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

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ABSTRACT

For the construction of the new port area Maasvlakte 2 in the Netherlands, a large amount of sand has to be extracted from the North Sea. The potential ecological effects of the 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 eider ducks in the Natura 2000 area 'Voordelta'. Within the impact-effect chain from dredging to eider ducks, a large number of uncertainties play a role. In the EIA safe assumptions were used for a lot of these uncertainties. The finally 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 or compensating measures. The main objective of this study was to give insight in the probability of occurrence of the possible effects of sand mining on eider ducks in the Voordelta. A probabilistic approach was used to analyse the uncertainties in the impact-effect chain and to find a method to take these uncertainties into account in the modelling of the ecological effect. The analysis showed that 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 have a large influence on the magnitude of the ecological impact. Factors that are not influenced at all by the sand mining are for example weather conditions and natural variations of population sizes. The final result was a probability density function of the impact of the sand mining on eider ducks. This result lead to the conclusion that the probability that the sand mining activities for Maasvlakte have a significant effect on eider ducks in the Voordelta is very small and can be considered negligible. The methodology that is used in this study is expected to be also applicable for the assessment of ecological effects of other human activities.

Keywords: ecological effects, EIA, probabilistic analysis, dredging

INTRODUCTION

Maasvlakte 2 is a large land reclamation project in the Netherlands for the extension of the port of Rotterdam. 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 EIA [BERKENBOSCH *et al*. (2007) and VERTEGAAL *et al.* (2007)]. One of the identified effects in this EIA was a temporary decrease of maximally 6.4% of the number of eider ducks (*Somateria mollissima*) in the Voordelta [BERKENBOSCH (2007)]. The Voordelta is a so-called 'Natura 2000 area' in the framework of the Birds and Habitat Directives of the European Union. If the ecological effects in this area are significant, it is legally obligatory to mitigate or compensate these effects.

Within the impact-effect chain from dredging process to eider ducks, a large number of uncertainties play a role. Some of these uncertainties are caused by unpredictable natural variations and some uncertainties are a consequence of lack of knowledge. In the deterministic approach of the EIA, mostly worst-case assumptions were made to deal with these uncertainties. Consequently the predicted ecological effect is a result of the accumulation of worst-case assumptions and can therefore be considered as an upper limit.

In order to evaluate the temporary effects in its context, not only the predicted effect, but also the probability of occurrence of the predicted effect is important. Information on the probability of occurrence of the ecological effects of the sand mining will be useful in the discussion about the necessity of mitigating and compensating measures.

The main objective of this study was to investigate this probability of occurrence of the possible ecological effects of the sand mining activities for Maasvlakte 2, resulting in a probability distribution of the change of the number of eider ducks. The methodology that was used to derive the probability distribution is described in this article. The secondary objective was to investigate if a probabilistic analysis is applicable for EIA's.

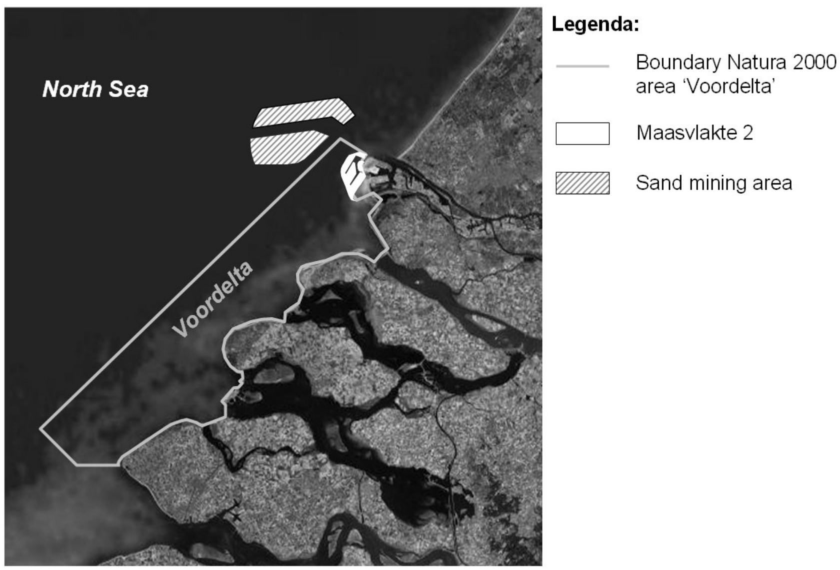


Figure 1 **Location of Maasvlakte 2, Natura 2000-area 'Voordelta' and sand mining areas, data from Rijkswaterstaat**

IMPACT-EFFECT CHAIN

The main impact-effect chain for the ecological effect of sand mining activities on eider ducks is described in this section. In the EIA also some other impact-effect relations were regarded. However, based on literature research [VAN KRUCHTEN (2008)] was concluded that these impact-effects relations can be neglected in the probabilistic approach. Figure 2 shows the impact-effect chain.

