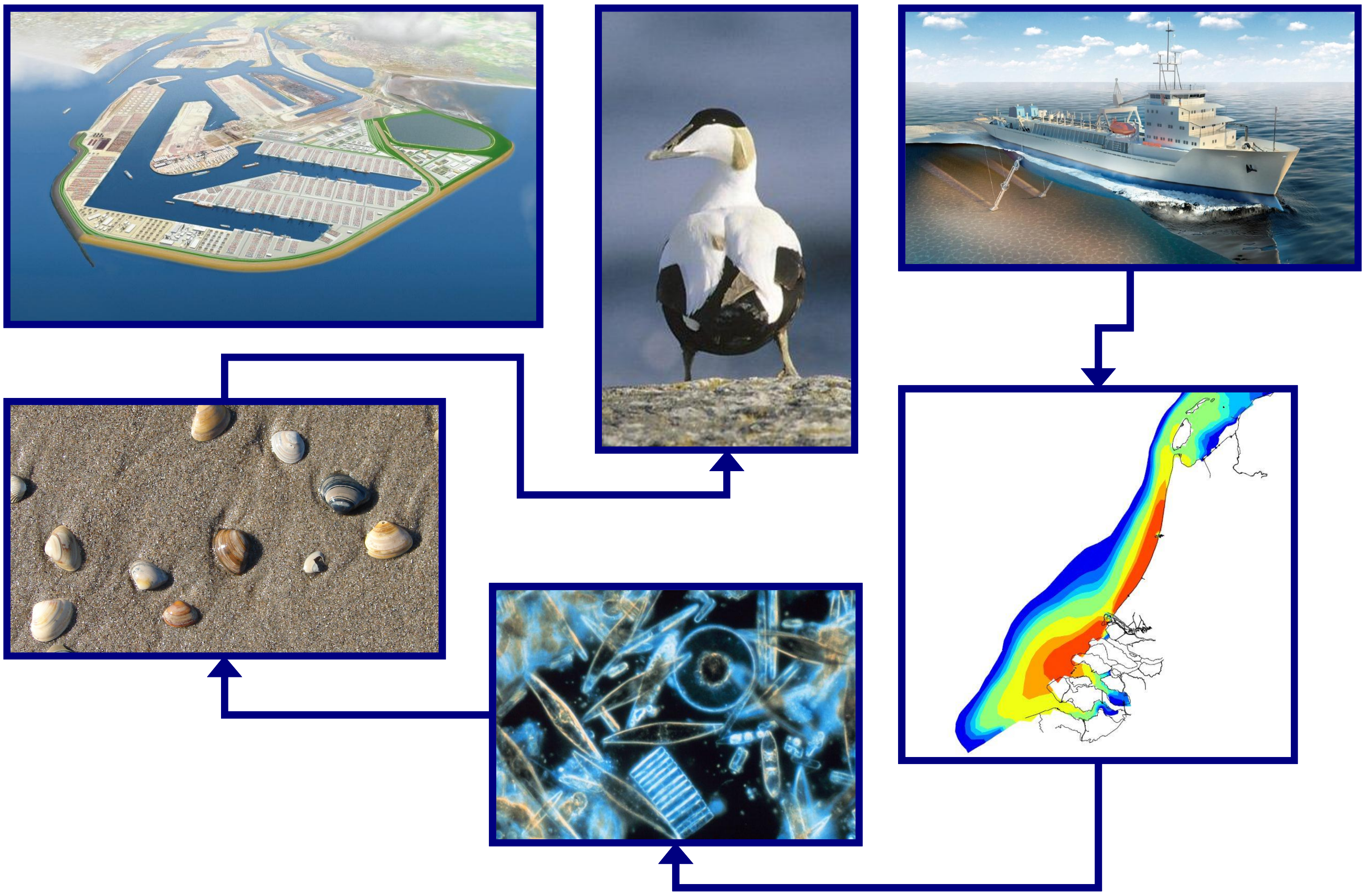
A probabilistic analysis of the ecological effects of sand mining for Maasvlakte 2



MSc Thesis

Y.J.G. van Kruchten

March 2008

Delft University of Technology

Havenbedrijf Rotterdam – Projectorganisatie Maasvlakte 2

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MSc Thesis
Faculty of Civil Engineering and Geosciences
Delft University of Technology
In cooperation with
Havenbedrijf Rotterdam N.V. – Projectorganisatie Maasvlakte 2
and
Deltares – WL | Delft Hydraulics

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Preface

This report is the result of my graduation research, which is the concluding part of the Master of Science program at the Faculty of Civil Engineering and Geosciences at Delft University of Technology, The Netherlands. The research has been conducted at the Port of Rotterdam Authority and at Deltares.

I would like to thank my graduation committee, Prof. drs. ir. J.K. Vrijling , Prof. dr. ir. M.J.F. Stive, dr. ir. P.H.A.J.M. van Gelder, ir. T. Vellinga, ir. R.J. Labeur, ir. W.G. Borst, dr. F. Heinis and drs. A.J. Nolte for their supervision and advises. I would also like to thank dr. O. van Tongeren for his comments and suggestions. Further I would like to thank all people who supported me and everyone who helped me by collecting data or by answering my questions on different subjects.

Special thanks go out to Erik and my family, who have been very supportive.

Delft, March 2008

Y.J.G. van Kruchten

Summary

For the construction of Maasvlakte 2 a large amount of sand has to be extracted from the North Sea. The potential ecological effects of these sand mining activities have been identified in an Environmental Impact Assessment (EIA). One of the identified effects in this EIA was an impact on the number of sea ducks in the Natura 2000 area 'Voordelta'.

The sand mining activities will cause an increase of the silt concentration along the North Sea coast. The light intensity decreases when more silt particles are suspended in the water column. A change of the light intensity can affect the growth of phytoplankton, as this growth is, among other things, dependent on the availability of light. An impact on the growth of phytoplankton can subsequently affect higher-order species in the food chain: phytoplankton is eaten by bivalves and bivalves form the main food of sea ducks like eiders.

Within this so-called impact-effect chain from sand mining to sea ducks, a large number of uncertainties play a role. In the EIA safe assumptions were used for a lot of these uncertainties. The final predicted impact is a result of the accumulation of several safe assumptions. Therefore, the probability of occurrence of this predicted impact might be small. Information on this probability of occurrence will be useful in the discussion about the necessity of mitigating and compensating measures.

The main objective of this thesis is to give insight in the probability of occurrence of the possible effects of sand mining on sea ducks in the Voordelta.

The research started by analysing which (uncertain) factors and processes have a large influence on the final result. Subsequently the uncertainties concerning the upper part of the impact-effect chain (from phytoplankton to sea ducks) are analysed more thoroughly. Apart from the factors that are directly influenced by the sand mining, also a large number of factors that are not influenced at all by the sand mining (for example weather conditions and natural variations of bivalve population sizes) turn out to have a large influence on the magnitude of the ecological impact.

In order to take these uncertainties into account in the modelling of the ecological effects, probability density functions were estimated for the relevant variables. These probability density functions are used in a Monte Carlo analysis. Within the Monte Carlo analysis a large number of sets of input variables were generated randomly from the probability density functions. For each set of input variables the impact on eiders is calculated. From the results of the Monte Carlo analysis a probability density function for the impact of sand mining on eiders is derived.

An increase of the silt concentration by the sand mining can affect bivalves in the Voordelta if a so-called mismatch occurs between the algal bloom and the birth of bivalve larvae (hatching). Due to the increased silt concentration the timing of the algal bloom will be delayed. The algal concentration that is necessary for bivalve larvae to grow optimally will be exceeded later. If the hatching of larvae takes place before this critical concentration is exceeded, a mismatch occurs and the larvae will be subject to a growth lag. An important worst-case assumption in the EIA was that a delay of the algal bloom leads directly to a mismatch. As the algal bloom mostly takes place during early April and the hatching at the end of May, the probability that a delay of the algal bloom indeed leads to a mismatch is very

small. Taking into account this probability leads to the main difference between the results of the probabilistic analysis and the deterministic, worst-case approach of the EIA.

In case of safe assumptions within the probabilistic analysis, the probability that the sand mining activities will not have an impact is 0.7. The probability of occurrence of impacts larger than a 10% decrease of the number of eiders in the Voordelta is only 0.03. In case of more realistic assumptions on for example the timing of the algal bloom and the hatching of larvae, the probability of occurrence of impacts larger than 10% decreases to $5*10^{-3}$. A decrease of 10% caused by the sand mining is small compared to the natural variation of the number of eiders that winter in the Voordelta. These results lead to the following main conclusion of this study:

> The probability that the sand mining activities for Maasvlakte 2 have a significant effect on eiders in the Voordelta is very small and can be considered negligible.

In this thesis is shown that giving insight in the probability of occurrence of significant ecological effects by using a probabilistic analysis is possible. The methodology that is used in this thesis is also expected to be applicable for the assessment of ecological effects of other human activities. Information on the probability of occurrence of ecological effects is relevant in the final decision making process whether mitigating or compensating measures should be taken. Therefore it is recommended to apply a probabilistic approach for EIA's in case it is expected that a deterministic, worst-case approach will not lead to the exclusion of significant effects.

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A = age of the bivalves [year] or age of larvae [d]

A_{ref} = moment at which the critical algal concentration is exceeded in the reference scenario [d]

BM = total biomass of a certain year class within the population [kg]

BM_i^j = total biomass of all individuals of age i in year j [kg]

$b1$ = coefficient 1 of salinity stress function [$g^{-1}.m^3$]

$b2$ = coefficient 2 of salinity stress function [$g^{-1}.m^3$]

Ccl = chloride concentration [$g.m^{-3}$]

CF = correction factor [-]

$Calg$ = algal concentration [$gC.m^{-3}$]

$\overline{Calg}$ = average algal concentration during a mismatch [cells ml^{-1}]

$Cdet_j$ = concentration of detritus component j [$gC.m^{-3}$]

Cim_k = concentration of suspended inorganic matter fraction k [$gDM.m^{-3}$]

D = delay of the moment at which the critical algal concentration is exceeded, caused by the sand mining activities [d]

D_{start} = delay of the moment at which net primary production starts, caused by the sand mining activities [d]

Ef = light efficiency factor [-]

Efc = critical light efficiency factor [-]

EM = factor to take into account the effect of a mismatch [-]

EQ = factor to take into account the effect of a changed food quality [-]

eb = background extinction coefficient [m^{-1}]

ea_i = specific extinction coefficient of an algae species type i [$m^2.gC^{-1}$]

eat = overall extinction coefficient of algae biomass [m^{-1}]

ed_j = specific extinction coefficient of a detritus component j [$m^2.gC^{-1}$]

edt = overall extinction coefficient of detritus [m^{-1}]

eo = extinction coefficient of other substances on the basis of relative salinity [m^{-1}]

eot = overall extinction coefficient of other substances as a function of salinity [m^{-1}]

es_k = specific extinction coefficient of a suspended inorganic matter fraction k [$m^2.gDM^{-1}$]

est = overall extinction coefficient of suspended inorganic matter [m^{-1}]

et = total extinction coefficient [m^{-1}]

FW = fresh weight [mg]

f = probability density [-]

fpa = fraction of photosynthetically active light in visible light [-]

fr = fraction of visible light reflected at the water surface [-]

fs = relative increase of the silt concentration [-]

G_i = growth factor for individuals of age i [-]

G = growth factor [-]

g = growth rate [$\mu m\ d^{-1}$]

H = moment of hatching of the larvae [d]

Ha = time step average depth of a water compartment [m]

I = depth average intensity of photosynthetic light [$W.m^{-2}$]

$Itop$ = visible light intensity at the top of a water compartment [W.m^{-2}]
i = index
kgp = potential specific growth rate [d^{-1}]
kgp^0 = growth rate per degree centigrade [°C^{-1}.d^{-1}]
$kmrt$ = specific mortality rate [d^{-1}]
$kmrt^0$ = specific mortality rate at 0 °C (d^{-1})
$ktmrt$ = temperature coefficient for mortality [-]
$krsp$ = specific maintenance respiration rate [d^{-1}]
$krsp^0$ = specific maintenance respiration rate at 0 °C [d^{-1}]
$ktgp$ = temperature at which kgp^0 is equal to zero [°C]
$ktrsp$ = temperature coefficient for maintenance respiration [-]
LS = shell length [µm]
$LS_{initial}$ = initial shell length, shell length at third day after fertilization [µm]
M = duration mismatch [d]
MY = mortality rate for whole year [-]
MS = mortality rate for summer period [-]
MW = mortality rate for winter period [-]
$m1$ = rate coefficient 1 of salinity stress function [d^{-1}]
$m2$ = rate coefficient 2 of salinity stress function [d^{-1}]
N = number of individuals of a certain year class [-]
NR = number of recruits (newborn larvae) [-]
P_m = probability of occurrence of a mismatch [-]
P = probability [-]
SAL = actual salinity [g.kg^{-1}]
$SALmax$ = maximal salinity (salinity value for *eot*=0) [g.kg^{-1}]
SR = survival rate of recruits [-]
SS = survival rate during summer [-]
SW = survival rate during winter [-]
SY = survival rate for whole year [-]
SY^j = survival rate in year j [-]
T = water temperature [°C]
TBM = total biomass of the population [kg]
t = time [d]
W = biomass of an individual bivalve of the specified year class [-]
WR = biomass of an individual recruit [kg]
Z = limit state function
μ = average
σ = standard deviation
Φ = the standard normal probability distribution function

1 Introduction

1.1 Background

Maasvlakte 2 will be created in the North Sea, directly to the west of the current port and industrial area of Rotterdam, the Netherlands. Maasvlakte 2 will provide new space for accommodating container transshipment, distribution activities and chemical industry and is located directly on deep water. The construction of Maasvlakte 2 is planned to start in 2008. The amount of sand necessary for the land reclamation and the construction of the sea defences is 425 Mm^3. Circa 15% can be extracted from the new harbour basins (so-called internal borrow areas) and another 15% will be mined after 2013, for maintenance of the 'soft part' of the sea defence, that will exist of dunes and beaches. The remaining part, circa 300 Mm^3, will be extracted from the North Sea, in front of Maasvlakte 2, beyond the -20 m depth contour line. An Environmental Impact Assessment (EIA) has been carried out to indicate among other things the effect of the sand mining on nature and environment.

The sand will be extracted by means of Trailing Suction Hopper Dredgers (TSHD’s). These sand mining activities will cause a release of fine sand and small silt particles. Silt particles (< 63 µm) can be transported over large distances by tidal currents, because of their small settling velocity. The North Sea water always contains a certain amount of Suspended Particulate Matter (SPM). This so-called background turbidity is generated by the combined effect of current velocities, tide, wave action, river discharges and primary production. A temporary increase of the SPM-concentration, caused by the release of silt, reduces the transparency of the water. A decrease of the transparency may have a negative effect on the growth of phytoplankton, which forms the base of the marine food chain. Ultimately this can affect the higher-order species in the food chain such as birds and fishes. Another effect of the increased turbidity is that birds are forced to fly further to clear water to find sufficient food for their chicks.

To determine the ecological impact of the sand mining operations, the relevant cause-effect relationships have been examined. The large number of assumptions, that have to be made regarding the morphological and ecological processes, and the large natural variability (of weather conditions and population sizes) makes that the results are uncertain.

The conclusion of the Environmental Impact Assessment was that the sand mining might have a temporary, negative effect on three species of ducks and two species of fish-eating birds in the Voordelta (see table 1.1). The Voordelta is a so-called 'Natura 2000 area' in the framework of the Birds and Habitat Directives of the European Union. This area is located relatively close to the sand-borrow area. If the ecological effects in this area are significant, it is legally obligatory to compensate these effects. For the fish-eating birds the maximum possible impact can be considered as insignificant. The question whether the effect on sea ducks in the Voordelta is significant or not, has been a subject of discussion.

Table 1.1 Predicted effect of sand mining on bird populations in the Voordelta (2009-2011) [BERKENBOSCH (2007)]

Ducks	Common Eider	Decrease of 0% - 6.4%
	Scaup	Decrease of 0% - 5.0%
	Common Scoter	Decrease of 0% - 7.1%
Fish-eating birds	Common Tern	Decrease of maximal 0.9%
	Sandwich Tern	Decrease of maximal 0.9%

The estimated maximum impact on ducks and fish-eating birds is a result of the accumulation of several worst-case assumptions. Therefore, the probability of occurrence of this impact might be small. Information on the probability of occurrence of these side-effects of the sand mining will be useful in the discussion about the necessity of mitigating and compensating measures.

Aim of this master thesis is to apply a probabilistic approach to evaluate (a part of) the impact-effect chain. This should lead to some insight in the probability of the possible effects of the sand mining on the protected birds in the Voordelta.

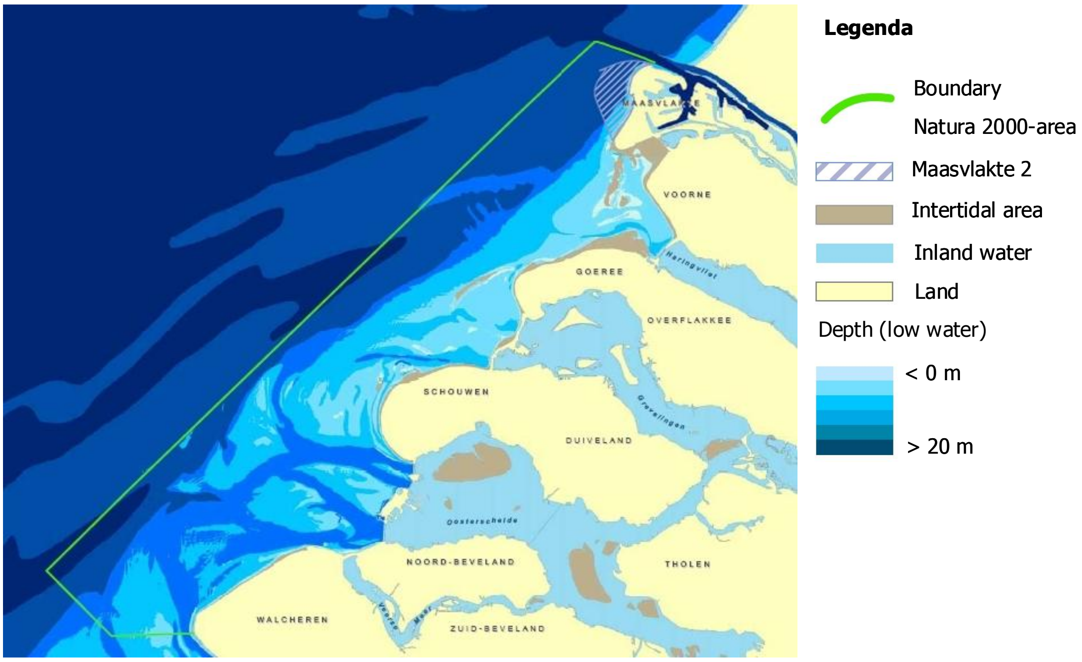


Figure 1.1 Location of Maasvlakte 2 and the Natura 2000-area [Rijkswaterstaat (2007b)]

1.2 Problem description

For the Environmental Impact Assessment of the construction of Maasvlakte 2, the effect of sand mining on the population of protected species of diving ducks was investigated by Projectorganisatie Maasvlakte 2 (PMV2). This investigation resulted in a prediction of the decrease of the population of eiders, common scoters and scaups in the Voordelta. However, this prediction is based on a combination of worst-case assumptions and can therefore be considered as an upper limit. In the EIA a temporary decrease of the number of sea ducks was predicted; the population size will return to their original state after several years. The maximum temporary decrease of the populations is an important factor in the discussion whether the effect is significant and if mitigating and compensating measures should be taken.

In order to evaluate the temporary effects in its context, also the probability of occurrence is, next to the effect itself, important. Unfortunately, the probability of occurrence of the effect that is mentioned in the EIA is in fact unknown.

Objective

The objective of this master thesis is to give insight in the probability of occurrence of the possible ecological effects of the sand mining. The result of the project should be a probability distribution of the change of the number of sea ducks in the Voordelta.

A secondary objective is to describe a methodology for applying a probabilistic approach to the determination of ecological effects in general and specifically for sand mining activities.

1.3 Report structure

In chapter 2 an overview is given of the ecological effects of sand mining for Maasvlakte 2 that were dealt with in the Environmental Impact Assessment. Also the methodology that was used for the EIA to quantify the impact of sand mining on sea ducks is discussed in this chapter.

The goal of this thesis is to model the impact of sand mining on sea ducks in a probabilistic way. The approach is explained in chapter 3 and worked out for different parts of the impact-effect chain in chapters 4, 5 and 6. The results of these chapters are finally combined in a Monte-Carlo analysis. The different scenarios for which a Monte-Carlo analysis is done and its results are shown in chapter 7. The conclusions and recommendations of this thesis are summarized in chapter 8. Finally in chapter 9 the use of applying a probabilistic approach for the prediction of ecological effects as well as the assessment of ecological effects is discussed.

Dutch translations of the names of animal species can be found in the 'Glossary English – Dutch'. An explanation of several terms which are not commonly used is given in the glossary.

2 Environmental Impact Assessment

The quantification of the ecological effects of the sand mining, which is the subject of this MSc thesis, was one of the large number of issues of the Environmental Impact Assessment (EIA) for Maasvlakte 2. Section 2.1 gives a brief overview of the issues in the EIA and the legislation that is relevant for the possible ecological impacts of the sand mining. The second section describes which possible ecological impacts of the sand mining have been taken into account in the EIA. This section also summarizes the conclusions of the EIA on the different ecological impacts. Section 2.3 describes the method that is used in the EIA to model the effect of sand mining activities on the number of eiders, scoters and scaups in the Voordelta.

2.1 Context EIA and Natura 2000

The goal of an EIA is to provide the information needed to allow full consideration of environmental interests in decisions on plans and projects with significant environmental impacts [www.eia.nl]. Two different EIA's were carried out to describe the influence of Maasvlakte 2 on nature and environment:

- EIA Zoning describes which environmental effects will occur when Maasvlakte 2 is operational;
- EIA Construction describes the consequences of reclaiming land and the sand extraction necessary to create the land.

These studies focused on matters on which reasonably an effect could be expected. Within the EIA Zoning the effects on traffic and transport, noise, air quality, external safety, water, light, nature, landscape and shared recreational use were investigated.

For the EIA Construction the main issues were:

- coast and sea (physical characteristics of the coast and sea area);
- environmental quality (air quality and noise);
- nature (disturbance and impairment seabed life, nature effects caused by increased silt concentrations, effects of space utilisation);
- nautical safety and accessibility;
- usage functions;
- archaeology;
- shared recreational use.

This master thesis will focus solely on the impact of an increased silt concentration (caused by the sand mining activities) on marine nature, which is part of the EIA Construction.

Especially for 'Natura 2000 areas' a quantification of the impact of Maasvlakte 2 on nature is important, as certain habitat types and bird species are legally protected in these areas. Natura 2000 areas are part of a European network of nature areas. EU member states must take all necessary measures to guarantee the conservation of habitats and certain species in these areas, and to avoid their deterioration. If a project potentially has significant consequences for a Natura 2000 area, everything reasonably possible must be done to prevent or at least mitigate the significant negative effects. If negative effects are unavoidable, it is mandatory to compensate the effects, to maintain the cohesion of Natura 2000 [MINISTERIE VAN LNV – DIRECTIE NATUUR (2005)].

Natura 2000
For the maintenance of biodiversity and the conservation of wild plants, animals and habitats, the European Union has initiated the establishment of a European ecological network, known as 'Natura 2000'. The network comprises 'special areas of conservation' (SAC) and 'special protection areas' (SPA), designated by the member states of the EU. Within the SAC's, the protection of certain habitat types and species is required under the Habitat Directive (Council Directive 92/43/EEC of 21 May 1992). The Bird Directive (Council Directive 79/409/EEC of 2 April 1979) seeks the protection of wild birds in the SPA's. Since October 2005, the protection of habitats and species within the Natura 2000 areas is incorporated in the Dutch amended Nature Conservation Act 1998. [www.europa.eu, MINISTERIE VAN LNV – DIRECTIE NATUUR (2005)]

The possible effects of sand mining activities for Maasvlakte 2 on habitats and species in the Natura 2000 area 'Voordelta' are described in the EIA Construction. An earlier study [HEINIS *et al*. (2007)] concluded that the sand extraction will not have significant effects in the Wadden Sea and the North Sea coastal zone.

2.2 Impact of sand mining on nature

For the EIA Construction has been investigated how the release of silt particles by dredging activities can affect protected habitats and species. The impact-effect relations are described in VERTEGAAL *et al.* (2007). An increase of the silt concentration will reduce the transparency of the water. This decrease of the transparency may have a negative influence on the growth of algae, which form the base of several food chains. An increased turbidity of the water might also hamper the catching of preys by fish-eating birds. Figure 2.1 shows the impact-effect relations in a simplified way. An explanation is given in the following subsections.

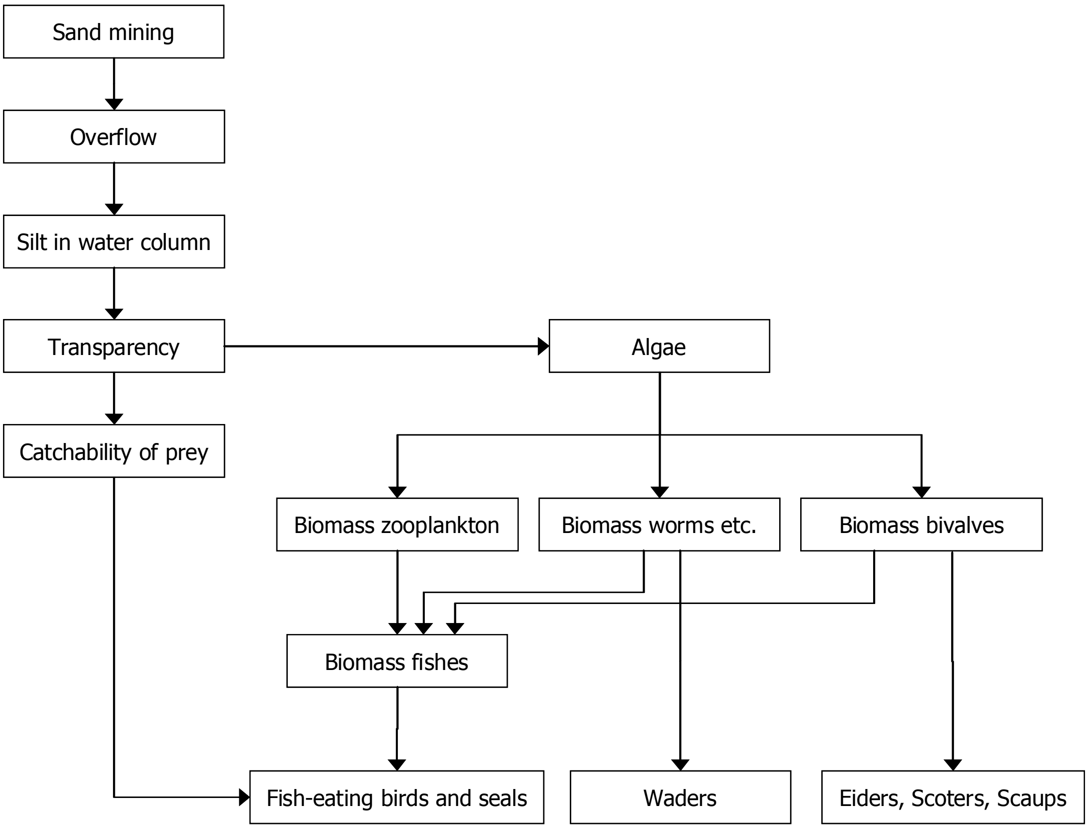


Figure 2.1 Possible relations between sand mining and impacts on species in the Voordelta [Vertegaal *et al.* (2007)]

2.2.1 Algae

Algae play a significant role in aquatic ecology. Microscopic forms that live suspended in the water column, called phytoplankton, provide the food base for most marine food chains. Phytoplankton forms the main food for bivalves* and zooplankton**. The main food for worms does not only consist of phytoplankton, but also bacteria and detritus are important food for worms. Detritus is non-living particulate organic matter, which includes (fragments of) the bodies of dead organisms and faecal material.

Phytoplankton needs sunlight to be able to convert carbon dioxide and water into glucose and oxygen. This process is called photosynthesis. Glucose is used by phytoplankton for respiration and growth. In the latter case glucose can be seen as a building material for other organic compounds. Besides glucose, phytoplankton needs nutrients (nitrogen, phosphorus and, for certain species, silicon) for its growth. The availability of these nutrients, as well as the availability of light can be limiting factors for the growth of phytoplankton. The production of organic compounds from inorganic matter is called 'primary production'.

An increase of the silt concentration will reduce the light intensity in the water column. This can lead to a (stronger) limitation of the growth of phytoplankton. In this way phytoplankton concentrations can be lowered by sand mining activities. Also the moment in spring, when the intensity of the sunlight becomes sufficient for algae to start growing, can be delayed by an increased silt concentration. (See for further explanation chapter 4)

*Molluscs with two-part shells

**Small floating animals, including e.g. copepods, krill, fish larvae and larvae of bivalves

During an expert meeting concerning the ecological effects of the sand mining for Maasvlakte 2 in the Voordelta, it was concluded that it is very unlikely that a decrease of the quantity of phytoplankton will affect higher levels of the food chain [report expert meeting in VERTEGAAL *et al.* (2007)]. This conclusion was based on the expectation that the ecosystem in the Voordelta is not limited by the quantity of available food. However, the combination of a decreased algal concentration and an increased silt concentration, as well as the timing of the availability of food, may have an effect on species of higher trophic levels.

Release of nutrients

The overflow of the trailing suction hopper dredgers will probably not only contain silt particles, but also nutrients, as the seabed also contains (organically bound) phosphorus and nitrogen. The impact of a release of these nutrients was not investigated for the EIA. The thickness of the layer of the seabed that contains nutrients, as well as the concentration of these nutrients is not known. Higher nutrient concentrations may enhance the growth of phytoplankton. More phytoplankton means more food for bivalves and zooplankton. However, as the availability of food is probably not a limiting factor for the growth of these organisms (see section 2.2.1), more phytoplankton does not unconditionally lead to more food for higher trophic levels like fishes and ducks. The possible impacts of the release of nutrients will be discussed further in section 4.2.2.

Toxic components

In case the sediment at a mining location is contaminated with heavy metals, also negative ecological impacts can be expected due to the release of these toxic components. However, from research to the seabed at the possible mining locations for Maasvlakte 2 has been concluded that the seabed exists of the so-called 'class 0'-sediment, which means that the seabed is not polluted [VAN LEDDEN *et al.* (2007)].

2.2.2 Higher trophic levels

As mentioned in the previous section, the quantity of food is probably not a limiting factor for the growth and survival of animals in the Voordelta. However, for some species not only the quantity of food, but also the food quality and the timing of the availability of food may be important. Food quality is defined as the ratio of the concentration edible matter (phytoplankton) over the concentration of inedible matter (silt). In the EIA was assumed that only the growth of bivalves may be hampered as a consequence of the decrease of this ratio.

The influence of this food quality on fish species that live in estuaries was investigated by Fox *et al*. (1999) [VERTEGAAL *et al.* (2007)]. The conclusion of the research was that the food intake of fishes is not affected by silt concentrations lower than 100 mg per litre. In the Voordelta, concentrations of 100 mg/l are only exceeded during storm conditions. During these conditions, the concentration of 100 mg/l will be exceeded not only in case of sand mining activities, but also in the reference situation [VERTEGAAL *et al.* (2007)].

Whether or not the decrease of the food quality or the timing of the availability of food will have an effect on the total biomass of zooplankton or worms, the subsequent effect on fishes or waders will not be significant according to the EIA. Firstly, because it is not likely that the total amount of available food for fishes and waders will become limiting. For example the number of waders near the Brielse Gat seems to be not (or hardly) related to the amount of available food, according to Heinis and Vertegaal (2002) [VERTEGAAL *et al.* (2007)]. Secondly as the Voordelta forms only a small part of the total habitat of most fish species. For example protected migratory fish species like the allis shad (*Alosa alosa*), river lamprey (*Lampetra* *fluviatilis*), sea lamprey (*Petromyzon marinus*) and salmons, only use the Voordelta as a 'stopover area', when they are migrating. For most fish species that spent a longer period of their life in the Voordelta, like the twait shad (*Alosa fallax*), the Voordelta is only a small part of their habitat (which includes the whole Dutch coastal zone for the twait shad) [VERTEGAAL *et al.* (2007)].

In the EIA, the timing of the availability of food was assumed to be only relevant for the larvae of bivalves. If the eggs hatch out before the phytoplankton bloom in spring, a so-called 'mismatch' occurs. This mismatch may cause a growth lag for the larvae. In these ways the total biomass of bivalves can be affected by the sand mining activities. This decrease of the biomass of bivalves was assumed to have a negative effect on the number of eiders, scaups and scoters in the Voordelta.

In the EIA was also assumed that the higher fine silt concentrations, as a result of the sand mining, may have temporary consequences for the common tern and sandwich tern, which hunt on sight. If the water close to the coast becomes so turbid that it is more difficult to see their prey fish, these birds may have to fly farther to get their food. In the breeding season, this may be at the expense of the breeding success and thus the size of the population. Indications that prey fish come closer to the water surface, if they believe they are less visible, have not been taken into account in the EIA [BERKENBOSCH (2007)]. In this thesis no attention will be paid on the possible ecological effects by the hampered catching of prey for fish-eating birds. The predicted effect in the EIA is small (<1%, see table 1.1) and obviously not significant.

2.2.3 Habitats

As mentioned in section 2.1, not only certain species are legally protected by the Nature Conservation Act 1998, but also for certain habitat types a good state of preservation should be maintained. The Natura 2000 area 'Voordelta' consists for 97% of 'habitat type 1110'. Habitat type 1110 is defined as: sandbanks which are permanently covered by seawater of small depth (seldomly larger than 20 m), including the water column above these banks and the channels between the banks and the accompanying ecological value [EUROPEAN COMMISSION DG ENVIRONMENT (2007) and Dutch Ministry of Agriculture, Nature and Food Quality - database habitattypes, www.minlnv.nl].

As a result of the sand mining activities, the silt-content of the seabed and the silt concentration in the water column will increase in the Voordelta. In the EIA is concluded that this will not affect habitat type 1110. The abiotic characteristics of the habitat are not affected in such a way that this will have a noticeable effect on the composition of the benthos [VERTEGAAL *et al.* (2007)].

2.2.4 Summary

Figure 2.2 shows an overview of this section. The grey boxes and dotted lines show which relations are very unlikely to exist. The existence of the relations between the orange and yellow boxes is possible. However, the maximal impact of the sand mining on the fish-eating birds and seals, as predicted in the EIA, is very small (<1%, see table 1.1). In this way only the 'orange path' remains: only the orange path lead to a predicted impact in the EIA (by using several worst-case assumptions) that might be significant. Therefore this thesis will focus on this path.

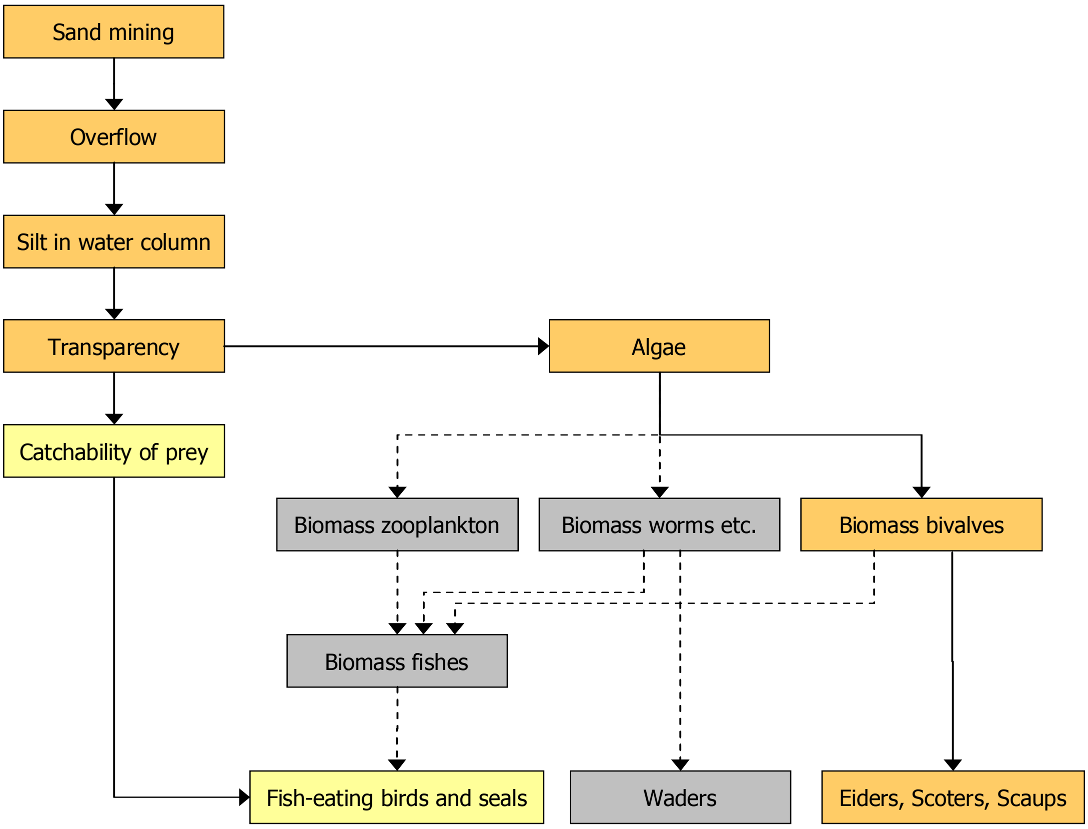


Figure 2.2 **Relations between sand mining and impacts on species that possibly exist (orange and yellow, continuous lines) and relations that are very unlikely to exist (grey, dotted lines) in the Voordelta**

2.3 Modelling the impact of sand mining

This section describes the method that is used in the EIA Construction to model the effect of sand mining activities on Common Eiders, Common Scoters and Scaups. The approach follows the impact-effect chain, which starts at the release of fine silt particles near the dredging vessel.

First, assumptions were made about the 'near field effects'; the release of silt particles near the trailing suction hopper dredger. Subsequently, the sedimentation and erosion of silt around the sandpit was modelled (mid field model). Within the 'far field model' the movement and spreading of the released silt along the Dutch coast was simulated. Together with the results of a model that simulated the background SPM-concentration, the results of the far field model were used as input for the modelling of primary production. On the basis of the results of the far field model and the primary production model, the impact on shellfish was modelled. Finally the effect on shellfish was translated to an effect on eiders, scoters and scaups. Figure 2.3 shows in a schematized way how the impact of the sand mining activities on ducks was modelled for the EIA. The next subsections give an overview of processes and relations that are included in the different calculation steps and the most important assumptions that were made for the EIA. This thesis will mainly focus on the last part of the impact effect chain; the ecological model.

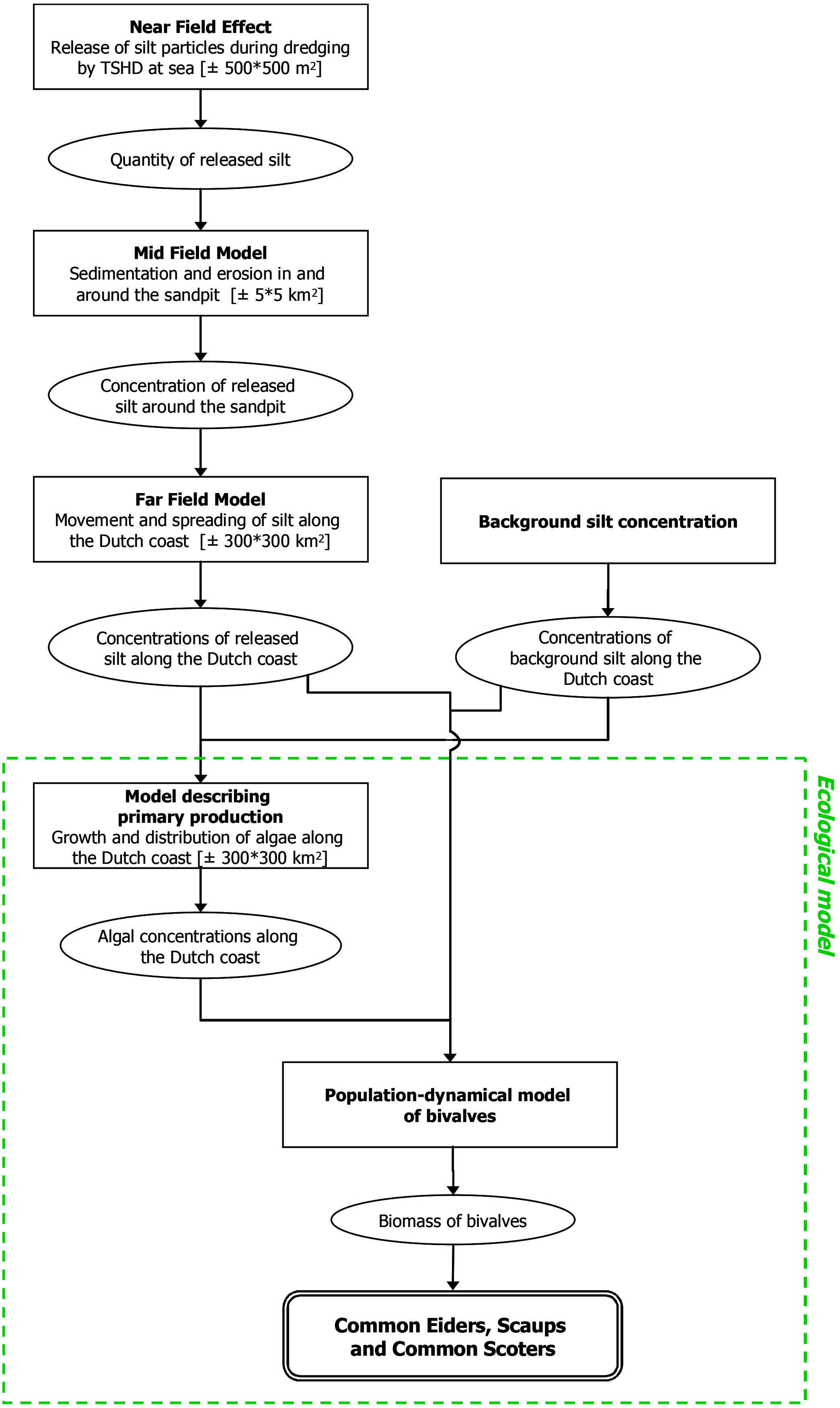


Figure 2.3 **Schematization of the calculation method of the EIA**

2.3.1 Near field

Trailing suction hopper dredgers will be used for the sand extraction in the North Sea. The near field area is the area directly around the trailing suction hopper dredger (TSHD), above the sandpit. While the dredger sails at a low speed, a sand-water mixture is pumped up from the sea bed. This sand-water mixture is pumped into the hold of the dredger. In this way the hold will be filled with this sand-water mixture, initially containing a relatively large amount of water, compared to the amount of sand. To obtain a more economic sand load, the dredging will go on for a while. During loading the majority of the sand-water mixture (the sandy part) will settle in the hold and the excess transport water will flow back into the North Sea. This overflowing water contains fine particles, up to 150 μm. The sand particles (> 63 μm) in the overflow will settle relatively quickly, but the silt particles (< 63 μm) may stay suspended in the water column. Tidal currents can spread these suspended particles over a large area.

The output of the near field model (quantity of released silt per unit of time and/or the thickness of a silt layer on the bottom of the sand pit) is dependent on the following near field processes and variables:

- the silt percentage in the seabed;
- the mining rate;
- the sedimentation of silt in the hold of the dredger;
- the behaviour of the overflowing fines: i.e. acting as a 'passive' or 'dynamic' plume;
- the release of fines during the land reclamation process.

Silt percentage and mining rate

The silt percentage in the seabed of the North Sea is not the same for all the possible sand mining locations. For the EIA three different locations were considered. Figure 2.4 shows the search area (30 km radius) for the sand extraction activities. The final choice of the location will be part of the 'design and construct' tender process in which the contractor plays an important role.

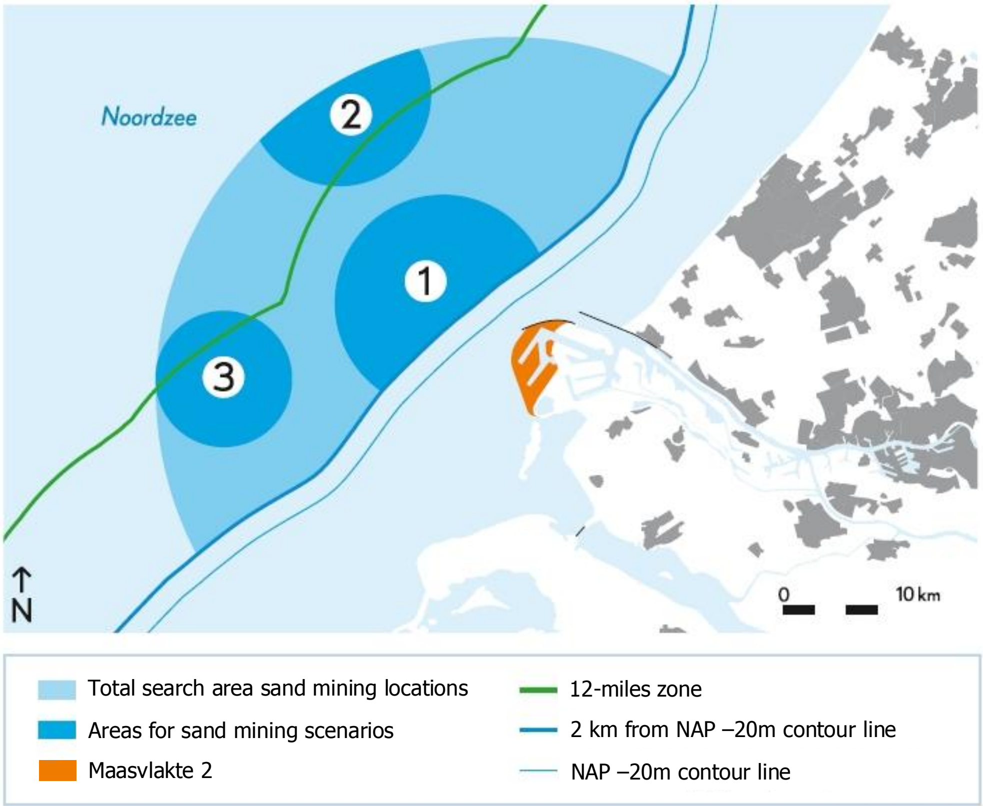


Figure 2.4 Search area for sand mining locations, figure from BERKENBOSCH *et al.* (2007)

Area 1 is located as close as possible to Maasvlakte 2. Sand mining in area 1 is the most economical option and most favourable option to limit the use of energy and thereby the emissions of NO_2, SO_2 and PM_{10}* into the environment [BERKENBOSCH *et al.* (2007)]. Because of its relatively large distance to the Voordelta, area 2 leads to the smallest ecological impact in the Voordelta. Area 3 has benefits for the mining of coarse sand (for building and industrial purposes, so-called concrete and masonry sand). The contractors prefer area 1 for the sand mining. In the EIA, a silt percentage of 2.5% is used for area 1. For areas 2 and 3 a silt percentage of 1.25% was used.

Not only the choice of the mining location, but also the mining rate is part of the 'design & construct' tender process. To take into account the possible choices of the contractor, several sand mining scenarios were defined for the EIA. Table 2.1 shows the definitions of some of these scenarios. All scenarios take into account the mining of 7.6 Mm^3 of sand during February/March 2008 for dune restoration near Delfland.

*Particulate Matter (diameter < 10 μm), particles suspended in the atmosphere (Dutch: fijn stof)

Table 2.1 Definition of sand mining scenarios [DESMIT *et al.* (2007)]

Name	Amount (Mm^3)	Location	Mining rate (Mm^3/year)	Duration (year), period	Ratio release in mining and reclamation area	Percentage silt in sediment (-)
S0-autonomous	19	Ter Heide, NAP -20 m	3.8/mnd	Feb - Apr '09 and '10	90:10	2.5
S1a	310	Area 1	150	2	90:10	2.5
S1b	310	Area 1	62	5	90:10	2.5
S1c	290	Area 1	100	2.9	90:10	2.5
S2	310	Area 2	150	2	90:10	1.25
S3	310	Area 1 (75%) and 3 (25%)	150	2	90:10	2.5 / 1.25

Release of silt during dredging and land reclamation

During the sand mining, silt particles will be released in the water column due to the overflow of water out of the hopper. Not all the silt particles that are extracted from the seabed will flow back into the sea. About 20% of the silt will remain in the hopper of the dredger [MASTBERGEN (2006)]. A part of the silt that remains in the hopper will be released during the land reclamation activities. The remaining part will be trapped in the newly reclaimed land and the soft sea defence. The magnitude of this part is dependent on the grain size distribution and the method and order of construction of Maasvlakte 2. The assumption for the EIA was that finally 100% of the extracted silt will be released, 85-90% at the sand mining location and 10-15% at the land reclamation site.

Passive or dynamic plume

The silt plume formed by the overflow of the dredger will partly behave as a passive plume and partly as a dynamic plume. In a passive plume all the silt particles will stay suspended in the water column. In a dynamic plume the silt particles will be transported towards the seabed, because of the density difference between the plume and the surrounding water. In this way a dynamic plume can accelerate the deposition process of material in and around the sandpit. On the other hand, the dynamic plume can also cause re-suspension of bed material, as a result of the impact of the density current on the seabed.

The magnitude of the part that behaves as a dynamic plume in reality is uncertain. However, for the EIA it has been assumed that 100% of the silt particles behave as a passive plume. The reasoning behind this assumption is that the silt particles that end up on the seabed will be eroded by the tidal currents and thus will be part of the SPM-concentration in the water column after a few tidal cycles (see next subsection).

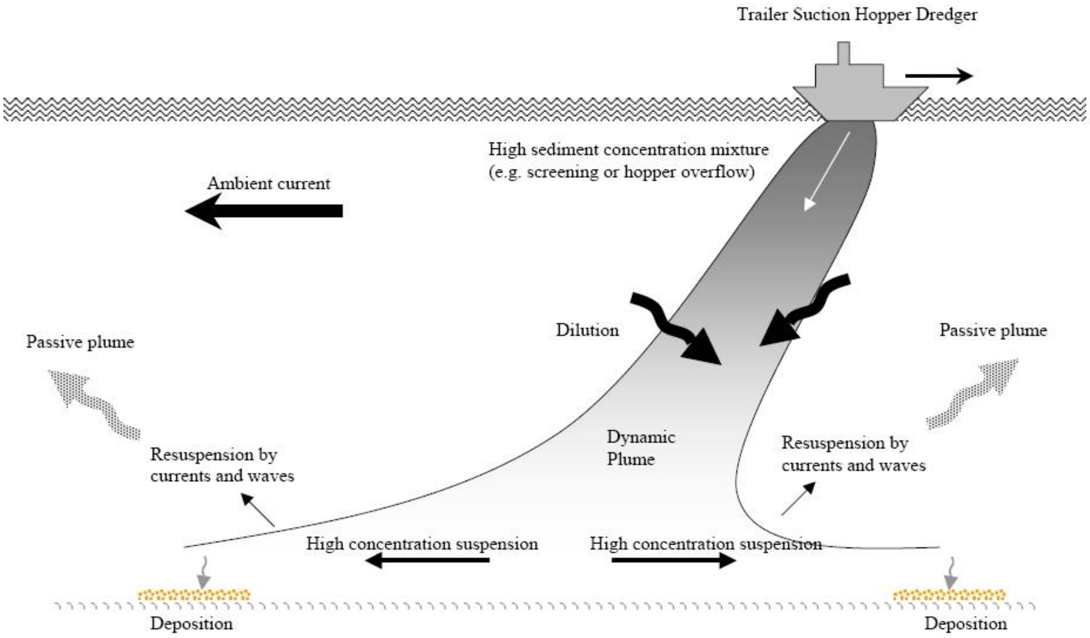


Figure 2.5 **Overview of dredge sedimentation processes, figure from W.F. BAIRD & ASSOCIATES LTD. (2004)**

The passive and dynamic plume [W.F. BAIRD & ASSOCIATES LTD. (2004)]

The overflow of the TSHD will be denser than the surrounding water, due to the high sediment concentration. Because of this density difference and its initial momentum, the overflow will descend towards the seabed as a *dynamic plume*. As the dynamic plume descends, ambient water is entrained into the plume, diluting the plume and slowing its downward descent. A proportion of the sediment may be 'stripped' from the plume into the surrounding water column to form a *passive plume*, while the remainder of the released material impacts upon the bed as a density current. Some material may be re-suspended into the water column as a result of the impact, while the rest of the material moves radially outwards across the seabed as a dense pancake-like plume, slowing with time. During this radial expansion settling of sediment occurs from the density current onto the bed. Initially, the mixing that occurs between the density current and the ambient water is limited. However, when the concentration and thickness of the density current are sufficiently low, and if the ambient currents are sufficiently high, then significant mixing occurs and sediment is released into the water column to form a *passive plume*. (See Figure 2.5)

2.3.2 Mid field

The mid field area is the area above and around the sandpit. The water movement and the silt transport were modelled by use of the numerical models Delft3D (WL|Delft Hydraulics) and FINEL2D (Svašek Hydraulics) [VAN DEN BOOMGAARD (2005)].

The model results show that there is no net deposition of silt particles during a tidal cycle [VAN DEN BOOMGAARD (2005)]. During the tidal phase with small flow velocities a small part of the suspended silt deposits, but all this particles are 're-suspended' during the tidal phase with high flow velocities.

However, the values of the deposition- and erosion parameters within the models are uncertain. Applying other values of these parameters, within the physically realistic margin, can lead to the conclusion that a net sedimentation of silt in the sandpit takes place (results vary from sedimentation of 0% till 65% of the silt) [VAN DEN BOOMGAARD (2005)].

Nevertheless, if silt deposits indeed in the sandpit, this silt will be dredged again. Even if the deposited silt is entrained into the seabed, the silt will be 're-dredged' after some time. Since the silt will be re-dredged or re-suspended by drag heads several times, the amount of silt that is permanently lost in the sandpit will probably be small.

Besides, the reduction of flow velocities in the sandpit (which causes suitable conditions for the deposition of silt) will not be significant if the sandpit has a small depth. Possibly, deposition of silt in the sandpits only takes place in the later phases of the sand mining.

Because of the re-dredging and resuspension of the silt that deposits on the bottom of the sandpit, also the behaviour as a passive or dynamic plume of the silt (see previous subsection) is of minor importance.

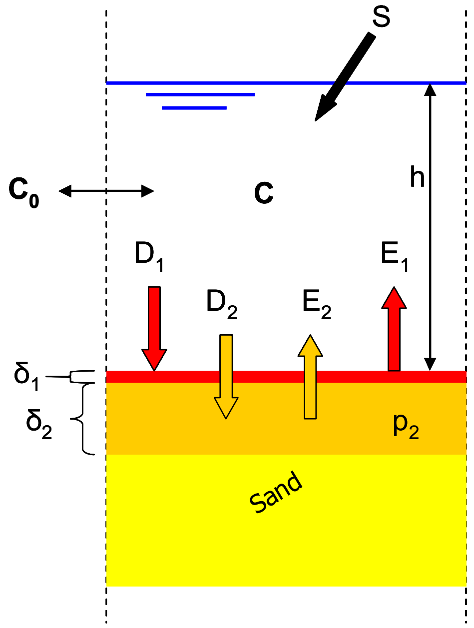
2.3.3 Far field

The far field model describes the spreading of the silt plume in the southern North Sea. Two different numerical models were deployed; a 2-dimensional model (using FINEL2D) and a 3-dimensional model (using Delft3D) [VAN PROOIJEN *et al.* (2006)].

Sediment and seabed characteristics

For the modelling of the silt transport, also the buffering of silt in the seabed is incorporated in the far field models. Fine sediment can be entrained into the seabed by several mechanisms. An example is the mechanism of over- and underpressures near the seabed that are generated by waves.

In the far field model the seabed is schematized as a 'near-bed layer' (δ_1 in Figure 2.6) on top of a 'buffering layer' (δ_2 in Figure 2.6). Fine sediment particles that deposit in the near-bed layer can be remobilized by tidal currents. Sediment particles that are entrained into the buffering layer can be released during storm conditions only. The amount of fines that can be entrained into the bed is limited by a minimum permeability of the bed.



h = water depth [m]
c = silt concentration [kg/m^3]
δ_1 = thickness of layer 1 (near-bed layer) [m]
δ_2 = thickness of layer 2 [m]
E = erosion flux [kg/(m^2/s)]
D = deposition flux [kg/(m^2/s)]
S = release rate of fines [kg/s]
p_2 = silt volume percentage in layer 2 [-]

Figure 2.6 Schematization of the seabed (not to scale) [VAN PROOIJEN *et al.* (2006)]

Due to the buffering of silt in the seabed, the impact of sand mining activities on the silt concentrations in the North Sea lasts longer than the extraction period. Gradually the amount of silt that is buffered in the seabed will be released and dispersed over a larger area. This effect will go on for several years after finishing the sand extraction activities.

The parameter settings for the modelling of water-bed exchange have an important influence on the predicted impact of sand extraction on silt concentrations. The parameter settings that were applied in the model are uncertain and difficult to calibrate due to lack of measured data. The model formulations of the far field model are given in appendix A. The influence of the uncertainty of the parameter settings on the final results (the impact on ducks) will be discussed in section 4.7.

Meteorological conditions

The meteorological forcing of the hydrodynamics in the models was based on the period 1996-2003. In the far field model, the measured wind and pressure fields, waves, river discharges and tide of this period are assumed to be the same for the period 2008-2015. The influence of different meteorological conditions on the results of the far field models is shown in section 4.7.

3-Dimensional effects

The 2-dimensional (FINEL2D) and the 3-dimensional (Delft3D) model show a difference in the movement of the plume towards the coast [VAN PROOIJEN *et al.* (2006)]. The modelled increase of the silt concentration in the Voordelta is higher in the 3D-approach. In the 3-dimensional model the suspended particles are swept to a larger extent towards the coast, resulting in a narrower zone with higher concentrations. This effect occurs due to the horizontal and vertical density gradients that are caused by the fresh water discharges of the Nieuwe Waterweg and the Haringvliet. Horizontal density differences result in a vertical circulation. The fresh water flows in the upper part of the water column whereas the salt water flows near the bed towards the coast. Since sediment concentrations are higher near the bed, this 3-dimensional effect causes a net advection of silt towards the coast. In FINEL2D, this effect was parameterised by assuming an extra advection velocity towards the coast. As it is not known in which model the 3-dimensional effects are captured best, the results of the Delft3D-model, which showed the highest increase of the silt concentration, were used as input for the modelling of primary production.

2.3.4 Primary production

The impact of sand extraction on primary production was simulated for the EIA by using the Delft3D-ECO (GEM) modelling framework. The model used for the EIA is 2-dimensional. The functioning of the Delft3D-ECO model will be explained in chapter 4.

The far field model did not take into account the background silt concentration. The background silt concentration has been modelled in a different way than the 'sand mining silt' concentration. The results of the far field model were superposed on the background concentration. The temporal and spatial variation of this summarized silt concentration was used as input for the Delft3D-ECO model.

2.3.5 Bivalves

For the EIA, the biomass of bivalves was assumed to be affected negatively by the increase of the silt concentration in two different ways [VERTEGAAL *et al.* (2007)]:

- The increased silt concentration reduces the penetration of sunlight in the water column, which leads to a delay of the algal bloom in spring. A time-lag between this bloom and the hatching of bivalve larvae (mismatch) hampers the growth of these larvae.
- The food quality, defined as the ratio of the algal concentration over the silt concentration, will be lowered. This will hamper the growth of bivalves.

Mismatch

Figure 2.7 shows the modelled variation of the phytoplankton concentration, using the meteorological conditions of 1997 [model results Delft3D-ECO model, WL|Delft Hydraulics, location: GR6, scen: 31]. As an example, a phytoplankton concentration of 0.3 gram carbon per cubic metre is supposed to be sufficient for the unlimited growth of larvae (the food concentration is sufficient for the larvae to grow optimally). A phytoplankton concentration of 0.3 gC/m^3 is exceeded at the 19th of April (see Figure 2.7). If the larvae hatch before April 19th, a 'mismatch' occurs; the growth of the larvae will be limited. If the larvae hatch after April 19th, a 'match' occurs; the newly-born bivalve larvae do not suffer a growth limitation, as sufficient food is available.