Sand extraction by trailing suction hopper dredgers will cause a release of fine sand and small silt particles that are present in the seabed. Silt particles (< 63 μm) can be transported over large distances by tidal currents because of their small settling velocity. In this way the sand mining causes a temporary increase of the concentration of the Suspended Particulate Matter (SPM) in a certain area of the North Sea. An increase of the SPM-concentration leads to a reduction of the transparency of the water and subsequently to a decrease of the light intensity in the water column.

Phytoplankton, which forms the base of the marine food chain, needs a certain light intensity for net primary production (production of organic compounds from inorganic matter). In case of net primary production the phytoplankton concentration increases. This concentration is low during winter and increases quite rapidly during spring. This is called the algal bloom. Due to the reduction of the light intensity in the water column by the increased silt concentration, the algal bloom will be delayed.

Phytoplankton forms the main food for bivalves and their larvae. Larvae of bivalves hatch at a certain moment in spring. If the hatching takes place before the algal bloom, the concentration of phytoplankton can be too low for the bivalve larvae to grow optimally. In this case a so-called mismatch occurs. As described by PHILIPPART *et al.* (2003) and BOS *et al.* (2006 and 2007), a mismatch between the availability of sufficient food and the hatching of the bivalve *Macoma Balthica* (Baltic tellin) can lead to a growth lag of these larvae. Assuming that also other bivalve species can be affected by a mismatch and that bivalves are not able to catch up a growth lag, the mismatch will have a negative impact on the total biomass of the bivalve population in the Voordelta.

In the Voordelta, eider ducks mainly feed on the bivalves *Cerastoderma edule* (cockles) and *Ensis directus* (American razor shell). A decrease of the total biomass of bivalves in the Voordelta can lead to a food shortage for these sea ducks. In this way sand mining activities can affect the number of eider ducks in the Voordelta.

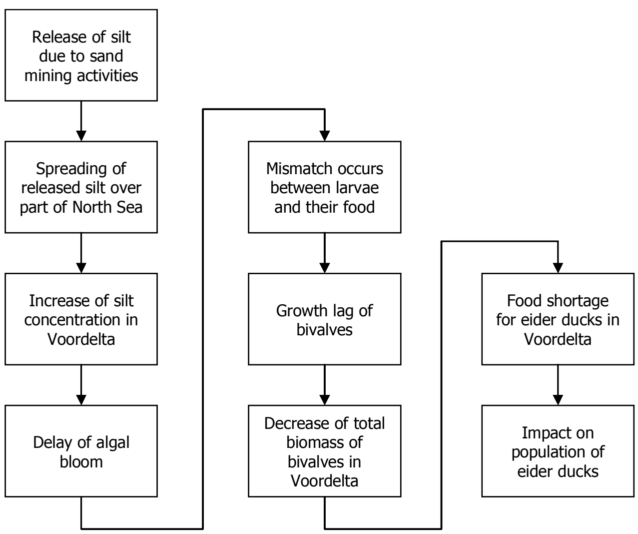


Figure 2 **Impact-effect chain**

METHOD

First the method which was used in the deterministic approach of the EIA was analysed to gain insight in the uncertainties in the modelling of the ecological effects of the sand mining. The relevant uncertainties, which have a large influence on the final result and accompanying uncertainty margin, have been investigated more thoroughly to find a method to incorporate these uncertainties in a probabilistic calculation. By taking into account these uncertainties in a probabilistic calculation, the use of worst-case or safe assumptions on these uncertainties can be prevented.

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 were 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 was calculated by using the model as shown in figure 3. From the results of the Monte Carlo analysis a probability distribution for the impact of sand mining on eiders was derived.

Figure 3 shows a schematization of the ecological model as used in the Monte Carlo analysis. An explanation of the different parts of this model is given in the next sections.

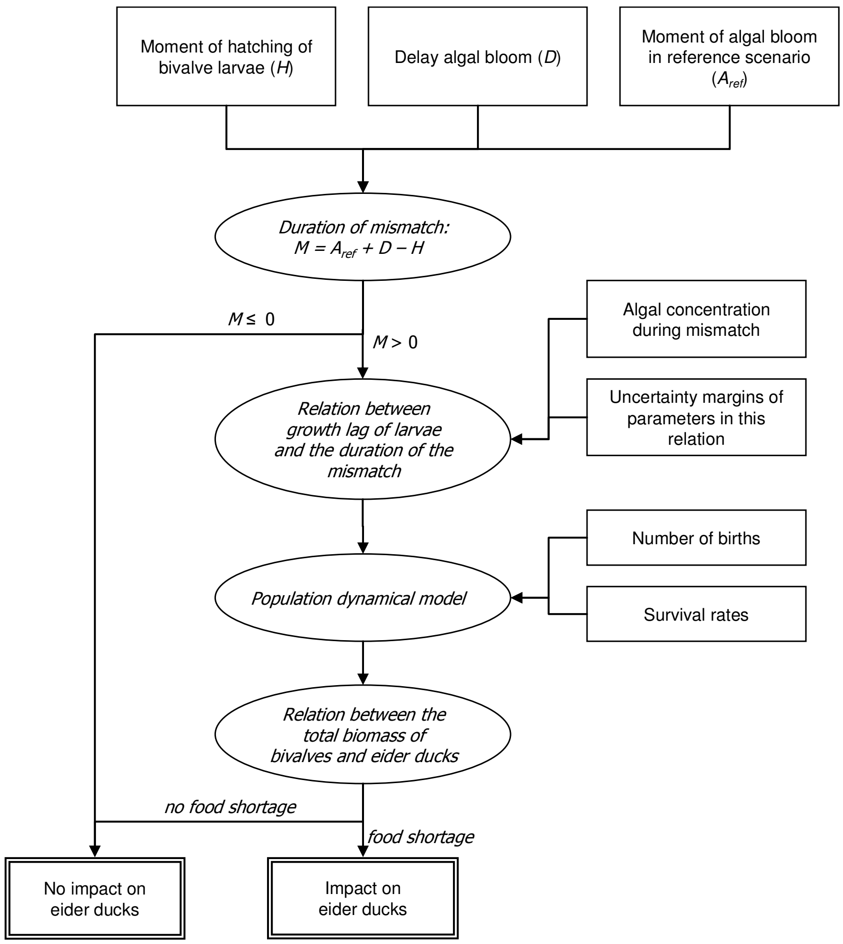


Figure 3 **Ecological model as used in the Monte Carlo analysis**

DELAY OF THE ALGAL BLOOM

The relation between the increase of the silt concentration and the delay of the algal bloom that was used in the probabilistic analysis, is based on the Delft3D-ECO model (Deltares). The ECO module of the numerical model Delft3D is normally used to simulate the bio(chemical) and biological processes related to growth of algae and nutrient dynamics. Within the probabilistic analysis, the formulas underlying this model were analysed to gain insight in the relation between the increased silt concentration and the delay of the bloom, as well as in the influence of other input variables on this relation. The analysis showed that not only the relative increase of the silt concentration determines the delay of the bloom, but that also short-term fluctuations of solar irradiance (among other things dependent on cloudiness) and silt concentrations (due to a changing wave climate) have a large influence on this delay.

Probability density functions for the delay of the algal bloom *D* have been derived by VAN KRUCHTEN (2008) on the basis of measurements of solar irradiance and modelled silt concentrations [model results Deltares], by using the formulas of the Delft3D-ECO model. Figure 4 shows the probability density functions of *D* for different values of the relative increase of the silt concentration *fs*.