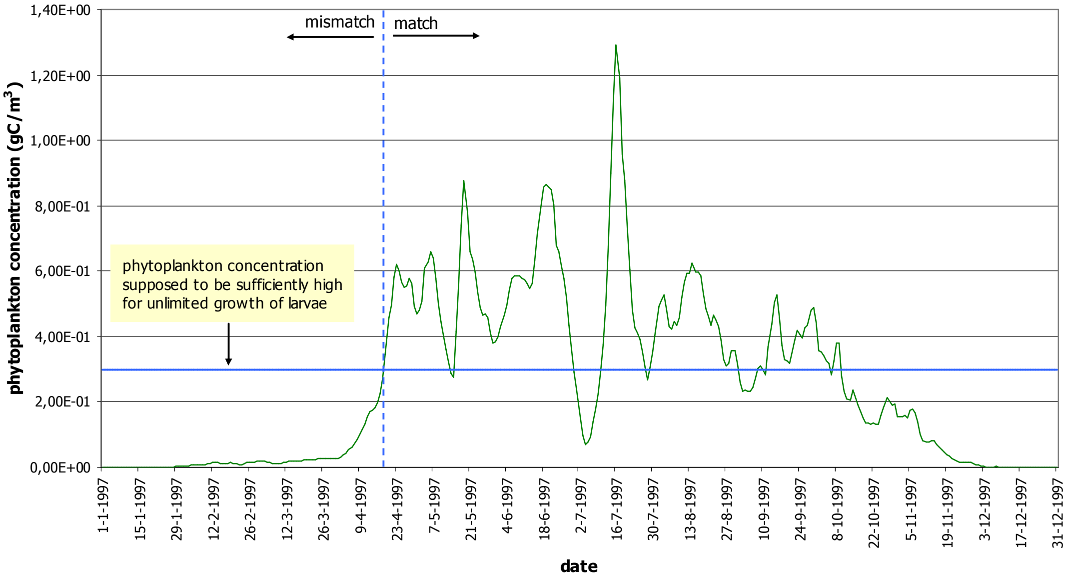


Figure 2.7 Illustration of the mismatch-principle

As a result of the increased silt concentration, caused by the sand mining, the moment that the phytoplankton concentration of 0.3 gC/m^3 is exceeded, can be delayed. Figure 2.8 shows the modelled phytoplankton concentrations for the reference scenario (S0-autonomous, green line) and a sand mining scenario (S1a, orange line). A worst-case assumption in the EIA was that (in the reference scenario) the larvae will hatch exactly at the moment that the phytoplankton concentration, at which growth is not limited by the availability of food anymore, is exceeded. This means that a delay of this moment, will directly lead to a mismatch (see Figure 2.8).

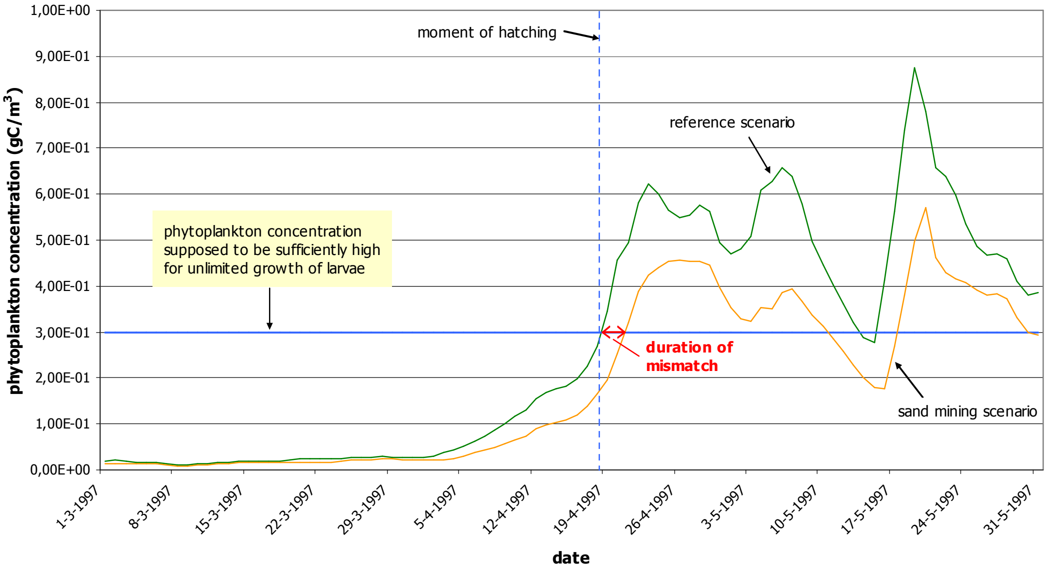


Figure 2.8 Duration of the mismatch

The longer the duration of the mismatch, the larger the growth lag of the larvae will be; if the period that the food concentration is insufficient lasts longer, the larvae 'are starving' for a longer period. The relative growth lag* of the young bivalves was assumed to be linearly dependent on the duration of the mismatch. In the EIA is also assumed that bivalves are not able to catch up this growth lag.

Food quality

Whether a relation between the growth of bivalves and the food quality exists is in fact unknown. Keeping in mind the precautionary principle, a relation between the food quality and the growth has been taken into account in the EIA. The relation between the decrease of the summer-averaged food quality and the growth lag of bivalves was assumed to be linear. This relation will be discussed further in section 5.4.

Precautionary principle

The precautionary principle does not have only one, unambiguous definition. In fact several interpretations and definitions exist [FAURE AND VOS (2003)]. One definition is: 'if a reasonable suspicion exists that activities can have negative consequences for the environment, measures should be taken in order to prevent these consequences or, if the prevention of these consequences is not possible, to offer protection against these consequences'. Even if a scientific proof of the existence of the causal relation between activity and consequence does not exist, preventing measures should be taken.

The precautionary principle is explicitly mentioned in Article 174 of the EC Treaty, which designates the principle as one of the fundamentals of the EC environmental policy. The precautionary principle also constitutes an important part of the Dutch environmental policy. [FAURE AND VOS (2003)]

Combined effect

A population-dynamical model was used in the EIA to calculate the combined effect of mismatches and lowered food quality on the total population of bivalves. The food of eiders, scoters and scaups consists of bivalves of several year classes. By using survival rates, growth factors and the number of bivalves that are born each year (recruits) the total biomass of bivalves in the Voordelta and the distribution over the different year classes was modelled for a reference scenario as well as for a sand mining scenario (taking into account the effect of mismatches and a decreased food quality). The relative decrease of the amount of food for ducks was finally calculated by comparing the results for the reference scenario and the sand mining scenario. The survival rates of bivalves and the number of recruits were kept constant for each year in the model for the EIA. In reality the number of recruits and the survival rates show a large variation. The effect of this variation will be discussed in sections 3.2.3 and chapter 5.

2.3.6 Ducks

In the EIA, the number of ducks was assumed to be directly proportional to the biomass of bivalves [VERTEGAAL *et al.* (2007)]. For example: if the total biomass of bivalves decreases by 20%, the number of eiders also decreases by 20%. Probably the relation between ducks and bivalves is not linear (see section 6.3). However, by using a linear relation an estimate was made of the impact of sand mining on eiders, scaups and scoters for the years 2008 - 2015.

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*The larvae will be a certain percentage smaller in case of a mismatch, then they would have been in case of a match. This percentage is the relative growth lag.

2.4 Discussion

The method (discussed in section 2.3) that was used to model the impact of sand mining on eider ducks in the Voordelta, contains several safe assumptions. For example:

- a delay of the algal bloom leads directly to a growth lag of bivalve larvae (possibly the larvae hatch after the delayed bloom, in this case a delay of the bloom does not matter);
- the relation between the number of eiders and the total biomass of bivalves is linear (maybe there is plenty of food for eider ducks in the Voordelta, a small decrease of the total biomass of bivalves does not matter in this case);
- the total amount of silt that is pumped up by the TSHD's, will be released in the North Sea.

Due to safe assumptions like these, the impact that is finally predicted can be regarded as an upper limit. The probability will be large that the sand mining has a smaller ecological impact than predicted or even no impact at all. This probability can be quantified by using a probabilistic approach. In the next chapter will be explained how a probabilistic approach will be applied in this thesis to predict the impact of sand mining on eiders. Also the effect of using several safe assumptions on the final result will be illustrated in chapter 3.

3 Probabilistic approach

In the modelling of ecological effects several uncertainties play a role; uncertainties due to a lack of knowledge as well as uncertainties on the natural variation of, for example, populations sizes and meteorological conditions. In a probabilistic approach it is possible to take into account these uncertainties, while the deterministic approach mostly takes a safe assumption as a starting point. The results of probabilistic calculations also give information about the probability of occurrence of a certain effect. A deterministic approach leads to a result, which can often be regarded as an upper limit, and does not give any information about the probability of occurrence.

Uncertainty margins of parameters within a model can be the combined result of natural variations and a lack of knowledge. Using a probabilistic approach can also give insight in which uncertainties contribute to a large extent to the uncertainty margin of the final result. If these uncertainties are caused by a lack of knowledge, further research to these subjects would be useful to improve the accuracy of the final result.

In section 3.1 is explained how the ecological effects of sand mining will be modelled in this thesis. In the second section the difference between a deterministic and a probabilistic approach will be illustrated on the basis of three simple examples.

3.1 Modelling approach

This thesis will focus on the 'ecological part' of the impact-effect chain that was defined in the EIA (see figure 2.2). A more detailed overview of this part of the impact-effect chain, from algae to sea ducks, is given in figure 3.1.

According to the research that was done for the EIA, sand mining can have an impact on sea ducks in two different ways:

1. due to a mismatch between bivalve larvae and a sufficiently high algal concentration (see section 2.3.5)
2. due to a decrease of the food quality for bivalves (see section 2.3.5).

A mismatch occurs if the larvae of bivalves hatch out of their eggs before the algal concentration has exceeded a certain critical value. As not enough food is available for the larvae to grow maximally, a mismatch may result in a growth lag of the larvae. In chapter 4 is determined at which moment the algal concentration exceeds the critical level in the reference scenario (A_{ref}), for how many days this moment is delayed by the sand mining (D), and when the spawning of bivalves takes place (H). By use of the estimated probability density functions of these variables, also the probability of occurrence of a mismatch is estimated in chapter 4.

To be able to take into account the relation between the growth of bivalves and the food quality, literature research is done to find more information on the shape of this relation and on the probability that this relation exists. The results of this literature research (section 5.4 and appendix F) indicate that the existence of this relation is very unlikely for the increase of the silt concentrations as predicted in the EIA. Therefore the relation between food quality and growth will not be taken into account in this thesis (the grey part of figure 3.1 is neglected).

The relation between the duration of a mismatch and the growth lag of larvae, as well as the uncertainty margin of the growth lag predicted by this relation, are estimated in section 5.3. By use of a population-dynamical model, the impact of this growth lag on the total population of bivalves is modelled. The variables that are used in this model, like the yearly number of births and survival rates, show a large year-to-year variation. For the stochastical variables in the population-dynamical model, probability density functions are determined in chapter 5. By varying these variables randomly, the natural variation of the population size of bivalves will be simulated.

To what extent the number of sea ducks in the Voordelta is dependent on the amount of bivalves is not known. In chapter 6 some relations are defined that will be taken into account in different scenarios for a Monte Carlo analysis. Although the EIA also predicts an impact on sea ducks like common scoters and scaups, chapter 6 will only focus on eiders.

Finally a Monte Carlo analysis will be done to give insight in the probability of occurrence of an impact on eiders and on the uncertainty margin of the predicted ecological effect. For a large number of input variables and parameters of the ecological model (figure 3.1), a probability density function is determined in chapters 4 and 5. From all these probability density functions, a large number of sets of input variables will be generated randomly. For all these sets the impact on eiders is calculated by the model. This large number of modelled impacts will indicate the shape of the probability density function of the impact on eiders of the sand mining for Maasvlakte 2.

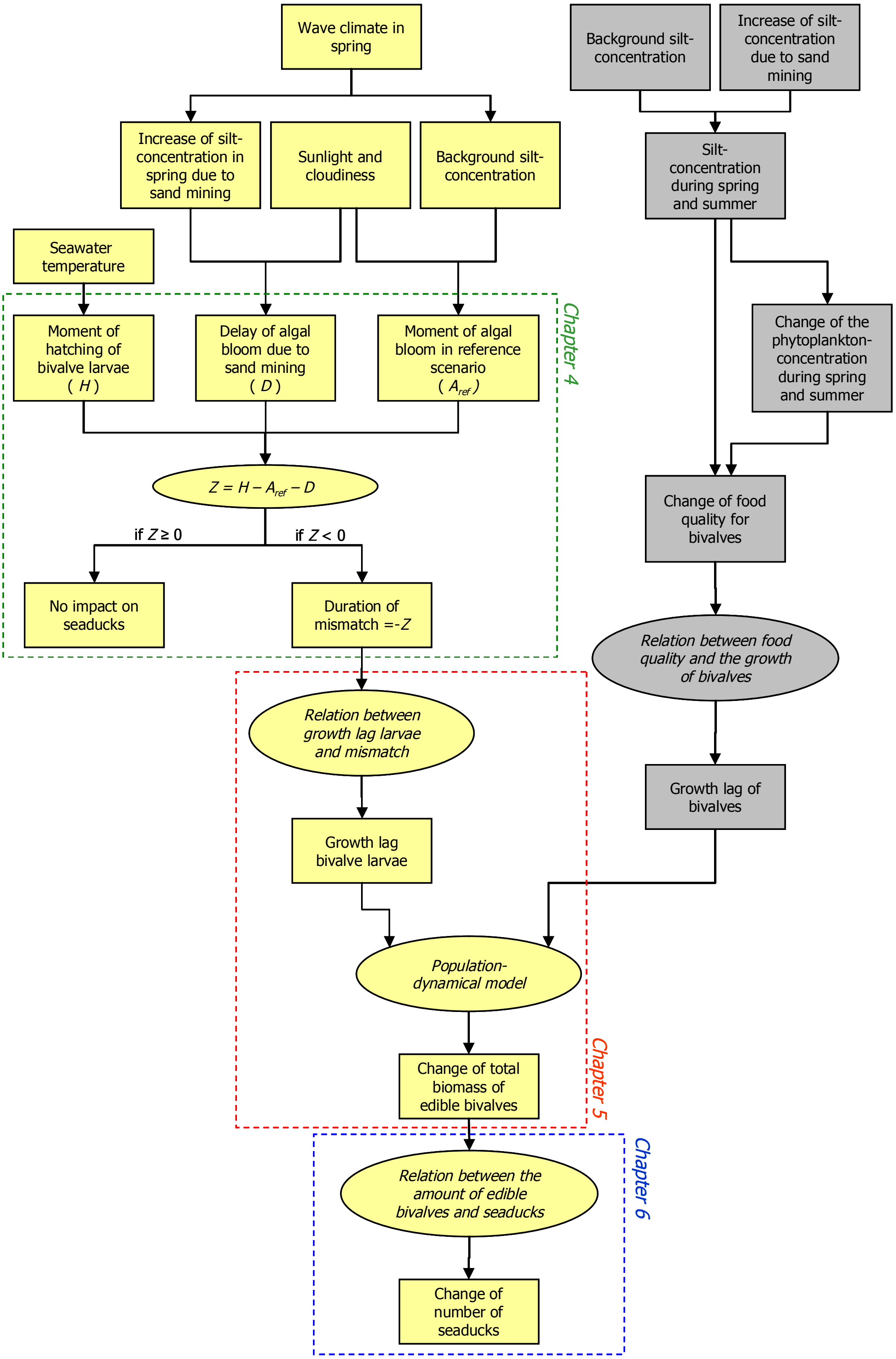

Figure 3.1 Overview of the modelling approach

3.2 Deterministic versus probabilistic approach

The following examples will illustrate the difference between a deterministic and a probabilistic approach. Examples 1 and 2 show how a deterministic approach can lead to an overestimate of an ecological effect. Example 3 illustrates how a deterministic approach can result in an apparent accurate prediction of an impact, while an accurate prediction is in fact not possible due to natural variations.

3.2.1 Example 1: Safe assumptions and uncertainty margins

In this example, a short, simplified impact-effect chain will be used to show some differences between a probabilistic and a deterministic approach. This simplified impact-effect chain is shown in figure 3.2.

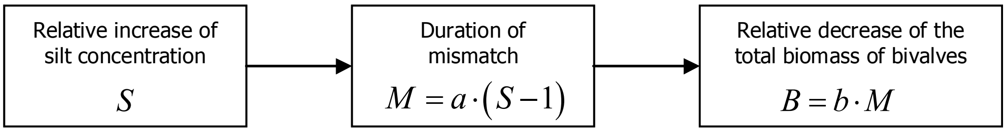

Figure 3.2 Simplified, shortened impact-effect chain

The values of several parameters and variables in the impact-effect chain of the sand mining for Maasvlakte 2, are not exactly known. For example, if an insufficient number of measurements (or no measurements at all) are available, or if the available measurements show a large scatter, it is not easy to decide which value should be used for calculations. In this fictitious example is supposed that the exact values of parameters a and b are not known.

Suppose that a large number of measurements of these parameters are available. A histogram of these fictitious measurements is shown in figure 3.3. In case of a deterministic approach, often a safe value is chosen to use for calculations, preventing that the final result underestimates the impact that will occur in reality. For example in case of parameter a, a value of 24 days might be used. In a probabilistic approach it is possible to take into account the uncertainty margin of a parameter. In case of parameter a, the shape of a probability density function can be estimated on the basis of the histogram (in this case a normal probability density function). The mean value μ and the standard deviation σ can be calculated from the measurements (μ=20 days, σ=4 days).

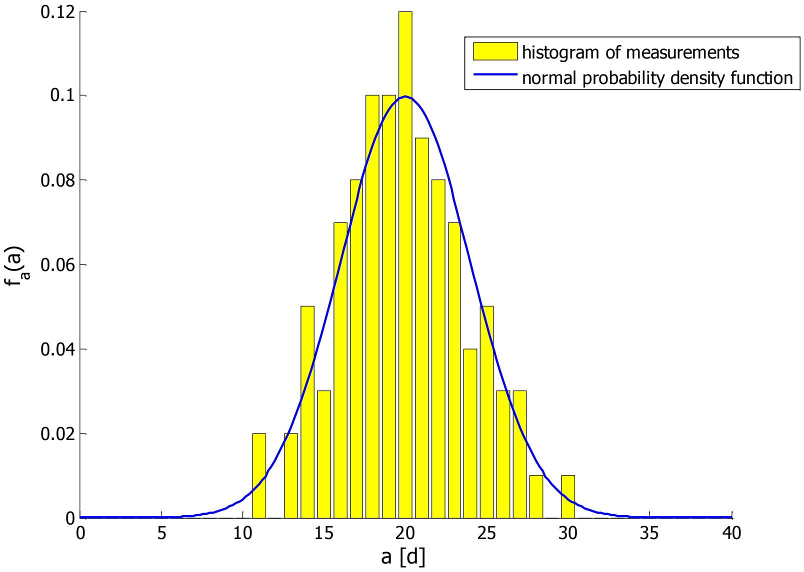

Figure 3.3 Histogram of (fictitious) measurements of parameter *a*, and a normal probability density function (μ=20 days, σ=4 days)

Figure 3.4 shows the normal probability density function and the cumulative distribution function (also called probability distribution function) of parameter *a*. From the cumulative distribution function can be derived that the probability that the value of *a* is smaller than 24 days (as chosen in the deterministic approach) is 0.84.

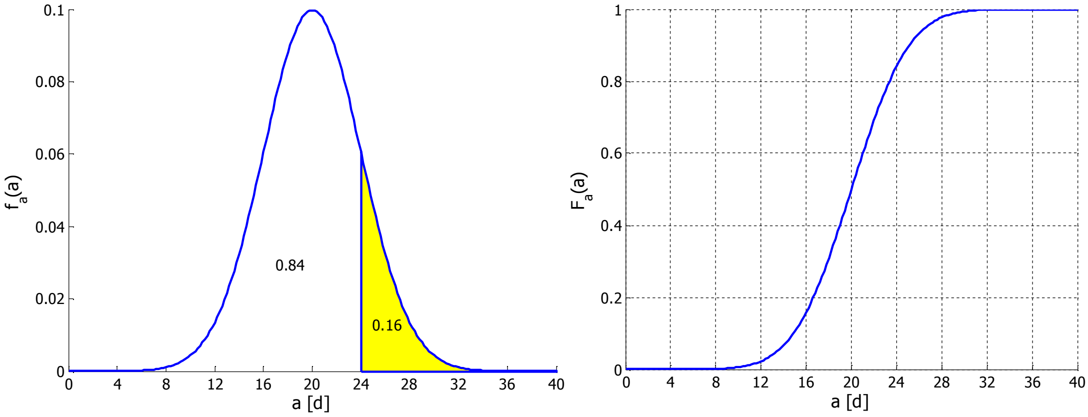

Figure 3.4 Normal probability density function and probability distribution function of parameter *a*

Figure 3.5 shows how the deterministic approach and the probabilistic approach lead to different results. Whereas the deterministic approach predicts a decrease of the total biomass of bivalves by 6%, the probabilistic approach shows that the final result contains a large uncertainty margin. The probabilistic approach results in a probability density function, which shows that the probability that the impact is 6% or larger, is only 0.07.

Appendix B shows some additional examples, in which also the value of input variable *S* is varied.

<table>
<tr><th>(Semi-) Probabilistic</th><th>Deterministic</th></tr>
<tr><td>

$S=1.5$

$a=N(\mu_a,\sigma_a)=N(20,4)$ d

</td><td>

$S=1.5$

$a=24$ d

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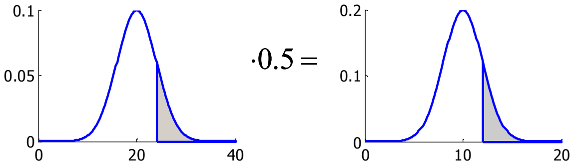
$M=a\cdot(S-1)$:



$\Rightarrow M=N(\mu_M,\sigma_M)=N(10,2)$ d

</td><td>

$M=a\cdot(S-1)=24\cdot 0.5=12$ d

</td></tr>
<tr><td>

$b=N(\mu_b,\sigma_b)=N(0.4,0.1)$ $\%\cdot\mathrm{d}^{-1}$

</td><td>

$b=0.5$ $\%\cdot\mathrm{d}^{-1}$

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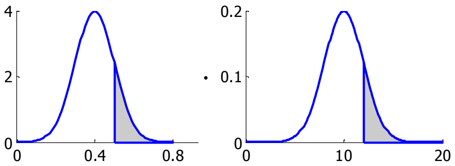
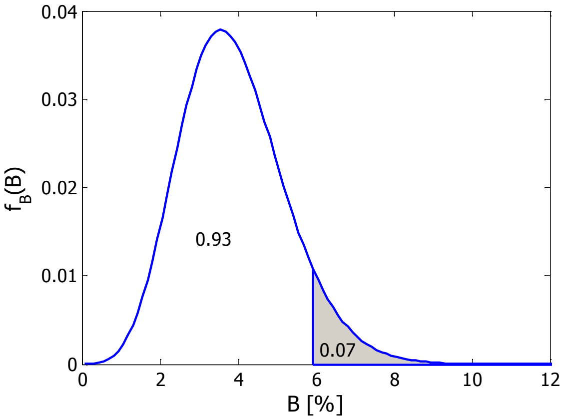
<tr><td>

$B=b\cdot M$:



$\Rightarrow B$:



$$f_B(B)=\int_{-\infty}^{\infty} f_b\left(\frac{M}{B}\right) f_M(M)\frac{1}{|M|}dM$$

</td><td>

$B=b\cdot M=0.5\cdot 12=6$ %

⇨ The deterministic approach leads to the prediction that the biomass of bivalves will decrease by 6%, while the probabilistic approach leads to the conclusion that the probability that B ≥ 6% is only 0.07.

</td></tr>
</table>

Figure 3.5 Difference between a probabilistic and a deterministic approach

3.2.2 Example 2: Probability of occurrence

For the EIA was assumed that a delay of the algal bloom, will always lead to a mismatch between the presence of bivalve larvae and a sufficiently high algal concentration. This mismatch leads to a smaller total biomass of the bivalve population in the Voordelta. Subsequently was assumed that this decrease will always affect the number of eiders that can winter in the Voordelta. In this subsection will be illustrated that these assumptions are worst-case assumptions.

Relation between eiders and bivalves

Figure 3.6 shows the possible relations between the number of wintering eiders in the Voordelta and the total biomass of the bivalve population. In case of a linear relation (as assumed in the EIA, blue line in figure 3.6) a decrease of the bivalve population will always affect the number of eiders. However, the total biomass of bivalves in the Voordelta shows a large annual variation. Possibly the number of eiders is not limited by the availability of food (=bivalves) during years with a large total biomass of bivalves. In this case the relation between eiders and bivalves can be described by the red or green line in figure 3.6. For these relations, it depends on the size of the bivalve population whether or not a decrease affects the number of eiders. For example, within range A (see figure 3.6) a decrease of the bivalve population due to sand mining activities does matter for all possible relations. Within range B, the decrease of the bivalve population will not (or hardly) affect the number of eiders, in case of the red or green relation.

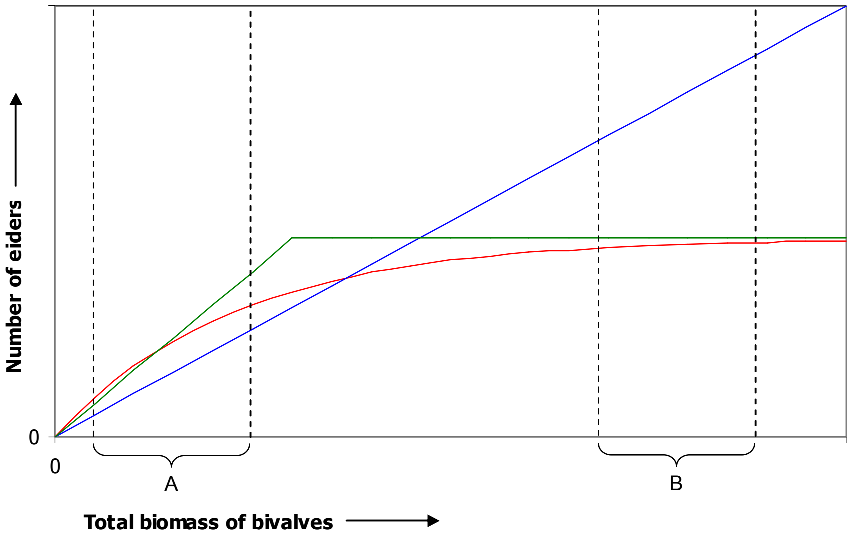


Figure 3.6 Possible shapes of the relation between eiders and bivalves in the Voordelta

The influence on the final result (a probability distribution of the impact on eiders) of using a linear instead of a non-linear relation like the red line of figure 3.6, is shown in section 7.2.2.

Occurrence of a mismatch

The assumption that the delay of the algal bloom always leads to a mismatch, only holds if (in the reference scenario) the hatching of larvae always takes place at the same moment as the algal bloom. However, as the hatching of larvae mostly takes place in May and the algal bloom in April (see chapter 4), the probability of occurrence of a mismatch due to the delay is much smaller than 1. This will be illustrated in this example.

A mismatch occurs when hatching takes place before the critical algal concentration* is reached. This can be schematized as the following limit state function:

$$Z = H - A \qquad (3.1)$$

With: Z = limit state function [d]
H = moment of hatching of the larvae [d]

---

*The minimal algal concentration at which the growth of larvae is not limited by the availability of food

A = moment at which the critical algal concentration is exceeded [d]

The probability of occurrence of a mismatch can be described as:

$$P_m = P(Z < 0) = P(H < A) = \iint_{Z \leq 0} f_{HA}(h,a)dhda \qquad (3.2)$$

With: P_m = probability of occurrence of a mismatch [-]

f_{HA} = joint probability density function of *H* and *A* [-]

Assuming *H* and *A* to be independent, the probability of a mismatch can be described by the following integral:

$$P_m = \int_{a=-\infty}^{a=\infty} \int_{h=-\infty}^{a} f_A(a) \cdot f_H(h)dhda = \int_{a=-\infty}^{a=\infty} f_A(a) \int_{h=-\infty}^{a} f_H(h)dhda \qquad (3.3)$$

With: f_A = probability density function for random values of *A* [-]

a = certain value of *A* [d]

f_H = probability density function for random values of *H* [-]

h = certain value of *H* [d]

The moment at which the critical phytoplankton concentration will be exceeded, can be delayed as a consequence of the sand mining activities. The value of *A*, in case of sand mining, can be schematised as:

$$A_{mining} = A_{ref} + D \qquad (3.4)$$

With: A_{mining} = moment at which the critical algal concentration is exceeded in case of sand mining activities [d]

A_{ref} = moment at which the critical algal concentration is exceeded in case of the reference scenario [d]

D = delay of the moment at which the critical algal concentration is exceeded, caused by the sand mining activities [d]

In this simple example the value of A_{ref} is assumed to be normally distributed with mean value μ_{Aref} and standard deviation σ_{Aref} and the value of D is assumed to be exactly known. In this case the mean value of A_{mining} is:

$$\mu_{A_{mining}} = \mu_{A_{ref}} + D \qquad (3.5)$$

The standard deviation of A_{mining} is:

$$\sigma_{A_{mining}} = \sigma_{A_{ref}} \qquad (3.6)$$

If also *H* is a normally distributed variable, with mean value μ_H and standard deviation σ_H, the mean value and standard deviation of limit state function Z can be written as:

$$\mu_Z = \mu_H - \mu_{A_{mining}} \tag{3.7}$$

$$\sigma_Z = \sqrt{\sigma_H^2 + \sigma_{A_{mining}}^2} \tag{3.8}$$

The reliability index is denoted as:

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{3.9}$$

which leads to a probability of occurrence of a mismatch P_m:

$$P_m = \Phi(-\beta) \tag{3.10}$$

Where:
Φ = the standard normal probability distribution function

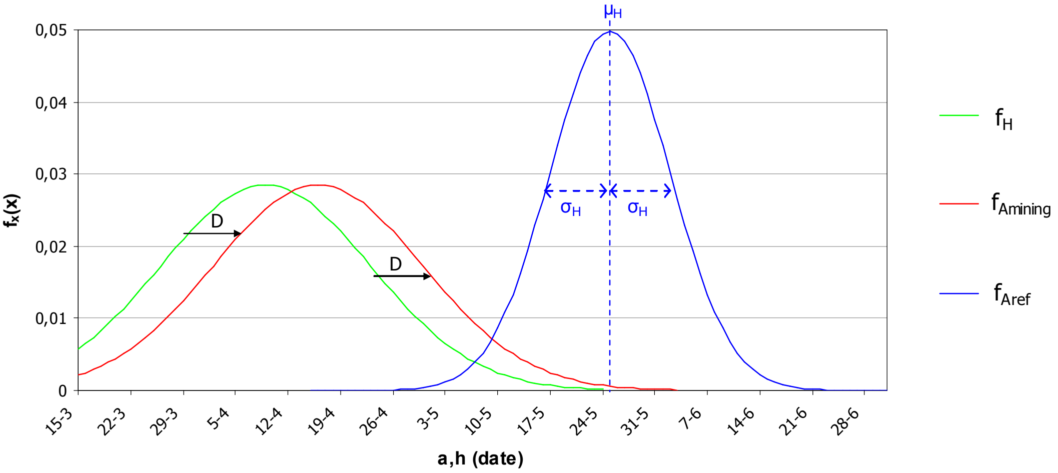


Figure 3.7 Probability density functions of f_H, f_{A_mining} and $f_{A\_reference}$

The probability of occurrence can be calculated by using equations 3.4 till 3.10 and the following realistic input variables (see sections 4.3-4.5):

- μ_{Aref} = April 9th, 100th day of the year;
- σ_{Aref} = 14 days;
- D = 7 days;
- μ_H = May 25nd, 146th day of the year;
- $\sigma_{H,}$ = 8 days.

By using these assumptions, the probability of occurrence of a mismatch is estimated at:

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_H - \mu_{A_{ref}} - D}{\sqrt{\sigma_H^2 + \sigma_{A_{ref}}^2}} = \frac{146 - 100 - 7}{\sqrt{14^2 + 8^2}} = \frac{39}{16} = 2.44$$

$$P_m = \Phi(-\beta) = \Phi(-2.44) = 7 \cdot 10^{-3}$$

In case of the deterministic approach, as applied in the EIA, a delay of the algal bloom always lead to a mismatch between algae and larvae (P_m=1). By applying a probabilistic approach, the probability of occurrence of a mismatch can be taken into account.

The duration of the mismatch (*-Z*) is always equal to the delay of the algal bloom *D* in case of the deterministic approach. In reality, the duration is dependent on the moment of hatching and the moment that the critical algal concentration is exceeded. Because of this, the duration of the mismatch (*-Z*) can be shorter or longer than *D*. In the latter case, there will also be a mismatch in the reference scenario. Next to the probability of occurrence of a mismatch, the variation of the duration of the mismatch (as a result of the variation of the moment of hatching and the moment of exceedance of the critical concentration) can be taken into account in a probabilistic approach.

3.2.3 Example 3: Static versus dynamic nature

If a mismatch occurs between larvae and algae, the growth of these larvae will be hampered. As a mismatch only affects the growth of larvae, only one year class* of bivalves will be affected by the mismatch that occurs in one specific year.

A population consists of several year classes. The total biomass of a year class in a certain year, is dependent on the biomass of this year class in the previous year and on the growth and survival rate (see appendix C for some remarks on this growth model):

$$BM_{i+1}^{j+1} = BM_i^j \cdot G_i \cdot SY^j \qquad (3.11)$$

BM_i^j = total biomass of all individuals of age *i* in year *j* [kg]

G_i = growth factor for individuals of age *i* [-]

SY^j = survival rate in year *j* [-]

Survival rates and also the number of births per year, show a large variation in nature. If constant values are used for these variables to model an ecological impact, nature is in fact assumed to be static. By means of a probabilistic approach, the dynamics of nature can be taken into account.

Suppose that the sand mining results in a growth lag of 30% for the larvae in one certain year, and that bivalves are not able to catch up this growth lag**. In case of a 'static nature' the impact on the amount of food for ducks would be easy to calculate, as the factors (number of births, survival rates) that determine the total biomass of bivalves and the distribution over the several year classes will be constant. However, in reality the total biomass of bivalves in the Voordelta shows a large variation. This variation is mainly caused by the fluctuation of the yearly survival rate and the large variation of the number of births of larvae (recruitment).

Figure 3.8 shows the total fresh weight of bivalves (of a fictitious population) and the distribution over the different year classes in case of a 'static nature'. If the sand mining would cause a mismatch in one year, it would not make a difference if the mismatch occurs in 2009 (impact on year class 'A') or 2010 (impact on year class 'B'). Assuming that cockles are edible by ducks after their second growing season (1 year old in Figure 3.8) and that

---

**the larvae will be 30% smaller than they would have been without the mismatch, during their whole life

* a year class exists of all individuals that are born in the same year

cockles do not get older that 5 years, a mismatch will have an impact on the food for ducks from one till five years after this mismatch. The magnitude of this impact would be the same in case of a mismatch for year class 'A' as for year class 'B', if nature is supposed to be 'static' (see Table 3.1).

Table 3.1 Growth factors and survival rates as used in this example (values based on EIA). Growth factor: weight(i year old) = growth factor * weight(i+1 year old)

Period	Growth factor (-)	Survival rate (-)
0 year old, Sep – 1 year old, Sep	3	0.52
1 year old, Sep – 2 year old, Sep	1.5	0.52
2 year old, Sep – 3 year old, Sep	1.3	0.52
3 year old, Sep – 4 year old, Sep	1.2	0.52
4 year old, Sep – 5 year old, Sep	1.1	0.52

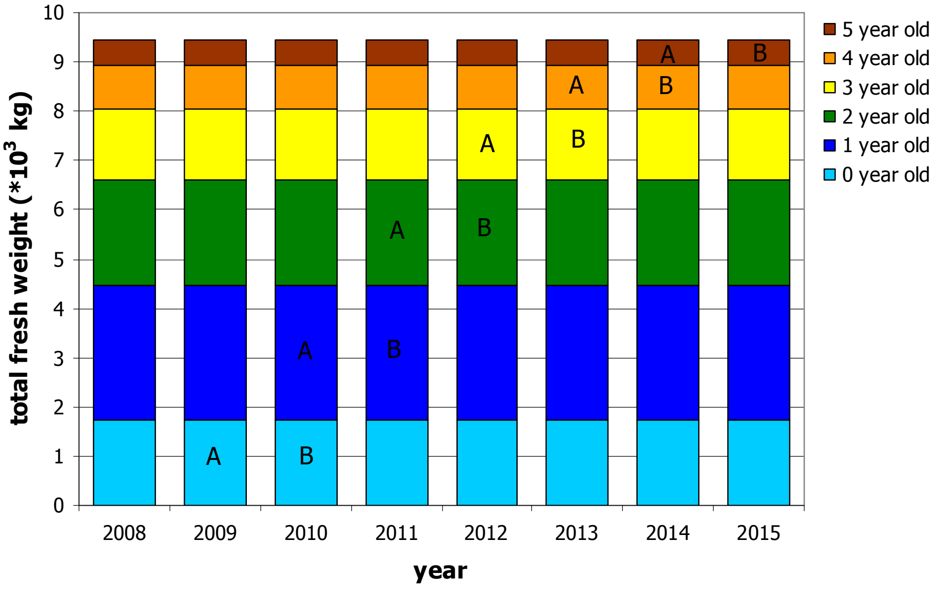


Figure 3.8 Total fresh weight of bivalves in September and the distribution over the year classes, in case of a static nature

Figure 3.9 shows the total fresh weight of cockles if the number of recruits (number of newly born bivalves) is varied. Mortality rates are kept constant in this example. The number of recruits of year class 'A' is much larger than for other year classes. A mismatch for year class 'A' would result in a larger impact on the available food for ducks in the following years, than a mismatch for year class 'B' (see Table 3.3).

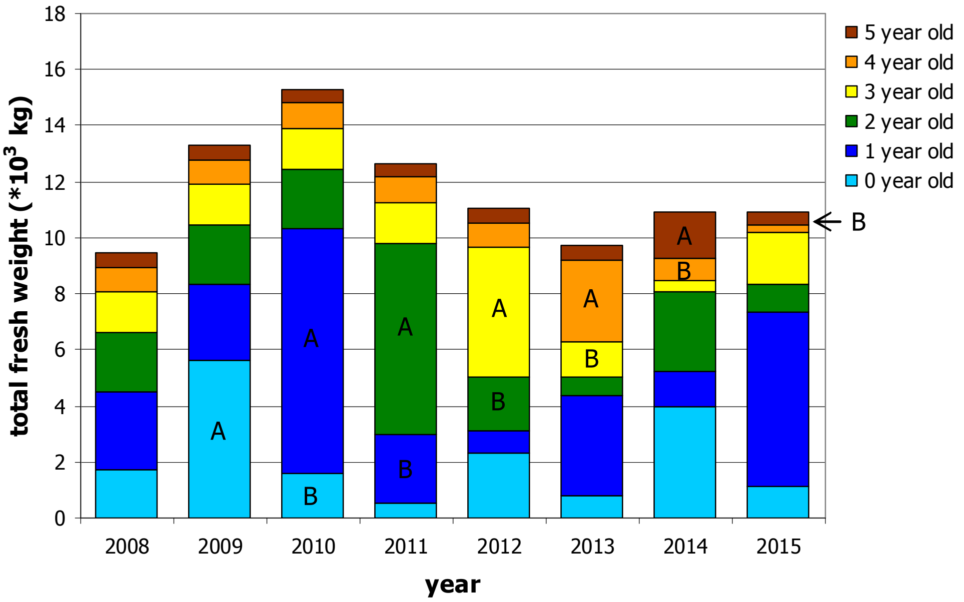


Figure 3.9 **Total fresh weight of bivalves in September and the distribution over the year classes, in case of a (partly) dynamic nature**

Table 3.2 Total fresh weight of 0-year old cockles in September, as used as input in this example

	Total fresh weight, 0-year old cockles, September (kg)							
Year:	2008	2009	2010	2011	2012	2013	2014	2015
Static nature	1750	1750	1750	1750	1750	1750	1750	1750
Dynamic nature	1750	5600	1600	500	2300	800	4000	1100

Table 3.3 Impact on total amount of food for ducks, if the year classes suffer a growth lag of 30%

	Year class that suffers growth lag	**Impact on total biomass of bivalves (all year classes) [-]**					
		Number of years after mismatch:					
		0	1	2	3	4	5
Static nature	A	0	-0.11	-0.08	-0.06	-0.03	-0.02
	B	0	-0.11	-0.08	-0.06	-0.03	-0.02
Dynamic nature	A	0	-0.19	-0.17	-0.16	-0.10	-0.07
	B	0	-0.06	-0.07	-0.04	-0.04	-0.01

In case of a probabilistic approach it is possible to take into account the effect of the natural variation of recruitment and survival rates. In this thesis this will be done by use of a Monte Carlo analysis; for a large number of randomly generated combinations of numbers of recruits and survival rates the impact of the sand mining will be calculated. This can give insight in, among other things, the uncertainty margin of the predicted impact that is caused by the stochasticity of nature.

In a deterministic approach, as applied in the EIA, it is only possible to take into account a 'static nature'. If nature is supposed to be static, an accurate prediction of the impact of a mismatch seems possible. In fact not only a lack of knowledge on the processes in nature, but also the variation of nature itself, makes that a prediction of ecological effects, will always contain a large uncertainty margin.

4 Phytoplankton and bivalve larvae

In the EIA is assumed that sand mining activities have an impact on populations of bivalves, because the sand mining can cause a 'mismatch' between the availability of phytoplankton and the presence of bivalve larvae in the water. As part of the effect-chain modelling, the Delft3D-ECO model (WL | Delft Hydraulics) was used to model the impact of an increased silt concentration on the quantity and timing of phytoplankton in the Voordelta. As explained in section 2.2.1, primary production is dependent on the availability of light and nutrients. Within the Delft3D-ECO model among other things the availability of light, the concentration of nutrients and the phytoplankton concentrations are modelled. An overview of the model formulations that are relevant for this study, is given in section 4.1. In section 4.2 is explained how sand mining activities may influence primary production, according to the model formulations.

The probability of occurrence of a mismatch, as well as the duration of this mismatch, depend on:

- the timing of the algal bloom in the reference scenario;
- the delay of this moment due to the higher silt concentration, which is a result of the sand mining activities;
- the moment of hatching of the bivalve larvae.

The timing of the algal bloom, and thereby also the delay as a result of the increased silt concentration, depend on many factors. In addition to the silt concentration, the weather conditions during spring are highly relevant. Natural variations in spring weather conditions are not or only indirectly taken into account in the Delft3D-ECO model. In section 4.3 is illustrated to what extent the delay, which is predicted by model, depends on the coincidental fluctuations of weather conditions. In section 4.4 the natural variation of the moment of the algal bloom in the reference scenario is determined on the basis of measurements. The moment of hatching of bivalve larvae is estimated in section 4.5. The results of sections 4.3, 4.4 and 4.5 are combined in section 4.6 to estimate the probability of occurrence of a mismatch.

Figure 4.1 shows the part of the modelling approach (see section 3.1) which is elaborated in this chapter.

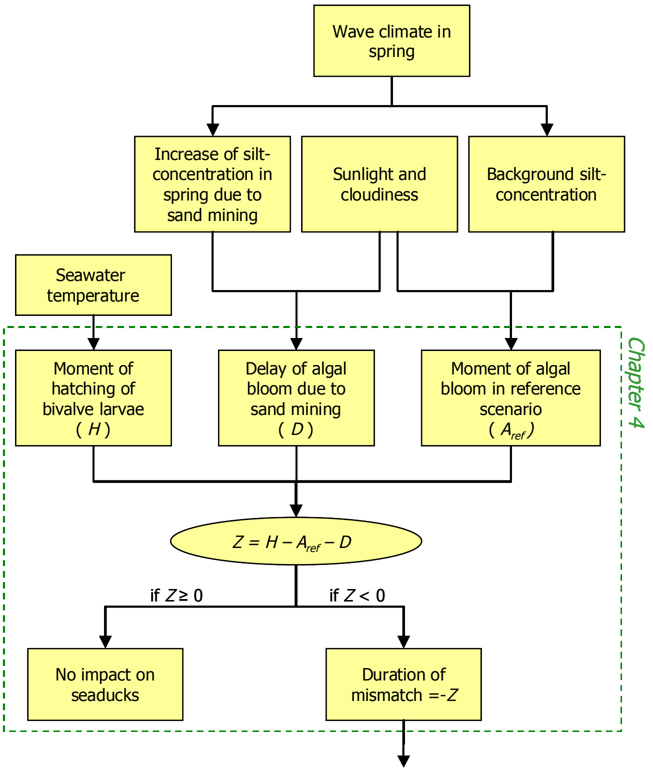


Figure 4.1 **Part of the modelling approach which will be elaborated in this chapter**

4.1 Modelling primary production

For the modelling of phytoplankton concentrations a 2-dimensional model was used. The first subsection gives an overview of the processes that are taken into account within this model. This subsection also explains which processes play an important role within the modelling of ecological effects of sand mining. Subsections 4.1.2 and 4.1.3 summarize the model formulations.

4.1.1 Overview of processes

The EIA assumed that the timing of the algal bloom in spring and the food quality (ratio of suspended edible, organic matter over suspended inedible matter) were important factors for the growth of bivalves. The assumption that a relation between food quality and growth exists, was a worst-case assumption in the EIA. The existence of this relation is unlikely for the expected change of the food quality as a result of the sand mining (see section 5.4). Therefore, this relation is not considered further in this report.

Nutrients and solar energy are necessary for primary production. Before the algal bloom, the availability of light forms the limiting factor. The concentration of nutrients is sufficiently high during spring (not to be limiting for algae growth). Because of this, uncertainties in the modelling of processes concerning the cycle of nutrients (grey in Figure 4.2), will not affect the prediction of the timing of the algal bloom (see also section 4.2.2).

Having excluded food quality and nutrient processes as relevant factors, the next subsections will focus on the processes that determine the delay of the algal bloom that is caused by the sand mining (white in figure 4.2). The influence of settling of phytoplankton is assumed to be negligible during spring.

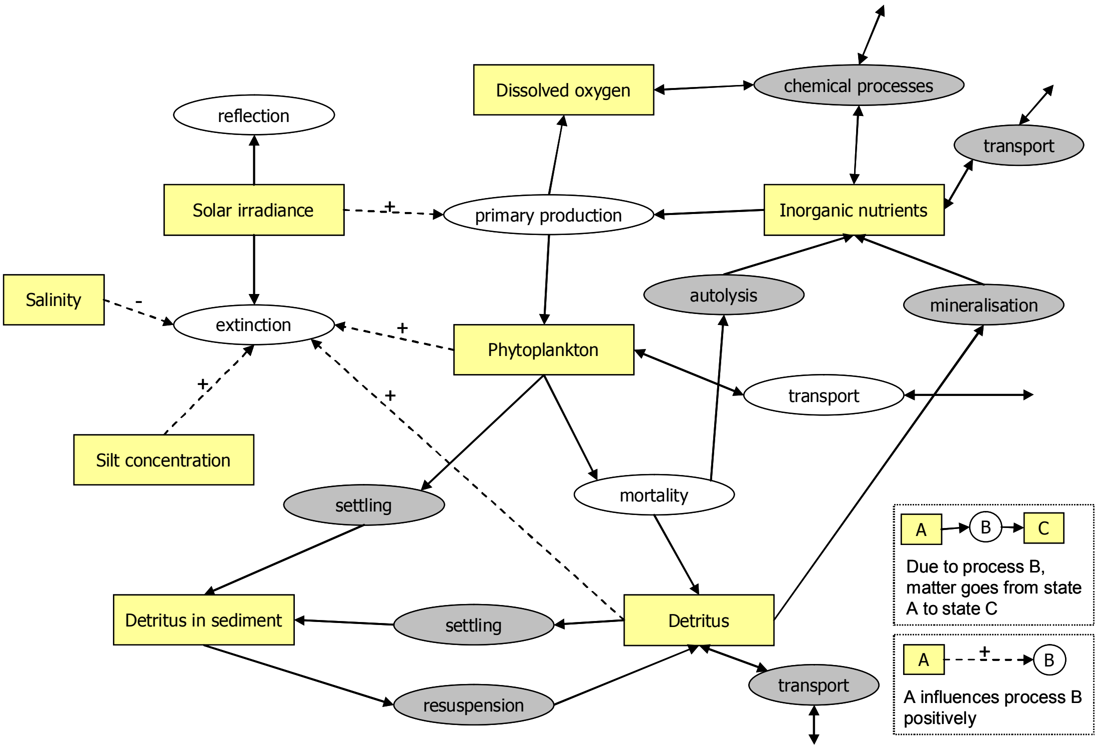


Figure 4.2 Simplified overview of processes that are incorporated in the Delft3D-ECO model

4.1.2 Algae species groups

The module BLOOM, which is part of the Delft3D-ECO model, is used to model phytoplankton concentrations. BLOOM is a multi-species algae model that is based on an optimisation technique that distributes the available nutrients and light among the algae species. The species composition is optimised to obtain the overall maximum growth rate under the given conditions. Within each phytoplankton species group three different types are distinguished. One type is best adapted to light limited conditions, one to nitrogen limited conditions and one to phosphorus limited conditions. During light limited conditions, the type that is adapted to light limited conditions will grow fastest (in the model), during nitrogen limited conditions the type that is adapted to these conditions, etc. [WL | DELFT HYDRAULICS (2006)].

Four species groups of phytoplankton were taken into account in the model for the EIA:

- marine diatoms;
- marine flagellates;
- dinoflagellates;
- *Phaeocystis**.

Within each species the three different types were distinguished. [WL | DELFT HYDRAULICS (2006)]

4.1.3 Model formulations

Growth of phytoplankton concentrations

The increase of the biomass of a certain algae species group is modelled as [derived from WL | DELFT HYDRAULICS (2005)]:

**Phaeocystis* are in fact a genus and not a species group. Diatoms, flagellates and dinoflagellates are in fact phyla or classes, which are ranked higher in the taxonomical order (kingdom – phylum – class – order – family – genus – species).

$$\frac{\partial Calg_i}{\partial t} = \left(kgp_i\left(T\right) \cdot Ef\left(Calg,...,...\right) - krsp_i\left(T\right) - kmrt_i\left(T, Ccl\right)\right) \cdot Calg_i \qquad (4.1)$$

With: $Calg$ = algal concentration [gC.m^{-3}]*
t = time
Ef = light efficiency factor, function of (among other things) $Calg$ [-]
kgp = potential specific growth rate [d^{-1}]
$kmrt$ = specific mortality rate [d^{-1}]
$krsp$ = specific maintenance respiration rate [d^{-1}]
i = index for algae species and type (-)
T = water temperature (°C)
Ccl = chloride concentration (g.m^{-3}).

From equation 4.1 the critical light efficiency factor can be derived [WL | DELFT HYDRAULICS (2005)]:

$$Efc_i = \frac{\left(krsp_i\left(T\right) + kmrt_i\left(T,...\right)\right)}{kgp_i\left(T\right)} \qquad (4.2)$$

with: Efc = critical light efficiency factor (-)

The algal concentration can only increase if: $Ef > Efc_i$, under the assumption that there is no nutrient limitation. If the concentration of nutrients in the water is lower than a certain threshold value, the algal concentration will not increase, despite condition 4.2 is fulfilled.

If the efficiency factor *Ef* is smaller than *Efc*, this does not mean that there is no primary production. However, the rate of primary production is smaller than the mortality and respiration rate. In this case there is no net primary production; the algal concentration does not increase.

Growth, respiration and mortality

The potential growth rate, mortality rate and maintenance respiration rate are all dependent on the seawater temperature [WL | DELFT HYDRAULICS (2005)]:

$$kgp_i = kgp_i^0 \cdot \left(T - ktgp_i\right), \qquad kgp_i \geq 0 \qquad (4.3)$$

$$krsp_i = krsp_i^0 \cdot ktrsp_i^T \qquad (4.4)$$

$$kmrt_i = kmrt_i^0 \cdot ktmrt_i^T \qquad (4.5)$$

with kgp^0 = growth rate per degree centigrade (°C^{-1}.d^{-1})
$ktgp$ = temperature at which kgp^0 is equal to zero (°C)
$krsp^0$ = specific maintenance respiration rate at 0 °C (d^{-1})
$ktrsp$ = temperature coefficient for maintenance respiration (-)
$kmrt^0$ = specific mortality rate at 0 °C (d^{-1})
$ktmrt$ = temperature coefficient for mortality (-)

---

*gram carbon per cubic metre

Algal mortality does not only depend on water temperature, but also on salinity and grazing by consumers. Grazing is not modelled explicitly in the applied Delft3D-ECO model, but is implicitly lumped into the mortality rate*. Salinity driven mortality is described as [WL | DELFT HYDRAULICS (2005)]:

$$kmrt_i^0 = \frac{m2_i - m1_i}{1 + e^{\left(b1_i \cdot \left(Ccl - b2_i\right)\right)}} + m1_i \qquad (4.6)$$

with: $m1$ = rate coefficient 1 of salinity stress function (d^{-1});
$m2$ = rate coefficient 2 of salinity stress function (d^{-1})
$b1$ = coefficient 1 of salinity stress function ($g^{-1}.m^3$);
$b2$ = coefficient 2 of salinity stress function ($g^{-1}.m^3$);

For the marine algae species groups applies:

$$kmrt_i^0 \approx m1_i \qquad (4.7)$$

Ergo, the potential growth rate, respiration rate and mortality rate are only dependent on water temperature in the model. Due to this, also the critical light efficiency factor Efc (equation 4.2) is only dependent on water temperature.

Light efficiency

The light efficiency factor *Ef* is mainly dependent on solar irradiance, the extinction of light in the water column and the water depth. The light intensity in the water column is modelled as [WL | DELFT HYDRAULICS (2005)]:

$$I = \frac{\left(1 - fr\right) \cdot fpa \cdot Itop \cdot \left(1 - e^{-et \cdot Ha}\right)}{et \cdot Ha} \qquad (4.8)$$

with: I = depth average intensity of photosynthetic light ($W.m^{-2}$)
fr = fraction of visible light reflected at the water surface (-)
fpa = fraction of photosynthetically active light in visible light (-)
$Itop$ = visible light intensity at the top of a water compartment ($W.m^{-2}$)
et = total extinction coefficient, dependent on among other things the algal concentration and silt concentration (m^{-1})
Ha = water depth (m)

The derivation of equation 4.8 is shown in figure 4.3. The parameters *fr* and *fpa* are considered constant and are not discussed further in this report.

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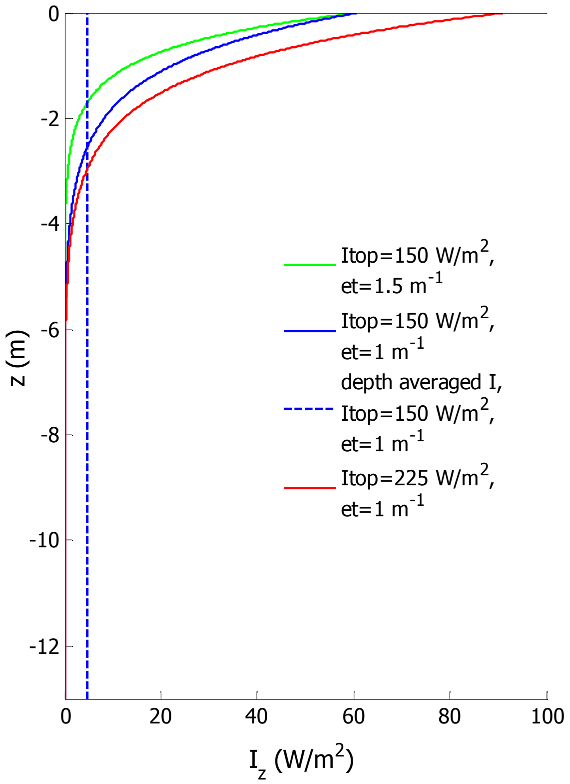
*There are process formulations for grazing included in the Delft3D-ECO model framework, but these were not applied in the model for the EIA.



$$I(z) = I_0 \cdot e^{et \cdot z}$$

Depth averaged light intensity:

$$I = \frac{1}{Ha} \cdot I_0 \cdot \int_{-Ha}^{0} e^{et \cdot z} dz$$

$$= \frac{I_0}{Ha} \left[\frac{1}{et} \cdot e^{et \cdot z} \right]_{-Ha}^{0}$$

$$= \frac{I_0}{et \cdot Ha} \left(1 - e^{-et \cdot Ha} \right)$$

$$I_0 = (1 - fr) \cdot fpa \cdot Itop$$

$$\Rightarrow I = \frac{(1 - fr) \cdot fpa \cdot Itop \cdot \left(1 - e^{-et \cdot Ha} \right)}{et \cdot Ha}$$

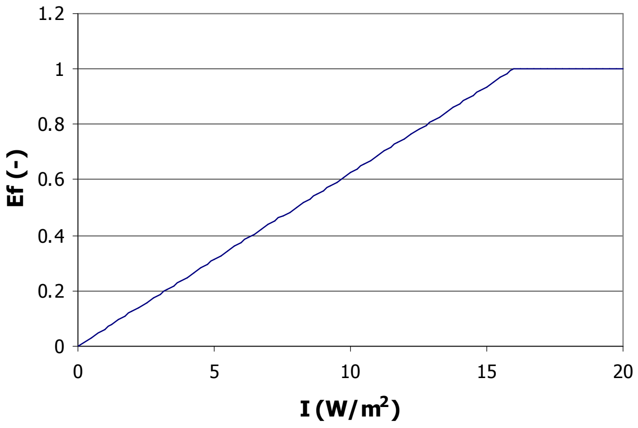
Figure 4.3 Light intensity over the water depth and the derivation of equation 4.8

Assumption underlying the model formulations (for the 2-dimensional model) are:

- algae are uniformly distributed over the water column;
- individual cells circulate through the water column.

These assumptions will not hold in case of large water depths and stratified water columns. In these cases, more algae will be present in the upper part than in the lower part of the water column. However, as water depths are limited in the Voordelta (< 20 m) and the water column is not stratified (at least not during spring, when the algal bloom occurs), using a 2-dimensional model is assumed to be reasonable for modelling primary production in the Voordelta.

Figure 4.4 shows the relation between *I* and *Ef* that was used in the model for the EIA.



$$for\ 0 < I < 16:\ Ef = \frac{1}{16} I$$

$$for\ I \geq 16:\ Ef = 1$$

Figure 4.4 Relation between the light efficiency factor *Ef* and the depth averaged light intensity *I*

Remark on model concept

As the maximal value of the efficiency factor (Ef_{max}=1), is already reached at light intensities of 16 W/m^2, the depth averaged efficiency factor will be smaller than the depth averaged light intensity divided by 16 (intensities in the upper part of the water column can be larger than 16 W/m^2, see figure 4.3):

$$\frac{1}{16}\cdot\frac{1}{Ha}\cdot\int_{-Ha}^{0} I(z)dz \neq \frac{1}{Ha}\cdot\int_{-Ha}^{0} Ef(z)dz \tag{4.9}$$

However, averaging the light intensity over the part of the water column where algae are uniformly distributed forms an important part of the model concept, on which several parameter settings are based. Therefore, the efficiency factor should be derived from the depth averaged light intensity. Using a depth averaged efficiency factor is inconsistent with the modelling concept.

Unless this apparent peculiarity in the model concept will be assumed that the results of the model are reasonable. This chapter will focus on the influence of unpredictable, short-term fluctuations on the predicted delay of the algal bloom by the model. Evaluating the model concept itself falls out of the scope of this thesis.

Extinction coefficient

The light intensity in a water column is dependent on solar radiation, cloudiness, reflection at the water surface, the water depth and the extinction coefficient. All light absorbing substances in the water column contribute to the extinction coefficient. Light absorbing substances are for example: algae, suspended and dissolved organic matter (detritus), suspended inorganic matter and water itself.

In the model, the total extinction coefficient is calculated as the sum of five contributions [WL | DELFT HYDRAULICS (2005)]:

$$et = eat + edt + est + eot + eb \tag{4.10}$$

with: eat = overall extinction coefficient of algae biomass (m^{-1})
edt = overall extinction coefficient of detritus (m^{-1})
est = overall extinction coefficient of suspended inorganic matter (m^{-1})
eot = overall extinction coefficient of other substances as a function of salinity (m^{-1})
eb = background extinction coefficient (m^{-1})

The background extinction coefficient is an input parameter. The other contributions are determined according to [WL | DELFT HYDRAULICS (2005)]:

$$eat = \sum_{i=1}^{n}(ea_i \cdot Calg_i) \tag{4.11}$$

$$edt = \sum_{j=1}^{m}(ed_j \cdot Cdet_j) \tag{4.12}$$

$$est = \sum_{k=1}^{2} (es_k \cdot Cim_k) \tag{4.13}$$

$$eot = eo \cdot \left(1 - \frac{SAL}{SALmax}\right) \tag{4.14}$$

with: ea_i = specific extinction coefficient of an algae species type i [$m^2.gC^{-1}$]

$Calg_i$ = biomass concentration of algae species group i [$gC.m^{-3}$]

ed_j = specific extinction coefficient of a detritus component j [$m^2.gC^{-1}$]

$Cdet_j$ = concentration of detritus component j [$gC.m^{-3}$]

es_k = specific extinction coefficient of a suspended inorganic matter fraction k [$m^2.gDM^{-1}$]

Cim_k = concentration of suspended inorganic matter fraction k [$gDM.m^{-3}$]

eo = extinction coefficient of other substances on the basis of relative salinity [m^{-1}]

SAL = actual salinity [$g.kg^{-1}$]

$SALmax$ = maximal salinity (salinity value for *eot*=0) [$g.kg^{-1}$]

n = number of algae species [-]

m = number of detritus components [-]

Two different suspended inorganic matter fractions were used in the model: the background silt concentration and the silt concentration that is caused by the sand mining activities. The silt concentrations that are used as input for the Delft3D-ECO model, are the silt concentrations in the upper part of the water column, averaged over a period of 7 days (moving average). These averaged concentrations are used, as algae are assumed not to be able to react quickly on short-term (daily) fluctuations of silt concentrations.

4.2 Limiting conditions

Light as well as nutrients (nitrogen, phosphorus and, for certain species, silicon) are necessary for primary production. Generally, the availability of light is the limiting factor during winter and spring. The availability of nutrients mostly becomes limiting when already a relatively high phytoplankton concentration has been reached. In this section is explained how sand mining activities may influence primary production, due to an increase of silt or nutrient concentrations.

4.2.1 Influence of sand mining in case of light limited conditions

The quantity of solar light that is available for primary production depends on the solar irradiance, cloudiness, reflection, the water depth and the total extinction coefficient. This total extinction coefficient is partly dependent on the concentration of suspended inorganic matter (like silt) in the water column (see equation 4.10). The influence of an increase of the concentration of suspended inorganic matter on primary production is illustrated in this subsection. In the figures in this subsection, the different components of the total extinction coefficient are drawn in realistic proportions (however, keep in mind that the extinction due to SPM shows large fluctuations in reality, see figure 4.13).

Solar irradiance is low during winter. Because of this, primary production is completely light limited during winter (*Ef* < *Efc*). An increase of the silt concentration during winter, as a result of sand mining activities, does not have any influence on primary production. Also in the reference scenario no light is available for primary production. This is illustrated by Figure 4.5. The total light available is indicated by an arrow at the left-hand side of the figure.

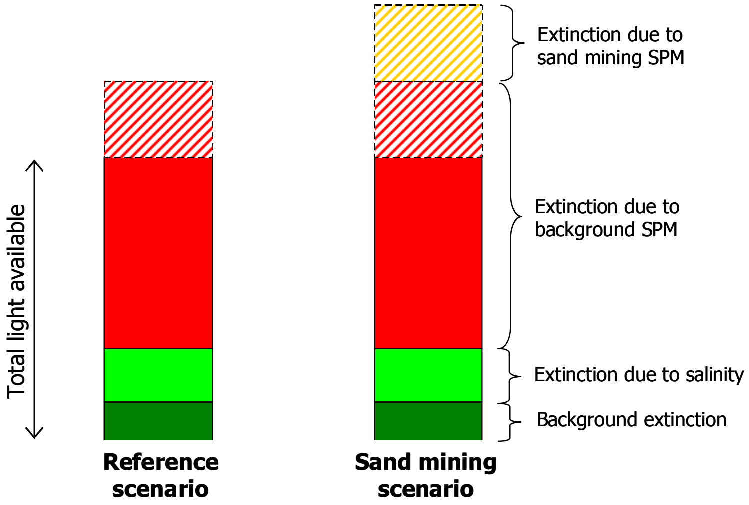


Figure 4.5 Light limited conditions during winter

During spring solar irradiance increases and due to less stormy weather conditions the SPM-concentrations decrease. Because of this, the light intensity in the water column will be sufficient for net primary production at a certain moment. In this case an increase of the silt concentration can make a difference between a sand mining scenario and the reference scenario. This is illustrated in Figure 4.6. In the reference scenario the light efficiency factor will earlier exceed the critical light efficiency factor ($Ef_{ref} > Efc$), than in the sand mining scenario ($Ef_{sand\ mining} < Efc$).

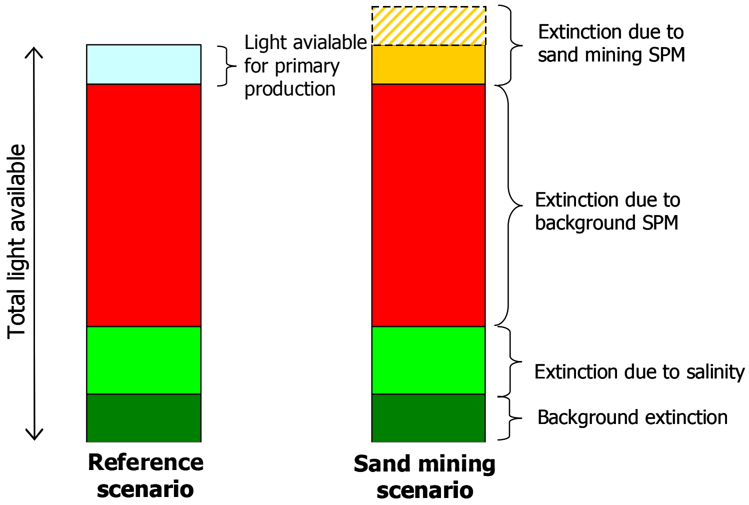


Figure 4.6 Light limited conditions during early spring

At a certain moment also in the sand mining scenario the critical light efficiency factor will be exceeded ($Ef > Efc$). Still, the light efficiency factor will be smaller in the sand mining scenario than in the reference scenario ($Ef_{reference} > Ef_{sand\ mining}$, $Ef_{reference} < 1$ and $Ef_{sand\ mining} < 1$), as more solar energy is available in the reference scenario. A smaller efficiency factor leads to a slower increase of the phytoplankton concentration (see equation 4.1).

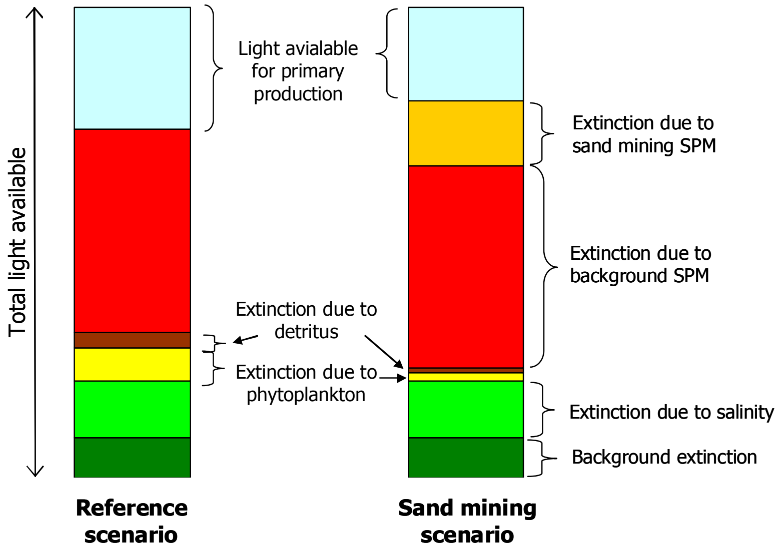


Figure 4.7 Light limited conditions during spring ($Ef_{reference} > Ef_{sand\ mining}$)

Primary production can go on until nutrients become limiting or until 'self-shading' occurs. In the latter case the total extinction coefficient has increased so far, due to the increased phytoplankton concentration, that the available light intensity becomes limiting again (see Figure 4.8).

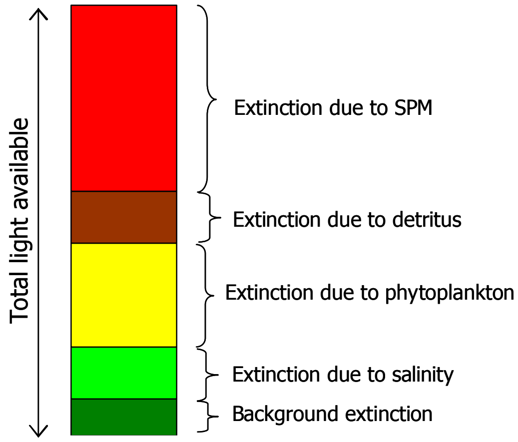
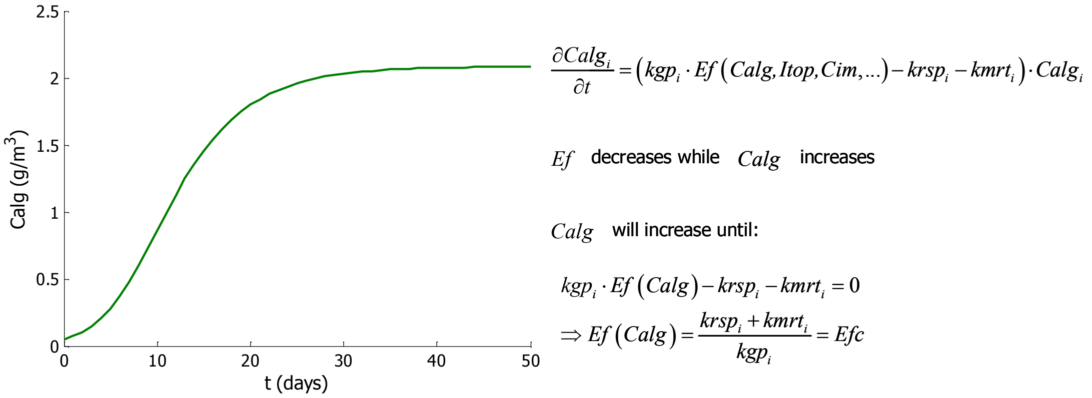


Figure 4.8 Light limited conditions during summer ($Ef \leq Efc$)

Figure 4.9 illustrates how the increase of the algal concentration will stop due to self-shading. The increase of *Calg* is shown for a constant solar irradiance (*Itop*) and a constant silt concentration (*Cim*).



$$\frac{\partial Calg_i}{\partial t} = \left(kgp_i \cdot Ef\left(Calg, Itop, Cim, \ldots\right) - krsp_i - kmrt_i\right) \cdot Calg_i$$

Ef decreases while $Calg$ increases

$Calg$ will increase until:

$$kgp_i \cdot Ef\left(Calg\right) - krsp_i - kmrt_i = 0$$

$$\Rightarrow Ef\left(Calg\right) = \frac{krsp_i + kmrt_i}{kgp_i} = Efc$$

Figure 4.9 Increase of the algal concentration until self-shading occurs

4.2.2 Influence of sand mining in case of nutrient limited conditions

If primary production is limited due to a low concentration of nutrients, an increase of the silt concentration does not influence the growth of algae. The light intensity is sufficient for the algae to grow until (nearly) no nutrients are left in the water column.

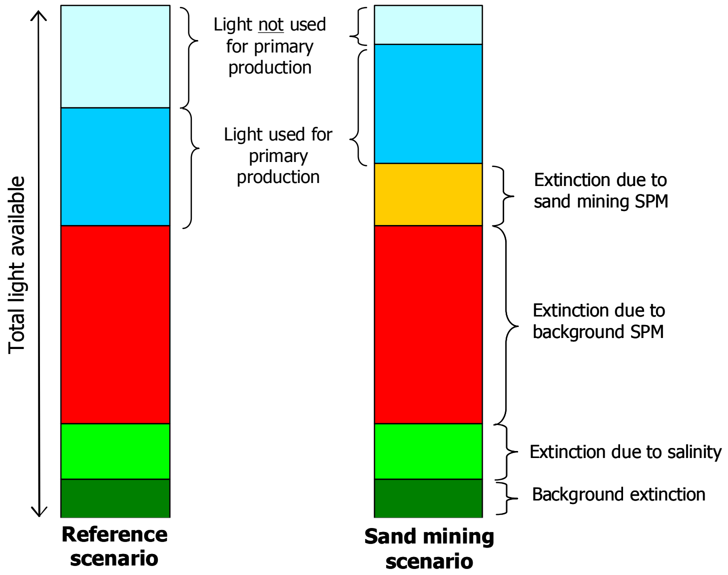


Figure 4.10 Nutrient limited conditions. Higher SPM-concentrations do not result in lower primary production [Desmit *et al.* (2007)].

Before the algal bloom, sufficient nutrients are available in the coastal zone. During the algal bloom, the nutrient concentration will decrease, while the phytoplankton concentration increases (the nutrients are used for primary production). The increase of the phytoplankton concentration will go on until either self-shading occurs, or the availability of nutrients becomes limiting. In this way the maximal phytoplankton concentration that will be reached during the bloom, is limited by the availability of light or nutrients.

If the maximal algal concentration during the algal bloom is limited by the availability of nutrients, sand mining activities may result in a higher maximal concentration, due to a release of nutrients. A positive effect of this higher maximal concentration is not expected, as the quantity of phytoplankton (after the bloom) is not a limiting factor for the growth of bivalves in the Voordelta (see section 2.2). The bivalves will not grow faster due to an increased phytoplankton concentration. Also no negative effects are expected; only in case of an extreme increase of nutrient concentrations and stagnant water, eutrophication (lack of oxygen in the water due to an excessive growth of algae) can take place. A strong increase of nutrient concentrations due to sand mining activities, as well as stagnant water, are very unlikely in the coastal zone.

As conditions are light limited before the algal bloom in the coastal zone, the possible release of nutrients in case of sand mining will not influence the timing of the algal bloom in the Voordelta.

4.3 Delay of the algal bloom

From the previous section can be concluded that the algal concentration, at which bivalve larvae can grow maximally, will be reached later in the sand mining scenario than in the reference scenario, because of to two mechanisms:

- net primary production starts later in case of a higher silt concentration (*Ef* exceeds *Efc* at a later moment);
- the increase of the algal concentration will be slower in case of a higher silt concentration ($Ef_{\text{sand mining}} < Ef_{\text{reference}}$, in case of equal weather conditions).

In this section a probability density function for the delay of the algal bloom (*D*) will be derived. This will be done on the basis of the model formulations as presented in section 4.1.

In subsection 4.3.1 is derived which variables are important for the delay of the moment at which net primary production starts (D_{start}, see figure 4.11). The influence of weather conditions on D_{start} is illustrated in subsection 4.3.2. In subsection 4.3.3 the probability density function for D_{start} is derived. The relevant variables for the growth of phytoplankton are determined in subsection 4.3.4. The probability density function of D_{start} and the natural variations of the relevant variables as determined in 4.3.4 are combined in 4.3.5 to derive the probability density function of *D*.

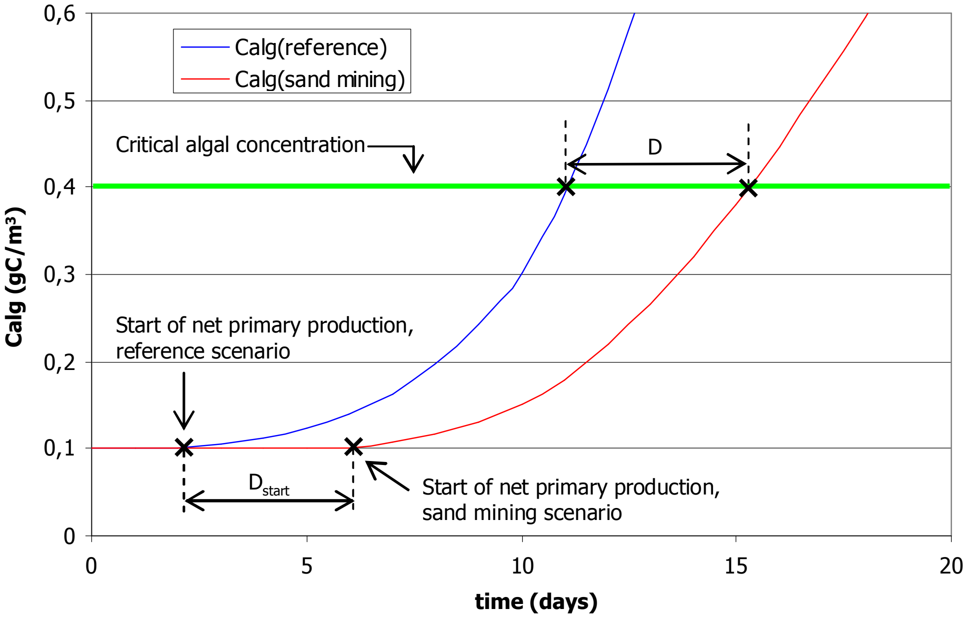


Figure 4.11 Illustration of D_{start} and D *

*Critical algal concentration = concentration at which sufficient food is available for larvae (the larvae will not be subject to a growth lag if the algal concentration is higher than the critical concentration)

4.3.1 Relevant parameters for D_{start}

Net primary production starts when the light efficiency factor *Ef* exceeds the critical light efficiency factor *Efc*. *Ef* is dependent on the variables extinction (*et*), the light intensity at the water surface (*Itop*) and the water depth (*Ha*). The extinction coefficient is a function of, among other things, the algal concentration and the silt concentration (see equation 4.10).

$$\begin{aligned} Ef &\approx \frac{1}{16} I = \frac{1}{16} \cdot \frac{\left(1-fr\right)\cdot fpa \cdot Itop \cdot \left(1-e^{-et\left(Cim,Calg,...\right)\cdot Ha}\right)}{et\left(Cim,Calg,...\right)\cdot Ha} \\ &= \frac{\left(1-0.1\right)\cdot 0.45}{16} \cdot \frac{Itop \cdot \left(1-e^{-et\left(Cim,Calg,...\right)\cdot Ha}\right)}{et\left(Cim,Calg,...\right)\cdot Ha} \end{aligned} \tag{4.15}$$

Efc is dependent on the potential growth rate, mortality rate and respiration rate, which are different for all algal species. The growth, mortality and respiration rates for marine algal species are solely dependent on temperature.

$$Efc_i\left(T\right) = \frac{krsp_i(T) + kmrt_i(T)}{kgp_i(T)} = \frac{krsp_i^0 \cdot ktrsp_i^T + kmrt_i^0 \cdot ktmrt_i^T}{kgp_i^0 \cdot \left(T - ktgp_i\right)} \tag{4.16}$$

Net primary production starts when the following condition is fulfilled:

$$Ef = \frac{1}{16} \cdot \frac{\left(1-fr\right)\cdot fpa \cdot Itop \cdot \left(1-e^{-et\left(Cim,Calg,...\right)\cdot Ha}\right)}{et\left(Cim,Calg,...\right)\cdot Ha} \geq Efc\left(T\right) \tag{4.17}$$

Equation 4.17 can be simplified for large water depths and large extinction coefficients, because:

$$\lim_{et\cdot Ha\to\infty} 1-e^{-et\cdot Ha} = 1$$

$$\Rightarrow Ef = \frac{1}{16} \cdot \frac{\left(1-fr\right)\cdot fpa \cdot Itop}{et \cdot Ha} \geq Efc\left(T\right) \tag{4.18}$$ *

Figure 4.12 illustrates that simplifying equation 4.17 to equation 4.18 is allowed for a large range of combinations of extinction coefficients and water depths. For example, in case of a water depth of 10 m, the relation is more or less linear for extinction coefficients larger than 0.5 m^{-1}.

Figure 4.12 shows which light intensity *Itop* (light intensity at the water surface) is necessary to exceed a light efficiency factor of 0.25, given a certain value of *et* and *Ha*:

*because of readability of formulas, the input variables between brackets are not consequently written in the equations

$$
\begin{aligned}
&Ef = 0.25 = \frac{1}{16} \cdot \frac{(1-fr) \cdot fpa \cdot Itop \cdot \left(1-e^{-et \cdot Ha}\right)}{et \cdot Ha} \\
&\Rightarrow Itop_{Ef=0.25} = 0.25 \cdot 16 \cdot \frac{et \cdot Ha}{(1-fr) \cdot fpa \cdot \left(1-e^{-et \cdot Ha}\right)} \\
&for\ large\ (et \cdot Ha): \\
&1-e^{-et \cdot Ha} \approx 1 \\
&\Rightarrow Itop_{Ef=0.25} \approx \frac{0.25 \cdot 16}{(1-fr) \cdot fpa} \cdot et \cdot Ha
\end{aligned}
\tag{4.19}
$$

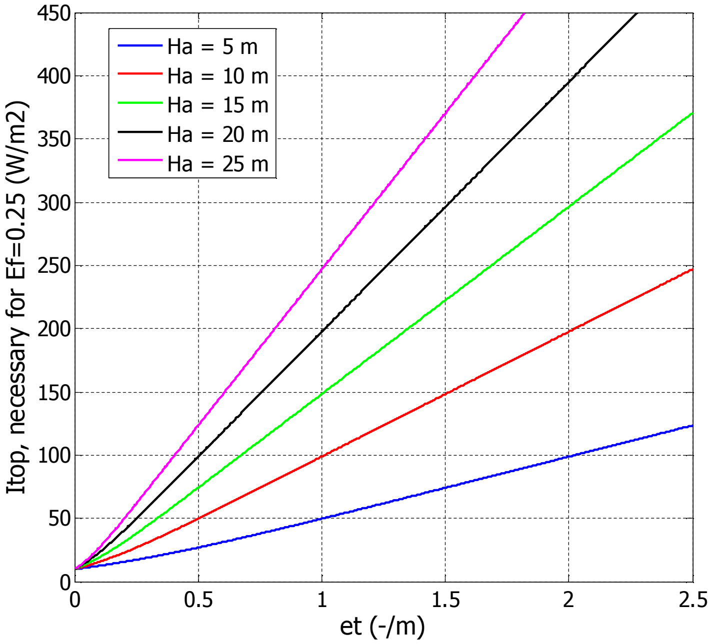


Figure 4.12 Combinations of the total extinction coefficient *et* and the light intensity at the water surface *Itop* for which the light efficiency factor *Ef*=0.25

Extinction coefficient

From all variables in equation 4.17 (the condition for the start of net primary production) only the extinction coefficient *et* is influenced by the sand mining activities. Figure 4.13 shows the modelled extinction coefficient for location 'Goeree 6 km' (GR6, see appendix J), for sand mining scenario 1a during the third year after the start of the sand mining activities [model results WL | Delft Hydraulics].

Before the start of primary production, the concentrations of phytoplankton and detritus are very small. Therefore, the extinction by phytoplankton and detritus is negligible before the algal bloom. Because of this, the formula for the extinction coefficient for can be simplified as follows for conditions before the algal bloom:

$$
\begin{aligned}
et &= eat + edt + est + eot + eb \approx est + eot + eb \\
&= es_{IM1} \cdot IM1 + es_{IM2} \cdot IM2 + eot + eb
\end{aligned}
\tag{4.20}
$$

With: $IM1$ = concentration of background silt [g m^{-3}]
$IM2$ = concentration of sand mining silt [g m^{-3}]
et = total extinction coefficient (m^{-1})

eat = overall extinction coefficient of algae biomass (m-1)
edt = overall extinction coefficient of detritus (m-1)
est = overall extinction coefficient of suspended inorganic matter (m-1)
es_k = specific extinction coefficient of a suspended inorganic matter fraction k [m^2.gDM^{-1}]
eot = overall extinction coefficient of other substances as a function of salinity (m-1)
eb = background extinction coefficient (m^{-1})

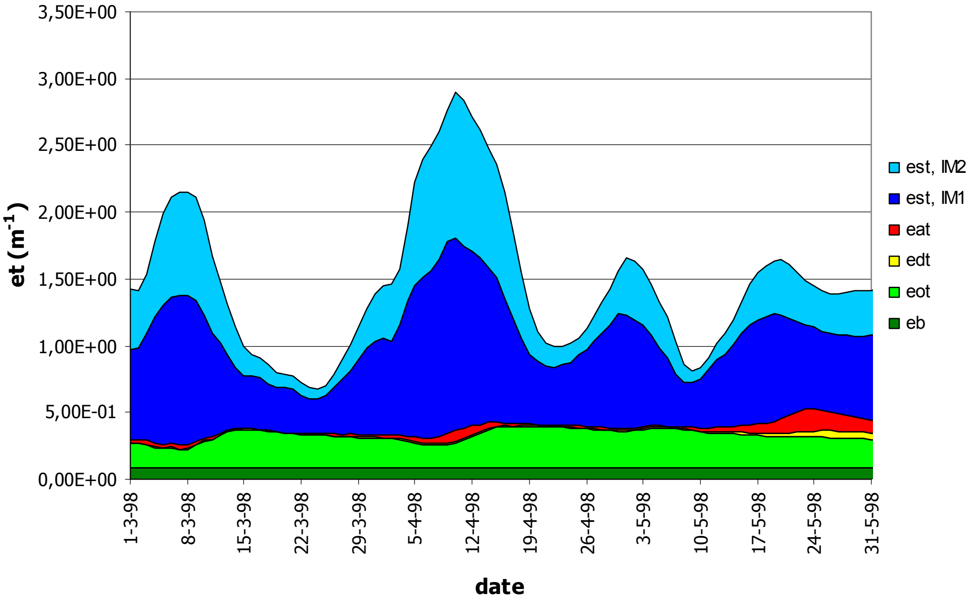


Figure 4.13 Extinction coefficient *et* for location GR6, scenario 1a, 3rd year after start sand mining [model results WL | Delft Hydraulics]

The total extinction coefficient *et* shows large fluctuations during spring. These fluctuations are mainly caused by the variation of the silt concentrations. Extinction coefficient *eb* is constant and *eot* is more or less constant. The fluctuations of the weekly averaged silt concentrations are mainly caused by varying wave conditions. During stormy conditions, the silt that is buffered in the seabed, will be remobilised and suspended. During calmer weather, these silt particles will be deposited or entrained into the seabed again (see model formulations of the far field (silt) model in appendix A).

Due to the sand mining activities the total amount of silt in the water column and the seabed below will increase by a certain amount. Assuming that the silt released during the sand extraction, has the same characteristics (grain size distribution, settling velocity, extinction coefficient etc.) as the background silt, the ratio between the concentrations of sand mining and background silt will be constant during short-term fluctuations of the total silt concentration*. Of course, in the long term this ratio will decrease, as the spatial differences in silt concentrations that are caused by the sand mining, will be flattened out (due to net transport of silt out of the area that is influenced by the sand mining). However, this long-term decline will be negligible during short periods (order of magnitude 1-3 months).

Assuming that the sand mining silt and the background have the same characteristics, the total extinction coefficient can be schematized as follows:

Reference scenario: $et = es_{IM1} \cdot IM1 + eb + eot$

Sand mining scenario: $et = es_{IM1} \cdot IM1 + es_{IM1} \cdot IM2 + eb + eot$

Assumptions: $es_{IM1} = es_{IM2}$

$$fs = \frac{IM1 + IM2}{IM1} = constant \qquad (4.21)$$

et in the reference scenario: $\Rightarrow et = es \cdot IM1 + eb + eot$ (4.22)

et in the sand mining scenario: $\Rightarrow et = es \cdot fs \cdot IM1 + eb + eot$ (4.23)

In this way the short-term fluctuations of *et* for the sand mining scenario, as well as the reference scenario, can be related to the fluctuations of *IM1*. The influence of the sand mining activities on the total silt concentration is now represented in the factor *fs*, which is more or less constant during a relatively short period.

Using equations 4.22 and 4.23 in condition 4.18 (condition for the start of net primary production) leads to:

$$Ef_{reference} = \frac{(1 - fr) \cdot fpa}{16} \cdot \frac{Itop}{(es \cdot IM1 + eb + eot) \cdot Ha} \geq Efc(T) \qquad (4.24)$$

$$Ef_{sandmining} = \frac{(1 - fr) \cdot fpa}{16} \cdot \frac{Itop}{(es \cdot fs \cdot IM1 + eb + eot) \cdot Ha} \geq Efc(T) \qquad (4.25)$$

Next to the silt concentration in conditions 4.24 and 4.25, the light intensity *Itop* shows large fluctuations during spring (see for example figure 4.17). The critical efficiency factor *Efc* however, is more or less constant during spring. This will be illustrated in the following.

Critical efficiency factor and temperature

Efc is dependent on the potential growth rate, mortality rate and respiration rate, which are different for all algal species. The growth, mortality and respiration rates for marine algal species are solely dependent on temperature (see equations 4.3-4.7). Figure 4.14 shows the relation between *Efc* and the seawater temperature for four different types of algae. As conditions are light-limited before the algal bloom, the types that are adapted to light limited conditions are used in Figure 4.14 (see section 4.1.2).

*In figure 4.13 the ratio between the extinction by sand mining and background silt does not seem to be constant, especially when the total silt concentration is decreasing. This is possibly a result of the separate modelling of the background and sand mining silt (see also appendix A). The sum of these separately modelled concentrations was used as input for the Delft3D-ECO model.

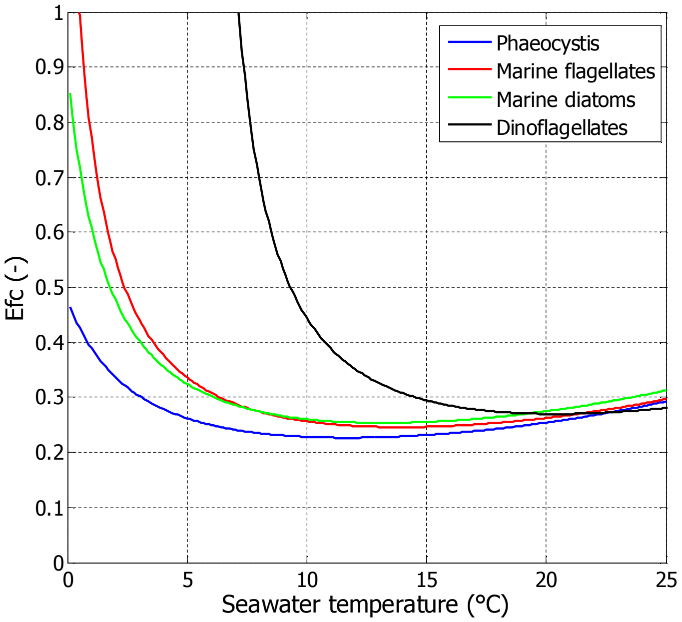


Figure 4.14 Relation between seawater temperature and the critical light efficiency factor *Efc*

During April and May, the seawater temperature increases from circa 7 to 15 °C [derived from daily measurements of seawater temperatures at Hoek van Holland (1970-1995) and Vlissingen (1970-1991), www.waterbase.nl,]. The variation of *Efc* within this range of temperatures is very small for *Phaeocystis*, marine flagellates and marine diatoms. Figure 4.15 shows the variation of *Ef* during spring, which is obviously much larger than the variation of *Efc*. Because of this, the influence of the variation of *Efc* on D_{start} can be neglected. The fluctuations of *Ef* in Figure 4.15 are mainly the result of fluctuations of the silt concentration and the solar irradiance (*Itop*).

As the critical light efficiency factor *Efc* is lower for *Phaeocystis* than for other species groups, net primary production of *Phaeocystis* will start first. As the total phytoplankton concentration during spring consists for a large part of *Phaeocystis*, diatoms and marine flagellates, exceeding the *Efc* for dinoflagellates is not necessary for inducing the algal bloom.

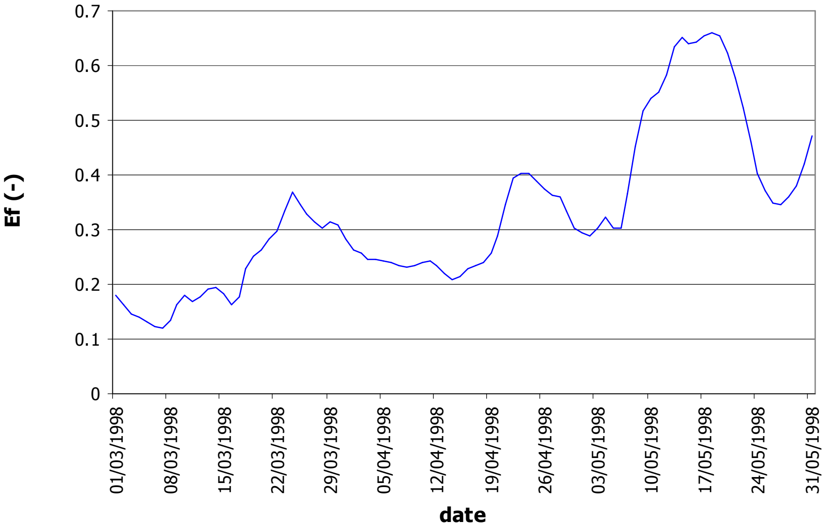


Figure 4.15 Variation of the light efficiency factor *Ef* during spring in modelling area 'Voordelta', as a result of fluctuations of *et* and *Itop* [calculated from model results of WL | Delft Hydraulics]

Conclusion

From all variables in equations 4.24 and 4.25, only *Itop* (the light intensity at the water surface) and *IM1* (background silt concentration) show large fluctuations during spring. The remaining variables are more or less constant. From this can be derived, that the moment at which net primary production starts (at a location with a certain depth *Ha*) is mainly determined by these variables. The combination of *Itop* and *IM1* that occurs at a certain day, determines whether or not net primary production can start.

Figure 4.16 shows for which combinations of *IM1* and *Itop* primary production can take place in the reference scenario (all combinations above the red line) and in the sand mining scenario (all combinations above the blue line). Figure 4.16 shows these combinations for a depth *Ha* of 13.3 m and *Efc*=0.25.

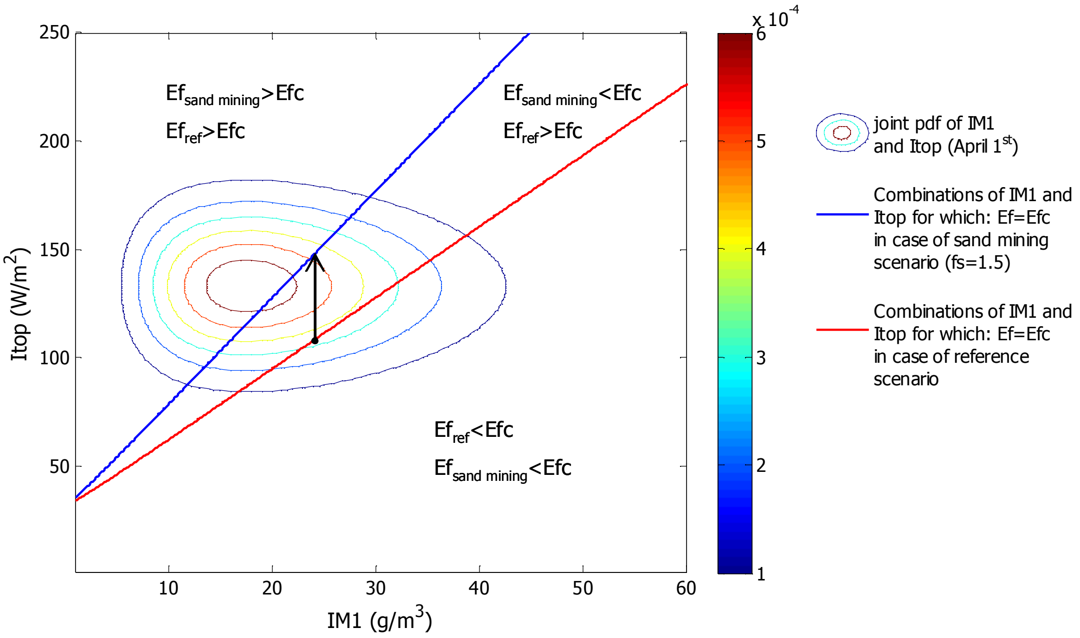


Figure 4.16 Combinations of *Itop* and *IM1* for which $Ef_{reference}=Efc$ (red line) and $Ef_{sandmining}=Efc$ (blue line) and the joint probability density function of *Itop* and *IM1* at April 1st

For more information on the joint probability density function (pdf) of the background silt concentration *IM1* and the light intensity at the water surface *Itop* is referred to appendix D.

4.3.2 Influence of weather conditions on D_{start}

This subsection illustrated the influence of the variations of IM1 and Itop on D_{start}, given a certain relative increase of the silt concentration (*fs*) by the sand mining activities.

Suppose that at April 1st the silt concentration $IM1=24$ g/m^3 and $Itop=108$ W/m^2. For this combination of IM1 and Itop the condition for net primary production is fulfilled for the reference scenario*:

$$\begin{aligned} Ef_{reference} &= \frac{(1-fr)\cdot fpa}{16}\cdot\frac{Itop}{(es\cdot IM1+eb+eot)\cdot Ha}\geq Efc(T) \\ &= \frac{(1-0.1)\cdot 0.45}{16}\cdot\frac{108}{(0.025\cdot 24+0.08+0.14)\cdot 13.3}\geq 0.25 \end{aligned}$$

Net primary production would have started on this day in the reference scenario. How many days later primary production will start in the sand mining scenario, depends on the time it takes for the weather 'to improve from a situation at the red line, to a situation at the blue line' (see figure 4.16).

Assuming that the silt concentration would be constant for the following days, the 'extra light intensity' ($\Delta Itop$) necessary for net primary production in the sand mining scenario can be calculated as follows:

---

*a salinity of 29.9 ‰ is used to calculate *eot* (equation 4.14). This is the average salinity measured at GR6 over the period 1975-2007 (496 measurements) [www.waterbase.nl].

Reference scenario:

$$Ef_{reference} = \frac{(1-fr)\cdot fpa}{16}\cdot\frac{Itop}{(es\cdot IM1+eb+eot)\cdot Ha} \geq Efc(T)$$

$$\Rightarrow Itop_{Ef_{reference}=Efc} = \frac{16\cdot Efc\cdot Ha}{(1-fr)\cdot fpa}\cdot(es\cdot IM1+eot+eb)$$

Sand mining scenario:

$$Ef_{sandmining} = \frac{(1-fr)\cdot fpa}{16}\cdot\frac{Itop}{(es\cdot fs\cdot IM1+eb+eot)\cdot Ha} \geq Efc(T)$$

$$\Rightarrow Itop_{Ef_{sandmining}=Efc} = \frac{16\cdot Efc\cdot Ha}{(1-fr)\cdot fpa}\cdot(es\cdot fs\cdot IM1+eot+eb)$$

Difference between scenarios:

$$\begin{aligned}\Delta Itop_{Ef=Efc} &= Itop_{Ef_{sandmining}=Efc} - Itop_{Ef_{reference}=Efc}\\ &= \frac{16\cdot Efc\cdot Ha}{(1-fr)\cdot fpa}\cdot\big((es\cdot fs\cdot IM1+eot+eb)-(es\cdot IM1+eot+eb)\big)\\ &= es\cdot(fs-1)\cdot IM1\cdot\frac{16\cdot Efc\cdot Ha}{(1-fr)\cdot fpa}\\ &= 0.025\cdot(1.5-1)\cdot 24\cdot\frac{16\cdot 0.25\cdot 13.3}{(1-0.1)\cdot 0.45} = 40\ \mathrm{W/m^2}\end{aligned} \tag{4.26}$$

Thus, the light intensity at the water surface *Itop* should increase by 40 W/m^2 (from 108 to 148 W/m^2, see arrow in figure 4.16) to start net primary production in case of the sand mining scenario. Figure 4.17 shows *Itop* during spring for 1997 and 1998 (these daily averaged light intensities were also used as input for the Delft3D-ECO model for the EIA). In 1997 *Itop* increased within 2 days from 108 to 148 W/m^2, while this increase took 16 days in 1998.

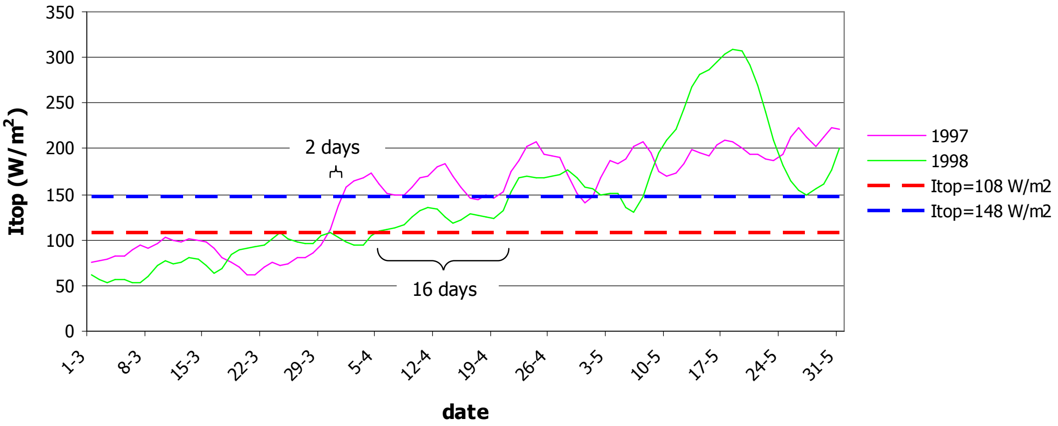


Figure 4.17 ***Itop* during spring in 1997 and 1998 [luminous intensities, measurements of daily averaged intensities of the KNMI, location De Kooy]**

This difference in number of days illustrates that the delay of the start of net primary production (for the same relative increase of the silt concentration) depends strongly on short-term fluctuations of weather conditions (*Itop* depends on solar irradiance and cloudiness). However, it does not show that the delay can be either 2 or 16 days. The assumption that *IM1* is constant, is not realistic for a period of 16 days. If *IM1* increases during this period, also the light efficiency factor *Ef* for the reference scenario may decrease to less than *Efc*; subsequently there will be no net production in the reference as well as the sand mining scenario (net primary production in the reference scenario stops). If *IM1* decreases, the delay of the start of net primary production might be smaller than 16 days.

Figure 4.18 shows the (modelled) variation of *IM1* during spring for 1998 and 1997.

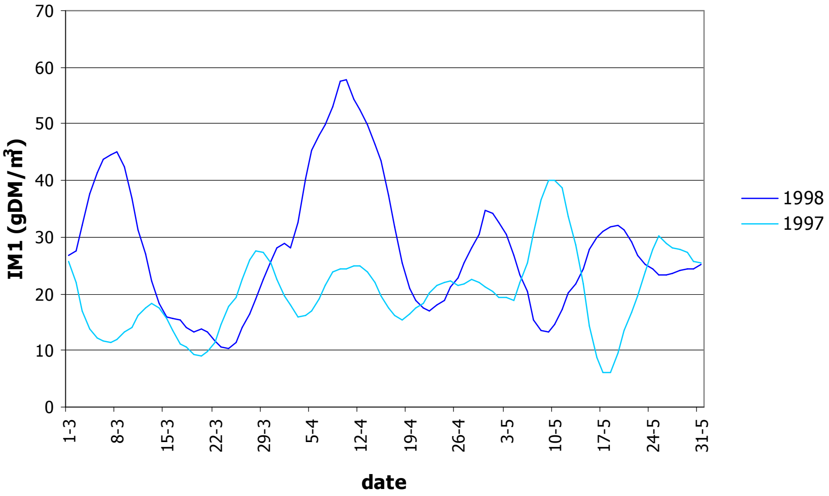


Figure 4.18 Modelled background silt concentration *IM1* (moving average over a period of 7 days) during spring in 1997 and 1998 [model results WL | Delft Hydraulics]

Modelling for the EIA

At the moment that the modelling of the primary production was done, it was not known that the delay of the algal bloom would also be important output of the model. The modelling of the phytoplankton concentrations for the EIA was focussed on the prediction of the decrease of monthly averaged phytoplankton concentrations, as a decrease of the food quality seemed to be the only factor that could affect bivalves. During the execution of the EIA, new insights indicated that the biomass of bivalves could also be affected by a mismatch. Probably other choices would have been made for the modelling of primary production, if the importance of the delay of the bloom was known earlier.

The background silt concentrations that were used as input for most model runs of the Delft3D-ECO model, were modelled in a different way than the sand mining silt concentrations. The short-term fluctuations of the *IM1* were not determined by using measurements of short-term weather conditions, but generated randomly. This modelled *IM1* sometimes drops abruptly from high to low concentrations (see figure 4.19). Due to this, the model shows often that net primary production starts at the same day in the reference as in the sand mining scenario. Consequently, the delay of the bloom *D* is often underestimated in the EIA. However, other safe assumptions in the EIA compensate for this underestimation.

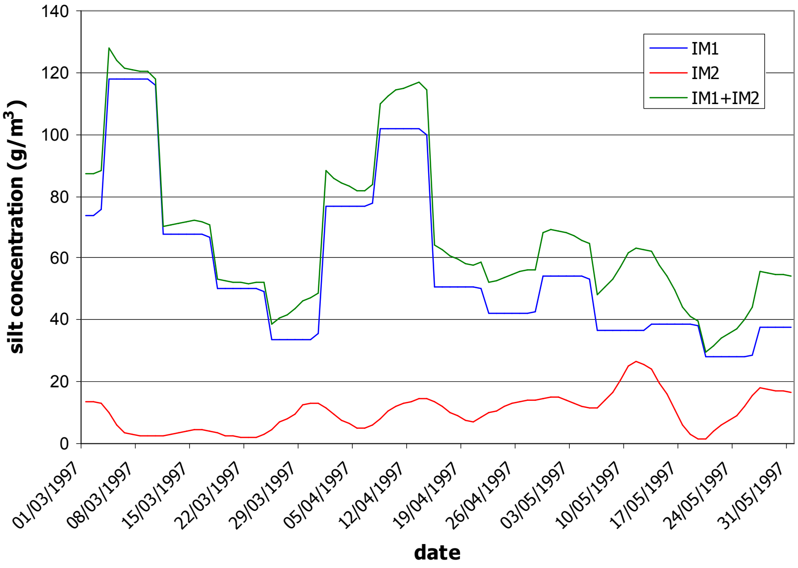


Figure 4.19 Background silt concentration *IM1* as modelled by the ZUNO-model [VAN PROOIJEN *et al.* (2006)] and the concentration of sand mining silt *IM2* as modelled by the far field model (see section 2.3.3) [model results WL | Delft Hydraulics]

4.3.3 Probability distribution of D_{start}

The previous subsection illustrated that the duration of D_{start} (delay of the moment at which net primary production starts) is strongly influenced by the fluctuations of the silt concentration *IM1* and light intensity *Itop*. D_{start} depends on how rapidly *IM1* and *Itop* increase or decrease, after the moment that net primary production would have started in the reference scenario. Also the combination of the change of *IM1* and *Itop* plays a role. If *IM1* decreases while *Itop* increases, D_{start} will be smaller than in case of a constant *IM1*. A simultaneous increase of *IM1* and *Itop* has the opposite effect.

Weather conditions at a certain day, are correlated to the weather conditions during the previous day(s). If conditions are stormy and cloudy at day 1 (high *IM1* and low *Itop*), calm and sunny weather conditions (low *IM1* and high *Itop*) are not likely to occur at day 2. As this correlation is not negligible, the duration of D_{start} can not be estimated by use of the joint probability density function of *Itop* and *IM1*. See for example the joint probability density function of figure 4.16., for *IM1* and *Itop* at April 1st. If the weather conditions at April 1st have to be estimated for example three months before, the joint probability density function is valid for the conditions at April 1st. Most likely are an *Itop* of circa 130 W/m^2 and a silt concentration *IM1* of circa 18 g/m^3. However, if *IM1* and *Itop* at March 31st are known and turn out to be for example, 40 g/m3 and 220 W/m2, high silt concentrations and a high value for *Itop* are more likely for April 1st than 18 g/m^3 and 130 W/m^2.

In order to estimate a probability density function for D_{start}, only the change of *Itop* will be taken into account and *IM1* will be assumed to be constant. As described in the previous section, the variation of *IM1* can have a positive as well as a negative effect on D_{start}. Under the assumption that this will not have a net effect on the probability density function of D_{start} this simplification is allowed.

From measurements of the daily averaged luminous intensities [KNMI, location De Kooy] has been derived by how much the intensity can increase during a period of 1 to 5 days (see appendix D). The results are shown in figure 4.20.

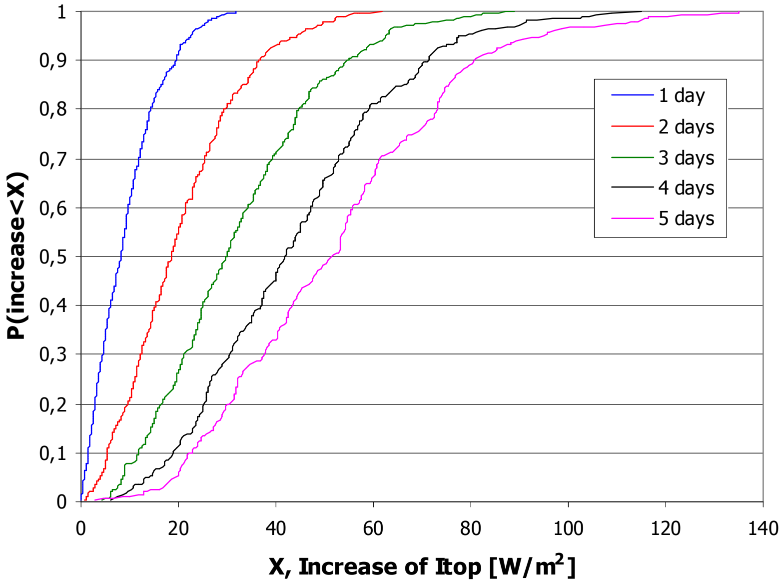


Figure 4.20 Probability distributions for the increase of the light intensity at the water surface *Itop*.

The increase of *Itop* that is necessary to have net primary production in the sand mining scenario can be calculated by equation 4.27 (see 4.26 for derivation):

$$\Delta Itop_{Ef=Efc} = es \cdot (fs-1) \cdot IM1 \cdot \frac{16 \cdot Efc \cdot Ha}{(1-fr) \cdot fpa} \tag{4.27}$$

Table 4.1 shows the results of ΔItop for:

- *Ha* = 13.3 m
- *Efc* = 0.25;
- *IM1*= 22 g/m^3

Table 4.1 *ΔItop* for different values of *fs*

fs (-)	1.1	1.2	1.3	1.4	1.5
ΔItop (W/m^2)	7	14	21	29	36

The depth of 13.3 m is the water depth at location GR6 and the average depth in the monitoring area 'Voordelta' (see appendix J for locations and areas). The background silt concentration of 22 g/m^3 is the average background silt concentration during spring (March-May) at GR6 [modelling results far field model, WL | Delft Hydraulics]. D_{start} will be smaller for smaller water depths (unless a higher *IM1* at shallower locations) and larger for deeper water. Using these average values is assumed to lead to reasonable results for the probability density function of D_{start} for the Voordelta. The transport of phytoplankton is also neglected in this approach. Possibly net primary production in a shallower area, causes already an increase of the phytoplankton concentration in a deeper area, while net primary production has not started yet at this deeper location. On the other hand, a net transport to deeper areas can lead to a slower increase of the phytoplankton concentration in the shallower areas.

The use of the average *IM1* at location GR6 is probably a safe assumption. *IM1* at GR6 is more often smaller than larger as the average *IM1* (see the pdf of *IM1* in appendix D). For a lower *IM1*, *ΔItop* is also smaller. In case of a high *IM1* net primary production does probably also not start in the reference situation.

Assuming that using the average values of Ha and IM1 and neglecting the transport of algae does not lead to an underestimation of D_{start} and its uncertainty margin, the probability distribution functions for D_{start} can be derived from Figure 4.20 and the values of *ΔItop* of table 4.1. For each value of *ΔItop,* the probability that this value is exceeded within 1, 2, 3, 4 or 5 days is derived from Figure 4.20. Lognormal probability distribution functions are fitted to these data and shown in Figure 4.21. The mean values and standard deviations are given in table 4.2.

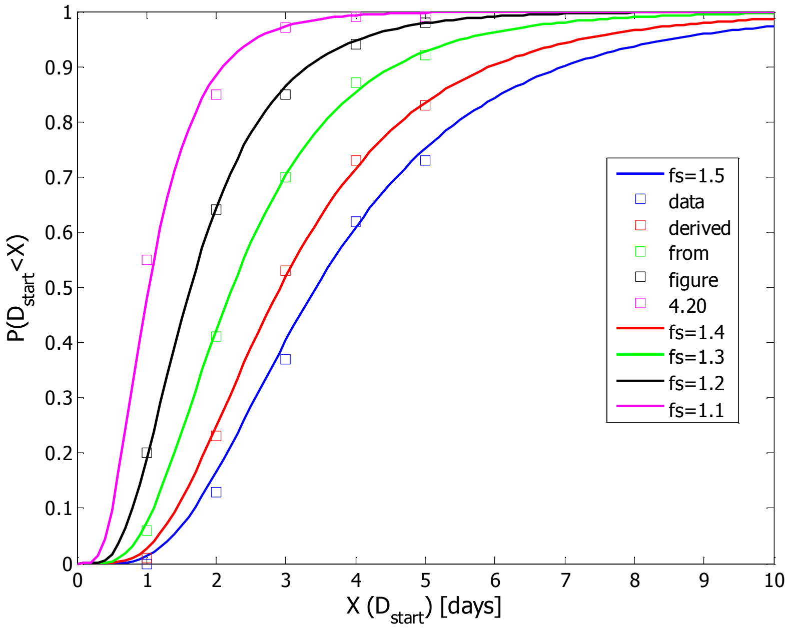


Figure 4.21 **Probability distributions of the delay of the start of net primary production D_{start} for different values of the relative increase of the silt concentration *fs***

Table 4.2 **Mean values and standard deviations of the lognormal probability density function of D_{start}**

fs (-)	1.1	1.2	1.3	1.4	1.5
μ (d)	1.2	1.9	2.6	3.4	4.0
σ (d)	0.7	1.1	1.6	2.0	2.4

4.3.4 Relevant parameters for *D*

Not only the start of net primary production is delayed by an increase of the silt concentration, but also the growth of the algal concentration will be slower. The time it takes for the algal concentration to reach a certain value, is influenced by a large number of (uncertain) variables. The influence of these variables on the delay of the algal bloom *D* will be illustrated in this subsection.

Weather conditions *Itop* and *IM1*

In case of equal weather conditions, the light efficiency factor *Ef* is smaller in case of the sand mining scenario, due to the higher silt concentration. Consequently the growth factor is also smaller:

$$Calg_{t+1} = Calg_t \cdot e^{\overbrace{\left(kgp_i \cdot Ef - krsp_i - kmrt_i\right)}^{\text{growth factor}}}$$

Figure 4.22 illustrates the influence of the increased silt concentration on the growth of the algal concentrations for different (constant) weather conditions. In case of relatively bad weather conditions (dotted line), it takes longer for the algal concentration to reach a certain value and the difference between the reference and sand mining scenario is larger.

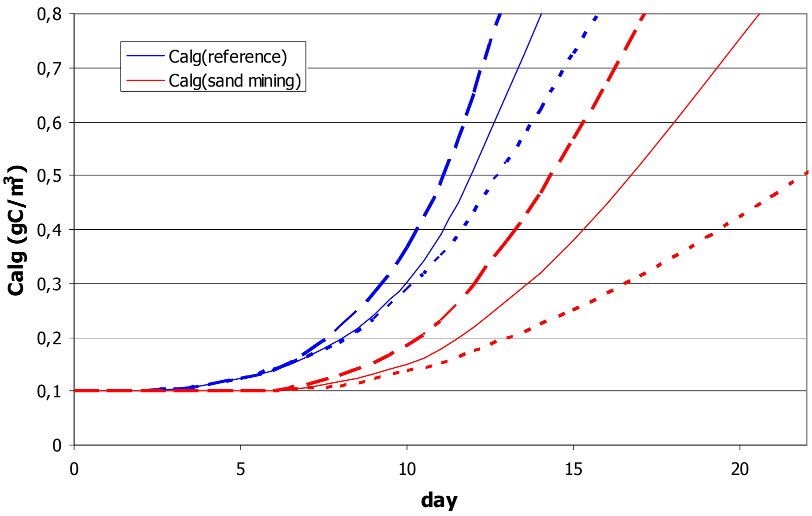


Figure 4.22 Influence of a smaller value of *Ef* on the growth of the algal concentrations, for different combinations of (constant) *IM1* and *Itop*

Figure 4.23 shows the joint probability density function of *IM1* and *Itop* and the values of *Ef* for several combinations of *IM1* and *Itop*. For the sand mining scenario, the value used for *fs* was 1.5.

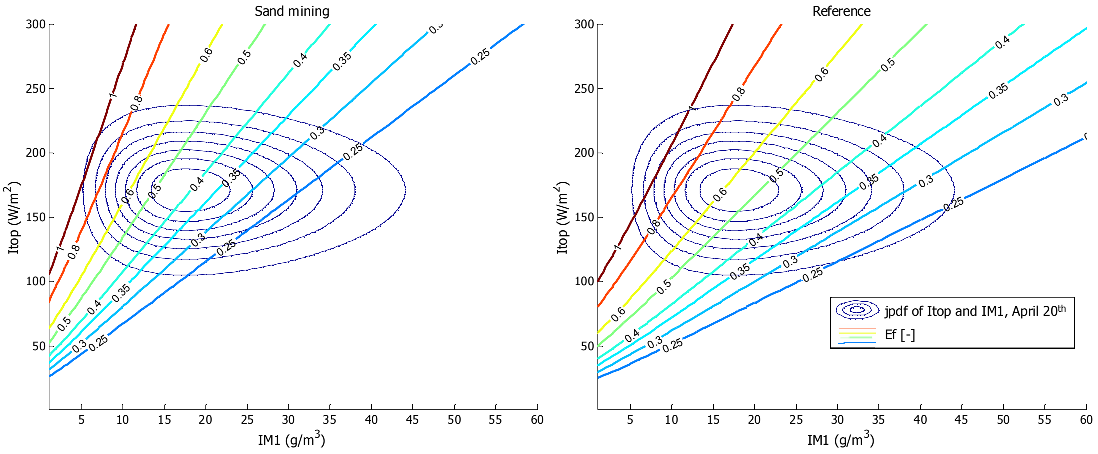


Figure 4.23 Joint pdf of the background silt concentration *IM1* and the light intensity at the water surface *Itop* and the values of the efficiency factor *Ef*

Figure 4.23 shows the joint probability density functions of *IM1* and *Itop* for April 20th. As the average value of *Itop* increases during spring, the light efficiency factor *Ef* will (on average) be larger during May than during April. Due to this, also the delay of the algal bloom will generally be shorter in May than in April.

Critical concentration

The critical concentration is the concentration at which bivalve larvae can grow maximally. The higher this concentration, the larger the delay of the bloom will be (see figure 4.22).

From laboratory experiments of Bos *et al.* (2006) and Bos *et al.* (2007) can be derived that this concentration is circa $4*10^3$ cells/ml (see section 5.3). To compare this concentration with modelled concentrations, it is necessary to convert cells/ml to grams of carbon per cubic metre. This conversion is roughly done by use of the following relation of Menden-Deuer and Lessard (2000) for the carbon content of phytoplankton cells:

$$\text{pgC cell}^{-1} = 0.216 \cdot volume^{0.939}$$

$volume$ = volume of the phytoplankton cell [μm^3]

The algal concentrations used by Bos *et al.* consisted only of edible algal cells. More than 95% of the cells were smaller than 10 µm and the remaining cells were smaller than 20 µm. A part of the modelled, natural concentration will consist of inedible cells (see section 4.4). Allowing for this inedible part, the following safe estimate is made of the critical concentration in gC/m^3:

- 95% of the algal cells used by Bos *et al.* are spherical cells with a diameter of 10 µm;
- 5% of the algal cells used by Bos *et al.* are spherical cells with a diameter of 20 µm.

This assumption leads to a critical concentration of 0.4 gC/m^3. The species composition of the phytoplankton population, which shows a large year-to-year variation, determines to a large extent if the critical concentration is in fact larger or smaller. The processes that determine the species composition of the phytoplankton population are unknown. In this thesis is assumed that the species composition is not influenced by the timing of the algal bloom. A constant value of 0.4 gC/m^3 will be used for the critical concentration.

Starting concentration

Besides the growth factor and the critical concentration, also the 'starting concentration' is an important factor for the delay of the bloom *D*. The starting concentration is the algal concentration at the moment that net primary production starts. This concentration may be the result of the transport of algae from areas where net primary production has started earlier. Figure 4.24 illustrates the influence of the starting concentration on *D*. *D* is larger for a low starting concentration.

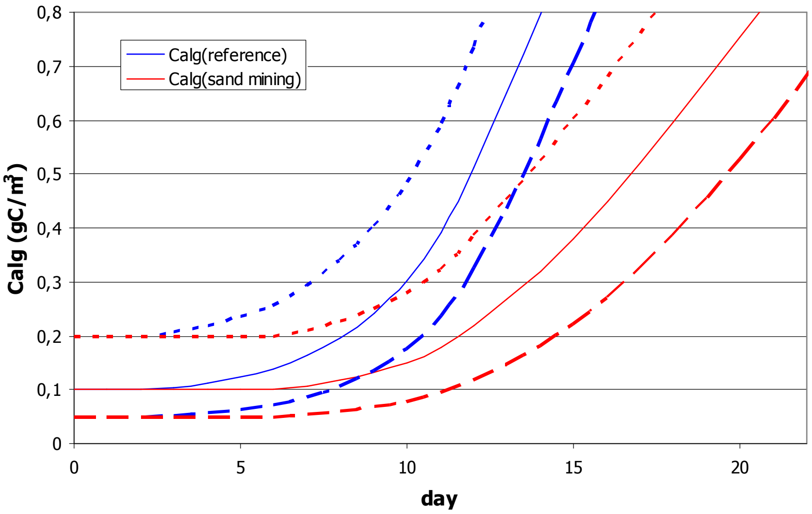


Figure 4.24 Influence of the algal concentration *Calg* at *t=0* on the delay of the algal bloom *D* (for equal, constant values of *Itop* and *IM1* and D_{start} = 5 days)

The relation between the starting concentration $Calg_{t=0}$ and the time *t* it takes to exceed the critical algal concentration can be described as:

$$\frac{\partial Calg}{\partial t} = \left(kgp \cdot Ef - krsp - kmrt\right) \cdot Calg$$

$$Calg_t = Calg_{t=0} \cdot \left(e^{(kgp \cdot Ef - krsp - kmrt)}\right)^t$$

$$Calg_t = Calg_{critical} = Calg_{t=0} \cdot e^{t(kgp \cdot Ef - krsp - kmrt)}$$

$$\Rightarrow \frac{Calg_{critical}}{Calg_{t=0}} = e^{t(kgp \cdot Ef - krsp - kmrt)}$$

$$\Rightarrow t\left(Calg = Calg_{critical}\right) = \frac{1}{kgp \cdot Ef - krsp - kmrt} \cdot \ln\left(\frac{Calg_{critical}}{Calg_{t=0}}\right)$$

Algal concentrations measured circa one month before the algal bloom vary between 0.03 and 0.3 gC/m^3 (see appendix E). Whether or not this starting concentration will be lower in case of sand mining conditions is not known.