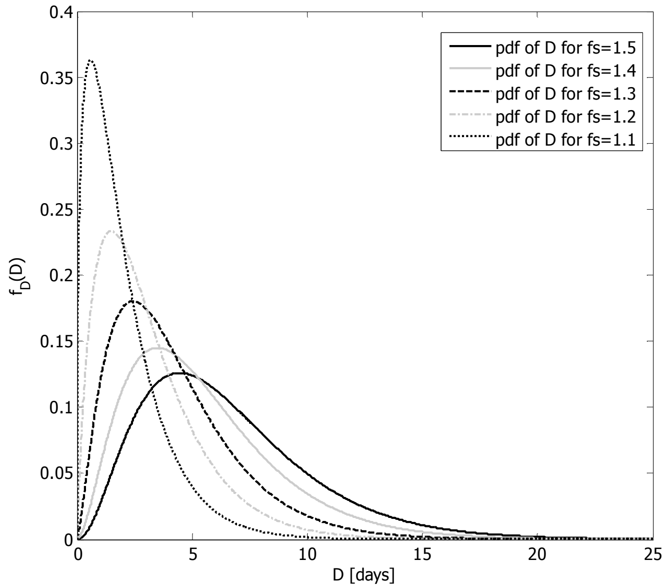
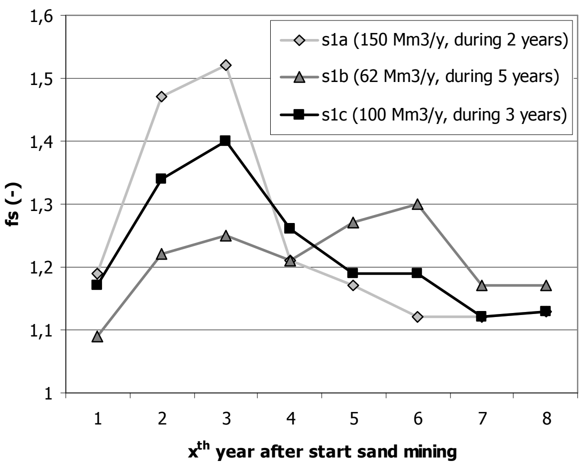


Figure 4 **Gamma probability density functions of the delay of the algal bloom *D* for different values of the relative increase of the silt concentration due to the sand mining *fs***

For the increase of the silt concentration by the sand mining, the same model results [VAN PROOIJEN *et al*. (2006), DESMIT *et al*. (2007)] have been used within the probabilistic analysis as in the EIA. These model results predicted an increase of the silt concentration for a period of 8 years after the start of the sand mining activities [VAN LEDDEN *et al*. (2007)]. The relative increase of the silt concentration *fs*, which is more or less constant during the relatively short spring period, is used in the probabilistic analysis. The values of *fs* for different sand mining scenarios are shown in figure 5.



$$fs = \frac{IM1 + IM2}{IM1}$$

fs = relative increase of the silt concentration [-]

$IM1$ = concentration of background silt [g.m^{-3}]

$IM2$ = concentration of sand mining silt [g.m^{-3}]

Figure 5 **Relative increase of silt concentration during spring *fs*, from the 1st to the 8th year after the start of the mining activities [derived from model results of Deltares, VAN PROOIJEN *et al.* (2006) and DESMIT *et al.* (2007)]**

Within the Monte Carlo analysis the ecological impact of the sand mining is modelled for a period of 13 subsequent years. As bivalves can get about 5 years old, a mismatch due to the increased silt concentration in the 8th year after the sand mining, can still have an impact on the bivalve population in the 13th year. For the delay of the algal bloom *D*, the probability density functions for the values of *fs* as shown in figure 5 have been used for each specific year (for the 1st till 8th year after the start of the sand mining).

The uncertainty margin of the results of the modelling of silt concentrations, as shown in figure 5, is not investigated in this study. The effect of this uncertainty margin on the final result is expected to be negligible compared to the influence of the uncertainty margins of other relevant input variables. The probability density functions of the delay *D* (figure 4) shows that even if the relative increase of the silt concentration would be predicted accurately, the value of *D* has a large uncertainty margin.

PROBABILITY OF OCCURRENCE OF A MISMATCH

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 assumption only holds if (in a reference scenario without sand mining) the hatching of larvae always takes place at the same moment as the algal bloom. However, as the hatching of larvae mostly takes place later than the algal bloom, the probability of occurrence of a mismatch due to the delay of the bloom is much smaller than 1. Besides, the timing of both events shows a large year-to-year variation.

The occurrence of a mismatch can be schematized by the following simple equation. A mismatch only occurs if:

$$Z = H - A_{ref} - D = -M < 0 \qquad \text{Equation 1}$$

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

A_{ref} = moment at which the critical algal concentration is exceeded in the reference scenario [days]
D = delay of the moment at which the critical algal concentration is exceeded, caused by the sand mining activities [days]
M = duration of the mismatch [days]

The critical algal concentration is defined as the minimal concentration at which the growth of larvae is not limited by the availability of food. The longer the duration of the mismatch period *M*, the larger the growth lag of the larvae will be.