Temperature and algae species group

The growth factor is not only dependent on *Ef*, but also on the potential growth rate *kgp*, the mortality rate *kmrt* and respiration rate *krsp* (see equations 4.3 to 4.5). These variables are dependent on temperature and differ per algae species group. Figure 4.25 shows the relation between the growth factor and temperature for different algae species groups.

Growth factor: $= e^{\left(kgp_i \cdot Ef - krsp_i - kmrt_i\right)}$

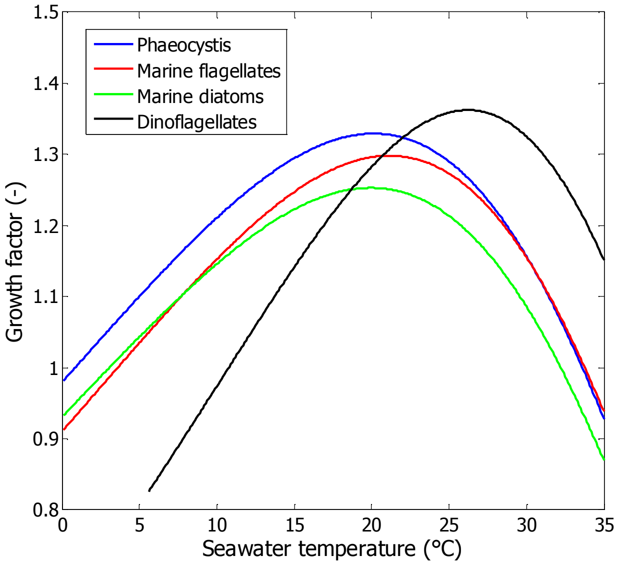


Figure 4.25 Relation between growth factor and seawater temperature, for a constant light efficiency factor (*Ef=0.4*)

Figure 4.26 shows the growth factor of *Phaeocystis* for different temperatures and efficiency factor. Within a period of circa three weeks (≈duration of the period between the start of net primary production and the algal bloom) seawater temperatures vary within a range of circa 2 °C. For the light efficiency factor *Ef* a variation between 0.3 and 0.8 is possible during such a period (see for example figure 4.15 and 4.23). These variations of *Ef* will cause much larger fluctuations of the growth factor than the variation of the seawater temperature. However, although the influence of the variation of *Efc* as a result of fluctuating seawater temperatures is negligible compared to the variation of *Ef*, the average seawater temperature during the algal growth does matter. In case of a seawater temperature of 12 °C, the algal concentration will increase faster than at a temperature of 8 °C. Due to this, the delay of the algal bloom as a result of a certain increase of the silt concentration will be larger in April than in May.

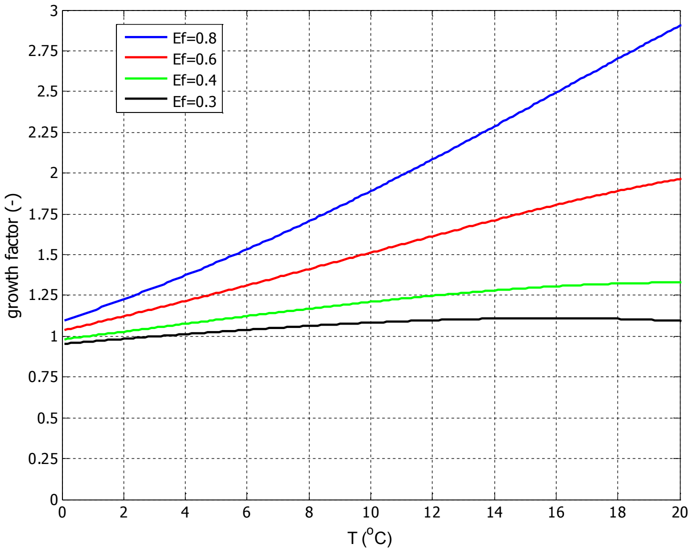


Figure 4.26 Growth factor of *Phaeocystis* for different values of seawater temperature *T* and light efficiency factor *Ef*

The algal concentration will increase faster if the algal population consists for a large part of *Phaeocystis*, as *Phaeocystis* grow faster than the other species groups.

4.3.5 Probability distribution of *D*

From the previous subsection can be concluded that the delay of the algal bloom is influenced significantly by the fluctuations of *Itop* and *IM1* and by the algal concentration at the start of net primary production. The variation of the seawater temperature turned out to be of minor importance. The fluctuations of *IM1* and *Itop* and the probability density function of D_{start} will be combined in this section to derive the probability distribution of *D* by use of a Monte Carlo analysis. For a large number of randomly generated sets of input variables, the delay of the algal bloom will be calculated. How the different input variables will be varied in this Monte Carlo analysis is explained in this subsection.

Starting concentration

On basis of the algal concentrations that were measured one month before the algal bloom (see appendix E), a uniform distribution with a lower limit of 0.03 gC/m^3 and an upper limit of 0.3 gC/m^3 is chosen for the variation of the starting concentration in the reference scenario. To take into account the possible, unknown impact of the sand mining on the starting concentration a factor *rs* will be taken into account with a value between 0.6 and 1 (uniform distribution).

$$rs = \frac{Calg_{t=0,sandmining}}{Calg_{t=0,reference}} \qquad (4.28)$$

$\boldsymbol{D_{start}}$

For each run of the Monte Carlo analysis, the value of D_{start} will be chosen randomly from the probability density functions of D_{start} (see section 4.3.3).

Temperature

A constant seawater temperature of 10.5 °C will be used. This is more or less the average seawater temperature during late April and the start of May [www.waterbase.nl]. The average temperature for this period has been chosen, as a delay of the bloom during this period may affect the bivalve larvae (the hatching of bivalve larvae hardly ever occurs earlier, see 4.5). The influence of varying this average seawater temperature (for each run of the Monte Carlo simulation) on the probability density function of *D* is expected to be negligible, compared to influence of changing weather conditions and the starting concentration (see appendix B for an example).

Algae species group

In the Monte Carlo analysis the growth, respiration and mortality rates for marine flagellates will be used. As the phytoplankton population will consist partly of *Phaeocystis* (which grow faster) it is a relatively safe choice to use the parameters for marine flagellates.

Growth of $Calg_{reference}$ between t=0 and t=0+D_{start}

Net primary production starts at t=0 for the reference scenario and at t=0+D_{start} for the sand mining scenario. The growth of the algal concentration in the period between is calculated per day, by use of equations 4.29 and 4.30.

$$Calg_{t+\Delta t} = Calg_t \cdot e^{(kgp\cdot Ef - kmrt - krsp)\Delta t} \tag{4.29}$$

$$Ef = \frac{1}{16}\cdot\frac{(1-fr)\cdot fpa\cdot Itop\cdot\left(1-e^{-et(IM1,Calg_t,\ldots)\cdot Ha}\right)}{et(IM1,Calg_t,\ldots)\cdot Ha} \tag{4.30}$$

For the weather conditions during this period, a combination of *IM1* and *Itop* is randomly chosen from the joint probability density function for April 15th, under the condition that:

$$Ef_{reference} > Efc \text{ and } Ef_{sandmining} < Efc$$

For *Ha* a depth of 13.3 m is used (see section 4.3.3) and for *eot* and *eb* respectively 0.14 and 0.08 m^{-1} (see 4.3.2).

Growth of $Calg_{reference}$ and $Calg_{sand\ mining}$ after $t = D_{start}$

Equations 4.29 and 4.30 are also used to calculated the growth of the algal concentrations in the period after $t=0+D_{start}$. For each period of three days, randomly a combination of *IM1* and *Itop* is chosen from the joint probability density function (for April 15th+t). The weather conditions during these periods of three days, are assumed to be uncorrelated to the weather conditions during the previous period of three days.

As the light efficiency factor for the sand mining scenario $Ef_{sand\ mining}$, just exceeds *Efc* at $t=D_{start}$, the average value of $Ef_{sand\ minng}$ can impossibly be much larger than 0.33 during the first period of three days (due to the correlation between weather conditions on successive days). Therefore the following condition is applied for IM1 and Itop during the first period of three days:

$$Efc < Ef_{sandmining} < 0.33$$

For the following periods of three days, the following condition is applied:

$$Ef_{sandmining} > Efc$$

In fact also conditions can occur for which $Ef_{sand\ mining}$ will be smaller than *Efc*. However during such conditions also the algal concentration in the reference scenario will increase very slowly or even decrease. This would not comply with the determination of A_{ref} (the moment at which the critical concentration is exceeded in the reference scenario) in section 4.4. At A_{ref} (or ca. 7 days after A_{ref}) the measured algal concentrations are much higher than 0.4 gC/m^3. Such rapid increase of the algal concentration would not be possible for weather conditions at which Ef_{sand} is smaller than *Efc*.

Figure 4.27 shows the modelled increase of the algal concentrations for one randomly generated set of weather conditions. For each run of the Monte Carlo analysis is determine when the critical concentration is exceeded in the reference and in the sand mining scenario. The difference is the delay *D*.

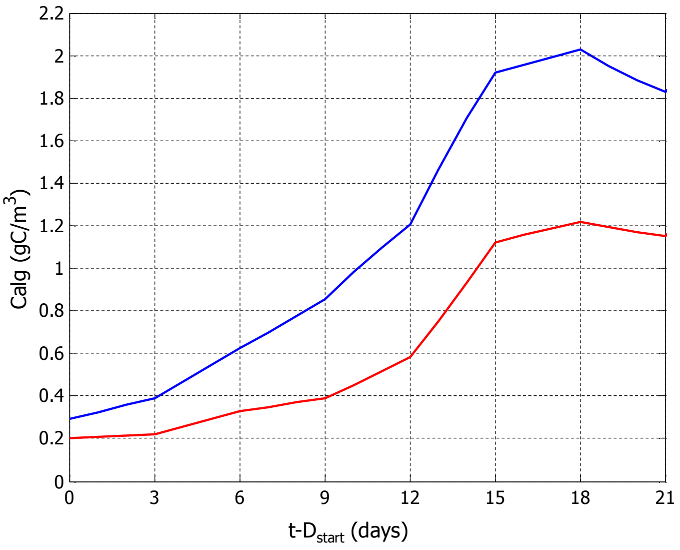


Figure 4.27 Modelled increase of *Calg*$_{reference}$ (blue line) and *Calg*$_{sandmining}$ (red line)

Figure 4.28 shows the results for *fs*=1.5. By using the computer program 'Bestfit' is determined that a gamma distribution fits best to these results. 'Bestfit' fits several distributions to the data and determines the best fitting distribution by using the chi-square test and the Kolmogorov-Smirnov test.

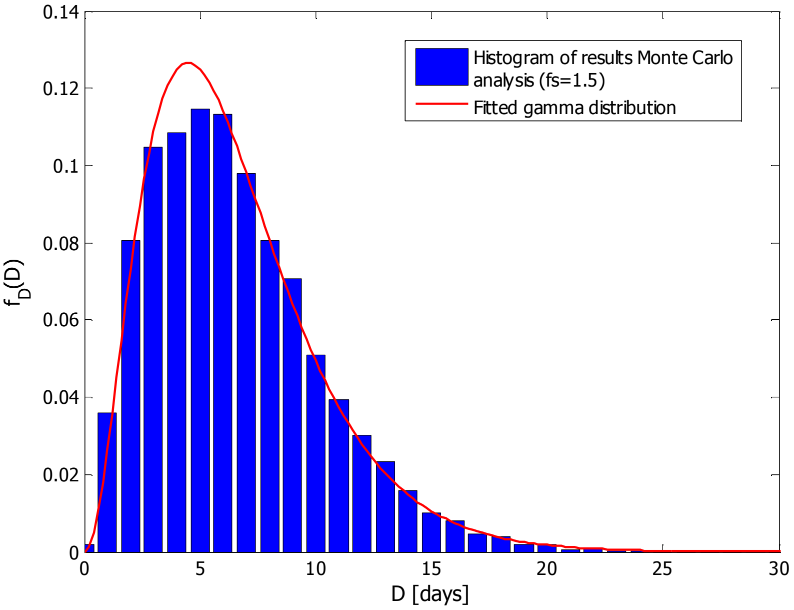


Figure 4.28 Result of the Monte Carlo analysis for *fs*=1.5 (relative increase of the silt concentration)

Figure 4.29 shows the gamma-distributions of D for different values of *fs*. The parameters of these probability density functions are given in Table 4.3.

Table 4.3 Parameters of the gamma-distribution of the delay of the algal bloom *D*

fs	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
μ_D [d]	2.0	3.1	4.2	5.5	6.6
σ_D [d]	1.7	2.3	2.7	3.3	3.7
$\Gamma(\alpha,\beta)$	Γ(1.41,1.43)	Γ(1.91,1.64)	Γ(2.37,1.78)	Γ(2.78,1.97)	Γ(3.15,2.08)

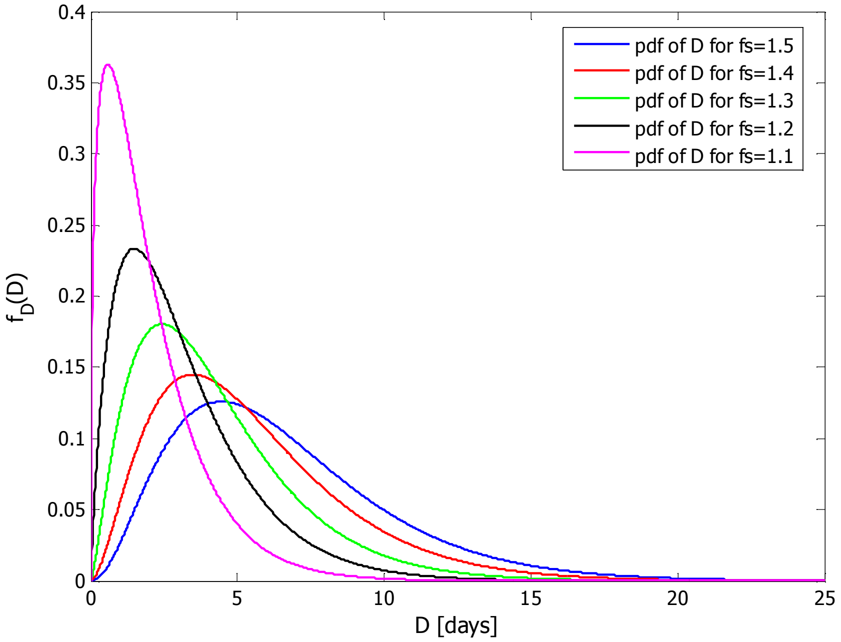


Figure 4.29 Gamma probability density functions of the delay of the algal bloom *D* for different values of the relative increase of the silt concentration due to the sand mining *fs*

Remark

The determination of the probability distribution of *D* has been described in detail. Due to a large number of (rough) assumptions and simplifications, this determination may seem quite inaccurate. However, this apparent inaccuracy should be compared to the accuracy of the determination of A_{ref} and *H*, which is done in the following sections. In the light of the inaccuracy of A_{ref} and *H*, a more accurate determination of the probability distribution of D is not useful (see also section 4.6).

4.4 Algal bloom

In this section is estimated at which date the algal bloom normally takes place (A_{ref}) and how large the natural variation of this moment is. Results of in situ measurements as well as remote sensing data are used to estimate A_{ref}:

- In situ measurements: within the framework of the national monitoring programme 'Monitoring Waterstaatkundige Toestand des Lands (MWTL)', which is carried out by RIKZ (Dutch National Institute for Coastal and Marine Management), phytoplankton concentrations are measured monthly at several locations along the Dutch coast. Data of measured concentrations of chlorophyll-a (=one of the main photosynthetic pigments in phytoplankton) are available for the period 1975-2007 [www.waterbase.nl]. For 1991-2005 also the algal concentrations in cells/m^3 and the estimated concentrations in gC/m^3 are available [RIKZ, not published].
- Remote sensing data: spectrometers on board of satellites measure the solar radiance spectrum which is backscattered by the water and its constituents. From these measurements of the colour of the sea, concentrations of chlorophyll-a can be derived. Data are available for the period 1998-2004 [ToRSMoN SeaWiFS CHL dataset (IVM/Institute for Environmental Studies), PETERS *et al.* (2005)].

In this thesis the moment of the algal bloom is defined as the moment at which the 'critical phytoplankton concentration' is exceeded. This critical concentration is the concentration at which sufficient food for larvae is available; the growth of the larvae is not hampered at this concentration. From the laboratory results of BOS *et al.* (2006) and BOS *et al.* (2007) can be derived that the growth of bivalve larvae is not hampered anymore at a phytoplankton concentration of circa $3.5*10^3$ to $4*10^3$ cells/ml (see section 5.3.2).

However, comparing the concentration of BOS *et al.* (2006) and the measured concentrations correctly is hardy possible as:

- the cell-size of the different observed phytoplankton species is not known (large edible cells will contain more nutrients for larvae than small cells);
- the quantity of cells that form colonies is unknown for most years and shows a strong variation*;
- the percentage of cells that are too large for larvae is not known and differs strongly per year (the species composition of the total phytoplankton population differs yearly);
- the nutritional value of cells of different species (groups) will be different, even if their volume is equal**;
- in both cases the concentration of detritus (dead organic matter, which is also edible for larvae) is not measured;
- relating chlorophyll-a concentrations to a number of cells per cubic metre is difficult, as the chlorophyll-a content is different for each phytoplankton species.

In section 4.3.4 the critical algal concentration in gC/m^3 was estimated at 0.4 gC/m^3. The chlorophyll-a-carbon ratio for flagellates is on average circa $2.3*10^{-2}$ gChl-a/gC. For diatoms this ratio is $5.3*10^{-2}$ gChl-a/gC [input Delft3D-ECO model, VAN PROOIJEN *et al.* (2006)]. By use of these ratios the critical algal concentration in chlorophyll-a per cubic metre is estimated at 10 to 15 mgChlf-a/m^3.

Besides the large uncertainty margin of the critical concentration, also the relatively long period between the measurements of the algal concentration makes it impossible to determine the moment of the algal bloom accurately. The frequency of the in situ measurements is monthly. The availability of remote sensing data depends on weather conditions; during cloudy days the backscattering of solar radiance from the sea cannot be measured.

Figure 4.30 shows the algal concentrations measured during 1997. At March 14th the concentration was $1.8*10^2$ cells/ml. At April 16th the algal concentration was much higher than the critical concentration: $3.7*10^4$ cells/ml. The date at which the algal concentration exceeded the critical concentration cannot be estimated accurately.

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* For example *Phaeocystis* can form colonies. Within a colony the cells are embedded in a jelly layer. The percentage of the *Phaeocystis* that forms colonies varies strongly; during the bloom of 2005 no colonies were formed, while 40% of the *Phaeocystis* formed colonies in 2006 (location: Goeree 6 km) [KOEMAN *et al.* 2006 and KOEMAN *et al.* (2007)].

** the content of organic carbon of a cell may be a good measure for the nutritional value of cells. Cells of diatoms are less carbon dense than cells of flagellates and dinoflagellates MENDEN-DEUER AND LESSARD (2000). On the other hand; the cells of diatoms might be larger on average than flagellate-cells.

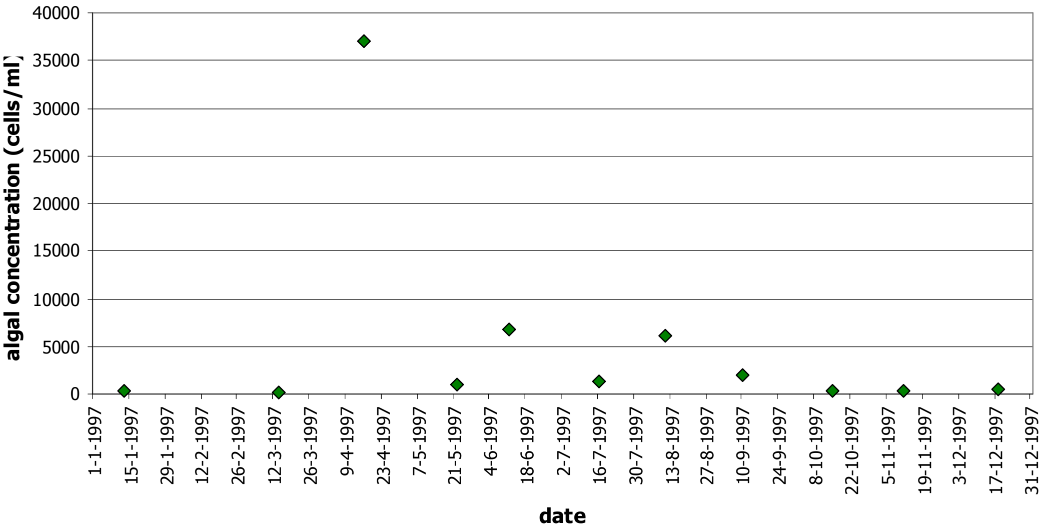

Figure 4.30 Measured algal concentrations in 1997, location GR6 [data from RIKZ, not published]

In appendix E an overview is given of all available measurements during spring. On the basis of these data, four different estimates are made of the mean value of A_{ref} and its standard deviation:

- Estimate 1: for each year A_{ref} is estimated at the date of the measurement at which the algal concentration was larger than 15 mgChl-a/m^3 (or >>4*10^3 cells/ml) minus ½ times the period between this date and previous measurement, or: the date at which the measured algal concentration was larger than 10 mgChl-a/m^3, but smaller than 15 mgChl-a/m^3;
- Estimate 2: date at which the measured algal concentration was >> 15 mgChl-a/m^3 (or >>4*10^3 cells/ml) minus ¼ times the period between this date and previous measurement, or: date at which (10 mgChl-a/m^3 < *Calg* < 15 mgChl-a/m^3);
- Estimate 3 (safe): date at which measured algal concentration > 10 mgChl-a/m^3 (or >5*10^3 cells/ml);
- Estimate 4 (very safe): date at which measured algal concentration > 20 mgChl-a/m^3 (or >8*10^3 cells/ml), or: date at which (10 mgChl-a/m^3 < *Calg* < 20 mgChl-a/m^3) plus ½ times the period between this date and the next measurement.

The different estimates of A_{ref}, for the period 1976-2007, are shown in appendix E. Table 4.4 shows the results.

Table 4.4 Estimates of the mean and standard deviation of the normal pdf of the timing of the algal bloom in the reference scenario (A_{ref})

	Estimate 1	**Estimate 2**	**Estimate 3**	**Estimate 4**
μ (A_{ref}) [date]	April 5th	April 9th	April 15th	April 17th
σ (A_{ref}) [days]	13	14	15	15

Figure 4.30 shows that the phytoplankton concentration drops down to less than 4000 cells/ml after the algal bloom (this does not occur every year). This seems to be contradictory with the assumption that the availability of food is not limiting for the growth of larvae after the algal bloom. However, concentrations of detritus are not measured. Detritus also forms part of the diet of larvae and exists among other things of dead phytoplankton and faecal matter. After the algal bloom, the amount of available food is probably still

sufficient for larvae, due to a high concentration of detritus (if the dead phytoplankton cells are not decomposed to inorganic nutrients yet, see figure 4.31).

If the availability of food for larvae can be limiting after the algal bloom, a delay of the bloom could also have a positive effect on the growth of larvae. As the hatching of larvae mostly takes place after the algal bloom (see next section), the delay can result in a higher phytoplankton concentration at the moment of hatching than in the reference scenario without this delay. However, in this thesis will be assumed that the food concentration for larvae is sufficiently high after the algal bloom.

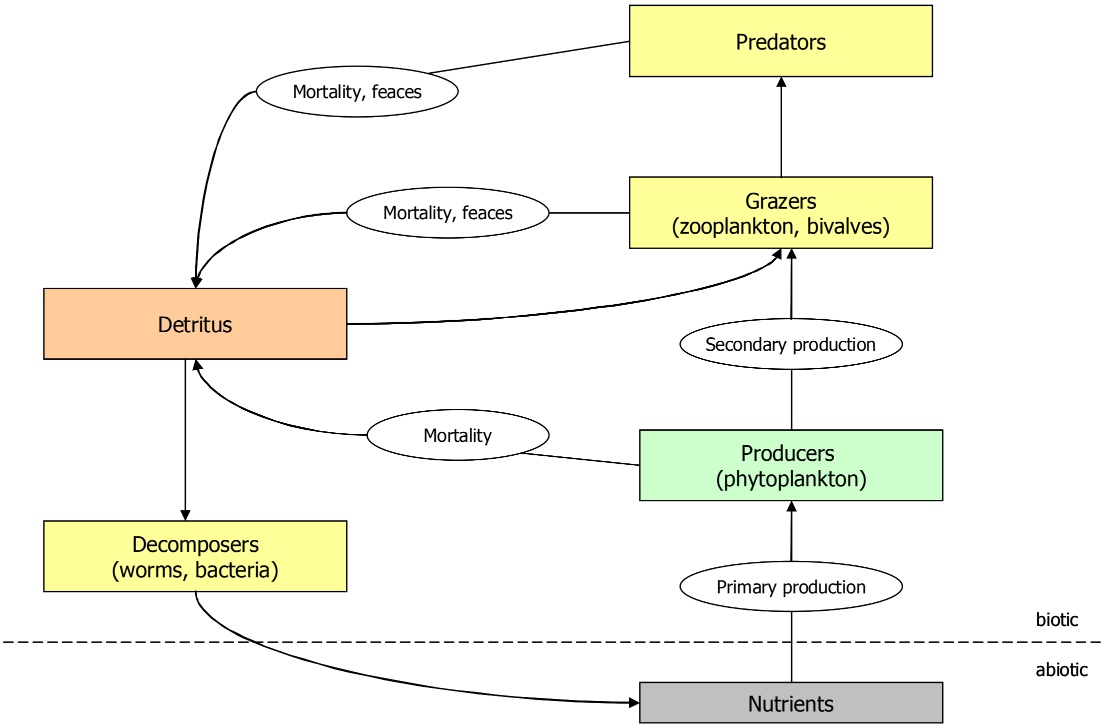

Figure 4.31 Cycle of nutrients

4.5 Moment of hatching

In the previous sections the average values of variables A_{ref} and D and their standard deviations have been determined on the basis of measurements or model formulations. Unfortunately far less is known about the third important variable of this chapter; the moment of hatching H. Only little information is available on the moment of hatching (or spawning) of cockles (C*erastoderma edule*) and American razor shells (*Ensis directus)*. Cockles and American razor shells form the main food for sea ducks in the Voordelta nowadays.

The hatching of bivalve larvae takes place some days after spawning. Spawning is the release of eggs and sperm by respectively female and male adult bivalves. After the simultaneous spawning of (a large proportion of) all adults of a population, the external fertilization takes place. Subsequently it takes a couple of days for the eggs to develop into D-larvae (called D-larvae because of their shape like the capital D). The moment at which the D-stage is reached is defined as the moment of hatching in this thesis. Assuming that the D-larvae are already able to eat phytoplankton, the larvae can be subject to a growth lag if the algal concentration is insufficiently high after reaching the D-stage. For some weeks after hatching, the larvae will be swimming and floating in the water. During this pelagic phase, the larvae develop a foot, which makes it possible to settle at the seabed. For cockles the pelagic phase lasts until 3-5 weeks after fertilization.

The spawning of cockles is expected to be induced by seawater temperatures. Whether a seawater temperature above a certain threshold value, or a sudden temperature rise is required to induce spawning is not known [www.marlin.ac.uk]. However, as the moment of spawning is probably dependent on water temperatures, this moment will not be influenced by sand mining activities. Also the spawning of American razor shells is expected to be induced by water temperature; during laboratory experiments of KENCHINGTON *et al.* (1998) razor shells started spawning at temperatures higher than 15 °C.

According to HONKOOP AND VAN DER MEER (1998), cockles spawn mostly in late May, when water temperatures of 12 - 15 °C are reached. CARDOSO *et al.* (2007b) found that spawning of cockles takes place around May in the Wadden Sea. Spawning of American razor shells is around May in the Wadden Sea [J. Cardoso].

On the basis of this limited amount of information, and taking into account that water temperatures during spring are generally higher in the Wadden Sea than in the Voordelta, is chosen to use the following probability density functions for *H* for further analysis:

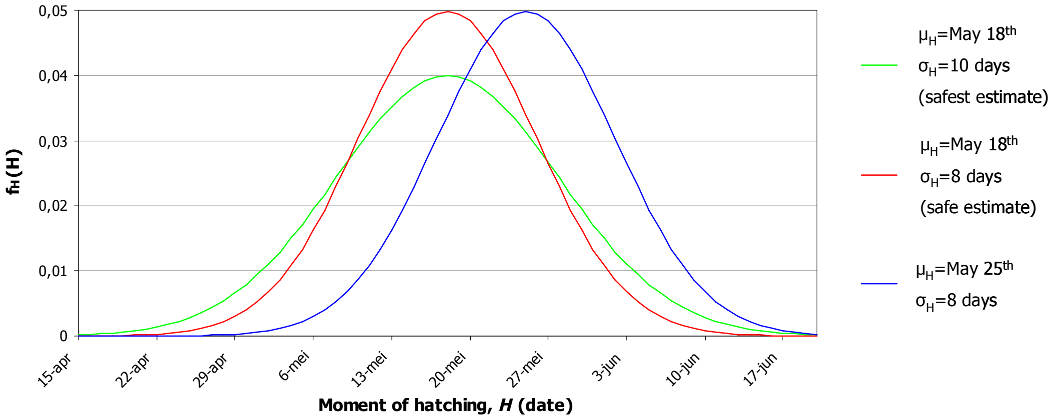

Figure 4.32 Estimated probability density functions for the moment of hatching *H*

4.6 Probability of occurrence of a mismatch

By using the probability density functions that were estimated in sections 4.3, 4.4 and 4.5, it is possible to determine the probability of occurrence of a mismatch. A mismatch occurs when:

$$Z = H - A_{ref} - D = -M < 0$$

With: Z = limit state function [d]
H = moment of hatching of the larvae [d]
A_{ref} = moment at which the critical algal concentration is exceeded in the reference scenario [d]
D = delay of the moment at which the critical algal concentration is exceeded, caused by the sand mining activities [d]
M = duration of the mismatch [d]

A mismatch occurs if *M* has a positive value. In case *M* has a negative value, a match occurs. The longer the duration of the mismatch period the larger the growth lag of the larvae will be (the relation between M and the growth lag will be derived in section 5.3).

Using the probability density functions of *A*, *H* and *D* (and assuming that these variables are not correlated), leads to the following distribution of *M*:

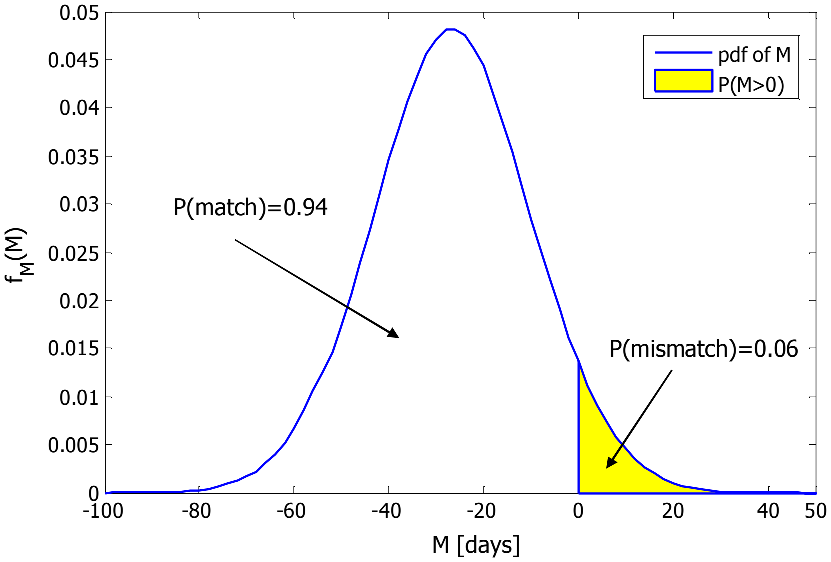

Figure 4.33 Probability density function of the duration of the mismatch *M*, for μ_{Aref}=April 15th, σ_{Aref}=15 days, μ_H=May 18th, σ_H=10 days, and the gamma distribution of *D* for *fs*=1.5

The yellow area in Figure 4.33 is the probability that a mismatch occurs. The surface and shape of this area differs for different parameters of the probability density functions of A_{ref}, *H* and *D* (see Figure 4.34).

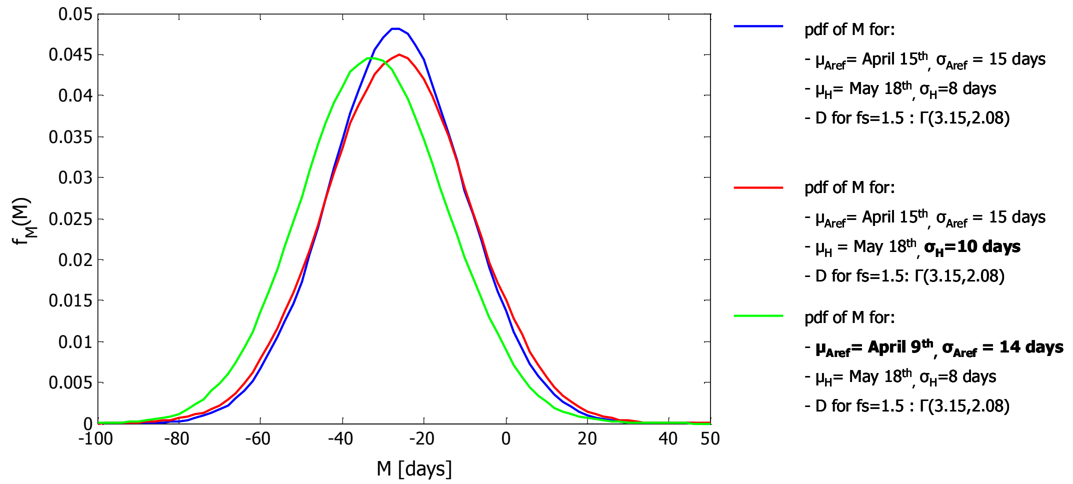

Figure 4.34 Probability density functions of *M* for different values of μ_{Aref}, σ_{Aref}, μ_H and σ_H

As *D* is not normally but gamma-distributed, the calculation method of chapter 3 cannot be applied to calculate the probability of occurrence of a mismatch. Therefore, this probability will be estimated by generating randomly a large number of sets of *H*, A_{ref} and *D* from their probability density functions. For each set the value of *M* is calculated. Subsequently, the probability of occurrence of a mismatch is calculated from the number of times that M is larger than 0 and the total number of sets. The results are shown in Table 4.5.

Table 4.5 Probability of occurrence of a mismatch for different combinations of the probability density functions for the moment of hatching *H*, the timing of the algal bloom A_{ref} and the delay of the algal bloom caused by the sand mining *D*

H (day)		A_{ref} (day)		D (days)		P(M>0)	P(M>0)
μ	σ	μ	σ	μ	σ	sand mining	reference
May 18th	8	April 5th	13	6.6 (fs=1.5)	3.7	0.01	0.002
May 18th	8	April 9th	14	6.6	3.7	0.03	0.008
May 18th	8	April 15th	15	6.6	3.7	0.06	0.02
May 18th	8	April 17th	15	6.6	3.7	0.07	0.03
May 18th	10	April 17th	15	6.6	3.7	0.08	0.04
May 25th	8	April 5th	13	6.6	3.7	0.003	0.0005
May 25th	8	April 9th	14	6.6	3.7	0.009	0.002
May 25th	8	April 15th	15	6.6	3.7	0.02	0.007
May 25th	8	April 17th	15	6.6	3.7	0.03	0.009
May 25th	8	April 9th	14	5.5 (fs=1.4)	3.3	0.007	0.002
May 25th	8	April 9th	14	4.2 (fs=1.3)	2.7	0.005	0.002
May 25th	8	April 9th	14	3.1 (fs=1.2)	2.3	0.005	0.002
May 25th	8	April 9th	14	2.0 (fs=1.1)	1.7	0.003	0.002
May 18th	8	April 15th	15	5.5	3.3	0.05	0.02
May 18th	8	April 15th	15	4.2	2.7	0.04	0.02
May 18th	8	April 15th	15	3.1	2.3	0.03	0.02
May 18th	8	April 15th	15	2.0	1.7	0.03	0.02

As only little information is available on the moment of hatching and the moment of the algal bloom, it is not possible to estimate the mean and standard deviations of the probability density functions (pdf's) of *H* and A_{ref} accurately. Using different, possible parameters of these pdf's leads to a larger difference in the probability of occurrence than using other parameters for the pdf of *D*.

The possible correlation between A_{ref}, *H* and *D* is neglected. In section 4.3.4 was explained that *D* will probably be smaller (on average) at the end of May than at the start of April. In this way *D* will be correlated negatively to the moment of the algal bloom A_{ref}. A negative correlation between A_{ref} and *D* will result in a smaller probability of occurrence of a mismatch. However, the effect of this correlation will be negligible compared to the effect of using too large or too small values for the parameters of the pdf's of *H* and A_{ref}. These parameters are easily over- or underestimated due to the lack of information.

Table 4.5 shows the probability that a mismatch occurs in one year. However, the sand mining activities for Maasvlakte 2 will increase the silt concentrations in the Voordelta during several years. The probability that a mismatch occurs during one of these years is much larger than the probability that a mismatch occurs in one specific year.

In the EIA, the increase of the silt concentration was modelled for a period of 8 years [Van Prooijen *et al.* (2006)]. In this thesis is assumed that the influence of the sand mining on the silt concentration in the Voordelta is negligible after this period. Figure 4.35 shows the relative increase of the silt concentration *fs* during spring (March-May) for the period of 8 years, for different sand mining scenarios.

Table 4.6 The relative increase of the silt concentration *fs* and the probability of occurrence of a mismatch for years 1-8 after the start of the sand mining activities, scenario s1a

Year	1	2	3	4	5	6	7	8
fs [-]	1.2	1.5	1.5	1.2	1.2	1.1	1.1	1.1
P(M>0), μ_H=05/25, μ_{Aref}=04/09	0.005	0.009	0.009	0.005	0.005	0.003	0.003	0.003
P(M>0), μ_H=05/18, μ_{Aref}=04/15	0.03	0.06	0.06	0.03	0.03	0.03	0.03	0.03

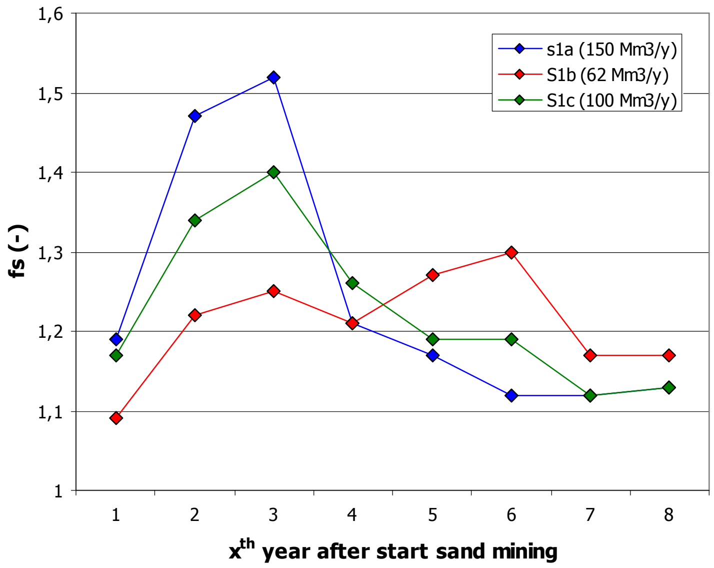

Figure 4.35 Relative increase of silt concentration during spring *fs*, from the 1st to the 8th year after the start of the mining activities, location GR6 [derived from model results of WL | Delft Hydraulics, VAN PROOIJEN *et al.* (2006) and DESMIT *et al.* (2007)]

The probability that no mismatch occurs during the period of 8 years can be calculated as follows:

$$\begin{aligned} P(no\ impact) &= P\left(\left(M_{year=1}<0\right)\cap\left(M_{year=2}<0\right)\cap\ldots\cap\left(M_{year=8}<0\right)\right) \\ &= P\left(M_{year=1}<0\right)\cdot P\left(M_{y=2}<0\right)\cdot\ldots\cdot P\left(M_{y=8}<0\right) \\ &= \left(1-P_{y=1}\left(M>0\right)\right)\cdot\left(1-P_{y=2}\left(M>0\right)\right)\cdot\ldots\cdot\left(1-P_{y=8}\left(M>0\right)\right) \end{aligned}$$

For the following assumptions on the probability density functions of the timing of the hatching of larvae *H* and the algal bloom in the reference scenario A_{ref}:

- μ_{Aref}=April 9th, σ_{Aref}=14 days;
- μ_H=May 25th, σ_H=8 days;

the probability that the sand mining does not have an impact on bivalves is **0.96**.

$$\begin{aligned} P(no\ impact) &= \left(1-P_{y=1}\left(Z<0\right)\right)\cdot\left(1-P_{y=2}\left(M>0\right)\right)\cdot\ldots\cdot\left(1-P_{y=8}\left(M>0\right)\right) \\ &= 0.995\cdot 0.991\cdot 0.991\cdot 0.995\cdot 0.995\cdot 0.997\cdot 0.997\cdot 0.997 = 0.96 \end{aligned}$$

For the following safe assumptions on the probability density functions of *H* and A_{ref}:

- μ_{Aref}=April 15th, σ_{Aref}=15 days;
- μ_H=May 18th, σ_H=8 days;

the probability that the sand mining does not have an impact on bivalves is **0.74.**

$$P(no\ impact) = 0.97\cdot 0.94\cdot 0.94\cdot 0.97\cdot 0.97\cdot 0.97\cdot 0.97\cdot 0.97 = 0.74$$

While the difference of the probability of occurrence of a mismatch in one specific year might seem small for different pdf's of H and A_{ref}, the probability that the sand mining does not have an impact at all, shows a large difference. This illustrates that the estimate of the pdf's of A_{ref} and H influences the final result (a probability distribution function for the impact on eider ducks) strongly. The uncertainty margins of μ_{Aref}, σ_{Aref}, μ_H and σ_H are much larger than the uncertainty margins of μ_D and σ_D. Therefore, doing more research to the moment of hatching of larvae and the algal bloom will be more effective to improve the accuracy of the final result, than improving the modelling of the delay of the algal bloom.

Table 4.6 shows the probability of occurrence of a mismatch for the sand mining and reference scenario. Also without sand mining activities a mismatch can occur. However, in a year that a mismatch occurs in the reference scenario, the duration of this mismatch would have been longer in the sand mining scenario. The longer the duration of the mismatch, the longer the impact on the bivalve larvae.

4.7 Summary

In this chapter probability density functions have been determined for the timing of the algal bloom in the reference scenario A_{ref}, the moment of hatching of bivalve larvae H and the delay of the algal bloom D, which is caused by the sand mining. These probability density functions will be used in a Monte Carlo analysis (see chapter 7) to determine a probability distribution for the impact of the sand mining on eiders in the Voordelta.

The parameters of the pdf of the delay of the algal bloom D depend on the relative increase of the silt concentration fs. The value of fs differs per year and variation of fs during the period after the start of the sand mining activities, is different for each sand mining scenario. The pdf's of D that will be used for the different years and sand mining scenarios are shown in Table 4.7. The values of fs for the different years and scenarios are based on the results of the far field modeling [VAN PROOIJEN *et al.* (2006) and DESMIT *et al*. (2007)] as shown in Figure 4.35 and Figure 4.36. The uncertainty margin of the results of the far field model is not known and will not be investigated in this thesis. The effect of this uncertainty margin on the final result (the probability distribution of the impact on eiders) is assumed to be negligible, compared to the influence of the uncertainty margins of other relevant parameters.

Table 4.7 Probability density functions of the delay of the algal bloom *D*, which will be used as input for the Monte Carlo analysis

Mining scenario		**Year:**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
s1a	**fs**	1.2	1.5	1.5	1.3	1..2	1.2	1.1	1.1
	Γ(α,β)	Γ(1.91, 1.64)	Γ(3.15, 2.08)	Γ(3.15, 2.08)	Γ(2.37, 1.78)	Γ(1.91, 1.64)	Γ(1.91, 1.64)	Γ(1.41, 1.43)	Γ(1.41, 1.43)
s1b	**fs**	1.1	1.2	1.3	1.2	1.3	1.3	1.2	1.2
	Γ(α,β)	Γ(1.41, 1.43)	Γ(1.91, 1.64)	Γ(2.37, 1.78)	Γ(1.91, 1.64)	Γ(2.37, 1.78)	Γ(2.37, 1.78)	Γ(1.91, 1.64)	Γ(1.91, 1.64)
s1c	**fs**	1.2	1.4	1.4	1.3	1.2	1.2	1.1	1.1
	Γ(α,β)	Γ(1.91, 1.64)	Γ(2.78, 1.97)	Γ(2.78, 1.97)	Γ(2.37, 1.78)	Γ(1.91, 1.64)	Γ(1.91, 1.64)	Γ(1.41, 1.43)	Γ(1.41, 1.43)

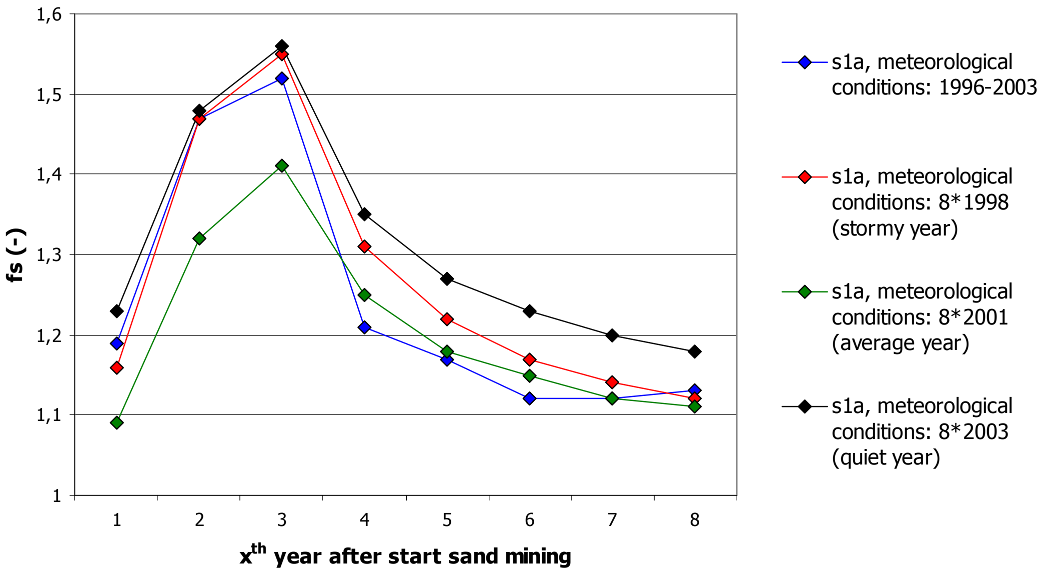

Figure 4.36 Relative increase of the silt concentration during spring (*fs*) for sand mining scenario s1a and different meteorological conditions, location GR6 [calculated from model results WL | Delft Hydraulics, DESMIT *et al.* (2007)]

In this chapter was shown that the delay of the algal bloom *D* does not only depend on the increase of the silt concentration by the sand mining *fs*. Also the unpredictable fluctuations of weather conditions influence the duration of this delay strongly. Subsequently the duration of a mismatch does not only depend on this delay *D*, but also on the moment at which the algal bloom would have taken place in the reference scenario (dependent on light intensities and concentrations of suspended matter) and on the moment of hatching of bivalve larvae (possibly dependent on seawater temperature). The duration of a mismatch caused by the sand mining, is strongly dependent on factors from outside the impact-effect chain (factors that are not influenced by the sand mining).

5 Bivalves

In the first section of this chapter some general information is given on the main bivalve species that are found in the Voordelta. In the second section the functioning of the population-dynamical model is explained. This model will be used to model the impact of mismatches, which only affect the bivalves of one year class, on the total bivalve population (see section 3.2.3). The influences of mismatches and food quality on the growth of bivalves are elaborated in sections 5.3 and 5.4. In sections 5.5, 5.6 and 5.7 is determined how the parameters of the population-dynamical model will be varied in the Monte-Carlo analysis in order to simulate the natural variation of the bivalve population size.

5.1 Bivalves in the Voordelta

Bivalve species that are predominantly found in the Voordelta are cockles (*Cerastoderma edule*) and American razor shells (*Ensis directus*). Cut trough shells (*Spisula subtruncata*), and nuns (*Macoma balthica*) are found in smaller quantities.

5.1.1 Razor shells (*Ensis*)

The American razor shell is in fact an exotic species, originating from the Atlantic coast of North America. Since 1979 American razor shells are found in Europe. Especially during the last few years, the population of American razor shells has increased considerably in the Voordelta. Razor shells are one of the most important bivalve species in the Dutch coastal waters nowadays. [WIJSMAN *et al.* (2006)]

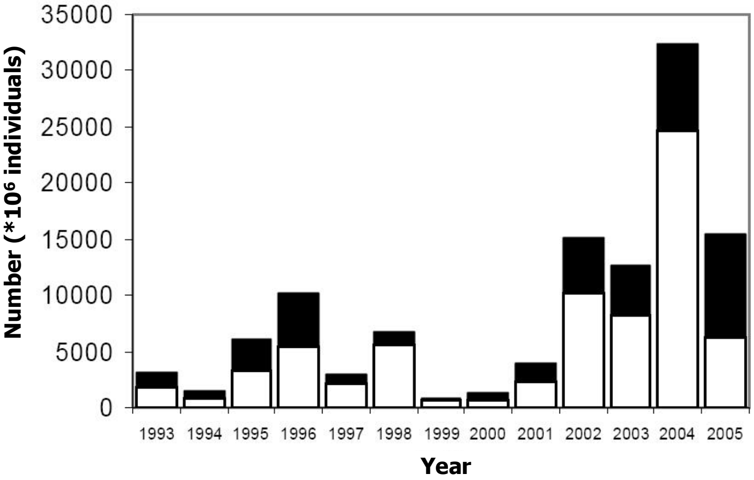

Figure 5.1 ***Ensis* in the Voordelta (amount of *Ensis* within the Natura 2000-area in white), calculated from inventories during spring (RIVO-CSO), figure from WIJSMAN *et al.* (2006)**

Razor shells seldom become older than 4 years [WIJSMAN *et al.* (2006)]. The shell length of razor shells of this age is 13.3 – 15.2 cm [Armonies and Reise (1999) in WIJSMAN *et al.* (2006)]. However, eider ducks prefer to eat razor shells of 5 to 10 cm [LEOPOLD *et al.* (2007)]. Common scoters prefer shells with a length of 3 to 9 cm [LEOPOLD *et al.* (2007)]. On the average, a length of 9 or 10 cm is already reached during the second growing season of razor shells.

In the EIA is assumed that the sand mining activities will result in a growth lag of bivalves, which subsequently causes a decrease of the total amount of edible bivalves for eiders and scoters. However, as razor shells are not edible for eiders and scoters during their whole life (they get too long for these ducks) it is unlikely that a growth lag will result in a significant decrease of the total biomass of edible razor shells. Razor shells with a growth lag reach the 'edible length' later, but are also edible until a higher age. As it is not likely that the sand mining will result in a decrease of the total biomass of edible razor shells, the variables and parameters of the population-dynamical model will be based on data about cockles. Cockles are the second most important food for eiders and scoters in the Voordelta.

Figure 5.2 American razor shell (*Ensis directus*), photo: YvK

5.1.2 Cockles (*Cerastoderma edule*)

Within the Voordelta, cockles are almost exclusively found in the Haringvliet estuary [Craeymeersch and Wijsman (2006)]. The amount of cockles shows a large fluctuation, mainly caused by the large variation of recruitment and mortality rates. Figure 5.3 shows the variation of the amount of cockles from 1993 to 2004.

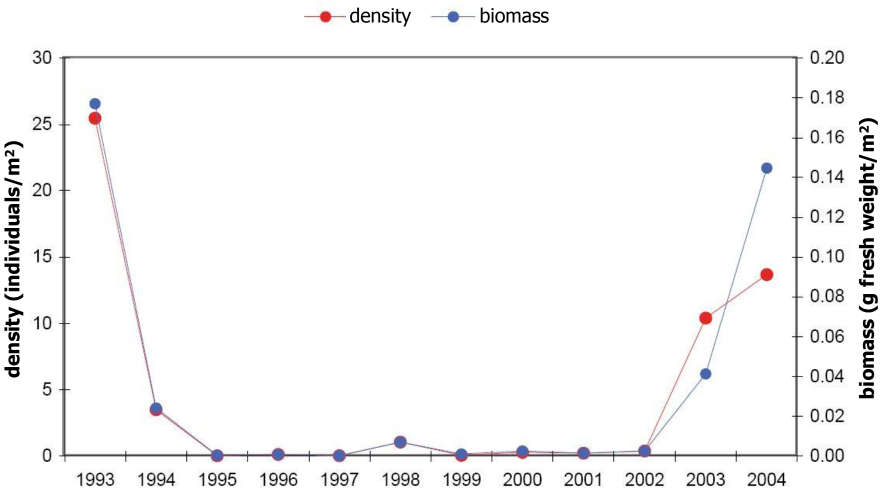

Figure 5.3 Density and biomass of cockles in the Voordelta, 1993-2004, figure from Rijkswaterstaat (2007a)

Eiders prefer to eat cockles with a length of 20 to 25 mm [Ens and Kats (2004)]. However, eiders are able to eat cockles until a length of 40 mm. This means that cockles are edible until an age of circa 5 years old (derived from the data of table 5.1). As hardly any cockles get older than 5 years, a growth lag probably leads to a decrease of the total biomass of edible cockles. Cockles are edible for eiders after their second growing season.

Table 5.1 **Measured shell lengths from Twisk (1990) [KAMERMANS *et al.* (2003)]**

Age:	**Shell length (mm)**	
	May	September
1-year old	13.15	23.11
2-year old	21.02	25.59
3-year old	25.68	30.49

Figure 5.4 **Cockles (*Cerastoderma edule*), photo: YvK**

5.1.3 Cut trough shells (*Spisula subtruncata*)

Until 1998 cut trough shells formed an important part of the diet of ducks in the Voordelta. After 1995, the population size decreased rapidly. Nowadays hardly any cut trough shells are found in the Voordelta. Subsequently, sea ducks changed their diet from *Spisula* to *Ensis*.

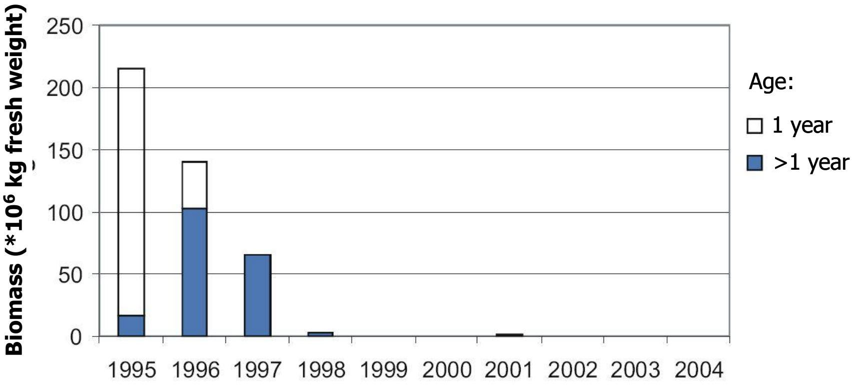

Figure 5.5 **Biomass of Spisula in the Voordelta, figure from CRAEYMEERSCH AND PERDON (2004)**

Like cockles, cut trough shells are also edible for ducks from 1.5 year old until their maximal age. An impact of sand mining activities on the growth of Spisula due to a mismatch is very unlikely, as Spisula spawns in June-July [CARDOSO *et al.* (2007a)]. The probability is very small that the algal bloom takes place after the spawning of *Spisula*.

Figure 5.6 Spisula, photo: YvK

5.2 Population dynamical model

A population of bivalves is built up of individuals of different year classes (a year class exists of all individuals that are born in the same year). In a population-dynamical model, the biomass of a certain year class in a certain year is calculated as a function of the biomass in the previous year, the growth rate and the survival rate. This is illustrated in figure 5.7.

The total biomass of a year class is:

$$BM = N \cdot W \tag{5.1}$$

With: BM = biomass of a certain year class within the population [kg]
N = number of individuals of a certain year class [-]
W = biomass of an individual bivalve of the specified year class [-]

The biomass per individual will increase during time because of growth. The number of individuals of a certain year class decreases, as a result of mortality. Growth and mortality are incorporated in the population-dynamical model by growth factors ($G > 1$, see also appendix C) and survival rates ($0 \leq S \leq 1$).

The sand mining activities for MV2 can have an impact on the total biomass of bivalves in the Voordelta due to a mismatch and due to a decrease of the food quality for bivalves (see chapter 2). A mismatch as well as a decrease of the food quality can hamper the growth of bivalves. Thus, the biomass of individual bivalves can be affected. An effect on the number of individuals is not expected (see section 5.7). The possible impacts of the mismatch and decreased food quality are taken into account in the model by factors EM ($0 \leq EM \leq 1$) and EQ ($0 \leq EQ \leq 1$) respectively (see sections 5.3 and 5.4).

The total biomass of 0-year old bivalves is September is calculated as:

$$BM_{A=0,i} = NR_i \cdot SR_i \cdot WR_i \cdot G_{A=0} \cdot EM_i \cdot EQ_i \tag{5.2}$$

With: NR = number of recruits (newborn larvae) [-]
SR = survival rate of recruits [-]
WR = biomass of an individual recruit [kg]
G = growth factor [-]
EM = factor to take into account the effect of a mismatch [-]

EQ = factor to take into account the effect of a changed food quality [-]
i = index for a certain year
A = age of the bivalves [year]

The total biomass of *j*-year old bivalves in September of year *i* is calculated as:

$$BM_{A=j,i} = BM_{A=j\text{-}1,i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=j} \cdot EQ_i \qquad (5.3)$$

With: SS = survival rate during summer [-]
SW = survival rate during winter [-]

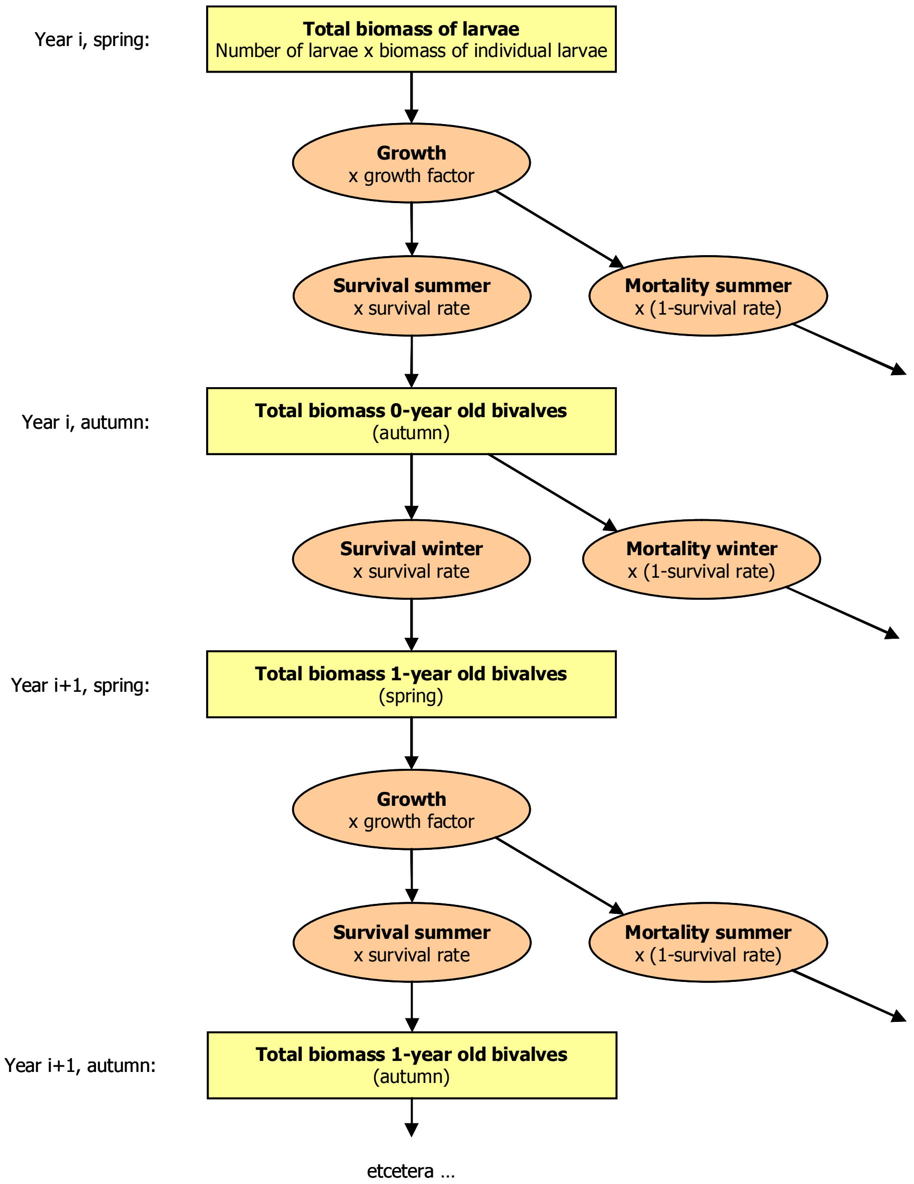

Figure 5.7 **Calculation of the total biomass of a certain year class within the population dynamical model. ***

Equations 5.1-5.3 and figure 5.7 illustrate the calculation of the biomass of one year class. To

---

*Bivalves such as cockles hardly grow during winter [Kamermans *et al.* (2003)]

calculate the total biomass of a population, the biomasses of all year classes have to be summarized. If bivalves can become 4 years old, the total biomass of a population of bivalves in a particular year can be modelled as follows:

$$
\begin{array}{rl}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i \cdot EQ_i = BM_{A=0,i} & \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} \cdot EQ_i = BM_{A=1,i} & \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} \cdot EQ_i = BM_{A=2,i} & \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot EQ_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} \cdot EQ_i = BM_{A=3,i} & \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot EQ_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot EQ_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} \cdot EQ_i = BM_{A=4,i} & \\
\hline
TBM_i & +
\end{array}
$$

Equation 5.4

With: BM = total biomass of a certain year class within the population [kg]
TBM = total biomass of the population [kg]

In the EIA all the variables of the population-dynamical model were assumed to be constant. In the probabilistic approach, the variation of these variables will be taken into account by means of a Monte Carlo analysis. The variables *NR*, *SR*, *SW* and *SS* show a large variation in nature. The value of *EM* contains a large uncertainty margin, as a result of lack of knowledge about the impact of mismatches on the growth of bivalves. In the following sections will be explained how the values of the variables in the population-dynamical model will be varied in the Monte Carlo analysis.

5.3 Effect of a mismatch

The effect of a mismatch of larvae and their prey (phytoplankton) has predominantly been investigated and demonstrated for commercial fish species. Unfortunately only little is known about the effect of a mismatch on the growth of bivalves. PHILIPPART *et al.* (2003) have shown in a correlation study that the variation in recruitment of balthic tellins (*Macoma balthica,* also called nuns) may be partly due to the match/mismatch of larvae and phytoplankton. To test the match/mismatch hypothesis for *Macoma balthica*, some laboratory experiments were done by Bos *et al*. [BOS *et al.* (2006) and BOS *et al.* (2007)]. The results of these laboratory experiments are the only data on which a quantitative relation between the duration of the mismatch and growth of bivalves can be based.

The laboratory experiments of Bos *et al*. are described in subsection 5.3.1. On the basis of the results of these experiments, a relation between the algal concentration and the growth rate of larvae is determined in 5.3.2. In subsection 5.3.3 a relation between the duration of a mismatch, the algal concentration and the growth lag of bivalves is derived.

The match/mismatch hypothesis

The match/mismatch hypothesis of Cushing (1975) [BOS *et al.* (2006)] states that variability in fish recruitment is caused by annual variation in temporal and/or spatial overlap between fish larvae and prey. The underlying assumptions are: (1) that spawning occurs at a fixed time with little annual variation and (2) that prey reproduction is coupled to primary production, which varies on a yearly basis due to environmental stochasticity.

Figure 5.8 Balthic tellins/nuns (*Macoma balthica*), photo: YvK

5.3.1 The laboratory experiments of Bos *et al.*

Bos [Bos *et al.* (2006) and Bos *et al.* (2007)] did two different laboratory experiments in which he exposed nun larvae to varying phytoplankton concentrations and measured the growth of these larvae.

First laboratory experiment [Bos *et al.* (2006)]

The goal of the first laboratory experiment was to test the match/mismatch hypothesis for bivalves. Bos *et al*. varied the fertilisation date and the food level for different batches with *Macoma balthica* larvae. The fertilisation date was varied by fertilising 6 batches with eggs (A, B, C, D, E and F) at different dates within the spawning season of the bivalve. Three 'food levels' were applied to the larvae. The first food level (SW1) consisted of filtered natural seawater. The concentration of larvae was set at 1 larva ml^{-1}. The second food level (SW5) was identical of that of SW1, but the concentration of larvae was set at 5 larvae ml^{-1}. The third food level (Control) consisted of UV-irradiated seawater enriched with $5.0*10^4$ cells ml^{-1} of the micro alga *Isochrysis galbana*. During the experiment, the seawater was changed three times per week. [Bos *et al.* (2006)]

Figure 5.9 shows the variation of the concentration of edible phytoplankton taxa in the seawater during the experimental period, for the food levels SW1 and SW5. Phytoplankton taxa with a maximum length of 20 µm were assumed to be palatable, since *Macoma balthica* larvae probably only ingest food particles up to the diameter of their mouth, i.e. up to circa 20 µm. Also phytoplankton taxa that formed chains or colonies were not considered suitable. The concentration of palatable phytoplankton cells was measured every time that the seawater was refreshed. How phytoplankton concentrations changed in the period between two refreshes of seawater is not known. Also the forming or disintegration of chains and colonies may cause a (unknown) variation of the concentration of palatable phytoplankton within this period (pers. comm. O. van Tongeren).

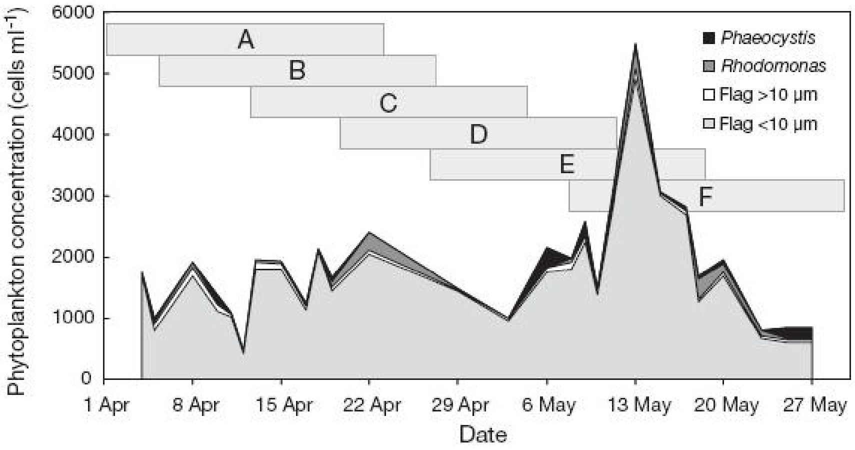

Figure 5.9 Concentration of palatable phytoplankton taxa during the experimental period in the seawater. The duration of the rearing period for each batch (A to F) of Macoma balthica larvae is indicated by blocks. Figure from Bos *et al.* (2006)

Bos *et al.* (2006) measured the shell length at several times during the experiment and calculated the growth rate with the following linear model:

$$LS = LS_{initial} + g \cdot (A - 3) \tag{5.5}$$

LS = shell length [µm]
$LS_{initial}$ = initial shell length, shell length at third day after fertilization [≈154 µm]
g = growth rate [µm d^{-1}]
A = age [d]

Table 5.2 Results of the first laboratory experiment of Bos *et al.* (2006)

	Larval concentration (ml^{-1})	Algal concentration (cells ml^{-1})	**Growth rate (µm d^{-1})**							
			Batch:							
			A	B	C	D	E	F	µ	σ
SW1	1	see figure 5.9	1.9	2.3	2.0	4.0	2.3	3.6	2.7	0.4
SW5	5	see figure 5.9	1.5	2.2	1.9	3.8	1.9	3.1	2.4	0.4
Control	1	$5.0 * 10^4$	5.5	5.2	4.5	5.5	3.0	5.1	4.8	0.4

Second laboratory experiment [Bos *et al.* (2007)]

The main goal of the second experiment of Bos *et al.* was to investigate the effects of temporary food limitation on development and mortality of *Macoma balthica* larvae. *Macoma balthica* larvae were reared under food limiting conditions, both quantitatively (high or low food level) and temporarily (starvation in the first, second or third week). Table 5.3 gives an overview of the phytoplankton concentrations to which the batches were exposed during week 1, 2 and 3. Starvation in the first week led to smaller larvae after 24 days than starvation in the second or third week. Also the measured shell lengths of the 24-day old larvae are shown in table 5.3.

Table 5.3 **Experimental set-up of 2nd experiment and resulting shell lengths and growth rates [Bos *et al.* (2007)]**

Batch:	**Food availability (palatable cells ml^{-1})**			Mean shell length at day 24 (µm)	Mean growth rate between days 3 and 24 (µm d^{-1})
	Week 1	Week 2	Week 3		
OHH	0	8*10^4	8*10^4	291.9	5.5
HOH	8*10^4	0	8*10^4	319.2	7.6
HHO	8*10^4	8*10^4	0	312.2	7.7
OLL	0	4*10^3	4*10^3	227.5	3.3
LOL	4*10^3	0	4*10^3	258.2	4.9
LLO	4*10^3	4*10^3	0	265.5	5.2

5.3.2 Growth rate

Figure 5.10 shows the measured growth rates of *Macoma balthica* for the different phytoplankton concentrations (averaged over 24 days). A sigmoid curve is fitted to these data:

$$g = \frac{a}{1 + e^{-b(\overline{Calg} - c)}} \tag{5.6}$$

g = growth rate [µm d^{-1}]
$\overline{Calg}$ = average phytoplankton concentration during the mismatch [cells ml^{-1}]
a, b, c = parameters [-]

A sigmoid curve is chosen as it will be hardly possible for bivalves to grow in case of low food concentrations; a large part of the ingested food will be necessary for respiration. If a certain high food concentration is exceeded, the availability of food will not longer be a limiting factor for the growth of the bivalves.

Two different curves are fitted to the data; one is only based on the data of the first experiment, the other curve is based on the data of the first as well as the second experiment. Batches *OLL* and *OHH* of the second experiment were left out of consideration for fitting the curves, as the complete absence of food during the first week obviously had a large effect on the shell length after 24 days. Therefore these results will certainly not be representative for cases with a more constant phytoplankton concentration (and the same average concentration).

The value of parameter *a* of equation 5.6 (the maximal growth rate) is based on the results of the 'control' food concentration of the first experiment and the results from batches *HHO* and *HOH* of the second experiment. The values of parameters *b* and *c* are subsequently optimized by using the least squares method; minimising the sum of the squared differences between the observations and the assumed model:

$$\chi^2 = \min_{\vec{\theta} \to \hat{\theta}} \sum_{i=1}^{N} \left\{ y_i - g\left(\vec{f}, \vec{\theta}\right) \right\}^2 \tag{5.7}$$

θ = set of parameters
y = observed growth rate

For the growth rate in case of the complete absence of phytoplankton, the following boundary condition has been used for fitting the curve:

$$g(\overline{Calg} = 0) < 0.05\ \mu\mathrm{m\ d^{-1}}$$

The optimisation has led to the following curves:

Based on the 1st experiment: $$g = \frac{4.8}{1 + e^{-0.0025(\overline{Calg} - 1850)}} \qquad (5.8)$$

Based on both experiments: $$g = \frac{5.5}{1 + e^{-0.0024(\overline{Calg} - 2000)}} \qquad (5.9)$$

Based on these results the phytoplankton concentration necessary for maximal growth is estimated at $4*10^3$ cells/ml ($g(\overline{Calg} = 4000) > 0.99 * g_{\max}$).

Given the large scatter of the measured data (see figure 5.10), equations 5.8 and 5.9 are not suitable for an accurate estimate of growth rates as a function of the phytoplankton concentrations. However, as the estimated concentration of 4000 cells/ml for maximal growth corresponds reasonably with results of Clausen and Riisgård (1996), this concentration will be used to determine if a mismatch occurs or not (see section 4.4). Based on laboratory experiments, Clausen and Riisgård (1996) estimated the algal concentration necessary for the maximal growth of adult blue mussels (Mytilus edulis) at 4500 cells/ml.

Whether fitting equation 5.6 to all measurements of the first experiment (SW1 and SW5) is correct is discussable (it is not known which larval concentration is more representative for the Voordelta). However, fitting the curves only to SW1- or SW5-data, would also lead to the conclusion that a concentration of $3.5*10^3$ to $4.0*10^3$ cells is sufficient for maximal growth. Also fitting a linear relation (between 0 and the concentration at which the maximal growth is reached) would lead to the same conclusion.

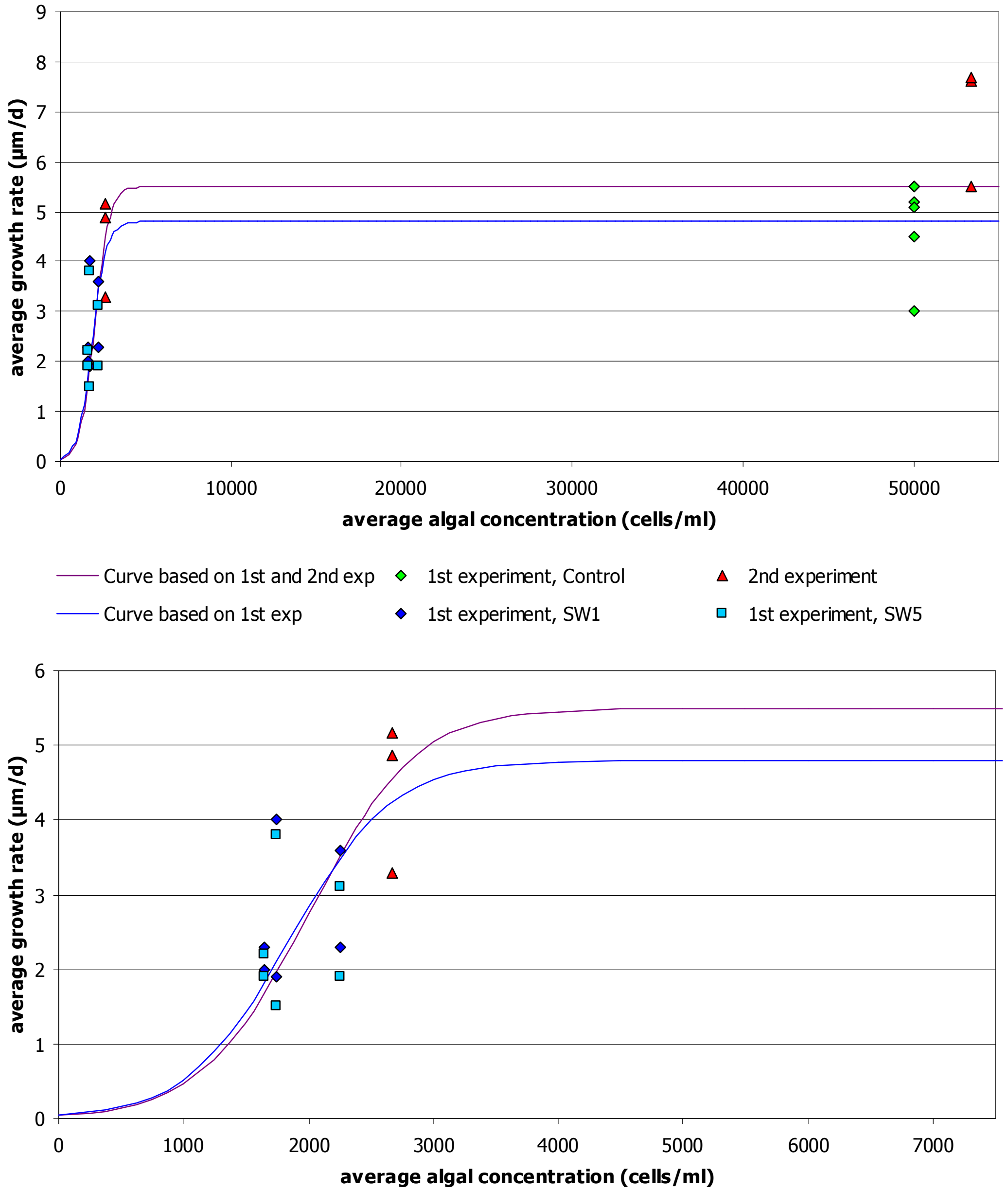

Figure 5.10 Relation between growth rates and food concentration, data measured by Bos *et al.* (2006) and Bos *et al.* (2007). The graph below is and enlargement of a part of the graph above.

5.3.3 Effect of the mismatch

The magnitude of the mismatch-effect on the biomass of newborn bivalves is dependent on the duration of the mismatch and the food concentration during this mismatch. The following formula will be used to estimate the effect of the mismatch, as a function of the growth rate (which is dependent on the food concentration) and the duration of the mismatch:

$$EM\left(M_{spawn}, g(\overline{Calg})\right) = 1 - GL\left(M_{spawn}, g(\overline{Calg})\right)$$

$$GL\left(M_{spawn}, g(\overline{Calg})\right) = 1 - \frac{WR_{mismatch}(M_{spawn}, g(\overline{Calg}))}{WR_{match}(g_{\max})} \tag{5.10}$$

$$= 1 - \left(\frac{LS_{initial} + (M_{spawn} - 3) \cdot g(\overline{Calg}) + (24 - M_{spawn}) \cdot g_{\max}}{LS_{initial} + 21 \cdot g_{\max}} \right)^{2.8}$$

With: EM = factor to take into account the effect of a mismatch [-]
M_{spawn} = duration of mismatch between the moment of spawning and the moment of the algal bloom [days]
g = growth rate [µm d^{-1}]
$\overline{Calg}$ = average phytoplankton concentration during the mismatch [cells ml^{-1}]
GL = relative growth lag, percentage that the larvae are smaller than they would have been without the mismatch [-]
$LS_{initial}$ = initial shell length, shell length at third day after fertilization (≈154 µm)

Equation 5.10 is based on the formula for the growth of the shell length as used by Bos (equation 5.5) and on the following relation between fresh weight and shell length of cockles from KESTELOO *et al.* (2006):

$$FW = 0.7280 \cdot LS^{2.8108} \tag{5.11}$$

FW = fresh weight [mg]
LS = shell length (µm)

The biomass of cockles is assumed to be linearly related to the fresh weight. Instead of the non-linear relation of equation 5.11, a linear relation between shell length and biomass was used in the EIA. Because of this, the estimated effect of a mismatch on the size of larvae is larger in this thesis than in the EIA.

Figure 5.11 shows the growth lag of larvae for different food concentrations and for a duration of the mismatch of 10 and 24 days, as calculated by equation 5.10. Equation 5.8 was used for the relation between food concentration and growth rate. The curves are compared to measurements of Bos *et al.* [BOS *et al.* (2006) and BOS *et al.* (2007)].

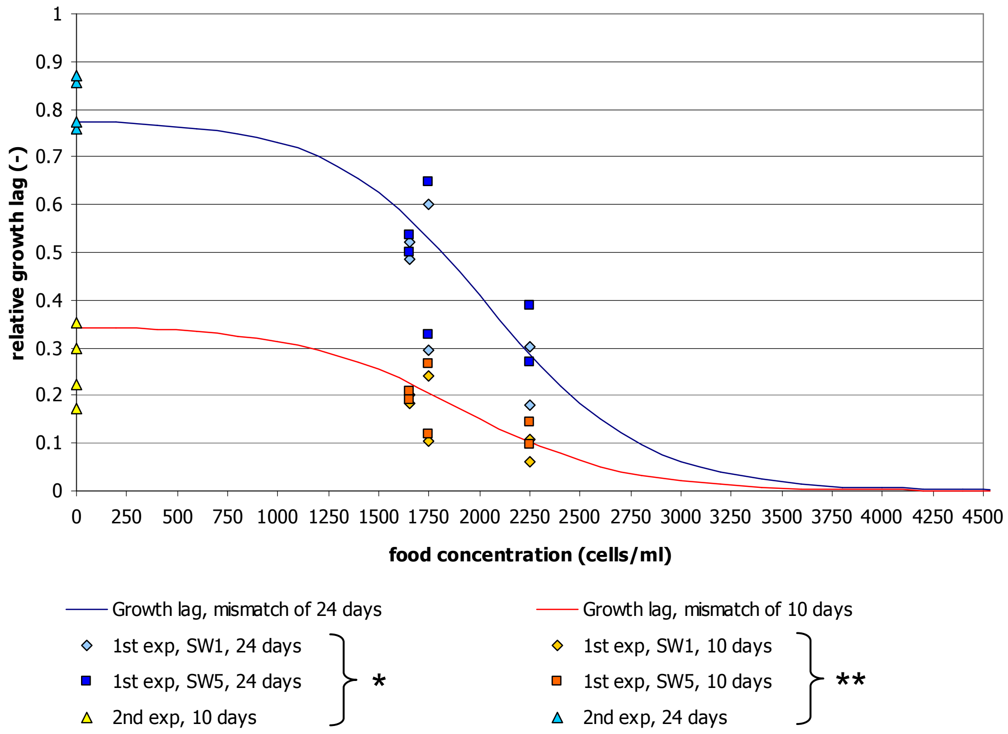

Figure 5.11 Effect of a mismatch as a function of food concentration and duration
***directly derived from measurements [Bos *et al.* (2006) and Bos *et al.* (2007)]**
****estimated from measurements**

As can be seen in figure 5.11, the growth lag due to a mismatch is not estimated accurately by equation 5.10. Also the measured growth lags, for the same food concentration and duration, show large differences. To take into account this scatter in the probabilistic approach, the effect of the mismatch *EM* will be calculated by use of equation 5.10 and subsequently be adjusted by a correction factor *CF*, randomly chosen from a normal distribution:

$$EM_{corrected} = 1 - GL(M, g(Calg)) \cdot CF \qquad (5.12)$$

The mean and standard deviation of *CF* is based on the ratio of the measured growth lags, over the growth lags calculated by equation 5.10 (correction factor *CF* in equation 5.12). For each measured growth lag *CF* is calculated. The results and the fitted normal distribution are shown in figure 5.12.

$$CF = \frac{GL_{measured}}{GL_{calculated}} \qquad (5.13)$$

CF = correction factor [-]

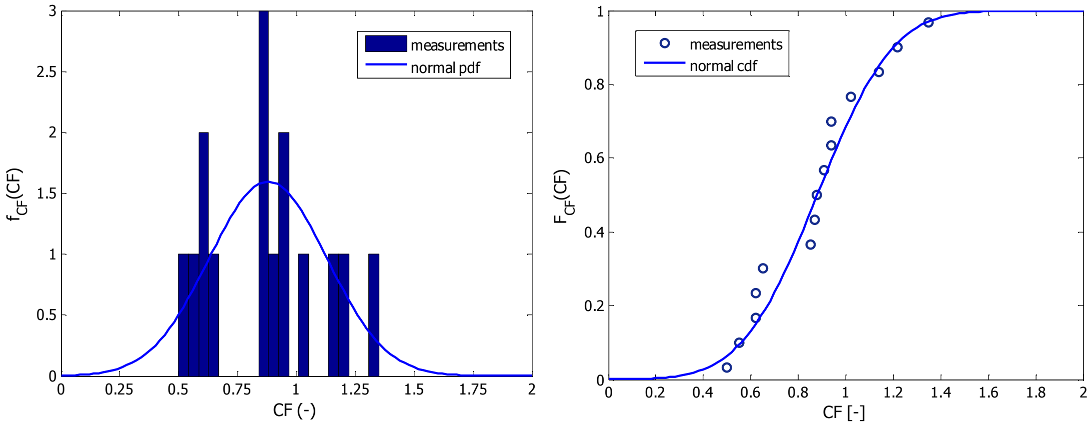

Figure 5.12 Histogram of correction factor *CF* and normal distribution (μ=0.88, σ=0.25)

Remarks

By equation 5.10 the size of the larvae, which are exposed to a mismatch, is compared to the size of larvae without a growth lag, both at an age of 24 days. The calculated effect of a mismatch would be smaller if the size of the larvae was compared at a higher age. The choice of the age of 24 days is quite arbitrary. More knowledge on the growth of larvae would be necessary to make a better founded choice. Until which age the growth of larvae can be modelled reasonably by the linear model of equation 5.5 is not known.

The experiments of Bos *et al.* were carried out for *Macoma balthica* larvae. To what extent the results are representative for cockles is unfortunately not known. So, the uncertainty margin of *EM* is in fact larger than the margin that will be taken into account by *N* in equation 5.11.

5.3.4 Input for the Monte Carlo analysis

The duration of the mismatch M is in the Monte Carlo analysis determined by the probability density functions of the moment of the algal bloom in the reference scenario A_{ref}, the moment of hatching H and the delay of the algal bloom D.

$$M_{hatch} = H - A_{ref} - D$$

In equation 5.10, the mismatch between spawning and the algal bloom, instead of the mismatch between hatching and bloom has been used. This formula will be adjusted as follows to be able to use M_{hatch} as input variable:

$$
\begin{aligned}
&M_{hatch} = M_{spawn} - 3 \\
&GL\left(M_{hatch}, g(\overline{Calg})\right) = CF \cdot \left(\frac{LS_{initial} + M_{hatch} \cdot g(\overline{Calg}) + (21 - M_{hatch}) \cdot g_{\max}}{LS_{initial} + 21 \cdot g_{\max}} \right)^{2.8} \\
&EM\left(M_{hatch}, g(\overline{Calg})\right) = 1 - GL
\end{aligned}
\tag{5.14}
$$

The initial shell length *LS* is the shell length at the moment of hatching (which was assumed to occur three days after spawning, see section 4.5). The value of *CF* will be chosen randomly from a normal probability density function (μ=0.88, σ=0.25). Besides the duration of the mismatch, also the algal concentration during this mismatch influences *EM*.

One month before the algal bloom, measured concentrations vary between 200 and 3800 cells/ml (see appendix E). For a long duration of the mismatch the average algal concentration can also be a concentration between circa 200 and 3800 cells/ml. However, in case of a short duration of the mismatch, very low concentrations are unlikely. Within for example 2 days, the algal concentration can impossibly increase from 200 to 4000 cells/ml (the critical concentration). Assuming that the algal concentration can maximally increase by a factor 2.5 during 1 day, the minimal concentration 2 days before the algal bloom is 640 cells/ml (=4000/2.5^2). The average algal concentration during the mismatch period of 2 days, will be much higher; circa 1800 cells/ml. Using low algal concentrations during short mismatch periods will overestimate the effect of a mismatch on the size of larvae. Therefore the algal concentration will be chosen from uniform distributions with different lower limits, dependent on the duration of *M* (see table 5.4).

Table 5.4 Upper and lower limits for the uniform probability density function of the average algal concentration during the mismatch, dependent on the duration of the mismatch

M [days]	1	2	3	4	5	6	7	>7
Upper limit [*10^3 cells/ml]	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Lower limit [*10^3 cells/ml]	2.5	1.7	1.3	1.0	0.8	0.6	0.4	0.2

Equation 5.8 will be used in the Monte Carlo analysis for the relation between the algal concentration and the growth rate. This growth rate will be used in equation 5.10 to calculate *EM*, which will be used as input for the population dynamical model.

$$
\begin{array}{rl}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i \cdot EQ_i = BM_{A=0,i} & \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} \cdot EQ_i = BM_{A=1,i} & \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} \cdot EQ_i = BM_{A=2,i} & \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot EQ_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} \cdot EQ_i = BM_{A=3,i} & \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot EQ_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot EQ_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot EQ_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot EQ_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} \cdot EQ_i = BM_{A=4,i} & \\
\hline
TBM_i & +
\end{array}
$$

Equation 5.15

Figure 5.13 shows the relation between the duration of the mismatch, the average algal concentration and the relative growth lag (for *CF*=0.88).

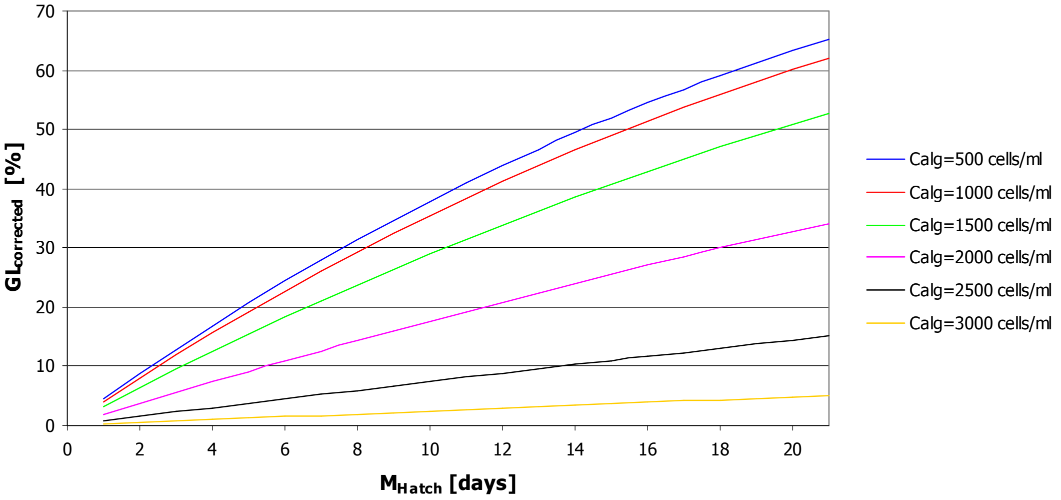

Figure 5.13 Relation between the duration of the mismatch M_{Hatch} and the relative growth lag for different algal concentrations

5.4 Food quality

As a worst-case approach a relation between the growth of bivalves and the quality of their food was taken into account in the EIA. Food quality is defined as the ratio of the concentration edible matter (phytoplankton) over the concentration inedible matter (silt). However, it is questionable if the relation between growth and food quality exists.

Bivalves like cockles and mussels feed by siphoning water in and out. In this way, the bivalves filter the organic as well as the inorganic part of the SPM. However, bivalves can only utilize the organic, digestible part of the SPM, such as phytoplankton, bacteria and decomposable detritus. For sorting the organic matter from the inorganic matter, bivalves have labial palps. These palps divert the non-utilizable particles from the mouth. Subsequently these particles are expelled as pseudofaeces [ESSINK (1999)].

5.4.1 Relation in the EIA

The relation between food quality and the size of bivalves that was used for the EIA, was based on a graph of BRINKMAN AND SMAAL (2003) (see Figure 5.14). BRINKMAN AND SMAAL (2003) related the fitness of the mussels (defined as the ratio of the biomass of the mussel over the fresh weight) to the food quality. A decrease of the fitness of bivalves, as a result of a lower food quality, might also lead to a smaller amount of food for ducks. The data in Figure 5.14 are measurements over the period 1976 to 2001. The food quality was calculated as the summer-averaged (Jul-Nov) chlorophyll-a concentration over the summer-averaged silt concentration. The fitness of the mussels was based on measurements within the period August-November. The measurements of 2001 were not taken into account by the calculation of the trend line (black line in the graph).

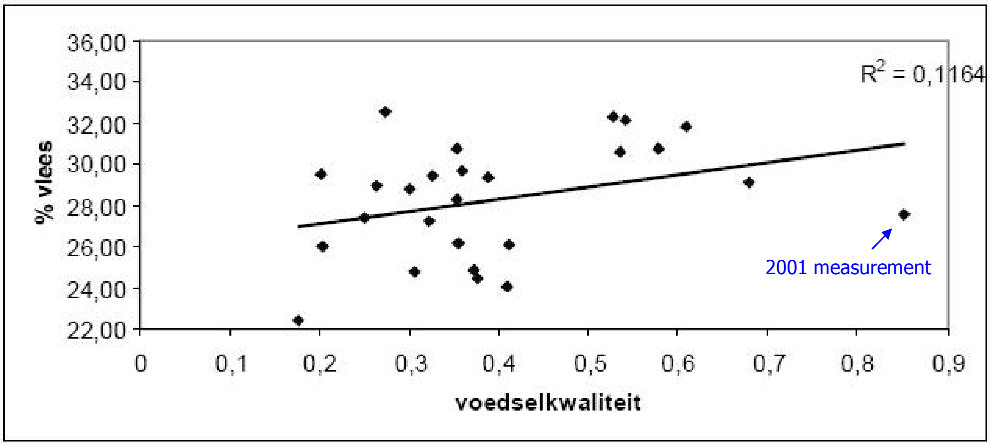

Figure 5.14 **Relation between fitness (=%vlees) of mussels and food quality (=voedselkwaliteit) (concentration chlorophyll (µg/l) / silt concentration (mg/l)), figure from BRINKMAN AND SMAAL (2003)**

On the basis of the data of Figure 5.14 it seems unlikely that a strong relationship between the fitness of mussels and the food quality exists. However, the data also do not proof that the relation does not exists. For the relation between the total biomass of bivalves and the food quality, also information about the size of the mussels is relevant, which is missing in BRINKMAN AND SMAAL (2003). Besides, calculating the average food quality as the summer-averaged chlorophyll-a concentration over the summer-averaged silt concentration, might lead to a result that differs significantly from the real summer-averaged food quality.

5.4.2 Literature research

To be able to take into account the relation between food quality and growth in a probabilistic approach, more and better data are desirable on the probability that the relation exists. If the relation indeed exists, also data are necessary about the shape of this relation. To find this information, literature research has been done. The results are summarized in this subsection. A more detailed description of the findings of the literature research can be found in Appendix F.

The assumption that a relation between food quality and growth exists might be based on the following hypotheses:

- in case of a decrease of the organic content of the SPM, the nett amount of food (organic matter) that the bivalves can eat per unit of time, also decreases;
- in case of a decrease of the organic content of the SPM, the energy costs of feeding increase and cannot be compensated by eating more in the same time (the nett energy intake decreases).

Based on research of ESSINK (1999), NAVARRO AND WIDDOWS (1997) and HAWKINS *et al.* (1996), it seems probable that the rate of food absorption (mg dry organic matter per hour) can be kept constant for SPM-concentrations up to 100 mg/l, regardless of the organic content. Based on model results of WL | Delft Hydraulics, an SPM-concentration of 100 mg/l is exceeded only during storm conditions (for the sand mining scenarios as well as for the reference scenario), which occur seldom during the growing season of bivalves (summer). The summer-averaged (near-bed) SPM-concentration changes from ca. 25 mg/l to 35 mg/l in the third year after the start of the sand mining (which is the year with the largest increase), in case of mining scenario 1a.

Results of Hawkins *et al.* (1996) even showed an increase of the net food intake for increasing SPM-concentrations ($8*10^1$ mg/l), independent of the organic content (which decreased by an increasing SPM-concentration). If the energy costs of feeding are higher in case of low food qualities, these extra energy costs may be compensated by the increase of the food absorption rate.

An increase of the energy costs of feeding in case of a lower food quality might be the result of an increase of the clearance rate (more water has to be siphoned, $l\ h^{-1}$) and the filtration rate (more matter has to be filtered, $mg\ h^{-1}$) and the ingestion of more inorganic matter. In Clausen and Riisgård (1996) is mentioned that from an energetic point of view, only an insignificant saving may be gained by reducing the filtration rate, according to Riisgård and Larsen (1995). If the other mechanisms cause a significant difference of the energy costs of feeding between a sand mining scenario and the reference scenario is not known.

5.4.3 Conclusion

Based on literature research, the validity of the first hypothetical explanation in section 5.4.2 of the relation between food quality and growth seems very unlikely for the range of SPM-concentrations and qualities in the Voordelta. The results of the literature research do not give a conclusive proof of the invalidity of the second hypothetical explanation. However, also no evidence is found in literature of an increase of the energy costs of feeding, in case of a decrease of the food quality. Therefore the assumption will be made that the change of the net energy costs of feeding due to the sand mining activities is negligible. The relation between food quality and the growth of bivalves will not be taken into account in this thesis.

This changes the population-dynamical model (equation 5.4) as follows:

$$\begin{array}{r}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i \cdot \xcancel{EQ_i} = BM_{A=0,i} \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot \xcancel{EQ_{i-1}} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} \cdot \xcancel{EQ_i} = BM_{A=1,i} \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot \xcancel{EQ_{i-2}} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot \xcancel{EQ_{i-1}} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} \cdot \xcancel{EQ_i} = BM_{A=2,i} \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot \xcancel{EQ_{i-3}} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot \xcancel{EQ_{i-2}} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot \xcancel{EQ_{i-1}} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} \cdot \xcancel{EQ_i} = BM_{A=3,i} \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot \xcancel{EQ_{i-4}} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot \xcancel{EQ_{i-3}} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot \xcancel{EQ_{i-2}} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot \xcancel{EQ_{i-1}} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} \cdot \xcancel{EQ_i} = BM_{A=4,i} \\
\hline
TBM_i
\end{array} +$$

Equation 5.16

5.5 Survival rates

Within the population-dynamical model three different survival rates are used (see equation 5.17); the survival rate for recruits (*SR*), the survival during winter (*SW*) and the survival during summer (*SS*). These survival rates are all dependent on different factors. The survival rate for recruits (*SR*) is mainly dependent on the abundance of predators of larvae (see section 5.7). Older bivalves are eaten by other predators, like starfish (*Asterias rubens*), necklace shells (*Euspira catena* and *Euspira nitida*), birds and ducks [Weber and Smit (2004)]. The presence of starfish and necklace shells will only influence the survival rate during summer, as these predators hardly need any food during winter, because of a lower metabolism. The predation of birds and ducks is largest during winter, as most of these predators only winter in the Netherlands. Besides the number of predators also the intensity of fishery and probably several unknown factors will influence the survival rate of bivalves. For the cockle population in the Haringvliet estuary, fresh water discharges are also an important cause for low survival rates [Leopold *et al.* (2007)].

$$\begin{array}{r}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i = BM_{A=0,i} \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} = BM_{A=1,i} \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} = BM_{A=2,i} \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} = BM_{A=3,i} \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} = BM_{A=4,i} \\
NR_{i-5} \cdot SR_{i-5} \cdot WR \cdot G_{A=0} \cdot EM_{i-5} \cdot SW_{i-5} \cdot SS_{i-4} \cdot G_{A=1} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=2} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=3} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=4} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=5} = BM_{A=5,i} \\
\hline
TBM_i
\end{array} +$$

Equation 5.17 **Population-dynamical model for the total biomass of a population (maximal age = 5 years), survival rates shaded**

Unfortunately no measurements of the survival rates of bivalves in the Voordelta are available. The survival rates will therefore be based on mortality rates in the Wadden Sea, Eastern Scheldt and Western Scheldt, that are given in KAMERMANS *et al.* (2003) (see table 5.5). The mortality rates of table 5.5 are measured for cockles older than 1 year and over the period from May till September. Assuming that the mortality rates in these areas are equally representative for the mortality rates in the Voordelta, the estimation of a probability density function is based on all data of table 5.5.

Table 5.5 **Mortality during summer, calculated from measured numbers of cockles in May (or June) and August (or September) [KAMERMANS *et al.* (2003)]**

Year	**Mortality percentage (%)**		
	Wadden Sea	Eastern Scheldt	Western Scheldt
1996	-	11	-
1997	24	-	-
2000	-	58	26
2001	31	34	20
2002	29	18	21

The computer program 'Bestfit' was used to find a probability distribution that fits well to the data. 'Bestfit' fits several distributions to the data and determines the best fitting distribution by using the chi-square test and the Kolmogorov-Smirnov test. On the basis of the results of 'Bestfit' is chosen to use a lognormal distribution (μ=27, σ=13) for the summer mortality percentage in the population dynamical model.

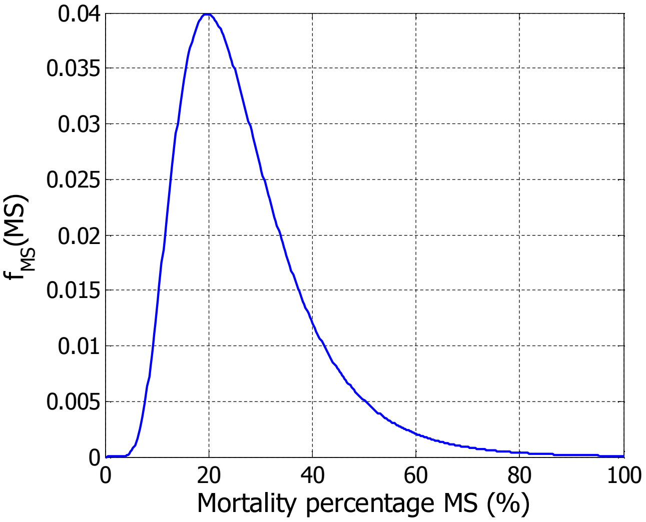

Figure 5.15 **Lognormal distribution for *MS* (mortality percentage during summer, μ=27, σ=13, truncated at 100%)**

Even less information is available on the survival rates during winter than on the survival during summer. In STICHTING ODUS (2001) is mentioned that ca. 65% of all cockles die during one year (based on measurements over the period 1993-1996 in the Wadden Sea). By use of this information the mean winter survival rate can be estimated as:

$$SY = 1 - MY = SS \cdot SW = (1 - MS) \cdot (1 - MW) = 1 - 0.65 = 0.35$$

$$\Rightarrow 1 - MW = \frac{SY}{1 - MS} = \frac{0.35}{1 - 0.27} \Rightarrow MW = 0.52 \qquad (5.18)$$

SY = survival rate for whole year (-)
MY = mortality rate for whole year (-)
MS = mortality rate for summer period (-)
MW = mortality rate for winter period (-)

In the EIA a yearly survival rate of 0.5 is used. In case of a smaller survival rate, the populations will be built up for a larger part from young bivalves (as can be derived from equation 5.17). Due to this the impact of sand mining by a mismatch, will be relatively larger in the first year after the mismatch, and will be smaller in the following years (4-5 years after the mismatch). The influence of the survival rates on the population composition is illustrated in Figure 5.16. This figure shows the population compositions for a constant number of recruits and constant survival rates.

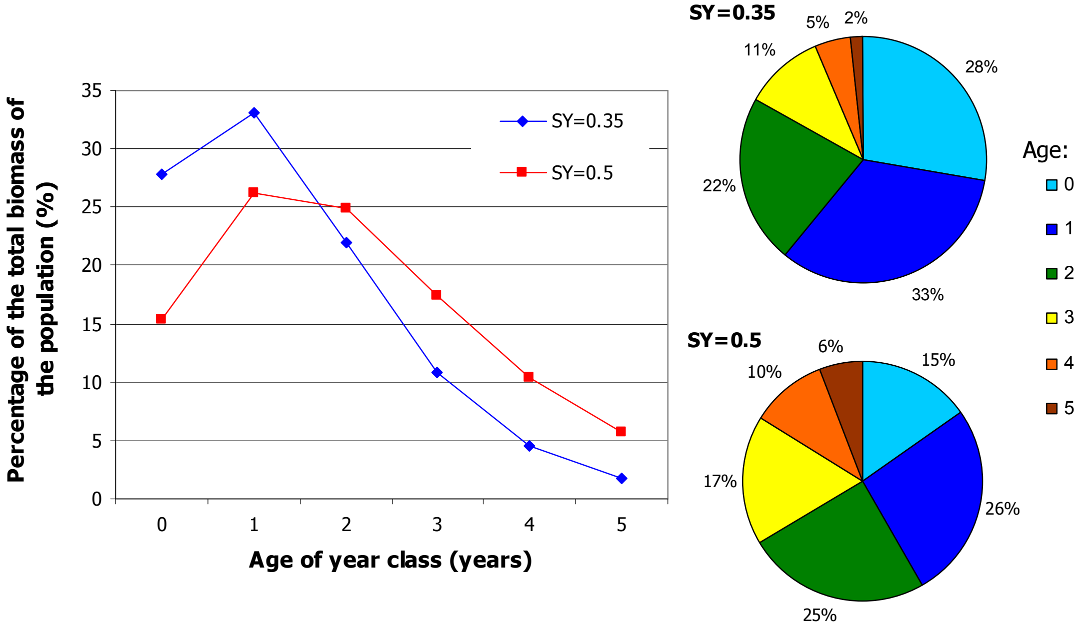

Figure 5.16 Population composition for different survival rates

The Monte Carlo analysis (see chapter 7) will be carried out for two different scenarios for the survival rates. The survival rates are equal to:

$SS = 1 - MS$ and $SW = 1 - MW$

For the mortality rates random values from lognormal distributions with mean values and standard deviations as given in table 5.6 will be used.

Table 5.6 Distributions of the mortality rates that will be used in the Monte Carlo analysis

	SY (-)	MS (-), lognormal distribution		MW (-), lognormal distribution	
		μ	σ	μ	σ
SR scenario 1	0.35	0.27	0.13	0.52	0.15
SR scenario 2	0.5	0.27	0.13	0.31	0.15

For some animal species the fluctuations of the population size is caused to a large extent by the interaction between predator and prey populations. In such case it would not be allowed to use randomly generated survival rates. However, predator-prey dynamics are of minor importance for bivalves and sea ducks. This is clarified in appendix H.

5.6 Growth

5.6.1 Growth models

In the EIA, the growth of bivalves was modelled as follows:

$$W_{Sep} = W_{May} \cdot a(A) \tag{5.19}$$

W_{Sep} = biomass of the bivalve in September [g]
W_{May} = biomass of the bivalve in May [g]
$a(A)$ = growth factor, which is dependent on the age *A* of the bivalve [-]

In the EIA was also assumed that bivalves are not able to catch up a growth lag. This assumption corresponds with equation 5.19, as the growth factor is not dependent on the size of the bivalve. This is also valid for other growth models that are commonly used as the following model [RIISGÅRD AND LARSEN (2000)]:

$$W_t = W_0 \cdot e^{\mu t} \tag{5.20}$$

W_t = mean body mass of bivalves on Day t [g]
W_0 = mean body mass of bivalves on Day 0 [g]
μ = growth rate [d^{-1}]

and the Von Bertalanffy growth curve [Fahy and Gaffney (2001) in WIJSMAN *et al.* (2006)]:

$$L_t = L_\infty \left(1 - e^{-k(t-t_0)}\right) \tag{5.21}$$

L = length of the bivalve [mm]
L_∞ = theoretical maximal length [mm]
k = relative growth rate [d^{-1}]
t_0 = theoretical age at which L=0 [d]

In all these growth models, which are suitable to predict *mean* biomasses or lengths of bivalves, growth factors are only dependent on time, not on the size of the bivalves. As a consequence, bivalves are not able to catch up a growth lag, according to these models. However, in KAMERMANS *et al.* (2003) a 'catching-up phenomenon' is mentioned; observations showed that small cockles grew faster than large cockles of the same age. KAMERMANS *et al.* (2003) determined the following relation between the biomass of cockles in May and their biomass in September:

$$W_{Sep} = 3.82 \cdot W_{May}{}^{0.51} \qquad (5.22)$$

A relation between the growth rate and the mass of a bivalve can be explained by the ratio of the surface area of the intestines (~length^2) over the total mass (~length^3). The amount of food that can be digested is dependent on the surface area of the intestines. The amount of nutrients that is necessary for growth and maintenance depends on the total biomass of the animal. The ratio between the surface area of the intestines and the total biomass is less favourable for large shellfish than for small shellfish. (pers. comm. O. van Tongeren)

The difference between growth models like equations 5.19 – 5.21 and equation 5.22 will be illustrated in the following example.

5.6.2 Example

In the Clyde Sea (Scotland) the parameters of the Von Bertalanffy growth curve are estimated as follows for *Ensis siliqua* [Muir (2003) in WIJSMAN *et al.* (2006)]:

$$L_t = 233.80 \cdot \left(1 - e^{-0.15(t+0.01)}\right) \qquad (5.23)$$

These parameters are probably fitted on data of mean lengths of razor shells of 1 to 4 years old (razor shells like *Ensis siliqua* seldom get older than 4 years [WIJSMAN *et al.* (2006)]). Probably it is also possible to fit a curve as equation 5.22 to these data, as illustrated in figure 5.17 (shape of curve is equal for razor shells of 1 to 4 years old):

$$L_{A=i+1} = 7.3 \cdot L_{A=i}{}^{0.6} \qquad (5.24)$$

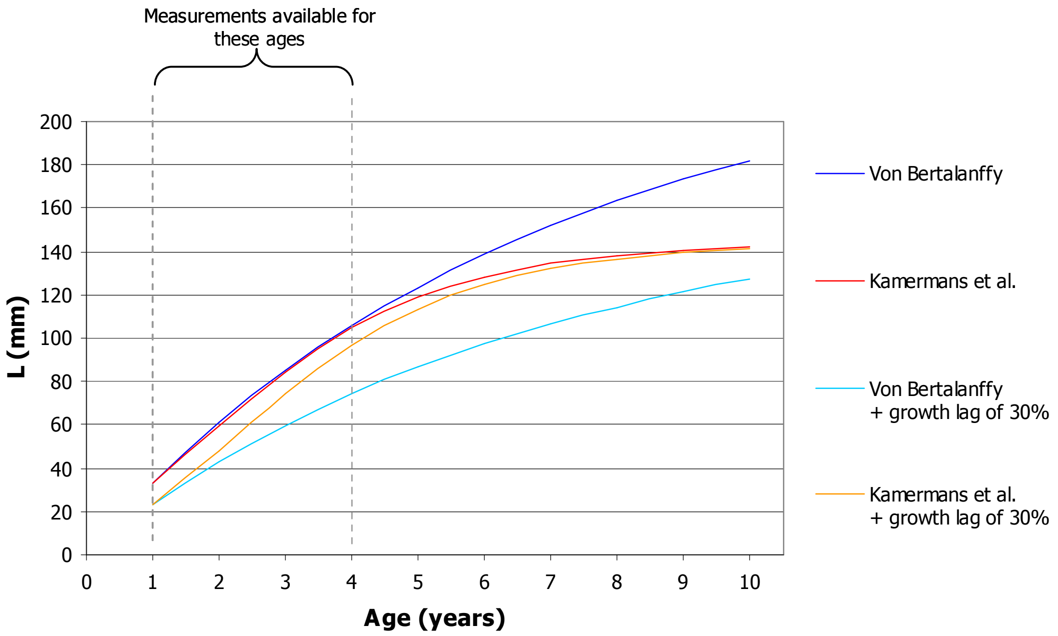

Figure 5.17 Different growth models fitted to the same data of *Ensis siliqua*

According to growth models like equations 5.19 – 5.21, bivalves that suffer a growth lag of 30% at the start of their life, will always be 30% smaller than bivalves without a growth lag. According to the model of KAMERMANS *et al.* (2003), the growth lag will be catched up for a large part; at an age of 4 years, the remaining growth lag is 7%.

Also observations of *Ensis directus* in the North Sea (see figure 5.18) show that the relative difference between the shell lengths of the smallest and largest animals that are found, is largest for young *Ensis*.

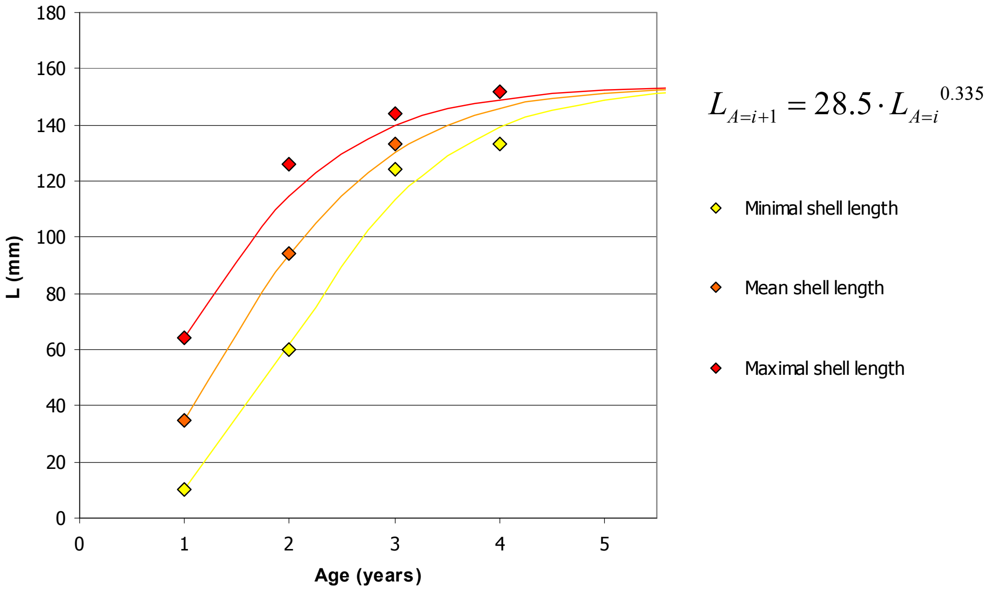

Figure 5.18 Growth model like eq. 5.16, fitted to data of Ensis directus in the North Sea [data from Armonies and Reise (1999) in WIJSMAN *et al.* (2006)]

Some remarks on the growth models that are used in this section are included in appendix C.

5.6.3 Relation between growth rates and the amount of bivalves

The amount of bivalves in the Voordelta might influence the growth rate, if the total food available for these bivalves and for others animals that eat the same food, becomes limiting (intra- and interspecific competition). Per individual less food may be available than necessary for the maximal growth rate. However, as food quantity is not a limiting factor in the ecosystem of the Voordelta [report expert meeting in VERTEGAAL *et al.* (2007)], no effect of intra- and interspecific competition on the growth rate will be taken into account in this thesis.

5.6.4 Growth in the Monte Carlo analysis

The Monte Carlo analysis (see chapter 7) will be done for two different scenarios for growth; once for a growth models like equation 5.19 (age-dependent growth rates) and once for the growth formula as determined by KAMERMANS *et al.* (2003) (equation 5.12, size-dependent growth rates).

The growth factors for the 'age-dependent growth' will be derived from equation 5.22, taking a fresh weight of 1.3 g for 1-year old cockles as a starting point [KAMERMANS *et al.* (2003)], see table 5.7. The biomass of cockles does not increase during autumn and winter.

Table 5.7 Growth factors *a(A)* in case of age-dependent growth

Age (year)	Fresh weight May (*10^{-3} kg)	Fresh weight September (*10^{-3} kg)	Growth factor *a(A)* (-)
0	0.12	1.3	10.8
1	1.3	4.4	3.4
2	4.4	8.1	1.9
3	8.1	11.1	1.4
4	11.1	13.0	1.2
5	13.0	14.2	1.1

The growth formula of KAMERMANS *et al.* (2003) is assumed to be valid for cockles in the Voordelta. The parameters of this formula will not be varied in the Monte Carlo analysis. Using other parameters would influence the population composition (see figure 5.19). If a population exists for a relatively larger part of young bivalves, the impact of a mismatch on the total population will be larger in the first years afters the mismatch and smaller for circa 4-5 years after the mismatch. The effect of using other parameters for growth, is comparable to the effect of using other survival rates (figure 5.16).

In 1985 Beukema *et al.* mentioned that the yearly growth of *Macoma balthica* is almost constant [WEBER AND SMIT (2004)]. Based on this, the yearly variation of the growth of cockles in the Voordelta is assumed to be negligible.

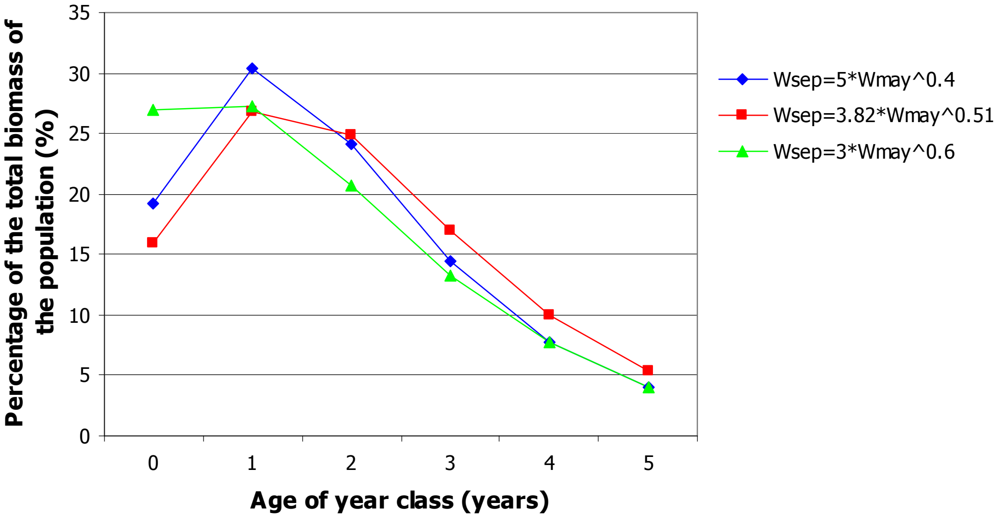

Figure 5.19 Population composition for different growth curves (yearly survival rate *SY*=0.5, recruitment is constant)

Possibly the size of adult cockles is underestimated by using the growth factors of table 5.7. Due to this, also the total biomass of the modelled cockle population will be underestimated. However, the goal of the population-dynamical model in this thesis is to reproduce the natural fluctuations of the population size and the variation of the population composition over the different year classes. As long as the growth factors lead to reasonable proportions between the different year classes, the underestimation does not matter. The size of the modelled population will be scaled to the population sizes in reality. The most important condition for this, is that the relative fluctuations of the population size (compared to the average population size) are equal for the modelled and real population.

For 'age-dependent growth' the population-dynamical model will not change compared to equation 5.15 (see equation 5.25). For $G_{A=0}$, $G_{A=1}$, $G_{A=2}$, $G_{A=3}$, $G_{A=4}$ *and* $G_{A=5}$, the growth factors of table 5.7 will be used. A constant value of 0.12 g will be used for *WR*.

$$\begin{array}{rl}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i = BM_{A=0,i} & \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} = BM_{A=1,i} & \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} = BM_{A=2,i} & \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} = BM_{A=3,i} & \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} = BM_{A=4,i} & \\
NR_{i-5} \cdot SR_{i-5} \cdot WR \cdot G_{A=0} \cdot EM_{i-5} \cdot SW_{i-5} \cdot SS_{i-4} \cdot G_{A=1} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=2} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=3} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=4} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=5} = BM_{A=5,i} & \\
\hline
 & + \\
TBM_i &
\end{array}$$

Equation 5.25

For the 'size-dependent growth' the population-dynamical model will change:

$$\begin{array}{rl}
NR_i \cdot SR_i \cdot a \cdot \left(WR \cdot EM_i\right)^{b} = BM_{A=0,i} & \\
NR_{i-1} \cdot SR_{i-1} \cdot a^{(b+1)} \cdot \left(WR \cdot EM_{i-1}\right)^{b^2} \cdot SW_{i-1} \cdot SS_i = BM_{A=1,i} & \\
NR_{i-2} \cdot SR_{i-2} \cdot a^{\left(b^2+b+1\right)} \left(WR \cdot EM_{i-2}\right)^{b^3} \cdot SW_{i-2} \cdot SS_{i-1} \cdot SW_{i-1} \cdot SS_i = BM_{A=2,i} & \\
NR_{i-3} \cdot SR_{i-3} \cdot a^{\left(b^3+b^2+b+1\right)} \cdot \left(WR \cdot EM_{i-3}\right)^{b^4} \cdot SW_{i-3} \cdot SS_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot SW_{i-1} \cdot SS_i = BM_{A=3,i} & \\
NR_{i-4} \cdot SR_{i-4} \cdot a^{\left(b^4+b^3+b^2+b+1\right)} \cdot \left(WR \cdot EM_{i-4}\right)^{b^5} \cdot SW_{i-4} \cdot SS_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot SW_{i-1} \cdot SS_i = BM_{A=4,i} & \\
NR_{i-5} \cdot SR_{i-5} \cdot a^{(b^5+b^4+b^3+b^2+b+1)} \cdot \left(WR \cdot EM_{i-5}\right)^{b^6} \cdot SW_{i-5} \cdot SS_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot SW_{i-1} \cdot SS_i = BM_{A=5,i} & \\
\hline
 & + \\
TBM_i &
\end{array}$$

Equation 5.26

a and *b* are the parameters of the growth model (equation 5.22):

$$W_{Sep} = a \cdot W_{May}{}^{b} = 3.82 \cdot W_{May}{}^{0.51} \qquad (5.27)$$

5.7 Recruitment

Recruitment is the birth of larvae and the survival during the larval phase. Long-term observations of recruitment of bivalves have shown that the inter-annual variation in recruitment is very large [Philippart *et al.* (2003)]. The natural variation of the size of bivalve populations is caused to a large extent by this variation in recruitment.

Measurements of the number of recruits or numbers of 0-year old bivalves in September are not available. Therefore, the number of recruits *NR* and the survival rate during their first growing season *SR*, will be varied in such a way in the Monte Carlo analysis, that the modelled variation of the population size corresponds with the natural variation. For the weight of the recruits *WR*, 0.12 g will be used (see table 5.7).

$$
\begin{array}{rl}
NR_i \cdot SR_i \cdot WR \cdot G_{A=0} \cdot EM_i = BM_{A=0,i} & \\
NR_{i-1} \cdot SR_{i-1} \cdot WR \cdot G_{A=0} \cdot EM_{i-1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=1} = BM_{A=1,i} & \\
NR_{i-2} \cdot SR_{i-2} \cdot WR \cdot G_{A=0} \cdot EM_{i-2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=1} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=2} = BM_{A=2,i} & \\
NR_{i-3} \cdot SR_{i-3} \cdot WR \cdot G_{A=0} \cdot EM_{i-3} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=1} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=2} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=3} = BM_{A=3,i} & \\
NR_{i-4} \cdot SR_{i-4} \cdot WR \cdot G_{A=0} \cdot EM_{i-4} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=1} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=2} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=3} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=4} = BM_{A=4,i} & \\
NR_{i-5} \cdot SR_{i-5} \cdot WR \cdot G_{A=0} \cdot EM_{i-5} \cdot SW_{i-5} \cdot SS_{i-4} \cdot G_{A=1} \cdot SW_{i-4} \cdot SS_{i-3} \cdot G_{A=2} \cdot SW_{i-3} \cdot SS_{i-2} \cdot G_{A=3} \cdot SW_{i-2} \cdot SS_{i-1} \cdot G_{A=4} \cdot SW_{i-1} \cdot SS_i \cdot G_{A=5} = BM_{A=5,i} & \\
\hline
TBM_i & +
\end{array}
$$

Equation 5.28

Hardly any knowledge is available on the reasons why the amount of recruits is very large or small in certain years. The number of recruits seems hardly dependent on the number of adults, but mainly on winter temperatures. High densities of recruits are often observed after severe winters. The main reason is probably the low number of shrimps and crabs (the most important predators of bivalve larvae) after cold winters. A second reason is the higher production of eggs after severe winters. [Philippart *et al.* (2003)]

A higher mortality of shellfish larvae as a consequence of a long duration of a mismatch between the hatching of larvae and the algal bloom sounds logically. However, the laboratory experiments of Bos *et al.* [Bos *et al.* (2006) and Bos *et al.* (2007)] do not confirm this hypothesis. In both experiments, the mortality rates were generally not higher in case of a mismatch or a lower food level. Therefore no relation will be taken into account between the number of recruits and a mismatch.

Recruitment in the Monte Carlo analysis

For the yearly variation of the number of recruits a lognormal distribution is chosen. The choice of this type of distribution is based on the following relation that is used by Weber and Smit (2004), to model the number of recruits of *Macoma balthica*:

recruit density$=518.3 \cdot e^{(-0.246 \cdot T)}$

With: T = winter-averaged seawater temperature (°C)

A normally distributed winter temperature will lead to a lognormal distribution of the number of recruits.

The mean and standard deviation of the lognormal distribution are subsequently adjusted to 'calibrate' the variation of the amount of bivalves that is generated by the model (by varying survival rates and recruitment) to the measured data of figure 5.20. The data of table 5.8 are used to compare the results of the model to the measured data. The standard deviation of the yearly amount of bivalves should be in the same order of magnitude as the mean amount. Only in circa 30% of the years the amount of bivalves should be larger than the average amount of bivalves. Only the bivalves of 1 year and older are considered; the number of 0-year old bivalves is often left out of account in measurements and these bivalves are probably too small for ducks to be eaten. The calibration of the model resulted in a lognormal distribution with an average value of $\mu=4$, and a standard deviation $\sigma=8$. The probability density function of the number of recruits (*NR*SR*) is shown in figure 5.21.

An important assumption is that the fluctuations of the population sizes that are observed in the past will also occur in future. The ecosystem will not reach a static equilibrium state, but is a dynamic system.

Table 5.8 Comparison of the natural variation of the population size and the variation as modelled by the population dynamical model

	Population size of bivalves			**Modelled population size**	
	Brielse Gat (shallow), fresh weight (*10^3kg)	Brielse Gat (deep), fresh weight (*10^3kg)	Voordelta, individuals (*10^9)	SY=0.35 fresh weight (*10^3kg)	SY=0.5 fresh weight (*10^3kg)
Mean	6.49	3.47	17.3	13	27
Standard deviation	5.98	4.45	22.7	17	27
P (total biomass > mean total biomass)	0.38	0.25	0.25	0.31	0.34

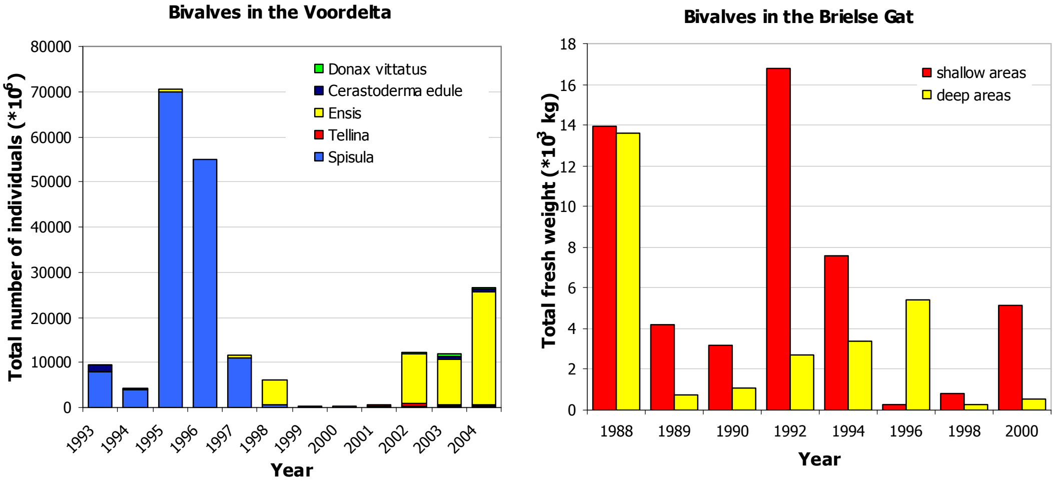

Figure 5.20 Variation of total amount of bivalves in the Voordelta and Brielse Gat (northern part of Voordelta), left figure: data from KNAW-CEME, edited by F. Heinis (not published), right figure: data from Heinis *et al.* (2006)

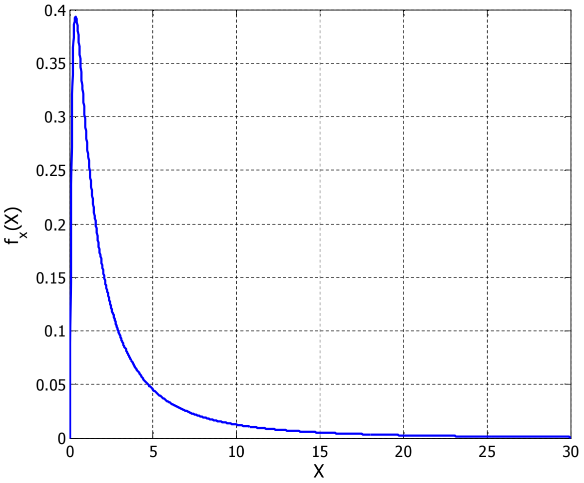

Figure 5.21 Lognormal distribution for the number of recruits, *NR*SR=X*, with $\mu_X=4$ and $\sigma_X=8$

Figures 5.22 and 5.23 show a random sample of the variation of the population size as generated by the population-dynamical model over 50 years. These figures show the influence of the yearly survival rate *SY* clearly: in case of the higher survival rate, the population consists for a relatively larger part of older bivalves.

The modelled population size is larger in case of the higher yearly survival rate; the same number of recruits (*NR*SR*) has been used, while the bivalves live longer on average. However, the main goal of the population dynamical model in this thesis, is to simulate the relative fluctuations of the population size. To compare the size of the modelled populations with real population sizes, the size of the modelled population should be scaled (see section 6.3).

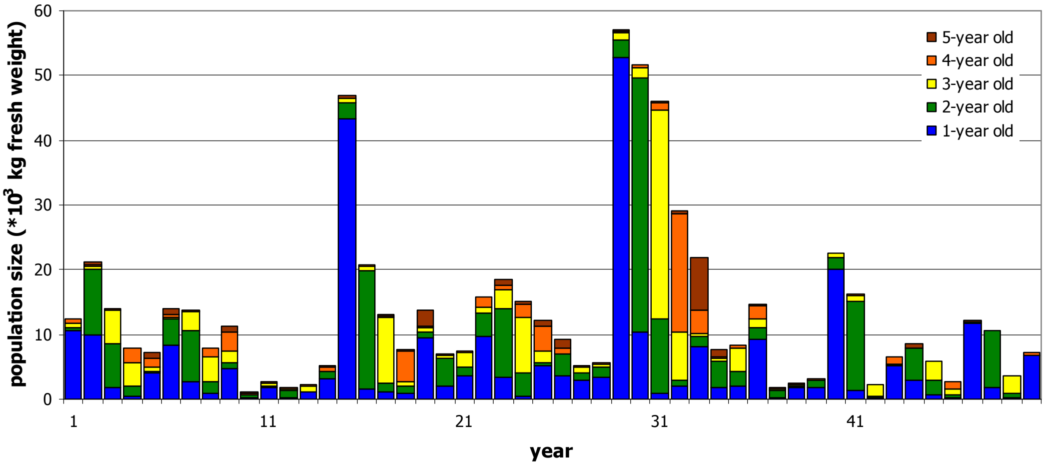

Figure 5.22 Variation of the population size of bivalves, as modelled by the population dynamical model, for a yearly survival rate *SY* of 0.35

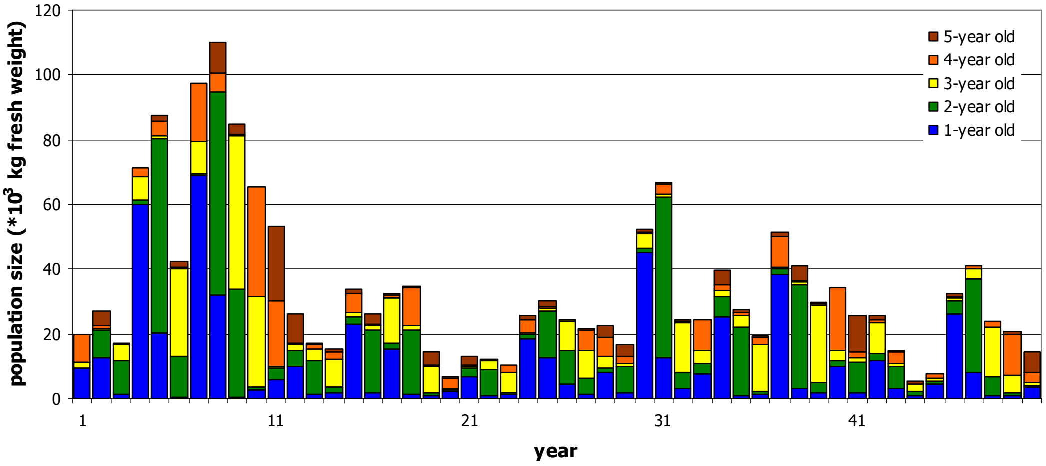

Figure 5.23 Variation of the population size of bivalves, as modeled by the population dynamical model, for a yearly survival rate *SY* of 0.5

5.8 Summary

In this chapter a relation between the duration of a mismatch, the algal concentration and the growth lag of bivalves has been derived. The effect of a decrease of the food quality on the growth of bivalves has been excluded.

Probability density functions for the survival rates of bivalves during winter and summer, as well as a probability density function for the number of recruits has been estimated. These pdf's will be used in the population-dynamical model to simulate the natural variation of bivalve population sizes. This model will be used within the Monte Carlo analysis (see chapter

7) to model the impact of a mismatch on the total bivalve population. A mismatch that occurs in one specific year, only affects the year class of the bivalves that are born in this year. The impact of the growth lag of this year class on the total biomass of the population, is strongly dependent on the composition of the population over the different year classes. The population composition and the total population size show a large natural variation. As a result of this natural variation, the impact a mismatch will have on the total population is not predictable in advance (as illustrated in section 3.2.3). By simulating the natural variation, the uncertainty that is induced by this natural variation can be taken into account in the modelling of the impact of sand mining on bivalves and eiders.

Bivalves are probably able to catch up a growth lag partly. However, since a conclusive proof fails, the Monte Carlo analysis will be done for two different growth models. According to one model, bivalves with a growth lag of 10%, will be 10% smaller than they would have been without the growth lag for their whole life. According to the second model, the bivalves will catch up this growth lag partly.

6 Common Eider

Sections 6.1 and 6.2 contain some general information on eider ducks in the Netherlands. This information gives an idea of the context in which a possible change of the number of eiders in the Voordelta has to be seen. In section 6.3 the relations between eiders and bivalves, that will be used in the Monte Carlo analysis are defined.

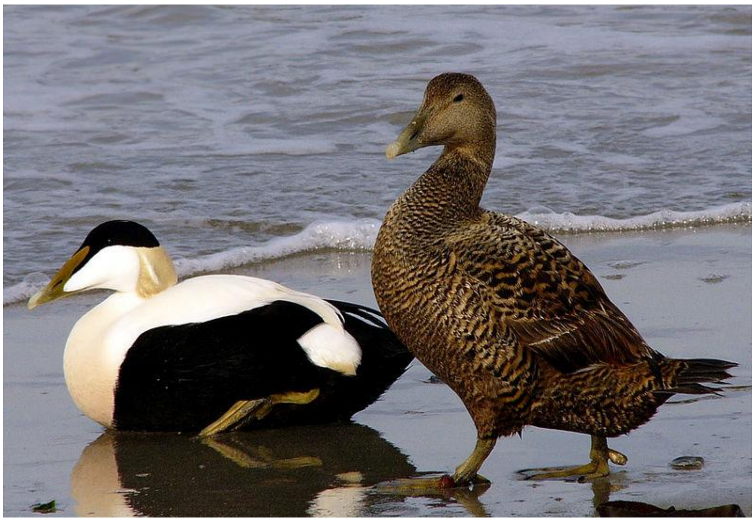

Figure 6.1 Male (left) and female Common Eider (Somateria mollissima), photo: Andreas Trepte, Marburg – Wikimedia Commons

6.1 Number of eiders in the Netherlands

The Common Eider (*Somateria mollissima*) is a large (50-71 cm body length) sea-duck, which is distributed over the northern coasts of Europe, North America and eastern Siberia [www.wikipedia.org]. Most eiders that are seen in the Netherlands are from the subspecies *Somateria mollissima mollissima*, also known as the European Eider. The number of eiders in the Netherlands shows a strong variation during the year. The number is largest during winter, when eiders, mainly from the Scandinavian coasts of the Baltic Sea, come to Denmark, Germany and the Netherlands to winter. In the Netherlands, most of these migratory eiders stay in the Wadden Sea and along the North Sea coast of the Wadden islands. A relatively small part stays in the Voordelta (see figure 6.2).

About 8,000 to 10,000 eiders [SOVON Vogelonderzoek Nederland] breed in the Netherlands and stay during the whole year [DE JONG *et al*. (2005)]. Most of these eiders breed along the coasts of the Wadden Sea. Only a small number (order of magnitude: 100 eiders) breeds in the Voordelta [SOVON Vogelonderzoek Nederland].

The number of eiders in the Netherlands, during winter, is counted yearly. At one day in January or February, the ducks are counted from a plane, which flies over a specified area in a systematic way [DE JONG *et al*. (2005)]. The results of these counts are shown in figures 6.2, 6.3 and 6.4.

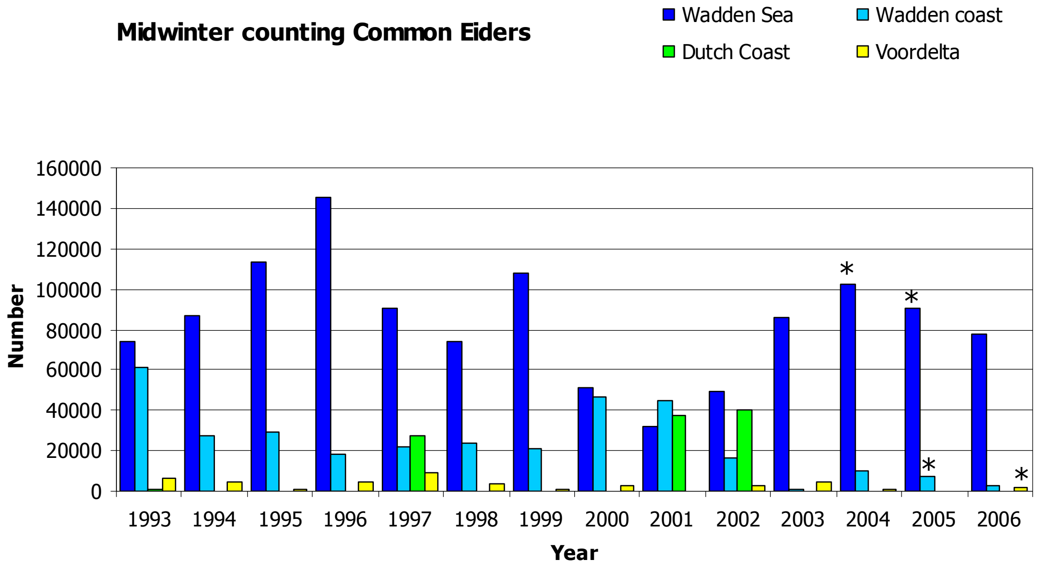

Figure 6.2 **Results midwinter counting of Common Eiders, data from ARTS AND BERREVOETS (2006)**
*** incomplete counting**

The variation of the number of eiders can be mainly explained by the variation of food availability and environmental conditions. As adult eiders do not have predators in the Netherlands, predation plays a minor role for the number of eiders in the Netherlands. Predators like gulls, ravens, rats and foxes only prey on eggs and ducklings. Adult eiders may still be hunted in Scandinavia; DESHOLM *et al.* (2002) mention that hunting on eiders is legal in Denmark, Finland, Norway and Sweden, up to a maximal total number of 115,000 eiders. Circa 80,000 eiders per year were shot at the start of the 21st century [RENEERKENS *et al.* (2005)].

During severe winters, eiders from the German and Danish Wadden Sea migrate relatively lately further southward to the Dutch Wadden Sea [RENEERKENS *et al.* (2005)].

During the winters of 1999-2000 and 2001-2002 a remarkably high number of dead eiders were found in the Wadden Sea. The most plausible cause of this high mortality seemed to be starvation, as a consequence of shortage of suitable food [ENS *et al.* (2002)]. For an important part, the dead eiders were from the local breeding population. Which is remarkable, as the number of eiders that only winter in the Wadden Sea, is much larger than the number of 'local eiders'. Apparently the migratory eiders are more capable to find alternative forage areas [RENEERKENS *et al.* (2005)]. In figure 6.2 an increase of the number of eiders in the North Sea (Wadden coast and Dutch coast) is visible for these winters.

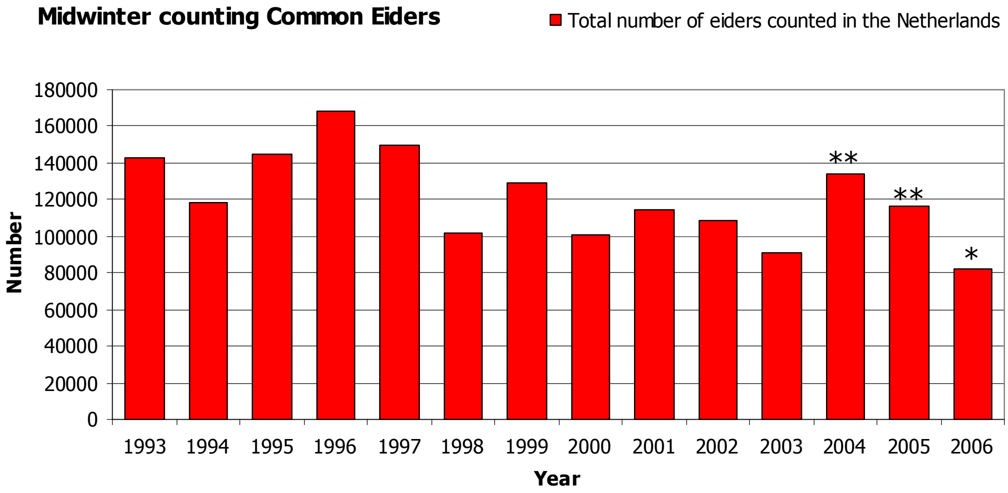

Figure 6.3 Results midwinter counting: total number of Common Eiders in the Netherlands, data from ARTS AND BERREVOETS (2006)
*** incomplete counting**
**** incomplete counting, estimation of uncounted part included**

Figure 6.4 shows the variation of the number of eider ducks in the Voordelta. The down going trend might be a result of the improving situation in the Wadden Sea [Expert meeting Eiders, August 2007]. Possibly fewer eiders fly further to the Voordelta if sufficient food is available in the Wadden Sea. It is not expected that eiders migrate from the Wadden Sea to the Voordelta, in case of a food shortage in the Wadden Sea [Expert meeting Eiders, August 2007].

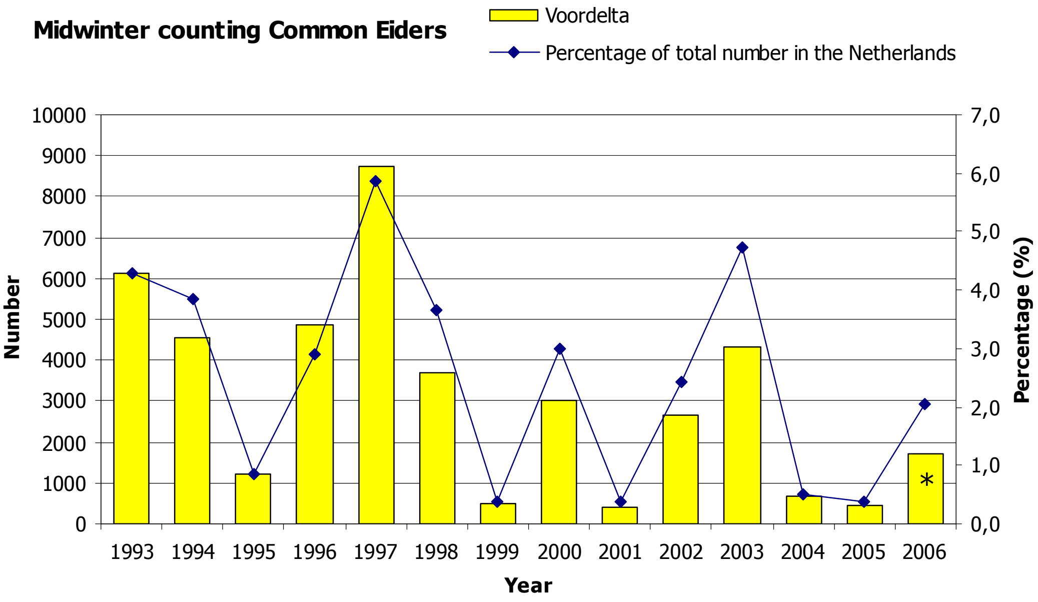

Figure 6.4 Results midwinter counting: Common Eiders in the Voordelta, data from ARTS AND BERREVOETS (2006)
*** incomplete counting**

6.2 Food

The diet of eiders mainly consists of bivalves. Eiders also eat shore crabs (*Carcinus maenas*), winkles (*Littorina littorea*), starfish, sea urchins and incidentally small fish, worms and shrimps [Reneerkens *et al.* (2005), Rijkswaterstaat (2007a), Leopold *et al.* (2007)]. Eiders find their food underwater, till depths of 10 m. Bivalves, like cockles are swallowed completely. The shells are crushed in the muscular stomach of the eider. Eiders are able to swallow shells up to a length of 4 cm [Reneerkens *et al.* (2005)]. However, razor shells (*Ensis* spec.) can be eaten up to lengths of 12 cm [Wijsman *et al.* (2006)]. Razor shells are cracked by the bill, before they are swallowed.

Eiders prefer to eat bivalves with thin shells. The energy costs of crushing the shells in the stomach can be considerable in case of an unfavourable ratio of the biomass over the weight of the shell. It is even possible that eiders die from starvation as a result of eating too many inferior bivalves [Ens and Kats (2004)]. However, this phenomenon does not play a role for cockle-eating eiders in the Voordelta. Cockles that are found in the Voordelta are always of high quality; the biomass is relatively high compared to the weight of the shell [Expert meeting Eiders, August 2007].

The eiders in the Voordelta are distributed over two areas; the outer part of the Haringvliet estuary (Hinderplaat) and the outer part of the estuary of the Grevelingenmeer (Bollen van Ooster). The distribution over these areas fluctuates yearly (see figure 6.5).

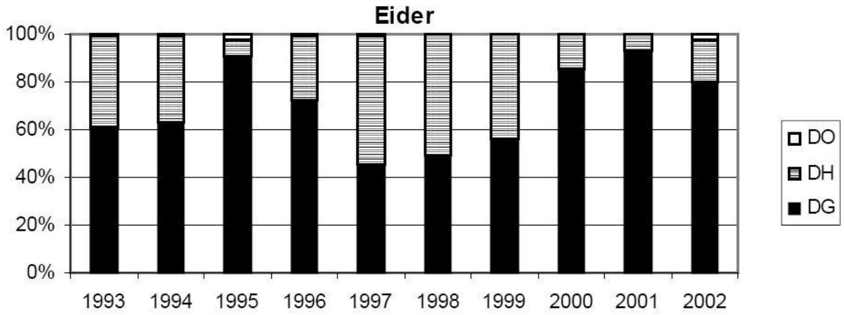

Figure 6.5 **Distribution of eiders over the Haringvliet estuary (DH), estuary of the Grevelingenmeer (DG) and the Oosterschelde estuary (DO), figure from Hoekstein *et al.* (2003)**

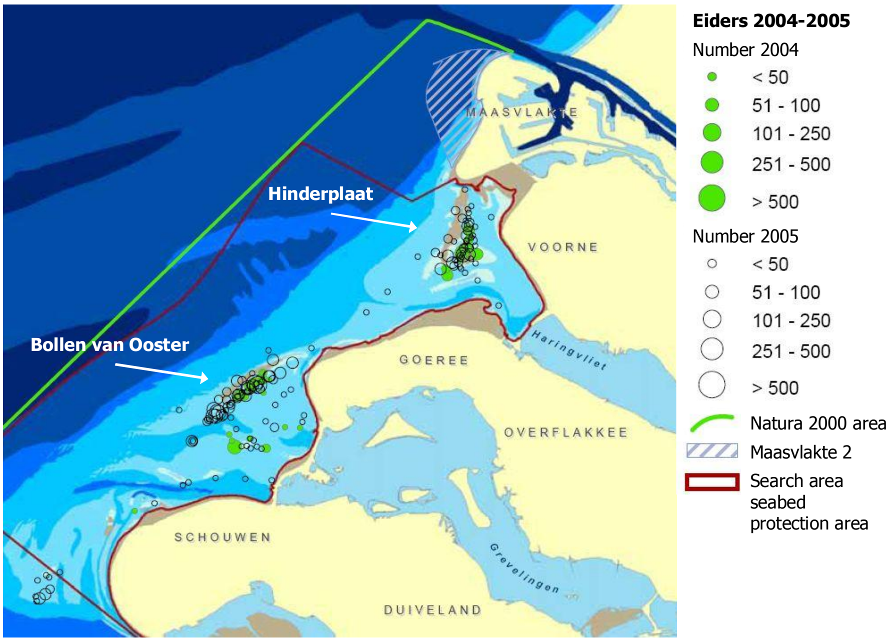

Figure 6.6 **Eiders in the Voordelta, winter 2004-2005, figure from Rijkswaterstaat (2007b)**

The eiders that winter near the Bollen van Ooster forage on American razor shells (*Ensis directus*). Razor shells are found in large quantities in this area. It is plausible that the eiders prefer to eat razor shells with a length of 5 to 10 cm [LEOPOLD *et al.* (2007)]. LEOPOLD *et al.* (2007) estimated the consumption of razor shells by eiders and scoters. If these ducks eat only razor shells, and if the yearly averaged number of eiders and scoters is respectively 1000 and 1850, the yearly consumption in the Voordelta is 100 million razor shells. Since 1993 the number of small razor shells (<10 cm) was always larger than 100 million razor shells (see figure 6.8). The minimal number of small razor shells was 405 million in 1999.

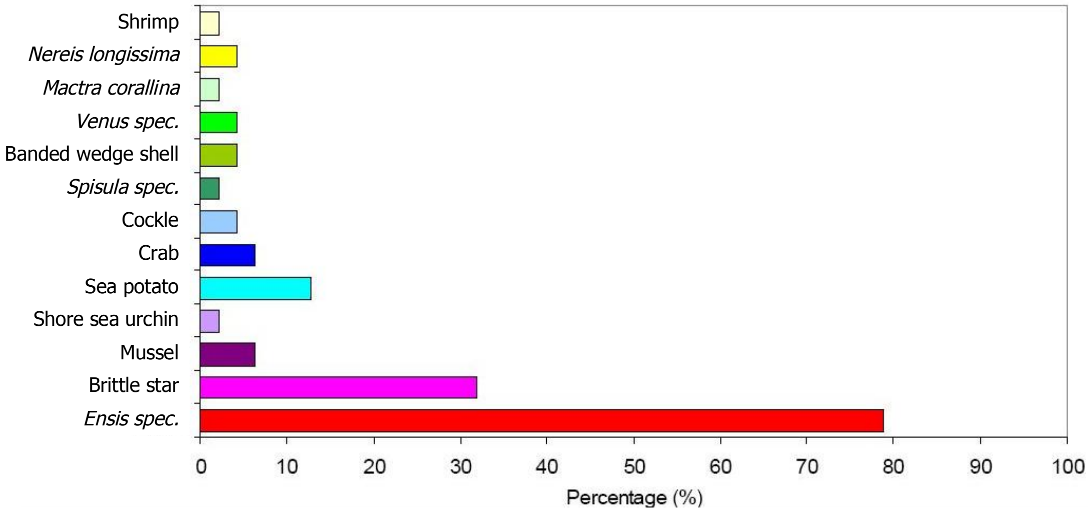

Figure 6.7 Percentage of faeces samples (of eiders, Bollen van Ooster, spring 2007), in which the residues of the different prey were found, figure from LEOPOLD *et al.* (2007)

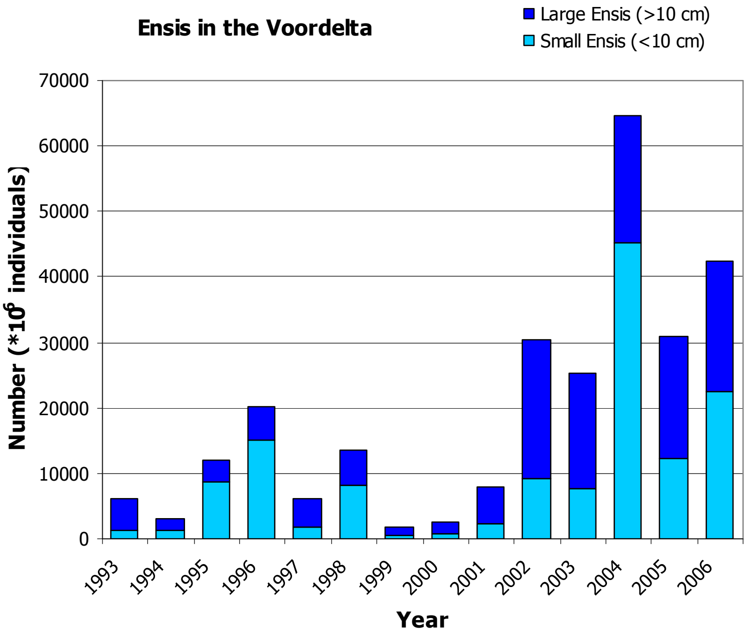

Figure 6.8 Numbers of razor shells in the Voordelta, data from Wageningen IMARES [LEOPOLD *et al.* (2007)]

The eiders in the Haringvliet estuary probably forage mainly on cockles (*Cerastoderma edule*). Other bivalve species in the Haringvliet estuary, which are also suitable as prey for eiders, are soft-shell clams (*Mya arenaria*), nuns (*Macoma balthica*) and cut trough shells (*Spisula subtruncata*) [LEOPOLD *et al.* (2007)]. The number of cockles in the Voordelta shows a strong variation, due to a variable number of recruits and incidentally low survival rates. In years with a relatively high number of cockles, these cockles will form a large part of the total biomass of benthos in the Haringvliet estuary.

Low survival rates of cockles in the Haringvliet estuary are caused by starfish, eiders and cockle fishery. However, high fresh water discharges of the Haringvliet are the most important cause of high mortality rates [Leopold *et al.* (2007)]. The cockle population is able to recover quickly, as can be derived from figure 6.9. The ability of the bivalve populations to recover makes that the impact of the sand mining will be temporary.

Data about the number of eiders and the biomass of bivalves in the Brielse Gat indicate that a relation exists between eider and bivalves in this area (see figure 6.9). The major part of all bivalves in this area are cockles. When the cockle population is recovered, after an almost complete disappearance, also the eiders come back to this area. It is not known if these are the same ducks as in the previous years. If the cockle-eating eider ducks eat razor shells in a year without cockles, or if they move to another area where they can find cockles is also not known. [Expert meeting Eiders, August 2007, Leopold *et al.* (2007)]

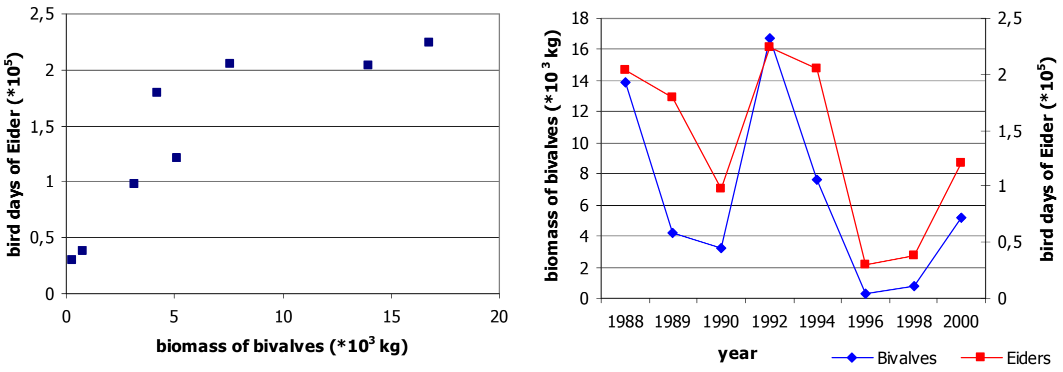

Figure 6.9 Relation between the number of bird days of the eider and the total biomass of bivalves in the Brielse Gat (part of the Haringvliet estuary), data from Heinis *et al.* (2002)

During the period 1993-1997 cut trough shells (*Spisula subtruncata*) were found in large numbers in the Voordelta and formed an important part of the diet of eiders in the Voordelta. The amount of *Spisula subtruncata* decreased during the following years, while the amount of *Ensis directus* increased. The eiders turned out to be able to switch over from eating *Spisula* to eating *Ensis*.

6.3 Relation between bivalves and eiders

As the amount of *Ensis* in the Voordelta is much larger than the amount needed by the sea ducks (see previous section), the number of sea ducks in the Voordelta is probably not related to the amount of bivalves. Indeed no correlation is visible between counted eiders and bivalves in the Voordelta (see figure 6.10).

Possibly only a relation exists between the cockle-eating eiders in the Haringvliet estuary and the size of the cockle population (see figure 6.9). Whether a decrease of the total biomass of cockles has an impact on the eider population, also depends on the flexibility of the eider ducks. If the eiders are able to find cockles elsewhere (for example in Belgium) or to change their diet to *Ensis*, no eiders will die due to a decrease of the amount of food in the Haringvliet estuary.

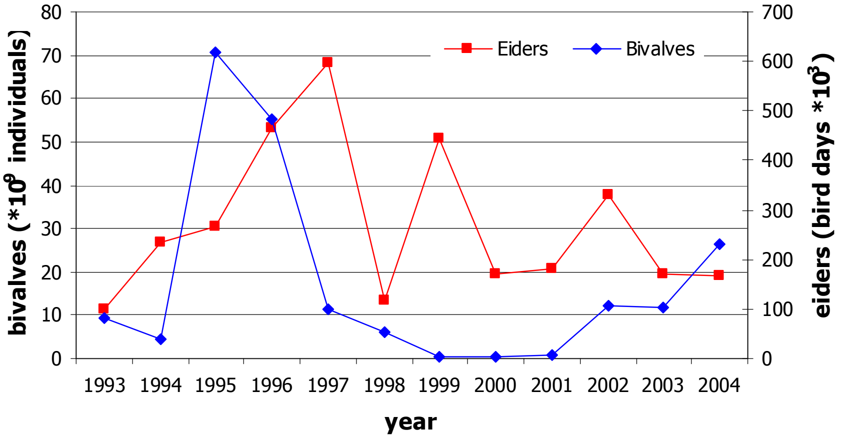

Figure 6.10 Total number of bivalves and eiders in the Voordelta, data from KNAW-CEME, edited by F. Heinis (not published)

As no information is available on the possibilities for eiders to find their food elsewhere, or to change their diet, it is not possible to take this into account in the Monte Carlo analysis. Therefore the Monte Carlo analysis will be done for three relatively 'pessimistic' relations between eiders and bivalves. In view of the preservation goal for eiders, migration of eiders to other areas might also be seen as a negative impact (the number of eiders in the Natura 2000 area decreases). In this thesis only starvation of eiders will be regarded as a negative impact. It does not matter if the eiders forage inside or outside of the Natura 2000 area.

Preservation goal for the Common Eider

Within Natura 2000 areas habitats and species that are characteristic for the specific area are protected (if protection is necessary to prevent danger for the survival of the species). The Common Eider is one of these species. The Dutch government has decided to designate the Voordelta as a Natura 2000 area. Such designation is done by means of a 'designation resolution'. This resolution includes among other things the preservation goals of protected species and habitats. For the Common Eider this preservation goal implies the conservation of the size and quality of the habitat with a bearing capacity for a population of 2500 birds on average (midwinter). [Ministerie van V&W (2007)]

Relation 1

The first relation is the most pessimistic: all eiders in the Voordelta are assumed to be dependent on one species of bivalves that can be affected by a mismatch*. This can only occur if the present, abundant population of *Ensis* disappears and if this Ensis population is not replaced by another species that is edible for eiders. The relation between the number of the edible bivalves and eiders is assumed to be linear (a linear relation was also used in the EIA). In fact a linear relation is not realistic; if the population of bivalves exceeds a certain, large size, the availability of food will no longer be the limiting factor for the number of eiders in the Voordelta.

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* for some bivalve species the probability of occurrence of a mismatch is very small: *Spisula* spawns in June-July [Cardoso *et al.* (2007a)], a long time after the algal bloom and blue mussels spawn in response to algal blooms according to Starr *et al.* (1990) [Bos *et al.* (2006)]. So, if the cockle population is replaced by for example *Spisula* or mussels, an impact of sand mining on the bivalves in the Voordelta due to a mismatch is not possible anymore.

Relation 2

Also the second relation starts from the assumption that all eiders in the Voordelta are dependent on one population of bivalves that will be affected by a mismatch. The relation between the number of bivalves and eiders will be based on the data of figure 6.9. Figure 6.11 shows the relation that is fitted to these data, and will be scaled to the average size of the fictitious, modelled population (see table 5.8).

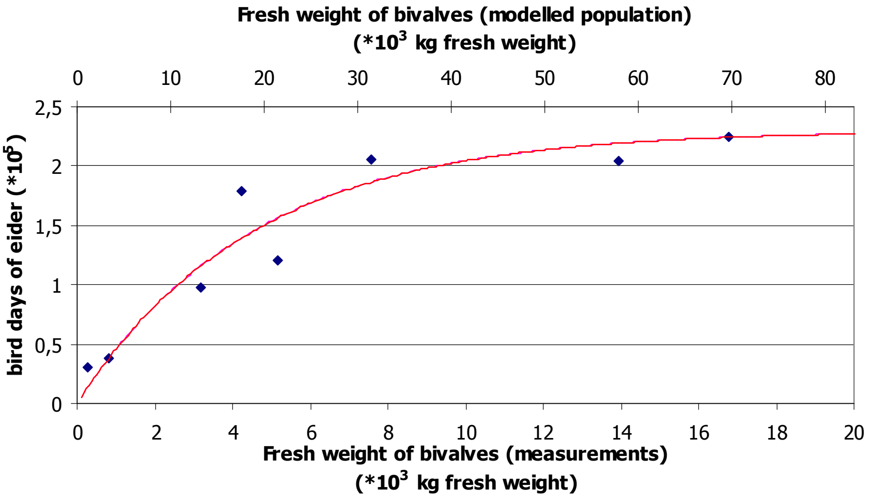

Figure 6.11 Relation between eiders and bivalves for the measurements at the Brielse Gat [data from HEINIS *et al.* (2002)] and for the modelled population (SY=0.35)

The following relation is fitted to the measurements at the Brielse Gat:

$$N_{eiders} = 2.3 \cdot \left(1 - e^{-0.22 \cdot TBM}\right) \qquad (6.1)$$

N_{eiders} = number of eiders [bird days]

TBM = total biomass of the bivalve population [*10^3 kg]

As the modelled bivalve population do not have the same size as the real populations, equation 6.1 should be scaled to be applicable for the modelled populations. Scaling equation 6.1 for the modelled population is allowed, as the modelled population shows relatively the same fluctuations as the real population (see table 5.8). For the modelled as well as the real population applies that only during one third of all years the population size is larger than the average population size. Due to this, the 'horizontal part' of the relation between bivalves and eiders (figure 6.11) applies just as often for the real as for the modelled population. If the modelled population was too often larger than the average size, this would have lead to an underestimation of the impact of sand mining on eiders.

In case the population size of bivalves is modelled by using a yearly survival rate of 0.35, the following relation will be used:

$$N_{eiders} = 2.3 \cdot \left(1 - e^{-0.102 \cdot TBM}\right) \qquad (6.2)$$

In case of a yearly survival rate of 0.5:

$$N_{eiders} = 2.3 \cdot \left(1 - e^{-0.0529 \cdot TBM}\right) \qquad (6.3)$$

Relation 3

For relation 3 is assumed that 60% of all eiders in the Voordelta are '*Ensis*-eaters' and the remaining 40% are 'cockle-eaters'. Nowadays there is plenty of food for the *Ensis*-eaters in the Voordelta. For relation 3 is assumed that the amount of food for the *Ensis*-eaters will not become limiting in future. For the cockle-eaters the same equations (6.2 and 6.3) will be used as in relation 3. The results of relation 3 will show an impact on eiders that is a factor 0.4 smaller than the impact predicted in case of relation 2.

7 Monte Carlo Analysis

7.1 Simulations

Within a Monte Carlo simulation, the impact of sand mining on eiders is calculated a large number of times (100,000). The input variables and the natural variation of the bivalve population size are different each for each run.

For each run within the Monte Carlo simulation, the values of A_{ref}, H, and D will be generated randomly from the probability density functions that were determined in chapter 4. Subsequently the duration of the mismatch M is calculated for the reference and for the sand mining scenario:

$$M_{sandmining} = A_{ref} + D - H \tag{7.1}$$

$$M_{reference} = A_{ref} - H \tag{7.2}$$

If $M_{sandmining}$ is smaller than 0, no mismatch occurs and consequently there will be no impact on eider ducks. If M is larger than 0, the impact of this mismatch on the total biomass of bivalves will be calculated. In order to do this, the natural variation of the size of the bivalve population (and the composition over the different year classes) is simulated for a period of 13 years after the start of the sand mining. For each year the number of recruits ($NR \cdot SR$) is randomly chosen and for each winter and summer the survival rates (SS and SW) are randomly chosen.

For each year (within the period of 1-8 years after the start of the sand mining), the impact of an eventual mismatch on the biomass of individual bivalves $EM_{reference}$ and $EM_{sand\ mining}$ is calculated. By use of equation 5.14, EM is calculated on the basis of the value of M and randomly chosen values of the correction factor CF and the algal concentration $Calg$

Within each run, the impact on the total biomass of bivalves is calculated for the determined factors $EM_{reference}$ and $EM_{sand\ mining}$ and the simulated natural variation of the bivalve population size and composition. In this way, the total amount of bivalves in the Voordelta is calculated for each year (within the period of 13 years), for the reference as well as the sand mining scenario.

Finally, for the reference and sand mining scenario is calculated how many eiders can possibly forage in the Voordelta. For each year the relative impact of sand mining on the number of eiders is calculated:

$$Impact = 1 - \frac{\left(Number\ of\ eiders\right)_{sandmining}}{\left(Number\ of\ eiders\right)_{reference}} \tag{7.3}$$

A schematized overview of the Monte Carlo analysis is given in appendix I.

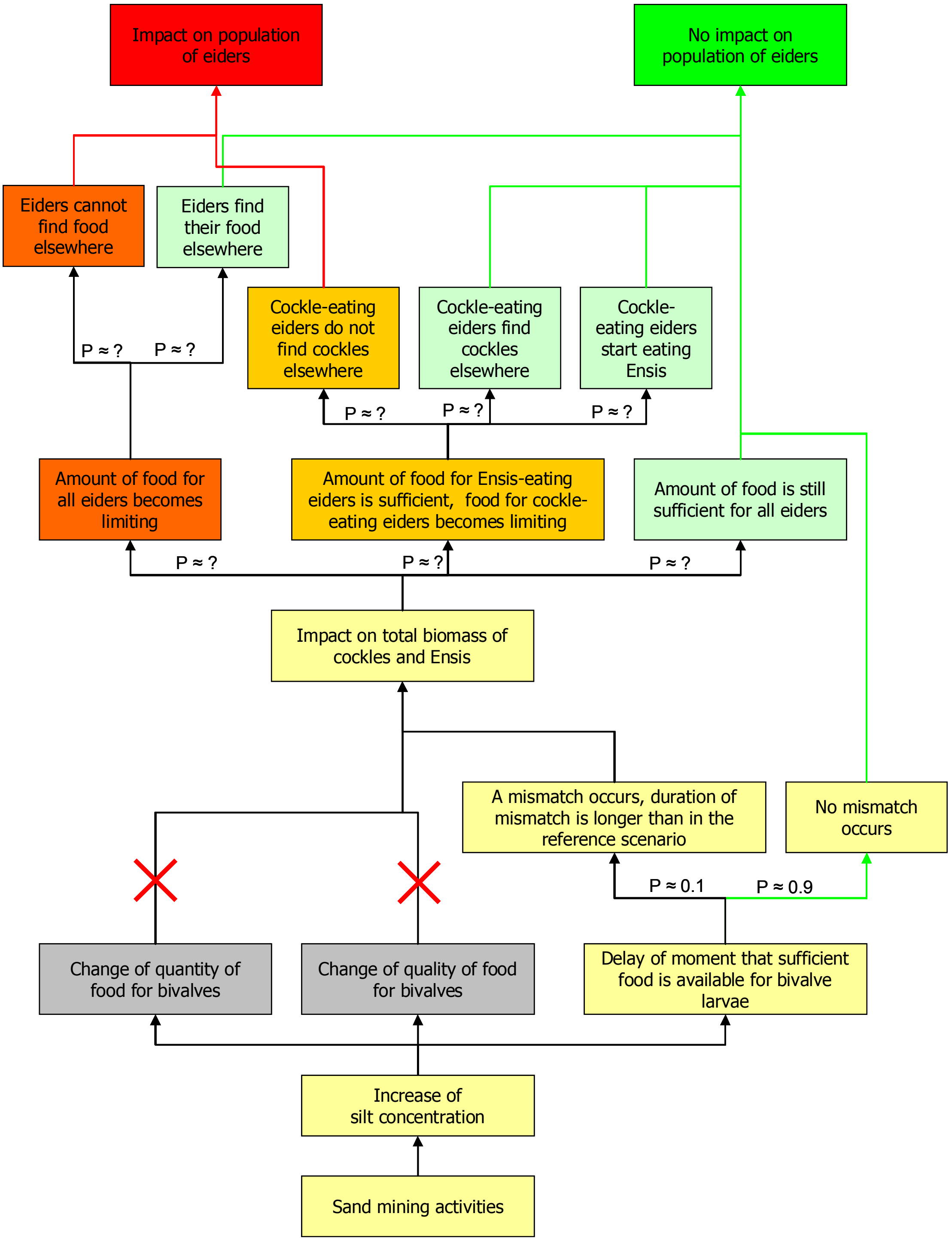

Figure 7.1 Overview of possible impact-effect relations

Unfortunately, taking into account all uncertainties in the Monte Carlo analysis is not possible. For example uncertainties like:

- Which average yearly survival rate is more realistic: 35 or 50%? (section 5.5)
- Is the growth of bivalves age- or size-dependent? (section 5.6)
- How is the number of eiders in the Voordelta related to the amount of bivalves? (chapter 6)
- Does the hatching of larvae in the Voordelta occur mid-May or during late May? (chapter 4)

Quantifying the likelihood of these different options is not possible. Therefore a Monte Carlo analysis is done for several scenarios, which incorporate these options.

Table 7.1 shows the scenarios for which a Monte Carlo analysis is done. For the relation between eiders and bivalves, only the 'pessimistic' relations (orange and dark-yellow in figure 7.1) are incorporated in the scenarios. As no information is available on the probability of occurrence of the green parts of figure 7.1, these green parts are neglected. Due to this, the results of the Monte Carlo analysis will probably still overestimate the probability of occurrence of an impact on eiders, and the impact itself.

Table 7.1 Simulations

Simu-lation	Percentage of eiders possibly affected	Relation between bivalves and eiders	Yearly survival rate (SY)	Growth rate depends on:	A_{ref} (μ,σ)	H (μ,σ)	Sand mining scenario
A	100%	Linear	0.35	Age	Apr-15, 15	May-18, 8	s1a
B	100%	Eq. 6.2	0.35	Age	Apr-15, 15	May-18, 8	s1a
C	100%	Eq. 6.3	0.5	Age	Apr-15, 15	May-18, 8	s1a
D	40%	Eq. 6.2	0.35	Age	Apr-15, 15	May-18, 8	s1a
E	100%	Eq. 6.2	0.35	Size	Apr-15, 15	May-18, 8	s1a
F	40%	Eq. 6.2	0.35	Size	Apr-15, 15	May-18, 8	s1a
G	100%	Eq. 6.2	0.35	Age	Apr-17, 15	May-18, 10	s1a
H	100%	Eq. 6.2	0.35	Age	Apr-9, 14	May-18, 8	s1a
I	100%	Eq. 6.2	0.35	Age	Apr-9, 14	May-25, 8	s1a
J	100%	Eq. 6.2	0.35	Age	Apr-5, 13	May-25, 8	s1a
K	100%	Eq. 6.2	0.35	Age	Apr-15, 15	May-18, 8	s1b
L	100%	Eq. 6.2	0.35	Age	Apr-15, 15	May-18, 8	s1c

7.2 Results

The results of the Monte Carlo analysis are shown in this section as probability distributions. These probability distributions show the probability (y-axis) that the impact that will occur in reality is larger than the possible impact *X* at the x-axis. The mentioned impacts are relative impacts (see equation 7.3).

7.2.1 Simulation B

Figure 7.2 shows the results of the Monte Carlo analysis for simulation B. The figure shows the probability distribution for the relative impact on the number of eiders in the Voordelta for each specific year and for the maximal impact that occurs during the period of 13 years. The largest impacts are expected to occur during the 4th and 5th year after the start of the sand mining. This was expected, as the duration of the mismatches will be longest (on average) for the 2nd and 3rd year after the start of the sand mining activities (see Figure 7.3). During these years, year classes II and III can be affected. These year classes will form a large part of the total amount of edible bivalves during the 4th and 5th year. During the 5th year also year class IV forms an important part of the total bivalve population. However, also this year class can be affected by relatively large mismatches. As 0-year old bivalves are assumed to be too small to be suitable food for eiders, no impact on eiders will occur during the first year.

The curve for the maximal impact during the period of 13 years, shows a larger probability of occurrence for a certain impact than the curves for the impact in one specific year. Also this is expected, as the probability that for example an impact of 5% occurs in year 2, or in year 3 or in year 4 etc., is larger than the probability that this impact occurs exactly in the 4th year. If a maximal impact of circa 10% occurs during the period of 13 years, in most of these cases only during 3, 4 or 5 years within this period impacts larger than 1% occur.

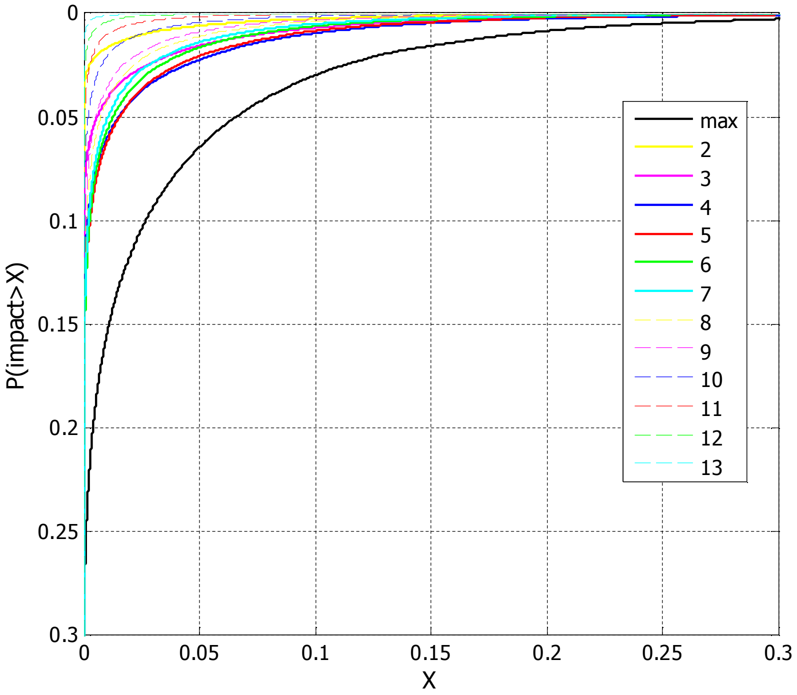

Figure 7.2 **Monte Carlo-results: probability distributions for the relative impact on eiders (*X*) in years 2 to 13 after the start of the sand mining and the maximal impact during the period of 13 years, simulation B**

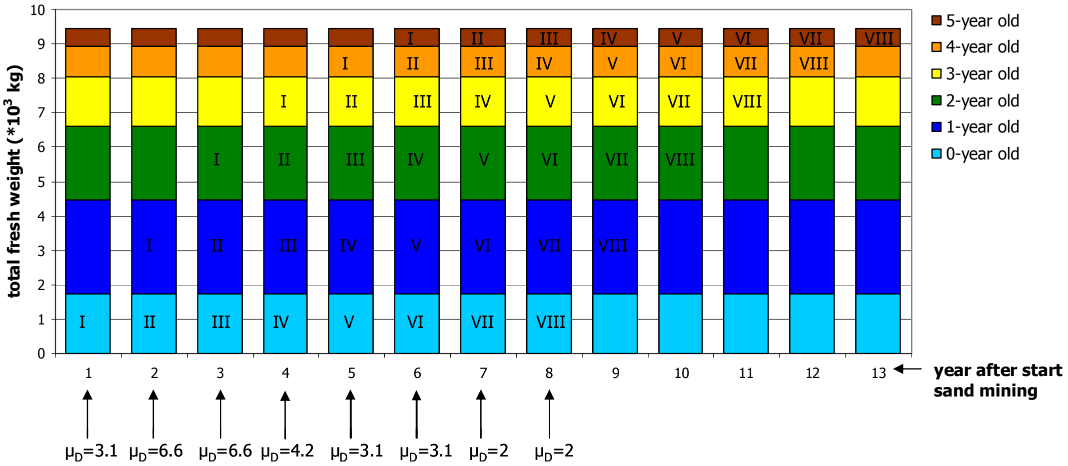

Figure 7.3 **Year classes that can be affected by a mismatch**

7.2.2 Simulations A and B

The difference between simulations A and B, is the relation between eiders and bivalves. For simulation *A* a linear relation was used (like in the EIA) and for simulation B the relation as shown in figure 6.11 (equation 6.2). As expected, the linear relation leads to the prediction of larger impacts. In case of a linear relation, the relative decrease of the number of eiders that can forage in the Voordelta, is equal to the relative decrease of the amount of food. In case of equation 6.2, the impact is relatively smaller if the amount of food in the Voordelta is large (other factors than the availability of food are limiting for the number of eiders that can forage in the Voordelta).

Figure 7.4 illustrates how using a linear relation between food and eiders, overestimates the impact on eiders.

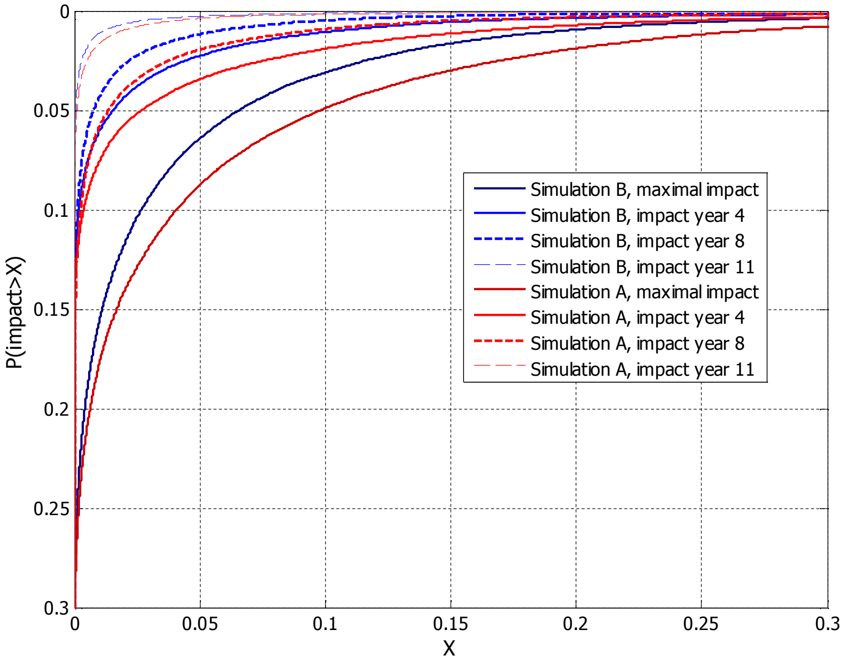

Figure 7.4 **Monte Carlo-results: probability distributions for the relative impact (*X*) in years 4, 8 and 11 after start sand mining and maximal impact, simulations A and B**

7.2.3 Simulations B and C

The difference between simulations B and C is the yearly survival rate *SY* of bivalves (see also section 5.5). In case of simulation B the survival rate of bivalves is on average 35%. For simulation C an average survival rate of 50% was used. In case of a larger survival rate, the population will consist for a larger part of older bivalves. This will lead to smaller impacts during the first few years after the start of the sand mining, but larger effects on the longer term.

Figure 7.5 shows the results of simulations B and C. The effect during the 11th year after the start of the sand mining is indeed larger for simulation C (larger survival rate). Simulation B predicts larger maximal effects. As a survival rate of 35% (on average) is more likely, using a survival rate of 50% leads to an underestimate of the possible impacts on eiders.

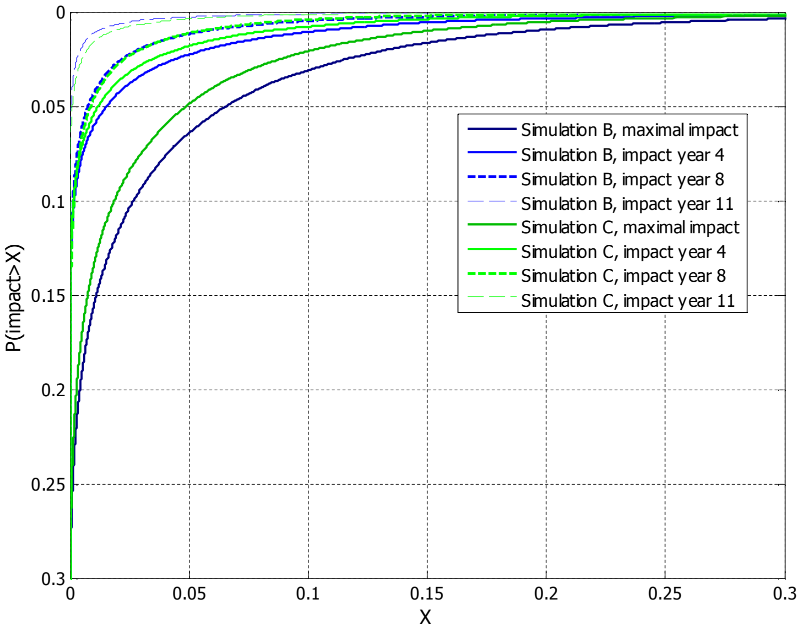

Figure 7.5 **Monte Carlo-results: probability distributions for the relative impact (*X*) in years 4, 8 and 11 after start sand mining and maximal impact, simulations B and C**

7.2.4 Simulations B, D, E and F

Simulation B shows the probability distribution of the impact on eiders for the assumptions that:

- Equation 6.2 (see figure 6.11) holds for all bivalves and eiders in the Voordelta (the abundance of Ensis in the Voordelta, on which 60% to 90% of all eiders forage, is neglected, see chapter 6);
- Bivalves are not able to catch up a growth lag.

For simulation D is assumed that only 40% of all eiders are dependent on a bivalve population that can be affected by a mismatch. The results of simulation E show the probability distribution of the impact if bivalves can catch up their growth lag partly (see section 5.6). The assumptions for D and E are combined in simulation F; for this scenario only 40% of all eiders is affected and the bivalves partly catch up their growth lags.

Compared to the results of simulation B, the predicted impacts (with an equal probability of exceedance) are reduce by 60% for simulation D, which is expected as only 40% of the eiders can be affected.

While the probability of occurrence of impacts larger than 5% was 0.065 for simulation B, this probability is only 0.02 and 0.01 for respectively simulations D and E. For simulation F this probability is even smaller than $2*10^{-3}$. This shows that the assumptions on the part of the eider population in the Voordelta that can be affected and on the catching up of growth lags by bivalves, make a large difference for the final result. This difference is much larger than the difference between simulations B and C (using a yearly survival rate of 35% or 50%).

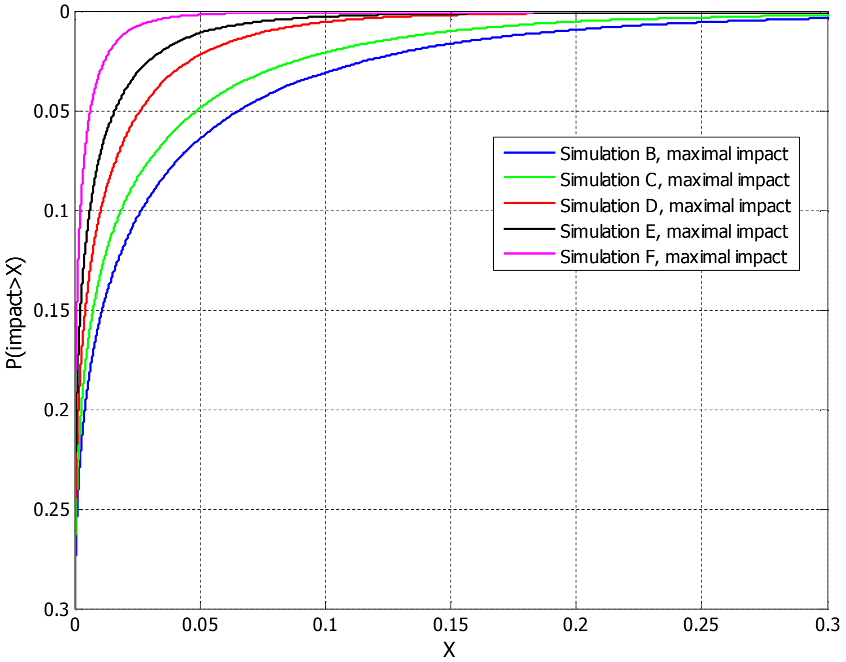

Figure 7.6 **Monte Carlo-results: probability distributions for the maximal relative impact (*X*), simulations B, C, D, E and F**

7.2.5 Variation of pdf's of A_{ref} and H

For simulation B, the moment of the algal bloom was on average at April 15th and the moment of hatching at May 18th. This combination leads to safe results, as the algal concentration that was measured at April 15th was mostly much higher than the critical concentration (concentration at which sufficient food is available for the larvae to grow maximally). In chapter 4 different probability density functions were determined for A_{ref} and H. Figure 7.7 shows the results of the Monte Carlo analysis for different combinations of the pdf's of A_{ref} and H. The differences between these results are very large.

Table 7.2 **Variation of A_{ref} and H**

Simulation	**A_{ref} (μ,σ)**	**H (μ,σ)**	
B	Apr-15, 15	May-18, 8	safe
G	Apr-17, 15	May-18, 10	very safe
H	Apr-9, 14	May-18, 8	
I	Apr-9, 14	May-25, 8	most realistic
J	Apr-5, 13	May-25, 8	

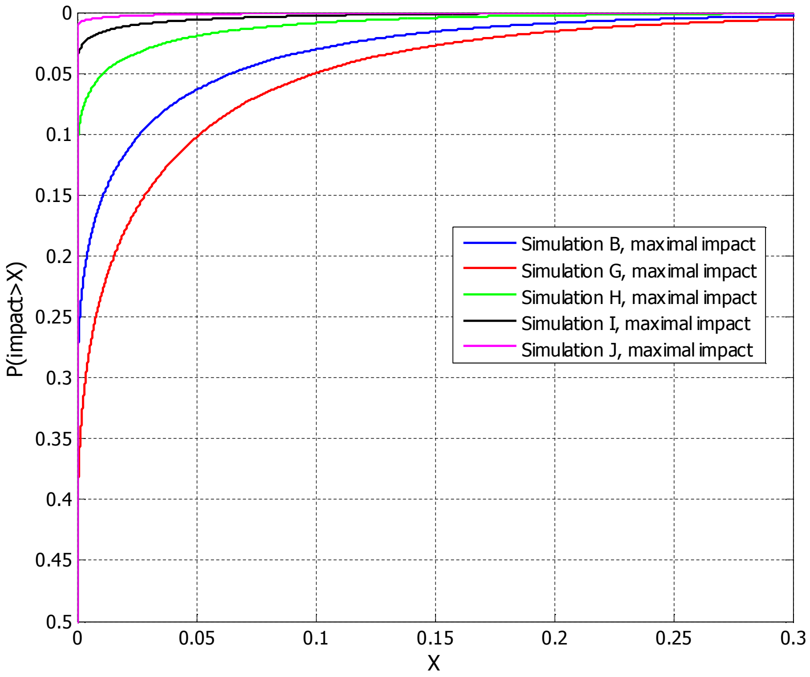

Figure 7.7 **Monte Carlo-results: probability distribution for the maximal relative impact (*X*), simulations B, G, H, I and J**

7.2.6 Sand mining scenarios

Figure 7.8 shows the results for different sand mining scenario's. The differences are very small. This can be explained by the large overlap of the probability density functions of the delay of the algal bloom *D* for different values of *fs* (the relative increase of the silt concentration), see chapter 4, Figure 4.29. Also the differences of the factor *fs*, between the different scenarios is small. For some years (within the period of 8 years) the increase of the silt concentration is more or less equal for the different scenarios. For other years the differences are relatively small. For example: during the 2nd year, *fs* is 1.5 for scenario s1a and 1.4 for s1c. The difference between the corresponding pdf's of *D* is small (see Figure 4.29), therefore the difference in the final result will also be small.

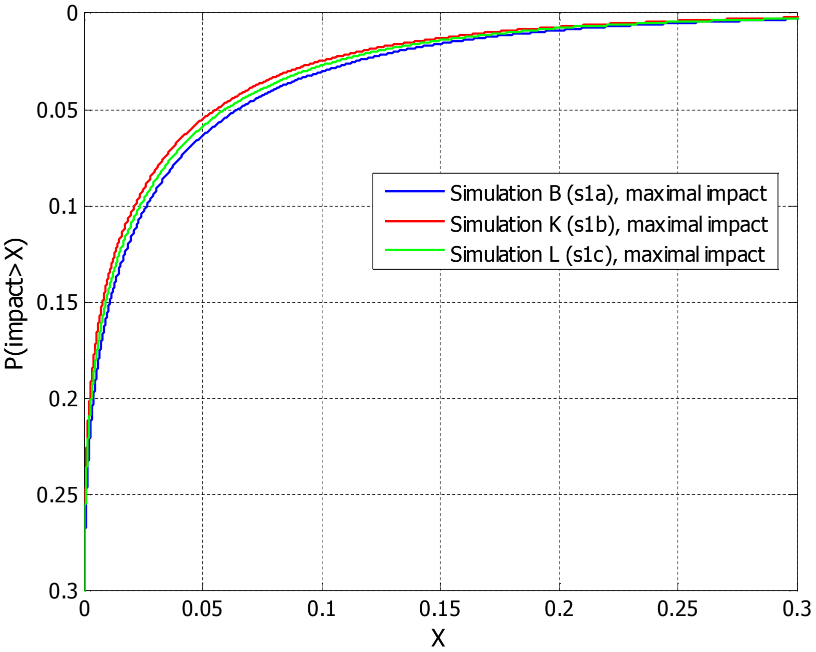

Figure 7.8 **Monte Carlo-results: probability distribution for the maximal impact, simulations B, K and L (different sand mining scenario's)**

7.3 Conclusion

The probability distribution of the impact on eiders is strongly influenced by the following assumptions:

- whether the amount of food for all eiders in the Voordelta or only for 40% of the eiders, which eat cockles, can become limiting if bivalves are subject to a growth lag;
- whether or not bivalves are able to catch up a growth lag partly;
- whether the algal bloom on average takes place at the start of April or mid-April (in the reference scenario);
- whether the hatching of bivalve larvae occurs on average at the end of May or mid-May.

Figures 7.9 and 7.10 show the influence of these assumptions on the probability distribution of the maximal impact on eiders.

The differences between the probability distributions of the impact on eiders for the different sand mining scenarios are small.

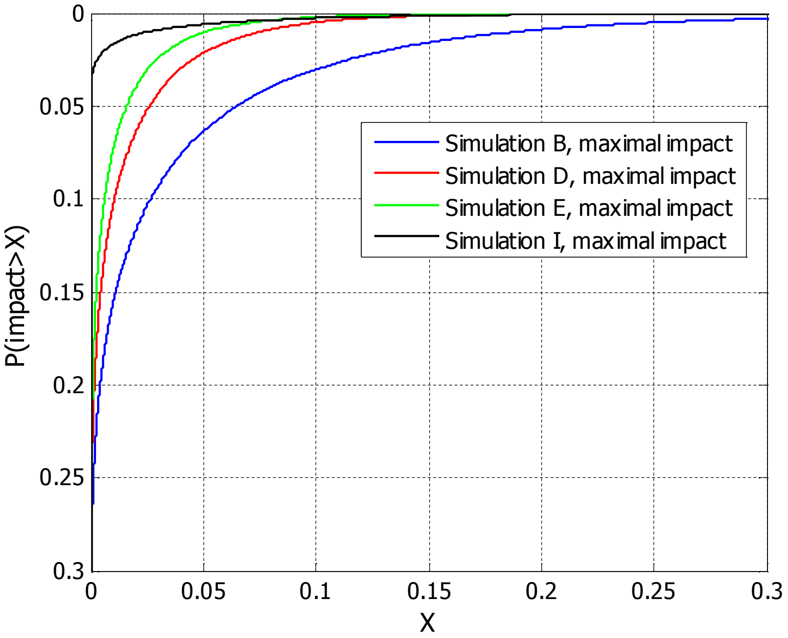

Figure 7.9 Monte Carlo-results: probability distribution for the maximal relative impact (*X*), simulations B, D, E and I

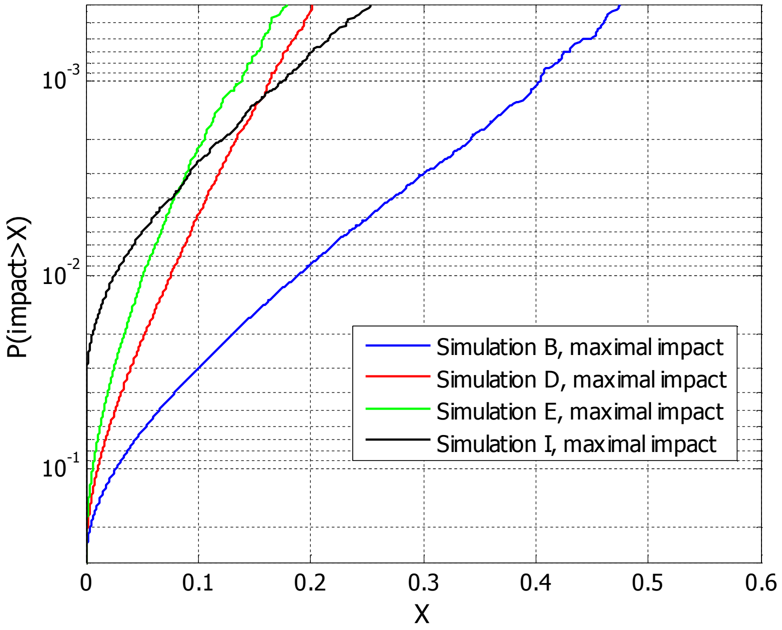

Figure 7.10 Monte Carlo-results: probability distribution for the maximal relative impact (*X*), simulations B, D, E and I, logarithmic scale

Table 7.3 Simulations

Simu-lation	Percentage of eiders possibly affected	Bivalves catch up growth lag?:	Timing of algal bloom A_{ref} (μ,σ)	Timing of hatching H (μ,σ)	Sand mining scenario
B	100%	No	Apr-15, 15	May-18, 8	s1a
D	40%	No	Apr-15, 15	May-18, 8	s1a
E	100%	Partly	Apr-15, 15	May-18, 8	s1a
I	100%	No	Apr-9, 14	May-25, 8	s1a

8 Conclusions and recommendations

8.1 Conclusions

8.1.1 Impact of sand mining on eider ducks

Main conclusion:	The probability that the sand mining activities for Maasvlakte 2 have a significant effect on eiders in the Voordelta is very small and can be considered negligible.

Even in case of safe assumptions, the probability that:

- the sand mining activities do not have an impact on eiders in the Voordelta at all is 0.7;
- the sand mining activities have an impact larger than 5% is only 0.06;
- the sand mining activities have an impact larger than 10% is only 0.03.

The mentioned impact is the maximal impact that occurs during the period of 13 years after the start of the sand mining. An impact of 10% means that the number of eiders that can winter in the Voordelta, is 10% smaller than it would have been without sand mining activities. As the effects of the sand mining will be temporary and the natural variation of the number of eiders in the Voordelta is relatively large, impacts smaller than 10% are considered not to be significant.

The probabilities on impacts mentioned above, are even smaller:

1. if the amount of food will only become limiting for the cockle-eating eiders (circa 40%) and not for the razor shell-eating eiders (circa 60%) as the current abundant amount of food for these eiders will not disappear;
2. if bivalves are able to catch up a growth lag partly;
3. if the algal bloom normally takes place at the start of April and the hatching of bivalve larvae occurs on average at the end of May, instead of the safe assumptions mid-April respectively mid-May.

It is very likely that one or more of these conditions correspond with reality. Though, proving this conclusively on the basis of data is not possible. The probabilities mentioned above are based on the safe assumption that conditions 1, 2 and 3 are not true. This assumption has a large influence on the probabilities, as the probability that:

- the sand mining activities do not have an impact on eiders in the Voordelta is 0.96 under condition 3;
- the sand mining activities have an impact larger than 5% is smaller than 0.02 if condition 1, 2 or 3 corresponds with reality;
- the sand mining activities have an impact larger than 10% is smaller than $5*10^{-3}$ if condition 1, 2 or 3 corresponds with reality.

Until now, the impact of the sand mining on the number of eiders that can potentially forage in the Voordelta has been considered. If eiders are able to winter in other areas or to change their diet to other (bivalve) species, the probability that sand mining activities for Maasvlakte 2 really affect the eider population is even smaller than mentioned above.

8.1.2 Difference between probabilistic approach and EIA

The difference between the results of the deterministic approach of the EIA and the results of the probabilistic approach is mainly caused by taking into account the probability of occurrence of a mismatch in the probabilistic approach. The worst-case assumption in the EIA that a delay of the algal bloom leads directly to a mismatch can be considered as the assumption that contributes most to the overestimation of the impact.

8.1.3 Predicting ecological effects

The impact of sand mining activities on eiders in the Voordelta, depends on a large number of factors that show large variations in nature. Due to these variations, the magnitude of the possible impact shows a large uncertainty margin. Also lack of knowledge about processes in the impact-effect chain influences the uncertainty margin of the result. However, even if all knowledge is available, it is still not possible to express a realistic prediction of ecological effects in only one number because of the unpredictable natural variations.

8.2 Recommendations

8.2.1 Reducing the uncertainty of the probability distribution

Assumptions on the behaviour of eiders, the timing of the food availability of larvae, the moment of hatching and the ability of bivalves to catch up a growth lag, have a large influence on the probability distribution of the impact on eiders. Even in case of safe assumptions the probability of occurrence of significant effects on eiders turned out to be small. If more knowledge is available on the subjects mentioned above, more realistic assumptions can be made, which will lead to even smaller probabilities on significant effects. However, this will probably not make any difference for the decision whether mitigating or compensating measures should be taken for the ecological effects of the sand mining for Maasvlakte 2. Because of this, reducing the uncertainty margin of the probability distribution by collecting more data and doing more research is not useful for this specific goal. However, more knowledge can be useful for EIA's concerning the effects of sand mining on bivalves and sea ducks, that will be carried out in future. For this goal, it is recommended to do more research on the following topics:

1. Food availability for larvae
   At which moment in spring is the food concentration for bivalve larvae sufficiently high? What is the natural variation in the timing of this moment?

2. Hatching of bivalve larvae
   When does the hatching of bivalve larvae take place on the average? How large is the yearly variation in the timing of this moment?

3. Behaviour of sea ducks
   Do sea ducks that winter in a specific area really depend on the size of the bivalve populations in this area, or are they able to find their food elsewhere in case of a food shortage in the specified area? Are, for example, sea ducks able to change their diet to other bivalve species or not?

4. Are bivalves able to catch up a growth lag (partly), or not?

8.2.2 Food quality

Differing opinions exist among ecologists about the relation between a decrease of the food quality (ratio of the silt concentration over the phytoplankton concentration) and the growth of bivalves. As the existence of the relation between food quality and growth is repeatedly a point of discussion for the quantification of impacts on bivalves, more knowledge on this relation is desirable. On the basis of literature research was concluded that the eventual existence of the relation between food quality and growth could be neglected within the probabilistic analysis of the ecological effects of the sand mining for Maasvlakte 2. Not for the specific case of the sand mining for Maasvlakte 2, but for the quantification of ecological effects of other sand mining activities in future, more research on this topic is desirable. More knowledge is necessary to draw reliable conclusions on the question whether or not the relation should play a role in the assessment of ecological effects of other sand mining activities.

9 Discussion

9.1 Probabilistic approach for EIA's

9.1.1 Advantages of a probabilistic approach

By using a probabilistic approach to quantify ecological impacts, insight is given in the probability of occurrence of certain impacts. Especially when significant impacts cannot be excluded on the basis of a deterministic approach, insight in the probability of occurrence of these impacts is useful in order to decide if mitigating or compensating measures should be taken. Deciding on the basis of the results of a deterministic approach will more often lead to the decision that measures (or a monitoring programme) are necessary. If the probability of occurrence of significant effects is for example only 10%, the probability is 90% that these measures are unnecessary.

The probability of occurrence of the possible significant impacts, as well as the costs of mitigating or compensating measures should be taken into account for a well-considered decision. Otherwise a large amount of money can be spent to prevent or compensate an effect of human activities, which even would not have been noticed by the protected animals.

For a lot of the possible effects of a particular project, conclusions on the significance of ecological impacts can be drawn by applying a deterministic, worst-case approach. In those cases, insight in the probability of occurrence of significant effects is unnecessary. In these cases, quantifying ecological effects by a probabilistic approach is not recommended, as this approach will take more time in general than an approach in which worst-case assumptions are used.

Next to insight in the probability of occurrence, a probabilistic approach also gives insight in:

- the relative influence of the various factors on the final result;
- the uncertainty margins and natural variation of the factors that play a role in the impact-effect chain.

Insight in the influence of factors and their uncertainty margins on the final result, is relevant for determining whether doing more research to a certain factor is useful or not. Whether or not ecological impacts can be monitored depends on the magnitude of natural variations. Therefore insight in these variations is useful.

Relevant factors in the impact-effect chain

In a deterministic approach, the influence of uncertainties in the first part of the impact effect chain on the final result, is larger than in case of a probabilistic approach. For example improving the accuracy of the far field modelling (spreading of the silt that is released during the sand extraction in the North Sea) seemed to be more important in the deterministic approach than in the probabilistic approach.

In the deterministic approach, a larger increase of the silt concentration leads to a larger delay of the algal bloom. A larger delay leads directly to a longer duration of the mismatch and this will subsequently lead to a larger impact on bivalves and eiders. As a change of the input variables at the first part of the impact-effect chain leads directly to different results at the end (the eiders), the accuracy of these input variables seems to be important in a deterministic approach.

The probabilistic approach showed that the probability of occurrence of a mismatch is not only dependent on the delay of the algal bloom (*D*) that is caused by the sand mining, but also on the moment of hatching of larvae (*H*) and the timing of the algal bloom in the reference situation (A_{ref}). Also the delay *D* turned out to be not only dependent on the increase of the silt concentration, but also on the short-term fluctuations of silt concentrations and solar irradiance. A large number of variables, which are not influenced by sand mining, appeared to be equally important for the possible duration of the mismatch as the increase of the silt concentration in the Voordelta.

In the deterministic approach, the output of the impact-effect chain is directly related to the increase of the silt concentration. From the probabilistic approach it appears, that other factors, which influence the impact-effect chain from the outside, also are important for the result. As long as the uncertainty margins of these other factors are large (due to lack of knowledge or due to natural variations), reducing a relatively small uncertainty margin of the increase of the silt concentration will not be useful.

Monitoring

Sand mining activities will cause an increase of the silt concentration, which can cause a delay of the algal bloom. A delay of the algal bloom can affect the total amount of bivalves and this may result temporarily in a smaller number of eiders in the Voordelta. However, measuring these possible effects after the start of the sand mining will not be possible. Silt concentrations, as well as the timing of the algal bloom, the total biomass of bivalve populations and the number of eiders show a large year-to-year variation. On the basis of a measurement of for example the number of eiders, the impact of the sand mining on this number cannot be derived, as it is impossible to determine how many eiders would have been in the Voordelta without the sand mining activities.

Figure 9.1 shows the variation of the number of eiders during the period 1993-2004. A decrease of 10% of this number (red line) is small compared to the natural variation. Therefore, concluding only on the basis of measurements whether the sand mining had an impact or not, is not possible.

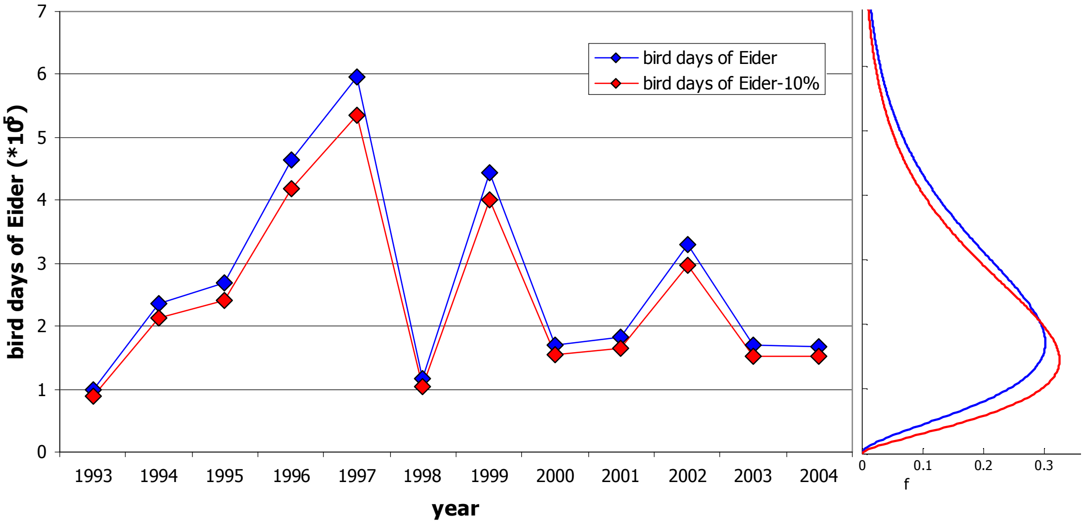

Figure 9.1 **Natural variation of the number of eiders in the Voordelta (blue line) [data from KNAW-CEME, edited by F. Heinis, not published)] and the number of eiders in case of an impact of 10%**

Although monitoring the ecological impacts of the sand mining is not possible, collecting field data on the actual values of various parameters after the start of the sand mining will be useful to gain more knowledge on factors and processes that play a role in the impact-effect chain. This knowledge will be useful for EIA's that will be carried out in future for other sand mining projects (see also section 8.2.1).

9.1.2 Methodology

In this thesis is shown that applying a probabilistic approach for the analysis of the ecological effects of sand mining for Maasvlakte 2 is possible. The methodology which is used in this thesis, is expected to be also applicable for the assessment of ecological effects of other human activities.

As mentioned in section 9.1.1, for a lot of projects can already be concluded on the basis of a deterministic, worst-case approach that the environmental consequences will not be significant. Before applying a probabilistic approach for a EIA, it is therefore recommended to estimate the ecological impacts first by a rough, deterministic, worst-case approach, as a probabilistic approach will take more time in general. If the roughly estimated affects are possibly unacceptable, applying a probabilistic approach for the quantification of the ecological effects is recommended.

The following methodology was applied in this thesis:

1. Determine which uncertainties have a large influence on the magnitude of the ecological effect (uncertainties concerning factors and processes within the impact-effect chain as well as uncertainties due to factors outside of the impact-effect chain);
2. Find a method to take into account these uncertainties within the modelling of the ecological effect;
3. Work out this method.

Generally the uncertainties at the end of the impact-effect chain will have the largest influence on the final result. In this thesis for example the uncertainties on the behaviour of the sea ducks have a larger influence than the uncertainties concerning the increase of the silt concentration by the sand mining. If the probability that sea ducks are able to fly to other areas to find their food, turns out to be large, only a small probability remains that the sand mining affects the sea ducks. A difference in the increase of the silt concentration only leads to slightly larger or smaller effects, while the uncertainty on the behaviour of the ducks makes the difference between the occurrence of an effect or no effect at all.

The uncertainties in an impact-effect chain will be uncertainties due to natural variations as well as uncertainties due to a lack of knowledge. In case of the impact of sand mining on sea ducks, an uncertainty caused by nature is for example the natural variation of the population composition of bivalves. After finding a method to simulate the natural variation, a Monte Carlo analysis was used to take into account the uncertainty induced by this natural variation on the final result.

In case of uncertainties due to a lack of knowledge, taking into account this uncertainty can be more difficult. For example the uncertainty whether bivalves are able to catch up a growth lag or not, had a large influence on the final result, but could not be incorporated in the Monte Carlo analysis. In this specific case it was not possible to determine on the basis of data or expert judgement how large the probability is that bivalves are indeed able to catch up a growth lag. No correct way was found to incorporate this specific uncertainty in the probabilistic analysis (to show the difference the assumption on this uncertainty makes, two different Monte Carlo simulations were done). This does not mean that in all cases uncertainties due to a lack of knowledge cannot be taken into account.

The methodology for applying a probabilistic approach is described very general in this section. Not for every uncertainty exactly the same calculation method will be applicable. The main difference between a probabilistic and a deterministic approach is that a lot of uncertainties can be taken into account in a probabilistic approach, while safe assumptions have to be made in a deterministic approach. The more relevant worst-case assumptions can be prevented by using a probabilistic approach instead of a deterministic, worst-case approach, the more advantageous the appliance of the probabilistic approach is.

9.2 Assessment of ecological effects

Official guidelines for the assessment of predicted ecological effects do not exist. After the quantification of the magnitude of ecological effects and the accompanying probability of occurrence, the following questions remain:

- Which effects are considered meaningful and which are not?
- Which probability that significant effects occur is unacceptable?

These questions cannot be answered on the basis of objective criteria only. The development of an assessment framework for ecological effects is recommended to make a more objective assessment possible. Within this framework the following aspects should play a role:

- Are the ecological effects permanent or temporary?
- How large is the impact of the human activities compared to the natural variation of the population size of a species?
- Will the population recover from the human impact quickly, slowly or not at all?
- If the effects concern a subpopulation in a specific area: what does this impact mean for the total population?
- Is the existence of the species threatened?

For the consideration whether compensating or mitigating measures should be taken, also an objective method to determine whether the costs of these measures are proportional to the loss of ecological values, would be useful.*

9.3 Impact on total population

Preservation goals for species that live within Natura 2000 areas prescribe that the carrying capacity of the Natura 2000 area for an average number of these species should be maintained. However, not all of these species are dependent on the amount of food they can find within the boundaries of the Natura 2000 area. For example birds may be able to fly to other areas if the amount of food in the Natura 2000 area is insufficient. Not only human activities, but also natural variations can result in an insufficient amount of food in a certain area. Because of this, it is likely that populations are able to cope with these fluctuations of the food availability within a specific area.

Such flexibility of species cannot be taken into account if only the amount of food in a certain area should be considered to quantify ecological impacts of human activities. Considering the

*the costs of compensating or mitigating measures cannot play a role in case of significant effects in Natura 2000 areas, in such case taking measures is legally obligatory food availability in all areas where a certain species can forage, leads to a smaller, more realistic probability that negative impacts occurs, than considering only one area. This will be illustrated in the following example.

Example

In this example a fictitious population of migratory sea ducks is considered. These sea ducks can forage in four different areas on bivalves during winter (see figure 9.2). The population sizes of the bivalve populations (*A, B, C* and *D*) in these areas show large fluctuations. All population sizes of bivalves are on average 20*10^3 kg, with a standard deviation of 4*10^3 kg. The size of the populations in a certain year is assumed to be normally distributed:

$$population\ size : N\left(\mu,\sigma^2\right) = N\left(20,4^2\right)$$

The total amount of food available for the sea ducks is on average:

$$\mu_{total} = \mu_A + \mu_B + \mu_C + \mu_D = 20+20+20+20 = 80\ (\cdot 10^3\ \text{kg})$$

The standard deviation of the total amount of food available is:

$$\sigma_{total} = \sqrt{\sigma_A^2+\sigma_B^2+\sigma_C^2+\sigma_D^2} = \sqrt{4\cdot 16} = 8\ (\cdot 10^3\ \text{kg})$$

Suppose that bivalve population *A* is affected by human activities and decreases by 10%; the average size of the population and its standard deviation changes as follows:

$$A_{impact} = 0.9\cdot A \Rightarrow A_{impact} : N\left(\mu,\sigma^2\right) = N\left(18,3.6\right)$$

If, for instance, a total of 60*10^3 kg food is necessary for sustaining the total sea duck population, the probability that the impact on population *A* leads to a shortage of food for the sea ducks is very small:

$$\mu_{total_{impact}} = \mu_{A_{impact}} + \mu_B + \mu_C + \mu_D - 60 = 18+20+20+20-60 = 18\ (\cdot 10^3\ \text{kg})$$

$$\sigma_{total_{impact}} = \sqrt{\sigma_{A_{impact}}^2+\sigma_B^2+\sigma_C^2+\sigma_D^2} = \sqrt{3.6^2+3\cdot 16} = 7.8\ (\cdot 10^3\ \text{kg})$$

$$\Rightarrow P\left(total_{impact} < 60\right) = \Phi\left(-\frac{\mu_{total_{impact}}-60}{\sigma_{total_{impact}}}\right) = \Phi\left(-\frac{78-60}{7.8}\right) = 0.01$$

For the total population the probability of occurrence of a food shortage is only 1%. Without the impact on population A, this probability was 0.6%:

$$P\left(total < 60\right) = \Phi\left(-\frac{\mu_{total}-60}{\sigma_{total}}\right) = \Phi\left(-\frac{80-60}{8}\right) = 0.006$$

If only population A is considered, assuming that one quarter of the total population has to forage in area A, the probability of occurrence of a food shortage for ducks increases from 10% to 20%:

Probability without impact: $P\left(A<15\right) = \Phi\left(-\frac{20-15}{4}\right) = 0.1$

Probability in case of impact: $$P\left(A_{impact} < 15\right) = \Phi\left(-\frac{18-15}{3.6}\right) = 0.2$$

Table 9.1 shows the results for different values of the quantity of food that is necessary for the whole sea duck population.

Table 9.1 Probability of occurrence of a food shortage

	Amount of food needed for the sea ducks ($*10^3$ kg)	Probability of occurrence of food shortage	
		Without impact on population A	In case of a 10% decrease of population A
One area	20	0.5	0.71
Four areas	80	0.5	0.6
One area	15	0.1	0.2
Four areas	60	0.006	0.01
One area	10	0.006	0.01
Four areas	40	<0.0001	<0.0001

Conclusion

Assuming that a part of a predator population is dependent on the amount of food of one prey population, leads to an overestimation of the probability of occurrence of a food shortage, if the individuals of the predator population are in reality able to forage on different prey populations. The fluctuation of the total amount of prey (sum of all prey populations within the habitat of the predator population) is relatively smaller than the fluctuation of the size of one specific prey population. Because of these effects, considering the impact of human activities on total population would be more realistic than considering the impact on the amount of food in a specified area.

Figures 6.2, 6.3 and 6.4 indicated that eiders are probably able to forage in different areas. For example the fluctuation of the number of eiders in the Voordelta is very large, while the fluctuation of the total number of eiders in the Netherlands is relatively much smaller. If all eiders in the Netherlands can be considered as one population, the importance of the Voordelta as a wintering area is relatively small. During winter only 1 to 5% of all eiders in the Netherlands forage in the Voordelta.

9.4 Summary

- In this thesis is shown that quantifying the probability of occurrence of significant ecological effects by using a probabilistic analysis is possible. For the ecological effects of the sand mining for Maasvlakte 2 this probability turned out to be very small. Such information is relevant in the final decision making process whether mitigating or compensating measures should be taken. Therefore it is recommended to apply a probabilistic approach for EIA's in case it is expected that a deterministic, worst-case approach will not lead to the exclusion of significant effects.
- The development of an assessment framework for ecological effects is recommended in which among other things the natural variation of population sizes and the ability for the population to recover after the impact should be taken into account.

- Regarding the impact on the amount of food for a certain population, within a specified area (which is prescribed by the current preservation goals), is stricter than regarding the impact on the population itself. The assessment of impacts on populations would be more correct than the assessment of impacts on the amount of food in specific areas.

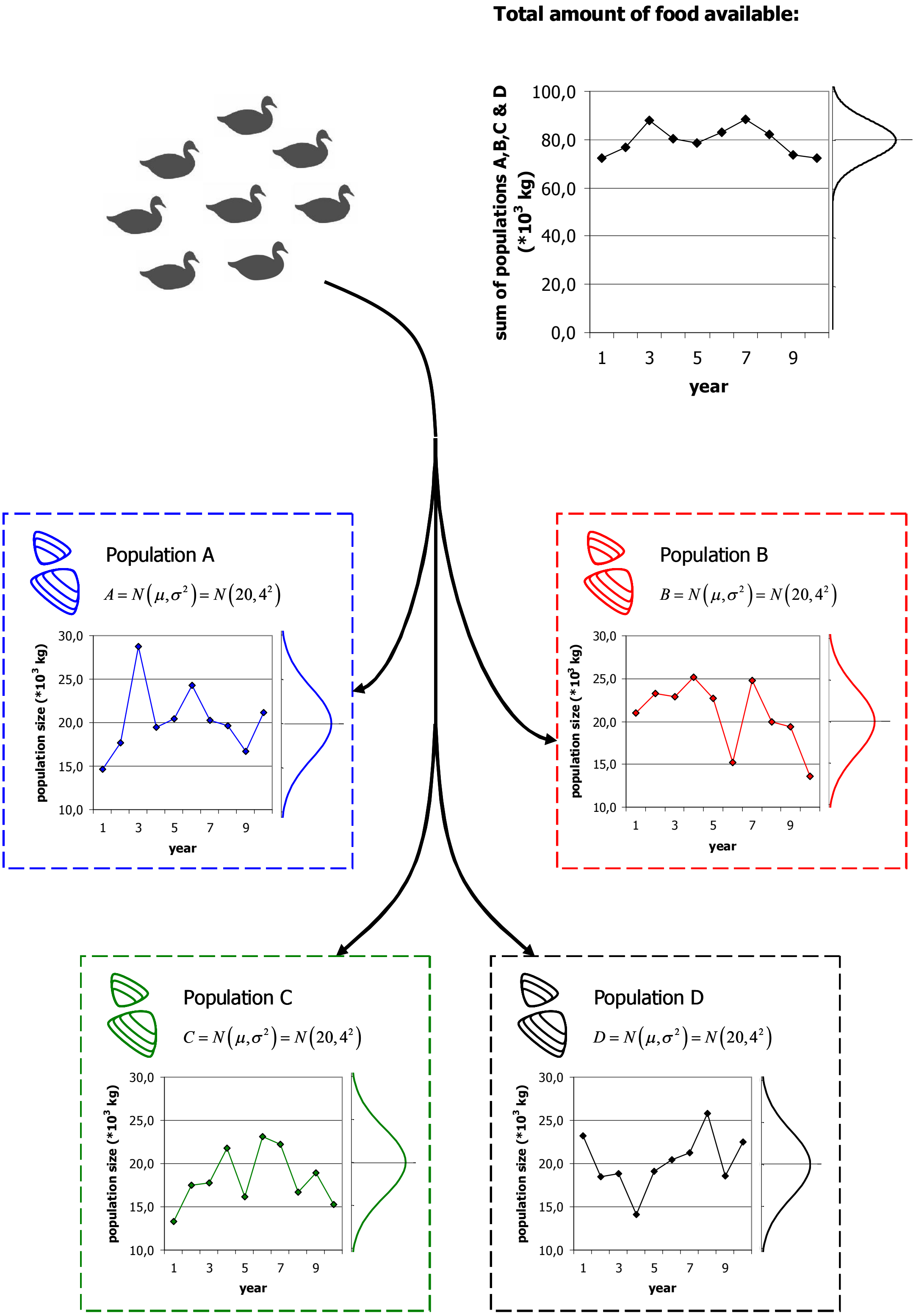

Figure 9.2 **The fictitious sea duck population is able to forage in four different areas**

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Glossary

Benthos
Benthos are the organisms which live on, in, or near the seabed. Animals belonging to the benthos are sometimes referred to as zoobenthos, while plants are referred to as phytobenthos. [Wikipedia]

Biomass of bivalves
The mass of the flesh of the bivalve, which is equal to the fresh weight, minus the mass of the shell and the enclosed seawater (equal to 'flesh weight').

Bird day
One bird day is equivalent to one bird that spends one day in a specific area.

Bivalves
Molluscs belonging to the class of *Bivalvia*. They typically have two-part shells, with both valves being symmetrical along the hinge line. [Wikipedia]

Clearance rate
Volume of water cleared of particles by suspension feeders per hour.

Detritus
Non-living particulate organic matter, which includes (fragments of) the bodies of dead organisms and faecal material.

Fines
Mud and fine sand.

Fresh weight
Total mass of a living bivalve, including the shell and the enclosed water.

Molluscs
Molluscs are members of the phylum *Mollusca*. Molluscs include a wide variety of animals such as bivalves, snails, slugs, squid and octopus.

Mud
Particles < 63 µm.

Primary production
Primary production is the production of organic compounds from atmospheric or aquatic carbon dioxide, principally through the process of photosynthesis. The organisms responsible for primary production are known as primary producers or autotrophs, and form the base of the food chain. In terrestrial ecoregions, these are mainly plants, while in aquatic ecoregions algae are primarily responsible. [Wikipedia]

Primary producers
Producers utilize energy from the sun and nutrients from the abiotic environment (carbon dioxide from the air or water, other nutrients from the soil or water) to perform photosynthesis and grow. In this way they produce organic matter from inorganic components.

Recruitment
Birth and survival of bivalve larvae.

Seston

Suspended particulate matter, including both inorganic and organic matter (equal to SPM).

Silt

In this thesis the term 'silt' is used for all particles smaller than 63 µm (mud). In fact only particles larger than 2 µm and smaller than 63 µm are silt particles. Particles smaller than 2 µm are called clay.

SPM

Suspended Particulate Matter, including both inorganic and organic matter (equal to seston).

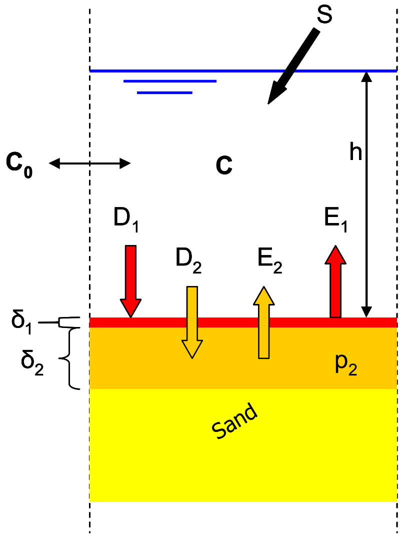
Trophic level

Trophic levels describe the position that an organism occupies in a food chain. Example: algae (producers) are eaten by bivalves (grazers), and bivalves are eaten by eider ducks (predators). Within this food chain the algae form the lowest trophic level, the bivalves the second trophic level and the eiders the highest trophic level.

Glossary English-Dutch

Allis shad	Elft
American razor shell	Amerikaanse zwaardschede (*Ensis directus*)
Balthic tellin	Nonnetje (*Macoma balthica*)
Banded wedge shell	Zaagje (*Donax vittatus*)
Bivalve	Tweekleppige
Blue mussel	Mossel (*Mytilus edulis*)
Brittle star	Slangenster
Cockle	Kokkel (*Cerastoderma edule*)
Common Eider	Eidereend
Common Scoter	Zwarte Zee-eend
Common Tern	Visdief
Copepod	Roeipootkreeftje
Cut trough shell	Halfgeknotte strandschelp (*Spisula subtruncata*)
Eider	Eidereend
Molluscs	Weekdieren
Necklace shell	Tepelhoren
Nun	Nonnetje (*Macoma balthica*)
Phylum	Stam (taxonomie)
Razor shell	Zwaardschede, mesheft
River lamprey	Rivierprik
Sandwich Tern	Grote Stern
Scaup	Toppereend
Sea potato / heart urchin	Zeeklit / hartegel
Sea urchin	Zee-egel
Shore crab	Strandkrab
Shore sea urchin	Zeeappel
Sea lamprey	Zeeprik
Twait shad	Fint
Wader	Steltloper
Winkle	Alikruik

Appendix A: Far field model



h = water depth [m]
c = silt concentration [kg/m³]
δ_1 = thickness of layer 1 (near-bed layer) [m]
δ_2 = thickness of layer 2 [m]
E = erosion flux [kg/(m²/s)]
D = deposition flux [kg/(m²/s)]
S = release rate of fines [kg/s]
p_2 = silt volume percentage in layer 2 [-]

Figure A.1 **Schematization of the seabed (not to scale) [Van Prooijen *et al.* (2006)]**

The following balance equations are used for the water column and the two bed layers [Van Prooijen *et al.* (2006)]:

$$h\frac{\partial c}{\partial t} = E_1 - D_1 + E_2 + D_2 + k\left(c_0 - c\right) + S$$

$$\rho_{dry}\delta_1\frac{\partial p_1}{\partial t} = D_1 - E_1$$

$$\rho_{dry}\delta_1\frac{\partial p_2}{\partial t} = D_2 - E_2$$

With: h = water depth [m]
c = SPM-concentration [kg/m^3]
E_1 = erosion flux from layer 1 [kg/(m^2/s)]
E_2 = erosion flux from layer 2 [kg/(m^2/s)]
D_1 = deposition flux to layer 1 [kg/(m^2/s)]
D_2 = deposition flux to layer 2 [kg/(m^2/s)]
k = diffusion coefficient [m^2/s]
S = release rate of fines [kg/s]
ρ_{dry} = density of silt [kg/m^3]
δ_1 = thickness of layer 1 [m]
δ_2 = thickness of layer 2 [m]
p_1 = silt volume percentage in layer 1 [-]
p_2 = silt volume percentage in layer 2 [-]

For the erosion of the near bed layer, the formulation of Partheniades is used [Van Prooijen *et al.* (2006)]:

$$E_1 = p_1 M_1 \left(\frac{\tau_b}{\tau_{e,1}} - 1 \right) \quad \text{if } \tau_\mathrm{b} > \tau_{e,1}, \text{ else } E_1 = 0$$

With: M = erosion rate [kg/(m^2/s)]
τ_b = bed shear stress [N/m^2]
τ_e = critical erosion shear stress [N/m^2]

The following formula is used for the wave-induced erosion from the buffering layer. The formula is based on the empirical formula of Van Rijn for the transport of sand particles in the range of 130 to 1500 µm [Van Prooijen *et al.* (2006)]:

$$E_2 = p_2 M_2 \left(\frac{\tau_b}{\tau_{e,2}} - 1 \right)^{1.5} \quad \text{if } \tau_b > \tau_{e,2}, \text{ else } E_2 = 0$$

$$M_2 = 3.3 \cdot 10^4 \rho_s \left((s-1) \cdot g \cdot d_{50} \right)^{0.5} D_*^{0.3}$$

$$D_* = d_{50} \left(\frac{(s-1) \cdot g}{v^2} \right)^{1/3}$$

$$s = \frac{\rho_s}{\rho_w}$$

With: d_{50} = grain diameter where 50% of the grain mass has a smaller diameter

The deposition of mud on the bed surface is given by [Van Prooijen *et al.* (2006)]:

$$D_1 = (1-\alpha) w_s c$$

With: α = coefficient which describes the distribution of deposited sediment between the surface layer and the sediment bed [-]
w_s = settling velocity [m/s]

The entrainment of fines into the seabed is given by [Van Prooijen *et al.* (2006)]:

$$D_2 = \alpha w_s c$$

It is assumed that entrainment of silt particles in the seabed occurs only if the mud percentage of the seabed is below a certain threshold value (p_{max}). So: $\alpha = 0$ if $p \geq p_{max}$.

This two-layer model has been validated with measurements of the SPM-concentration near Noordwijk and with some observations of the mud percentage of the seabed. A setting of the above parameters was found that leads to a quite good reproduction of the measured SPM-concentrations by the model. However, the available measured data are insufficient to result in a unique set of parameter settings. Also an other parameter setting might be able to reproduce the data of the measuring location quite well. Possibly this parameter setting results in other SPM-concentrations in the Voordelta.

Appendix B: Probabilistic and deterministic

Figure B.1: Changing the value of input variable *S* from 1.5 t 1.45, leads directly to a change of the final result *B* in the deterministic approach, which may be considered as a large difference. For the (semi-)probabilistic approach, changing the value of *S* leads to a somewhat different probability density function of *B*. Generally this difference will be considered smaller and less relevant than the difference in case of the deterministic calculation.

Figure B.2 illustrates that taking into account the uncertainty margin of *S* does hardly have an effect on the final result, if this uncertainty margin is small compared to the uncertainty margins of other factors within the impact-effect chain.

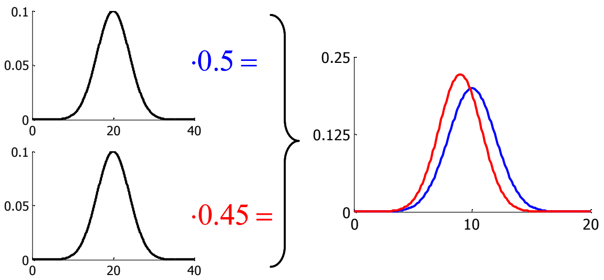
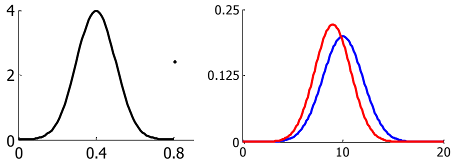
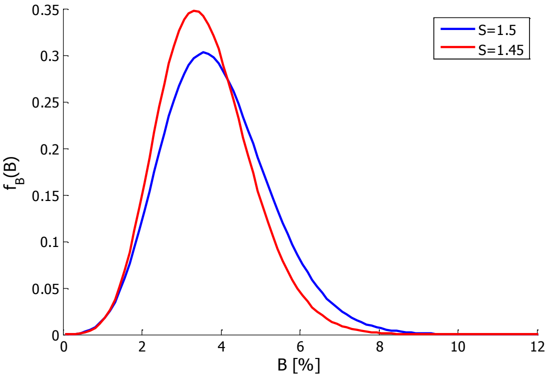
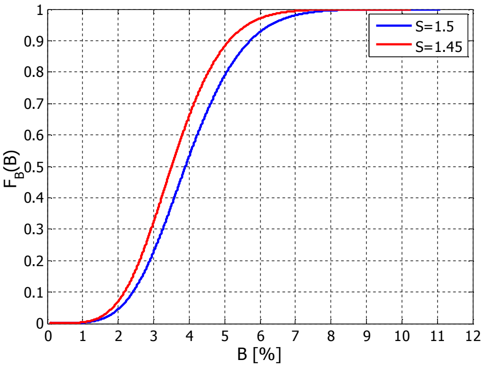
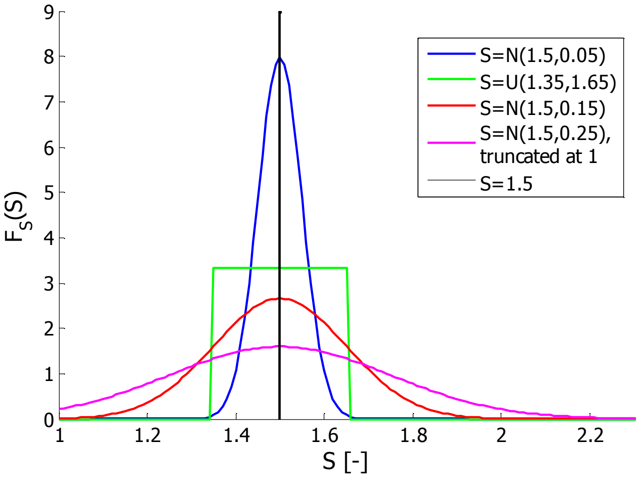
(Semi-) Probabilistic	**Deterministic**
$S=1.5$ $S=1.45$ $a=N\left(\mu_a,\sigma_a\right)=N\left(20,4\right)$ d	$S=1.5$ $S=1.45$ $a=24$ d
$M=a\cdot\left(S-1\right):$  $\Rightarrow M_{S=1.5}=N\left(\mu_M,\sigma_M\right)=N\left(10,2\right)$ d $\Rightarrow M_{S=1.45}=N\left(\mu_M,\sigma_M\right)=N\left(9,1.8\right)$ d	$M_{S=1.5}=a\cdot\left(S-1\right)=24\cdot 0.5=12$ d $M_{S=1.45}=a\cdot\left(S-1\right)$ $=24\cdot 0.45=10.8$ d
$b=N\left(\mu_b,\sigma_b\right)=N\left(0.4,0.1\right)$ $\%\cdot\mathrm{d}^{-1}$	$b=0.5$ $\%\cdot\mathrm{d}^{-1}$
$B=b\cdot M:$  $\Rightarrow B:$   	$B_{S=1.5}=b\cdot M=0.5\cdot 12=6$ % $B_{S=1.45}=b\cdot M=0.5\cdot 12=5.4$ %

Figure B.1 Example 1

Probabilistic

$S:$



$$a = N(\mu_a, \sigma_a) = N(20,4)\ \text{d}$$

$$b = N(\mu_b, \sigma_b) = N(0.4,0.1)\ \%\cdot\text{d}^{-1}$$

$B = a \cdot b \cdot (S-1):$

$\Rightarrow B:$

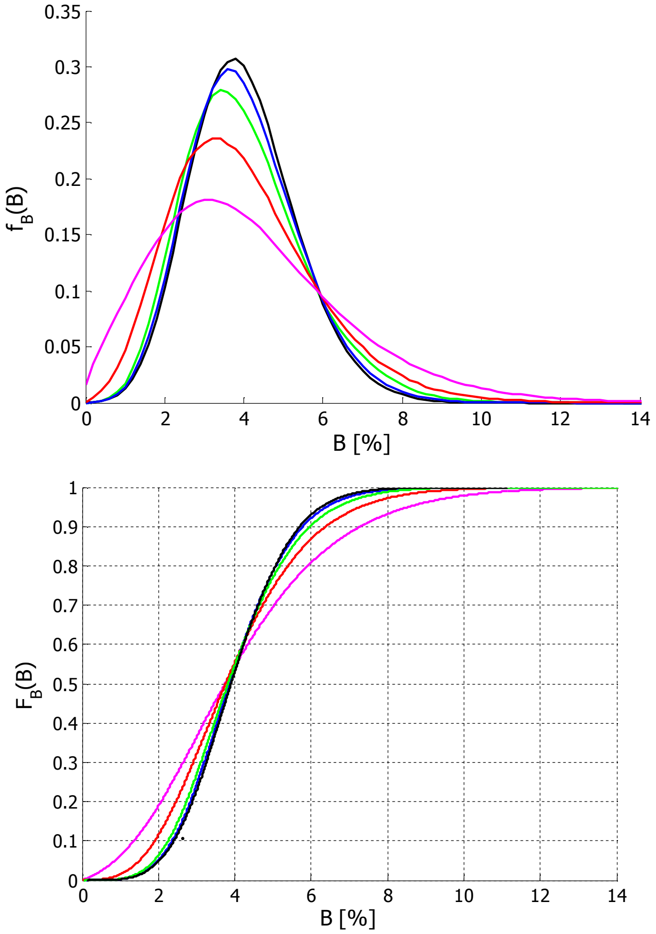


Figure B.2 Example 2

Appendix C: Growth models

The growth model of section 3.2.3, which is also used in the population dynamical model of chapter 5, uses the factor *G* to take into account the growth of individual bivalves over one year. The biomass of the individual bivalves is calculated per time step of one year in this way.

$$BM_{i+1}^{j+1} = BM_i^j \cdot G_i \cdot SY^j \tag{9.1}$$

BM_i^j = total biomass of all individuals of age *i* in year *j* [kg]

G_i = growth factor for individuals of age *i* [-]

SY^j = survival rate in year *j* [-]

The growth of bivalves during the year is actually not known. Probably the bivalves only grow during spring and summer and possibly their fresh weight even decreases during winter. The data available about the size of bivalves are mostly from measurements which are done only once or twice a year. Therefore, the development of bivalves during the year is not known and cannot be described by a continuous growth model (like for example the growth model of phytoplankton, equation 4.1).

Figure C.1 illustrates how the growth factor *G* is determined on the basis of yearly measurements of the size of an individual bivalve. The blue and green lines show how the biomass of an individual bivalve possibly develops during its life.

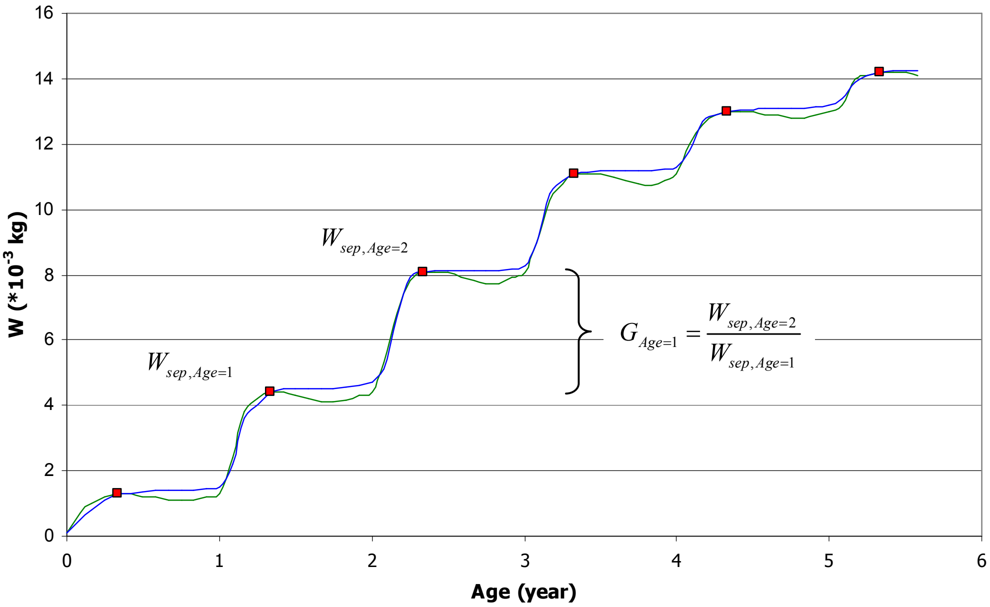


Figure C.1 **Determination of growth factor G and the possible development of biomass during the year**

Two of the growth models that are mentioned in section 5.6, equations 5.20 and 5.21, seem to indicate that they describe the growth of bivalves continuously. However, also these growth models are probably based on measurements that are only done once or twice per year. Relations like 5.20 and 5.21 are fitted to these data, but do not necessarily describe the growth of the bivalves during the year correctly.

In the figures of section 5.6 (figures 5.17 and 5.18) the growth of bivalves is shown as a continuous line. This is not fully correct; for example in case of equation 5.22, the biomass of the individual bivalves is in fact only known in May and September. However, in order to show the decrease of the relative size difference of the largest and smallest bivalves more clearly, continuous lines are used instead of markers for the biomass in May and September.

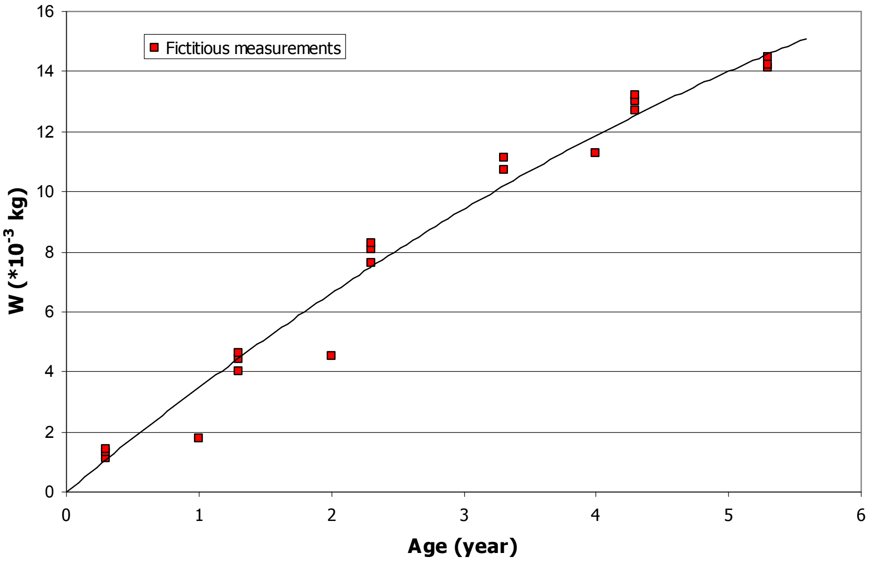


Figure C.2 **Growth model, fitted to measurements, which possibly does not describe growth during the year correctly**

In the population-dynamical model also the survival of bivalves is calculated per time step of one year. The daily survival rate is expected to be variable and not constant during the year.

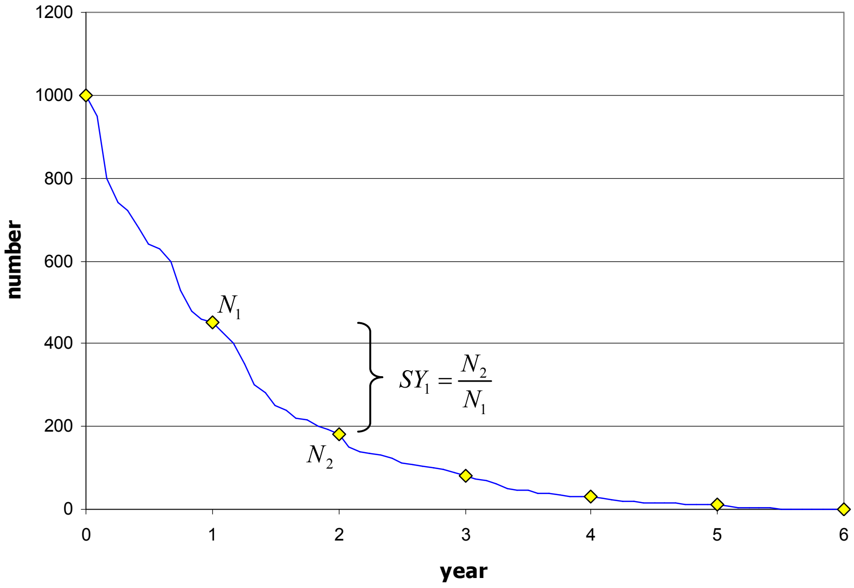


Figure C.3 **Possible decrease of the number of bivalves of one specific year class and the derivation of *SY***

Appendix D: Additional figures for chapter 4

Probability density function of Itop

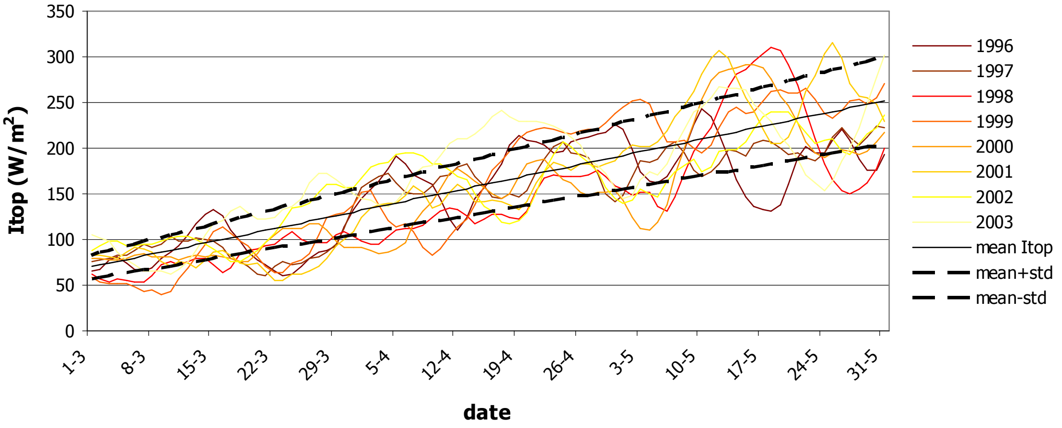


Figure D.1 Itop during spring, 1996-2003 [daily averaged, measured luminous intensities at De Kooy, KNMI]

The light intensity at the water surface Itop at a certain day during spring, is assumed to be normally distributed with:

$$\mu_{Itop} = 2 \cdot (t-60) + 68 \qquad [\mathrm{W/m^2}]$$

$$\sigma_{Itop} = 0.19 \cdot \mu_{Itop} \qquad [\mathrm{W/m^2}]$$

With: t = time [daynumber]

Probability distribution of the increase of *Itop*

The measured light intensities of figure D.1 are used to derive the probability distributions of the increase of *Itop* (Figure 4.20). For each period of 1, 2, 3, 4 or 5 days the increase of *Itop* has been determined. However, data were excluded if the value of *Itop* at the end of the period was exceeded in the period between (in such case primary production in the sand mining scenario would have started already) or if values smaller than *Itop* at the first day occurred during this period (the net primary production in the reference scenario would have stopped). On the basis of all remaining data of the increase of *Itop* the probability distribution has been drawn.

Probability density function of IM1

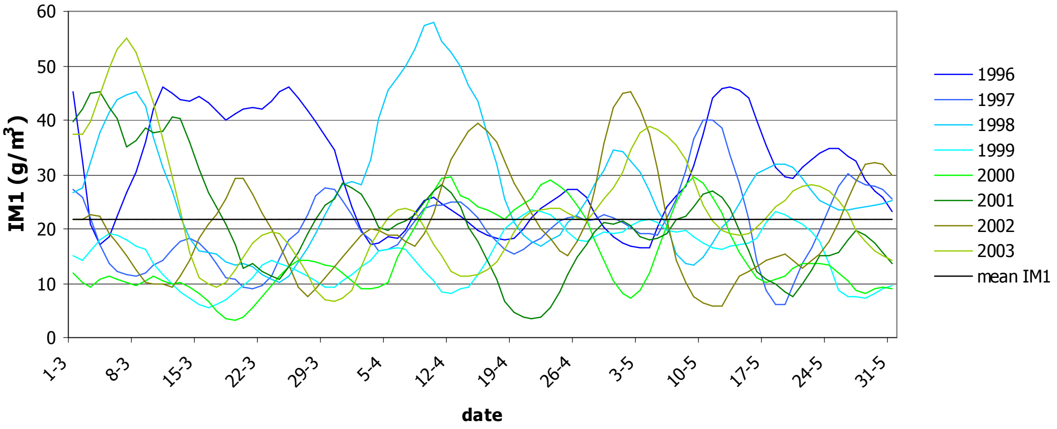


Figure D.2 Modelled IM1 (moving average over a period of 7 days) during spring for meteorological conditions of 1996 – 2003 [model results WL | Delft Hydraulics, DESMIT *et al.* (2007)]

The variation of the parameters of the pdf of *IM1* during time is assumed to be negligible for the period March-May.

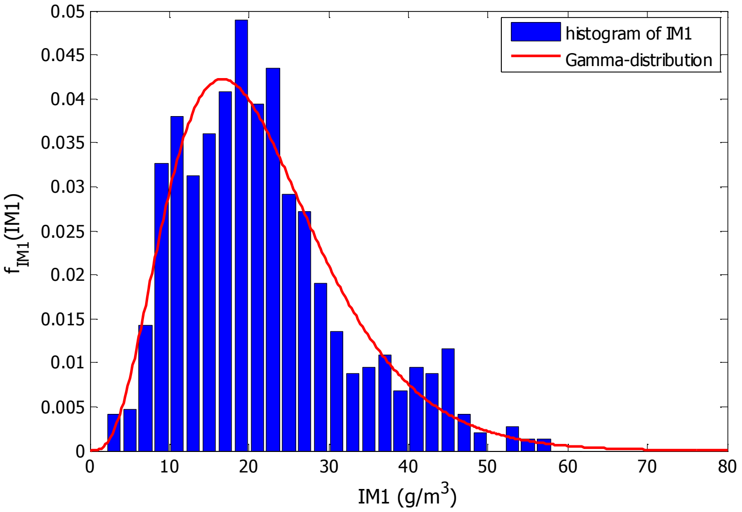


Figure D.3 Gamma-pdf of IM1, Γ(4.27,5.09)

Joint probability density function of IM1 and Itop

IM1 and Itop are assumed to be uncorrelated.

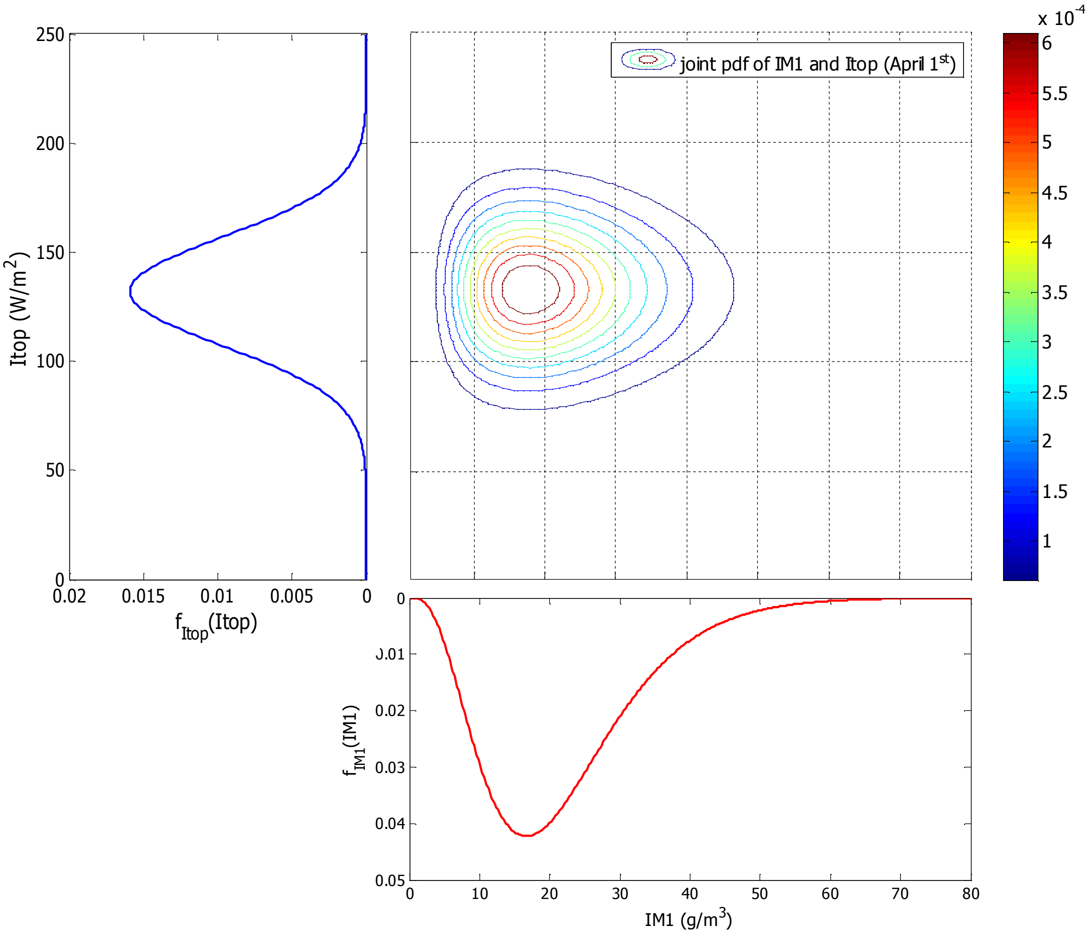


Figure D.4 Joint probability density function of ***IM1*** and ***Itop*** for April 1st

Appendix E: Algal bloom

References data:
In situ measurements: RIKZ, national monitoring programme 'Monitoring Waterstaatkundige Toestand des Lands (MWTL) – biomonitoring fytoplankton',
chlorophyll-a concentrations: www.waterbase.nl
cell concentrations: not published
Remote sensing data: ToRSMoN SeaWiFS CHL dataset, IVM/Institute for Environmental Studies.

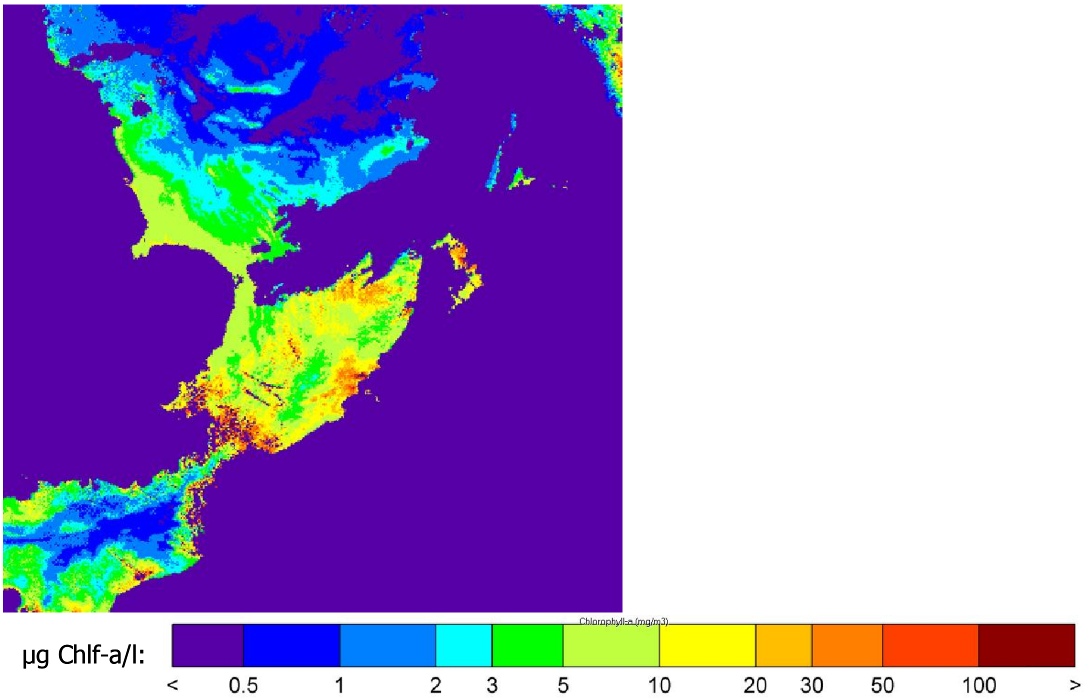


Figure E.1 **Example of remote sensing data, May 17th, 2004 [ToRSMoN SeaWiFS CHL dataset, IVM/Institute for Environmental Studies]**

Table E.1 Available data of measured algal concentrations during spring

Year	Date	In situ measurements		Remote sensing	Period between measurements (days)
		Concentration (µg Chl-a /l)	Concentration (*10^3 cells/l)	Concentration >10 µg Chlf-a /l ?	
1975	June 5th	**44.2**			-
1976	March 16th	10.0			-
	April 7th	**33.0**			22
1977	April 5th	8.5			-
	April 19th	**47.8**			14
1978	April 11th	5.0			-
	April 26th	**20.8**			15
1979	April 3rd	7.7			-
	April 18th	**36.8**			15
1980	April 10th	4			-
	April 23rd	**15.5**			13
	May 7th	**22.7**			14
1981	March 17th	2.5			-
	March 31st	**13.1**			14
	April 14th	**24.1**			14
1982	March 23rd	4.4			-
	April 20th	**28.8**			28
1983	March 28th	9.9			-
	April 26th	**15.4**			29
	May 9th	**91.6**			13
1984	February 27th	2.1			-
	April 15th	**13.8**			43
	April 24th	**13.9**			9
	May 28th	**24.4**			34
1985	March 4th	9.4			-
	June 4th	**24.0**			92
1986	April 2nd	9.3			-
	April 15th	**21.8**			13
1987	February 17th	3.1			-
	March 9th	**13.7**			21
	March 31st	**34.0**			21
1988	March 23rd	3.8			-
	April 19th	7.7			27
	June 20th	2.6			62
1989	March 15th	6.7			-
	April 12th	**22.7**			28
1990	January 4th	2.3			-
	April 17th	**23.3**			104
1991	March 11th	5.3	1.5		-
	April 8th	**16.6**	**27.5**		28
1992	March 3rd		1.6		-
	March 9th	2.3			6
	April 9th	**18.7**	**15.3**		31
1993	April 14th	8.6	0.8		-
	May 17th	**21.3**	**37.4**		33

1994	March 2nd	8.3	0.6		-
	March 28th	**13.2**	0.9		26
	May 2nd	**122.0**	**71.8**		35
1995	March 9th	3.6	0.5		-
	March 30th	**15.2**	2.5		21
	May 3rd		**37.9**		34
1996	March 12th	8.7	1.4		-
	April 17th	**53.4**	**28.5**		36
1997	March 14th	2.6	0.2		-
	April 16th	**19.4**	**37.0**		33
1998	February 10th	3.1	0.6		-
	March 19th			No	38
	April 14th	**34.0**	**12.8**		26
	May 8th			**Yes?**	24
	May 9th			**Yes**	1
1999	March 19th	5.4	0.5		-
	March 29th			No	10
	April 14th		**4.0**	No?	16
	April 15th	**29.6**			1
	April 27th			**Yes**	12
	May 25th	1.6	**27.1**		28
2000	March 12th			No	-
	March 13th		**4.1**		1
	March 14th	5.6			1
	April 8th			No	25
	April 11th			No	3
	April 14th	5.6	2.2		3
	May 5th			**Yes?**	21
	May 6th			**Yes**	1
2001	February 15th	3.0	1.6		-
	February 24th			No	9
	March 12th			No	17
	March 14th	**17**	**11.1**		2
	April 2nd			No?	19
	April 3rd			**Yes**	1
	April 10th	**46.0**	**38.0**		7
	April 16th			No	6
2002	March 11th	5.5	3.8		-
	March 29th			No	18
	April 5th			No	7
	April 6th			**Yes**	1
	April 17th	**52.0**	**5.5**		11
2003	March 11th	9.5	3.4		-
	March 23rd			No	12
	April 14th	**37.8**	**42.1**		22
	April 15th			**Yes**	1
	April 16th			**Yes**	1
	April 17th			No?	1
	April 18th			No	1

	April 23rd			**Yes?**	5
	April 29th			**Yes**	6
2004	January 6th	1.6	0.6		-
	February 20th			No	45
	March 12th		**25.9**		21
	March 15th	**14.4**			3
	March 30th			No	15
	March 31st			No	1
	April 1st			No	1
	April 15th	**31.2**	**11.9**	No	14
	April 17th			**Yes?**	2
	April 21st			No?	4
	April 23rd			**Yes**	2
2005	March 16th	3.2	2.9		-
	April 20th	**10.4**	**14.1**		35
2006	March 17th	5.5			-
	April 27th	**15.2**			41
	May 18th	**34.2**			
2007	March 22nd	5.0			-
	April 19th	**54.2**			28

In table E.1 question marks are used if the Voordelta was not entirely visible at the satellite images due to clouds. Due to this, it is not known for sure whether or not the chlorophyll-a concentration was higher than 10 µg/l.

Table E.2 Estimates of A_{ref}

Year	Estimate 1	Estimate 2	Estimate 3	Estimate 4
1976	March 27th	April 1st	April 7th	April 7th
1977	April 12th	April 15th	April 19th	April 19th
1978	April 19th	April 22nd	April 26th	April 26th
1979	April 11th	April 14th	April 18th	April 18th
1980	April 23rd	April 23rd	April 23rd	April 30th
1981	March 31st	March 31st	March 31st	April 7th
1982	April 6th	April 13th	April 20th	April 20th
1983	April 26th	April 26th	April 26th	May 3rd
1984	April 15th	April 15th	April 15th	May 11th
1985	No data available for April and May			
1986	April 9th	April 12th	April 15th	April 15th
1987	March 9th	March 9th	March 9th	March 21st
1988	Bloom not measured			
1989	March 29th	April 5th	April 12th	April 12th
1990	April 10th	April 13th	April 17th	April 17th
1991	March 25th	April 1st	April 8th	April 8th
1992	March 25th	April 1st	April 9th	April 9th
1993	May 1st	May 9th	May 17th	May 17th
1994	April 15th	April 23rd	May 2nd	May 2nd
1995	April 16th	April 24th	May 3rd	May 3rd
1996	March 30th	April 8th	April 17th	April 17th
1997	March 31st	April 8th	April 16th	April 16th
1998	April 1st	April 7th	April 14th	April 14th

1999	April 14th	April 14th	April 15th	April 15th
2000	March 13th	March 13th	May 9th	May 9th
2001	March 13th	March 13th	March 14th	March 14th
2002	April 6th	April 6th	April 6th	April 6th
2003	April 3rd	April 8th	April 14th	April 14th
2004	March 12th	March 12th	March 12th	March 12th
2005	April 3rd	April 11th	April 20th	April 20th
2006	April 7th	April 17th	April 27th	May 8th
2007	April 5th	April 12th	April 19th	April 19th
Average:	**April 4th**	**April 9th**	**April 15th**	**April 17th**
Standard dev.:	**13 days**	**14 days**	**15 days**	**15 days**

Table E.3 Algal concentration measured circa one month before the algal bloom [RIKZ, not published]

Date	1991/03/11	1992/03/03	1993/04/14	1994/03/28	1995/03/30	1996/03/12
Algal concentration (gC/m^3)	0.16	0.04	0.08	0.24	0.20	0.07
Algal concentration (*10^3 cells/ml)	1.5	1.6	0.8	0.9	2.5	1.4

Date	1997/03/14	1998	1999/03/17	2000/02/21	2000/04/14	2001/02/15
Algal concentration (gC/m^3)	0.03	-	0.03	0.08	0.10	0.07
Algal concentration (*10^3 cells/ml)	0.2	-	0.5	3.2	2.2	1.6

Date	2002/03/11	2003/03/11	2004	2005/03/16
Algal concentration (gC/m^3)	0.28	0.24	-	0.09
Algal concentration (*10^3 cells/ml)	3.8	3.4	-	2.9

For 1998 and 2004 the results of the measurements one month before the algal bloom are not available.

Appendix F: Food quality and growth

This appendix summarizes the results of the literature research on the impact of food quality on the growth of bivalves.

The assumption that a relation between food quality and growth exists might be based on the hypothesis that more energy is necessary for filtration, sorting and the production of pseudofaeces in case of a smaller organic content of the SPM, while the net food intake does not increase (the use of more energy is not compensated).

ESSINK (1999)

ESSINK (1999) concluded that enhancement of mean SPM-concentrations with 10-20% will not cause problems for growth of the blue mussel, except when dredging or dumping leads to a more frequent exceeding of a certain threshold concentration, at which mussels reduce their filtration rate. In 1979, Widdows *et al*. found that the filtration rate of 3-cm large mussels is maximal at an SPM-concentration of 125 mg/l. At 225 mg/l of SPM, filtration rate had decreased to 30% and at 250 mg/l to zero [ESSINK (1999)].

Table F.1 shows the change of the food quality and (near-bed) SPM-concentrations in the third year after the start of the sand mining activities, as predicted by the model results [model results WL | Delft Hydraulics]. In the third year after the start of the sand mining, the modelled change of the food quality and SPM-concentrations was largest. Based on these data, a frequent exceedance of the SPM-concentration of 125 gDM/m^3, at which bivalves start reducing their filtration rate, is not likely. According to the conclusions of ESSINK (1999), the increase of the silt concentration due to the sand mining activities probably does not influence the growth of bivalves in the Voordelta. However, ESSINK (1999) does not give information on the combined effect of an increase of the concentration of inorganic matter and a decrease of the concentration organic matter, which will be the case in the sand mining situation.

Table F.1 Range of variation of food quality, derived from model results of WL | Delft Hydraulics

Third year after start sand mining, location 'Goeree 6 km'	Sand mining scenario 1a		Reference scenario	
	organic content (-)	SPM-concentration (mg/l)	organic content (-)	SPM-concentration (mg/l)
Summer-averaged (June-August) food quality	$1 * 10^{-1}$	$3.5 * 10^{1}$	$1.5 * 10^{-1}$	$2.5 * 10^{1}$
Minimal food quality during summer	$3 * 10^{-2}$	$7.5 * 10^{1}$	$5 * 10^{-2}$	$5 * 10^{1}$
Maximal food quality during summer	$2 * 10^{-1}$	$2 * 10^{1}$	$3 * 10^{-1}$	$1.5 * 10^{1}$

NAVARRO AND WIDDOWS (1997)

NAVARRO AND WIDDOWS (1997) investigated the suspension-feeding activity of cockles (*Cerastoderma edule*) in response to a wide range of experimental seston concentrations. The results suggest that cockles can compensate efficiently for a decrease in food quality over a wide range of seston concentrations (1.6 to 300 mg/l) by maintaining an effective preingestive mechanism of selection for organic particulate matter, as well as increasing filtration and rejection rates.

Figure F.1 shows the seston concentrations and the accompanying organic contents, that were used in the experiments of NAVARRO AND WIDDOWS (1997).

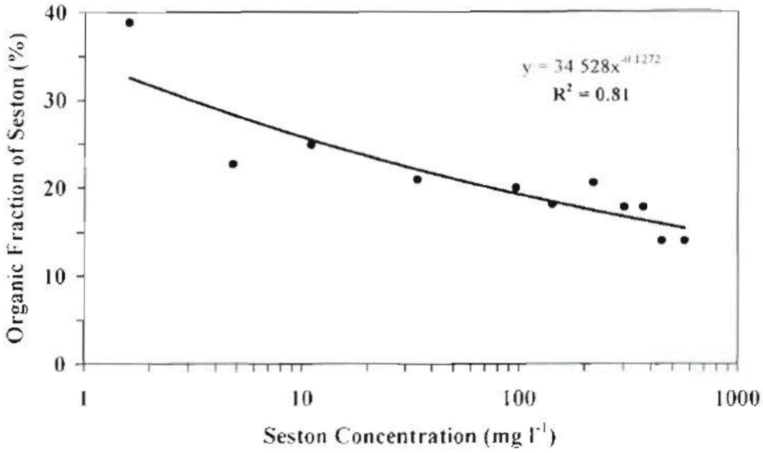


Figure F.1 Experimental seston concentrations; relationship between the organic fraction and total seston concentration, figure from NAVARRO AND WIDDOWS (1997)

The clearance rate (l h^{-1}) of cockles was highest at the lowest seston concentrations [NAVARRO AND WIDDOWS (1997)]. Possibly a low concentration of organic matter results in a high clearance rate; more water has to be siphoned to filter sufficient food out of the water. The total filtration rate (inorganic + organic matter, mg h^{-1}) increased with seston concentration up to a maximum at a concentration of 300 mg l^{-1}. Above ca 300 mg l^{-1} there was a decline of the total filtration rate (see figure F.2) [NAVARRO AND WIDDOWS (1997)].

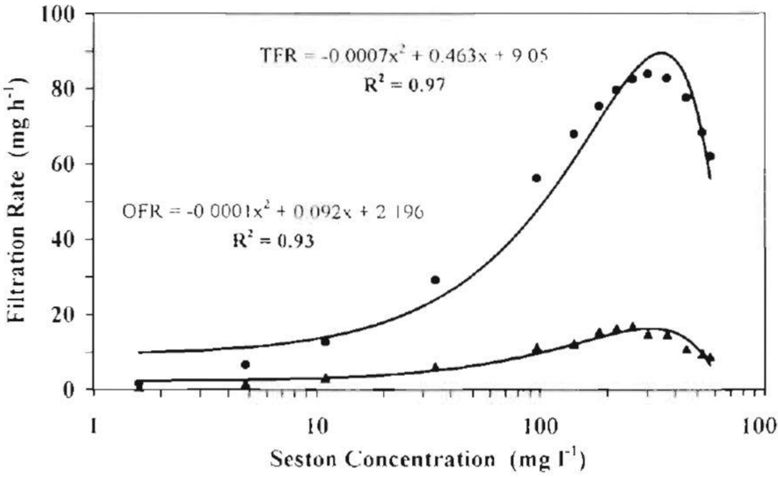


Figure F.2 *Cerastoderma edule*. Total (●, TFR) and organic (▲, OFR) filtration rates in relation to seston concentration, figure from NAVARRO AND WIDDOWS (1997)

The filtered matter contains organic and inorganic matter. Cockles are able to select rather efficiently the organic particles for ingestion and the inorganic part for rejection as pseudofaeces. This selection results in an organic enrichment of the food ingested. At seston concentrations below ca 100 mg l^{-1} (20% organic content) the physiological sorting and selection mechanism appeared to be very effective, but the ability to select declined abruptly at higher concentrations. Due to this, the organic content of the ingested matter decreased at these higher concentrations.

Subsequently from this ingested matter, the cockles also reject a part a faeces, the other part (a part of the ingested organic matter) is absorbed. By a rather effective selection of the organic matter for absorption, the rate of food absorption can be kept constant for a large range of seston concentrations (1.6 to 250 mg l^{-1}). At concentrations higher than 250 mg l^{-1} the absorption rate declined rapidly (see figure F.3). [Navarro and Widdows (1997)].

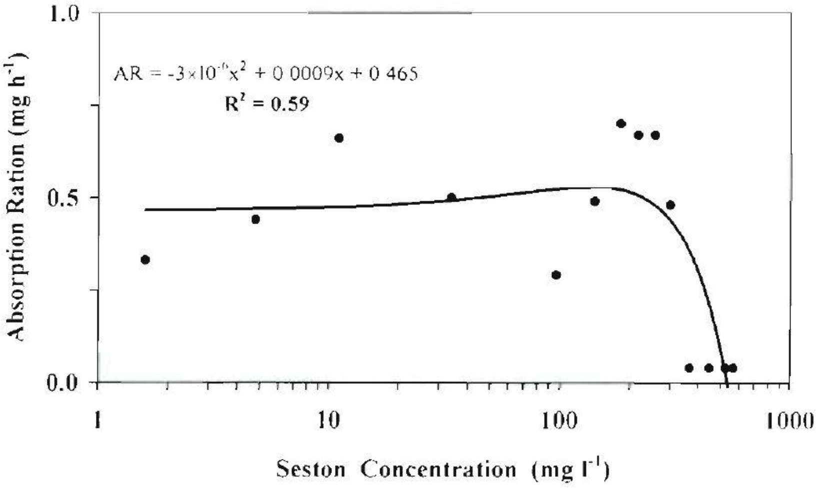


Figure F.3 *Cerastoderma edule.* Absorption rate in relation to seston concentration, figure from Navarro and Widdows (1997)

The research of Navarro and Widdows (1997) was mainly focused on the influence of fluctuation of the seston quality and quantity as a result of tidal currents. During periods of high ebb or flood currents inorganic and organic matter is stirred up from the seabed. Due to this the concentration of inorganic matter, as well as the concentration of organic matter increases. The sand mining activities however result in an increase of the concentration of inorganic matter and a decrease of the concentration of organic matter. If the relations between seston concentrations and filtration rates and absorption rates of Navarro and Widdows (1997) are also valid for the seston in the Voordelta is questionable. However, the validity of some hypothetical relations between growth and food quality can be excluded on the basis of the results of Navarro and Widdows (1997), as will be explained in the following.

Seston concentrations are higher and the organic content is smaller in the sand mining scenario than in the reference scenario. This might result in a difference in growth if:

- the food absorption rate of cockles is significantly smaller due to the sand mining;
- the intake of the same amount of food costs more energy in case of the sand mining.

A decline of the food absorption rate was observed in the experiment of Navarro and Widdows (1997) for seston concentrations higher than 300 mg l^{-1} (organic content of 18%). This is the result of the decline of the filtration rate (at seston concentrations higher than 300 mg l^{-1}) and the selection efficiency (at seston concentrations higher than 100 mg l^{-1}). If the decline of the filtration rate is a result of the high seston concentration and not of the low organic content (which corresponds with Essink (1999), bivalves stop siphoning water at too high seston concentrations), no decline of the food absorption rate is expected due to the sand mining. As the concentrations in the Voordelta are much lower than the concentrations at which a decline of the filtration rate is observed.

The effect by the decrease of the selection efficiency can not be excluded on the basis of the research of NAVARRO AND WIDDOWS (1997). However, more information is given by HAWKINS *et al.* (1996) (see below).

In case of a lower concentration of organic matter, bivalves need to siphon more litres of water in the same time (higher clearance rate), to ingest the same quantity of organic matter per unit of time. In case of the combination of a decrease of the organic content and an increase of the seston concentration, not only the clearance rate will be higher, but also the filtration rate (more matter has to be filtered in the same time). The organic fraction of this filtered matter will be lower, so also the selection efficiency has to increase, to be able to maintain a constant absorption rate.

NAVARRO AND WIDDOWS (1997) did not investigate the energy costs of siphoning, filtering and the selection mechanisms for cockles, or the impact on the growth of the variation of seston quantity and quality. An impact on the growth of bivalves can not be excluded on the basis of the results of NAVARRO AND WIDDOWS (1997). However, in CLAUSEN AND RIISGÅRD (1996) is mentioned that from an energetic point of view, only an insignificant saving may be gained by reducing the filtration rate, according to Riisgård and Larsen (1995). This party invalidates the reasoning behind the negative effect on growth because of the higher energy costs. Higher energy costs in case of a lower organic content of the ingested matter seem more likely, as this gives an explanation of the use of the preingestive selection.

HAWKINS *et al.* (1996)

HAWKINS *et al.* (1996) investigated the growth of blue mussels (*Mytilus edulis*) in turbid environments. The conclusions were that rates of organic absorption increased with seston filtration rate, and net energy balance increased despite the decreasing organic content of particles available at higher seston concentrations. HAWKINS *et al.* (1996) monitored the clearance rate, selection efficiency, ingestion rate and absorption efficiency of mussels in natural conditions (mussels, collected in Normandy, were transferred to a mud-flat in the bay of Marennes-Oléron, France). The organic content of available seston decreased with increasing abundance of up to about 90 mg l^{-1} total particulate matter. Figure F.4 shows the range of the seston concentrations and qualities in the observations of HAWKINS *et al.* (1996).

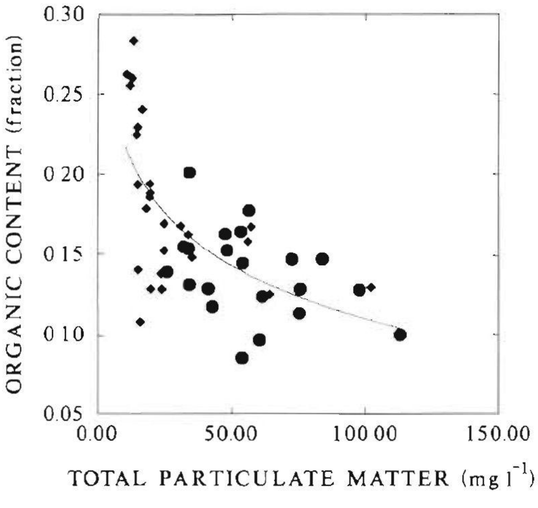


Figure F.4 Relationship between organic content and seston concentration, where data were collected at 2 neap tides (●) and 2 spring tides (◆). Figure from HAWKINS *et al.* (1996)

HAWKINS *et al.* (1996) observed an increase of the clearance rate by an increasing seston concentration, which contradicts the observations of NAVARRO AND WIDDOWS (1997). However, also Iglesias *et al*. observed a positive relation between seston concentration and clearance rate in 1992 [HAWKINS *et al.* (1996)]. An increase of the clearance rate (l h^{-1}) also leads to an increase of the filtration rate (mg h^{-1}).

A second observation of HAWKINS *et al.* (1996) that also does not completely correspond with NAVARRO AND WIDDOWS (1997) is an increase of the selection efficiency by an increasing filtration rate. Despite of the slight decrease of the organic content of the filtered matter, the organic content of the ingested matter increases (see figure F.5).

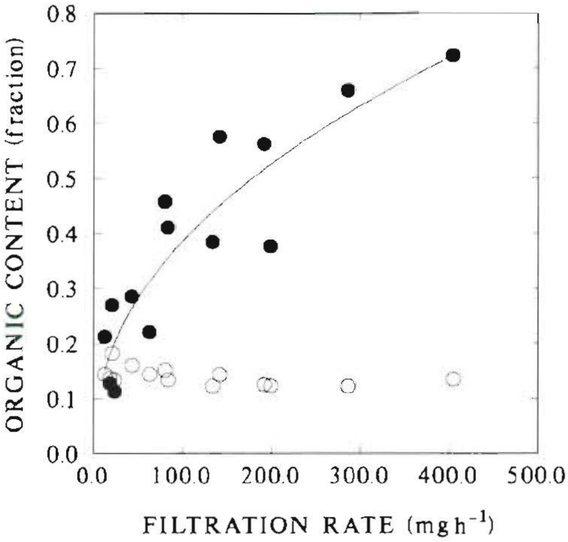


Figure F.5 ***Mytilus edulis*. Organic content of filtered matter (○) and organic content of ingested matter (●) in relation to filtration rate in mussels standardized to 1 g dry flesh weight. Data are the mean of separate determinations upon 10 replicate mussels. Figure from HAWKINS *et al.* (1996)**

Finally the observations of HAWKINS *et al.* (1996) lead to a positive relation between the net energy balance (J h^{-1}) and the seston concentration, independent of the organic content of the available seston (see figure F.6). To calculate the net energy balance from the absorption rate of organic matter, a linear relation between heat losses and the rate of energy absorption was used.

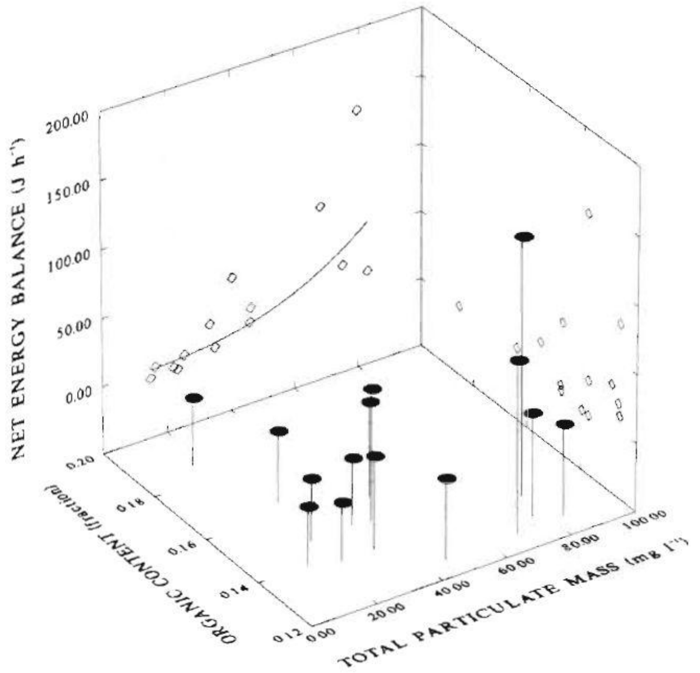


Figure F.6 *Mytilus edulis*. Net energy balance in relation to both the organic content and seston concentration in mussels standardized to 1 g dry flesh weight. Data are the mean of separate determinations upon 10 replicate mussels. Figure from HAWKINS *et al.* (1996)

Corresponding with the observations of NAVARRO AND WIDDOWS (1997), also HAWKINS *et al.* (1996) did not observe a decline of filtration rates for the range of seston concentrations in the Voordelta. NAVARRO AND WIDDOWS (1997) did observe a decrease of selection efficiency for seston concentrations higher than 100 mg l^{-1}. If a relation between selection efficiency and the organic content exists or not, could not be concluded on basis of the results of NAVARRO AND WIDDOWS (1997). HAWKINS *et al.* (1996) measured the selection efficiency for seston with a lower organic content, and did not observe a negative relation between the organic content and the selection efficiency. The observation of a positive relation between filtration rate and selection efficiency might even indicate that mussels can adapt well to seston with lower organic contents. In case of a lower organic content, more water has to be siphoned to filter the same amount of organic matter. By increasing the clearance rate (l h^{-1}), also the filtration rate (mg h^{-1}) will increase, which may lead to an improvement of the selection efficiency (according to observations of HAWKINS *et al.* (1996)). The existence of a positive relation between clearance rate and selection efficiency has not been investigated. However, if a high clearance rate enhances the functioning of the selection mechanism, this might explain the contradicting observations of HAWKINS *et al.* (1996) and NAVARRO AND WIDDOWS (1997) on the relation between selection efficiency and seston concentration.

Also HAWKINS *et al.* (1996) did not include the energy costs of feeding in relation to the changing seston concentrations and qualities. HAWKINS *et al.* (1996) however observed that the rate of net energy absorption (J h^{-1}) increased by increasing seston concentrations. This extra energy intake might compensate the higher energy costs of the siphoning, selection and pseudofaeces production.

Conclusions

No conclusive proof can be given on the non-existence of a relation between growth and food quality for bivalves. Based on ESSINK (1999), NAVARRO AND WIDDOWS (1997) and HAWKINS *et al.* (1996) bivalves seem to be able to maintain a constant food absorption rate for the range of seston concentrations and qualities in the Voordelta, also in case of sand mining activities for Maasvlakte 2. A reduction of growth, as a result of lower food absorption rates in case of sand mining activities, can be excluded.

An impact on growth as a consequence of higher energy costs can not be excluded. However, it is also not known if the energy costs of feeding are significantly higher in case of sand mining activities. Besides, according to the results of HAWKINS *et al.* (1996), higher energy costs are possibly compensated. No literature has been found in which indications are given for the existence of the relation between seston quality and the growth of bivalves.

The validity of the main part of the hypothetical reasons why a relation between food quality and growth would exists for bivalves, can be excluded by the conclusions of ESSINK (1999), NAVARRO AND WIDDOWS (1997) and HAWKINS *et al.* (1996). As for the remaining part no evidence is found in literature, the relation will not be taken into account in this thesis. Besides, data on which a relation can be based are completely lacking.

Appendix G: Food web

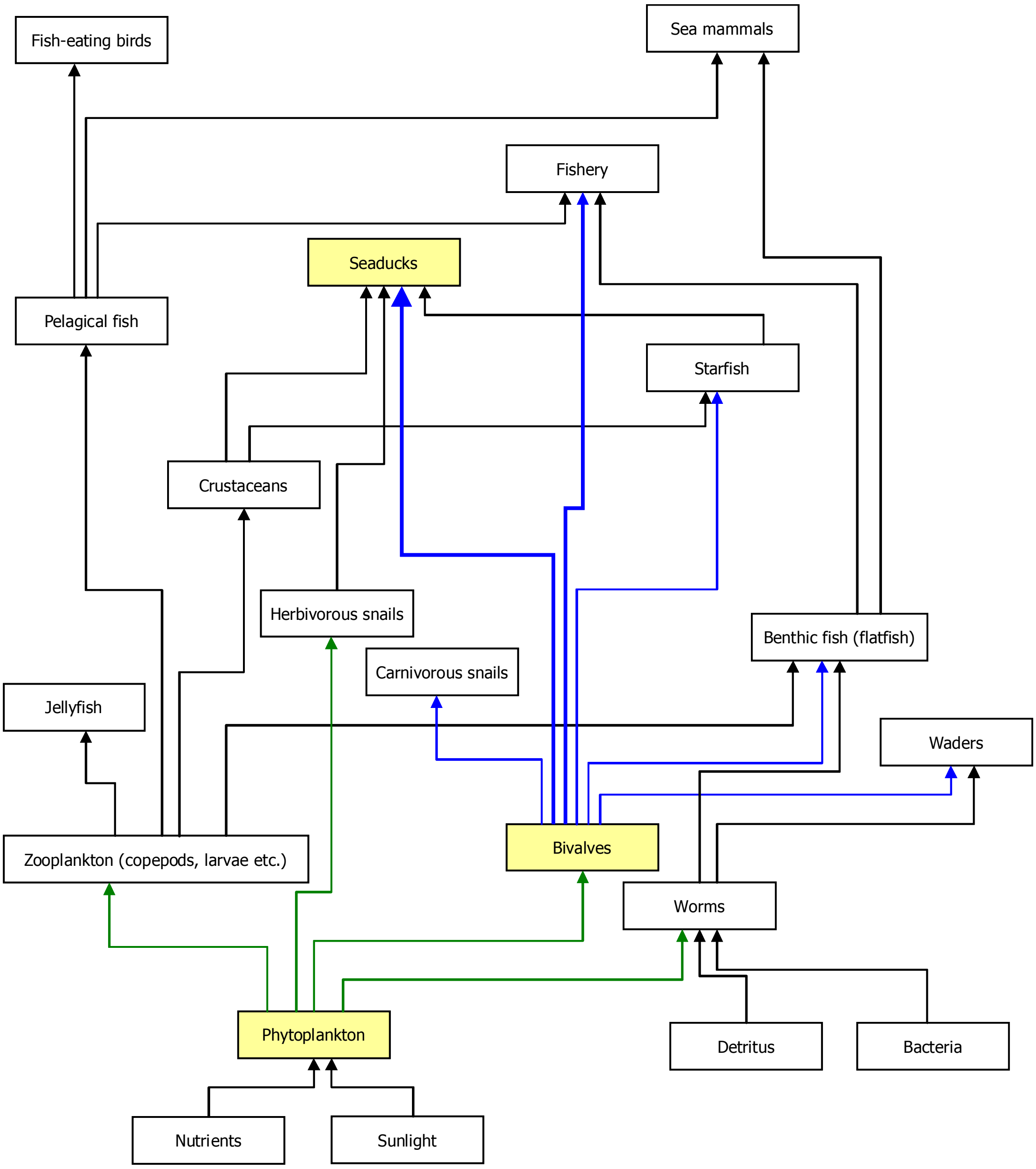


Figure G.1 Simplified food web of the Voordelta

The species (groups) that play a role in this thesis are coloured yellow in figure G.1. Sea ducks and fishery are the main predators of bivalves in the Voordelta. As individual snails like necklace shells or starfish will not eat a lot of bivalves (compare the size of these predators to the size of bivalves), predation by these species can only play a significant role if large numbers of these species were found in the Voordelta. Benthic fishes only eat the siphons (used for the filtering of water) of bivalves. This only hampers the intake of food for bivalves. Waders eat the bivalves that are found in very shallow areas and bivalves that are drift ashore.

Based on information of WIJSMAN *et al.* (2006), RIJKSWATERSTAAT (2007a), www.wikipedia.org and www.natuurinformatie.nl.

Appendix H: Population dynamics

If the survival rate of a certain species depends mainly on the intensity of predation, a relation can exist between the size of the prey population and their survival rate. The number of predators can be influenced by the amount of prey, as described by the well-known example of rabbits and foxes: in case of a large number of rabbits, the population of foxes grows, subsequently the number of rabbits decreases due to the large population of foxes, and so on. In such (idealized) case it will be possible to relate survival rates to the amount of prey (including a time lag-effect, dependent on how quickly the size of the predator-population reacts on the amount of prey). The interaction between predator and prey relations is described by the Lotka Volterra-model [BEGON *et al*. (1990)]:

$$\begin{aligned}\frac{\partial N}{\partial t} &= rN - a'CN \\ \frac{\partial C}{\partial t} &= fa'CN - qC\end{aligned} \qquad \text{(H.1)}$$

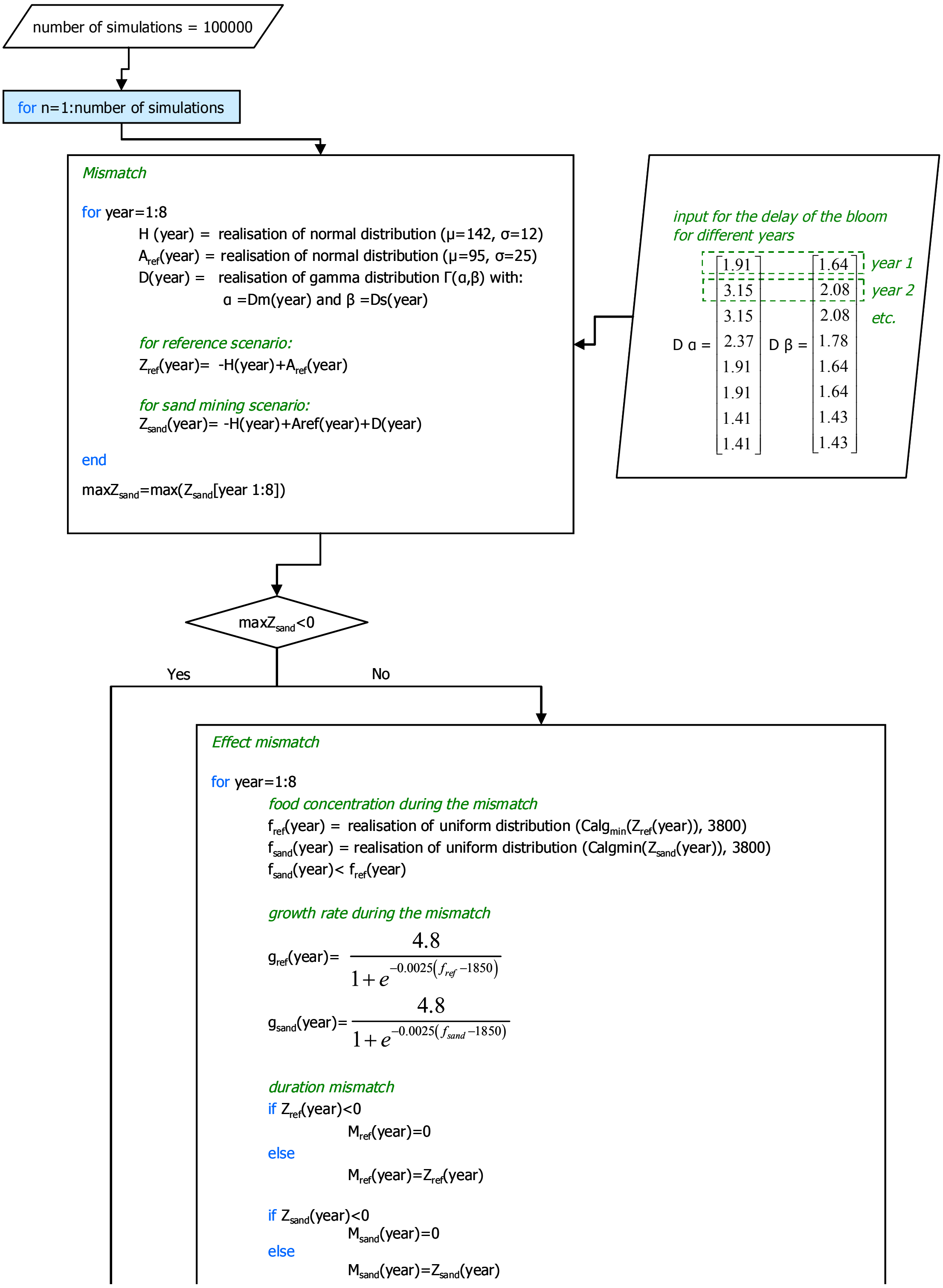
With:
N = Number of prey [-]
C = Number of predators [-]
a' = attack rate or search efficiency [-]
r = birth rate [-]
f = predators efficiency for turning food into offspring [-]
q = mortality rate [-]
$a'CN$ = rate at which food is consumed by predators [-]

However, the idealized rabbits-foxes case does not hold for bivalves and their main predators in the Voordelta (sea ducks) due to the following differences:

- Whereas the survival rate of rabbits is mainly dependent on the number of predators, the survival rate of bivalves is also influenced strongly by other factors (for example fresh water discharges).
- In the rabbits-foxes case, prey and predators live in the same area. The main predators of bivalves (eiders and scoters) are migratory birds. Because of this, the population size of the predators does not only react on the availability of prey in the Voordelta (wintering area), but also on conditions in the breeding area. Possibly the population size of the sea ducks does not react at all on the size of a certain bivalve population; the ducks will fly to another wintering area if the bivalve population in a certain area is insufficiently large. The sea ducks just winter where they can find sufficient bivalves.
- The number of births is related to the number of adult rabbits in the rabbit-foxes case. The number of births of bivalves is hardly related to the number of adults (see section 5.7). Due to this, the prey population sometimes shows a very rapid increase (r in equation H.1 is not constant). The unpredictable variation of the number of births influences the fluctuation of the prey population to a larger extent than the interaction between the predator and prey populations.

Due to these large differences, the model as described by equation H.1 is not applicable for the bivalves-sea ducks case. Predator-prey dynamics hardly influence the fluctuations of the population size of bivalves and will therefore not be taken into account in the population dynamical model of chapter 5.

Appendix I: Monte Carlo analysis



```
number of simulations = 100000

for n=1:number of simulations

    Mismatch

    for year=1:8
            H (year) = realisation of normal distribution (μ=142, σ=12)
            $A_{ref}$(year) = realisation of normal distribution (μ=95, σ=25)
            D(year) = realisation of gamma distribution Γ(α,β) with:
                    α =Dm(year) and β =Ds(year)

            for reference scenario:
            $Z_{ref}$(year)= -H(year)+$A_{ref}$(year)

            for sand mining scenario:
            $Z_{sand}$(year)= -H(year)+Aref(year)+D(year)

    end
    $maxZ_{sand}$=max($Z_{sand}$[year 1:8])

    $maxZ_{sand}$<0

    Effect mismatch

    for year=1:8
            food concentration during the mismatch
            $f_{ref}$(year) = realisation of uniform distribution ($Calg_{min}$($Z_{ref}$(year)), 3800)
            $f_{sand}$(year) = realisation of uniform distribution (Calgmin($Z_{sand}$(year)), 3800)
            $f_{sand}$(year)< $f_{ref}$(year)

            growth rate during the mismatch
            $g_{ref}(year)= \frac{4.8}{1+e^{-0.0025(f_{ref}-1850)}}$
            $g_{sand}(year)= \frac{4.8}{1+e^{-0.0025(f_{sand}-1850)}}$

            duration mismatch
            if $Z_{ref}$(year)<0
                    $M_{ref}$(year)=0
            else
                    $M_{ref}$(year)=$Z_{ref}$(year)

            if $Z_{sand}$(year)<0
                    $M_{sand}$(year)=0
            else
                    $M_{sand}$(year)=$Z_{sand}$(year)
```

input for the delay of the bloom for different years

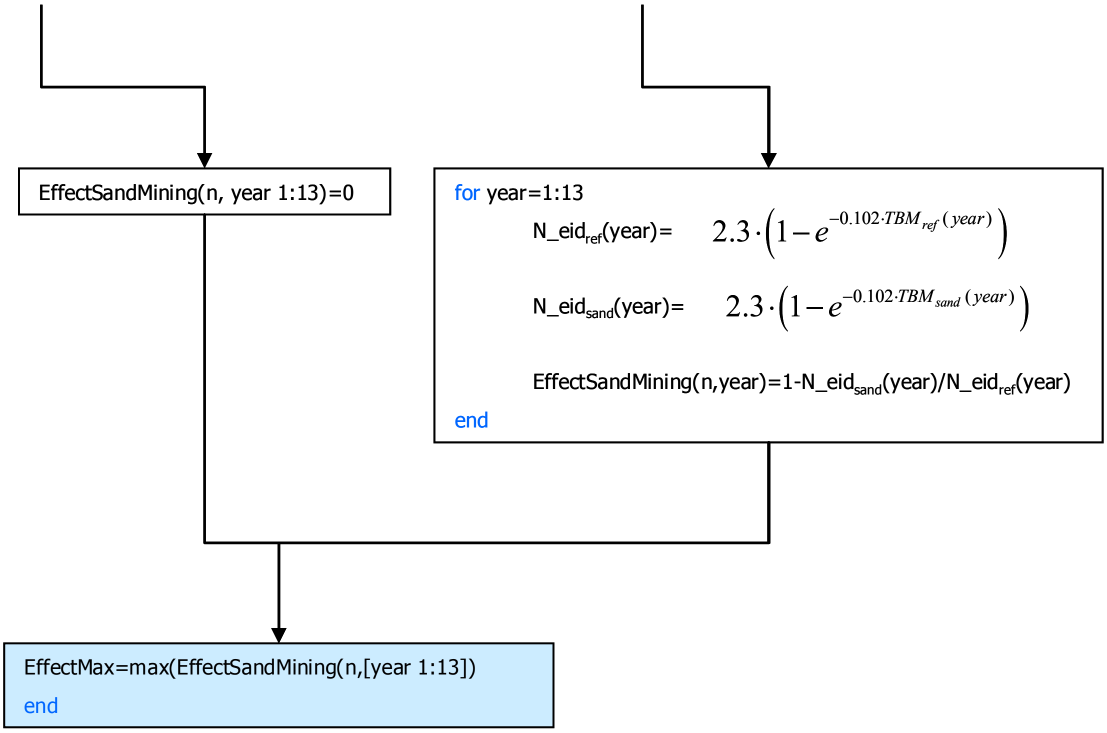
$$D\alpha = \begin{bmatrix} 1.91 \\ 3.15 \\ 3.15 \\ 2.37 \\ 1.91 \\ 1.91 \\ 1.41 \\ 1.41 \end{bmatrix} \quad D\beta = \begin{bmatrix} 1.64 \\ 2.08 \\ 2.08 \\ 1.78 \\ 1.64 \\ 1.64 \\ 1.43 \\ 1.43 \end{bmatrix}$$

```
        growth lag
        $Gl_{ref}(year) = 1-\left(\frac{154+M_{ref}(year)\cdot g_{ref}(year)+4.8\cdot(21-M_{ref}(year))}{154+4.8\cdot 21}\right)^{2.8}$
        $Gl_{sand}(year) = 1-\left(\frac{154+M_{sand}(year)\cdot g_{sand}(year)+4.8\cdot(21-M_{sand}(year))}{154+4.8\cdot 21}\right)^{2.8}$

        correction factor
        CF(year)=   realisation of normal distribution (μ=0.88, σ=0.25)

        effect mismatch
        $E_{ref}(year)=1-Gl_{ref}(year)*CF(year)$
        $E_{sand}(year)=1-Gl_{sand}(year)*CF(year)$

    end
```

```
    population-dynamical model
    for year = -4:13
        Recruitment (0.12=biomass of recruit)
        NR_SR(year)=0.12*(realisation of lognormal distribution with mean=4 and stdev=8)
        Survival rates
        SW(year)= realisation of lognormal distribution with mean=52 and stdev=15
        SR(year)= realisation of lognormal distribution with mean=27 and stdev=13
        Growth factor for different ages
        Gr=[10.8 3.36 1.86 1.37 1.17 1.09]

        for age = 0:5
        biomass of bivalves in september (done for reference and sand mining scenario)
```

	year=-4	....	year=1	year=2	....	year=13
age=0	BM(0,-4)	....	BM(0,1) *Gr(A=0)*E(y=1)	.	....	BM(0,13)
age=0.5	BM(0.5,-4)	....	BM(0.5,1) *Gr(A=1)*SW(y=2)*SR(y=2)	.	....	.
age=1	.	....	.	BM(1 ,2)	....	.
age=2	.	....	.	.	....	.
age=3	.	....	BM(3,1) *Gr(A=4)*SW(y=2)*SR(y=2)	.	....	.
age=4	.	....	.	BM(4,2)	....	.
age=5	BM(5,-4)	....	.	.	....	BM(5,13)

```
        end
        total biomass of edible bivalves
        $TBM_{ref}(year)=BM_{ref}(Age=1,year)+ BM_{ref}(Age=2,year)+...+ BM_{ref}(Age=5,year)$
        $TBM_{sand}(year)=BM_{sand}(Age=1,year)+ BM_{sand}(Age=2,year)+...+ BM_{sand}(Age=5,year)$
    end
```



```
EffectSandMining(n, year 1:13)=0
```

```
for year=1:13
    N_eid_ref(year)=   $2.3\cdot\left(1-e^{-0.102\cdot TBM_{ref}(year)}\right)$
    N_eid_sand(year)=  $2.3\cdot\left(1-e^{-0.102\cdot TBM_{sand}(year)}\right)$
    EffectSandMining(n,year)=1-N_eid_sand(year)/N_eid_ref(year)
end
```

```
EffectMax=max(EffectSandMining(n,[year 1:13])
end
```

Appendix J: Areas and locations

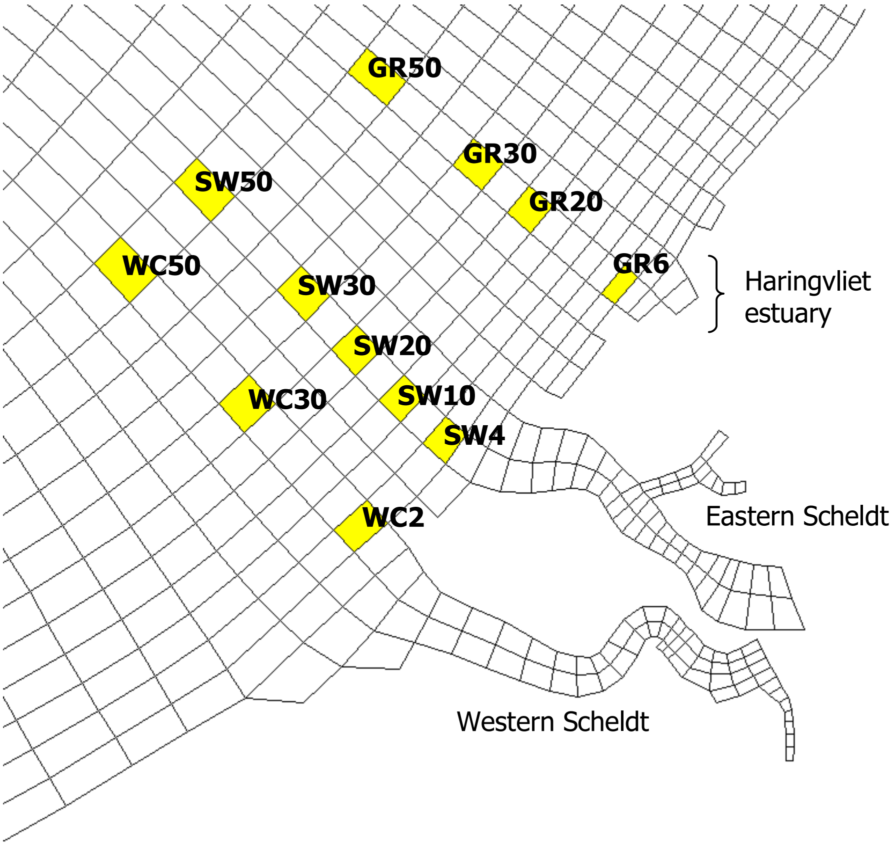


Figure J.1 Definition of locations, indicated in a small part of the grid for the Delft3D-ECO modelling of primary production

GR6 = Goeree 6 km
GR20 = Goeree 20 km
Etc.

SW4 = Schouwen 4 km
WC2 = Walcheren 2 km

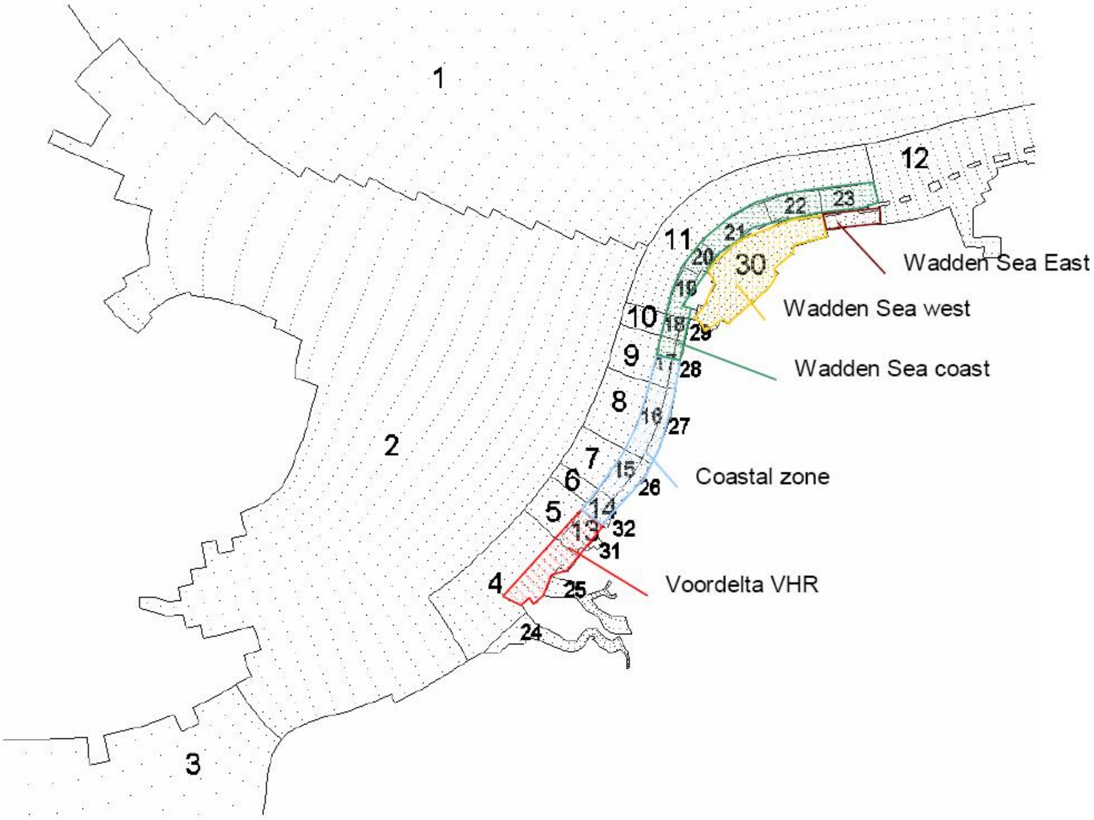


Figure J.2 Definition of monitoring areas as used in the Delft3D-ECO model, figure from DESMIT *et al.* (2007)