In the deterministic approach of the EIA was assumed that: $A_{ref} = H$, which leads to: $D = M$, and a probability of 1 that a delay of the bloom results in a mismatch.

The probabilistic approach is illustrated in figure 6, which shows an example of the probability density functions of the moment of the algal bloom and the moment of hatching. In this example the algal bloom (in the reference scenario) takes place on average on April 9th and the hatching on May 25th. The large year-to-year variation of the timing of the algal bloom and the moment of hatching is expressed by the standard deviations of the probability density functions. In this simplified example a delay of the bloom *D* of 7 days is used. In case of an increased silt concentration due to sand mining, the algal bloom takes place on average on April 16th.

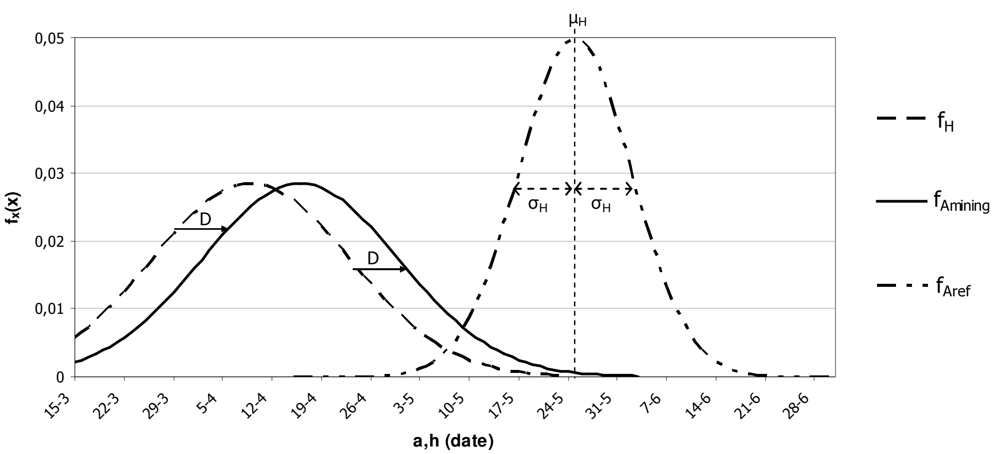


Figure 6 **Probability density functions of *H*, A_{ref} and A_{mining} (= $A_{ref} + D$)**

The small overlap between the probability density functions of A_{mining} and *H* in figure 6 indicates that the probability of occurrence of a mismatch $P(A_{mining}>H)$ is small. A mismatch will only occur if the algal bloom takes place relatively late and the hatching relatively early. Also in the reference scenario a mismatch can occur. However, its probability of occurrence is larger in the sand mining scenario. Given the probability density functions of *H*, A_{ref} and the delay *D*, the probability of occurrence of a mismatch can be calculated. For the example of figure 6 the probability that a mismatch occurs in a certain year with a delay of the bloom *D*, is only $7*10^{-3}$.

On the basis of data and expert judgement, the mean values μ and standard deviations σ of the normal probability density functions of *H* and A_{ref} were estimated by VAN KRUCHTEN (2008). Unfortunately, as the amount of data and expert judgement on *H* and A_{ref} is limited, the accompanying probability density functions could only be estimated roughly. Because of this and the high sensitivity of the final result on these estimated probability density functions, the Monte Carlo analysis was done twice. One time for probability density functions, which are expected to be realistic estimates, and one time for a safe assumption on these probability density functions.

RELATION BETWEEN MISMATCH AND GROWTH LAG

A relation between the duration of the mismatch period, the algal concentration during this period and the growth lag of the larvae, has been derived from laboratory results of BOS *et al.* (2006) and BOS *et al*. (2007). BOS *et al*. investigated among other things the effect of a mismatch on the growth of *Macoma balthica* larvae. Also the uncertainty of this relation has been taken into account by using a normally distributed correction factor in the Monte Carlo analysis. This probability density function was derived by the difference between the measured growth lags in the laboratory experiment and the growth lags as calculated by using the relation. For the uncertain algal concentrations during the mismatch period also probability density functions were derived, which are partly dependent on the duration of the mismatch M.

In the deterministic approach of the EIA the safe assumption was made that bivalves are not able to catch up a growth lag. In case of a growth lag of a larvae of for example 20% (the larvae is 20% smaller than it would have been without a mismatch), the bivalve will be subject to a growth lag of 20% for its whole life. However, it is likely that bivalves are able to catch up a growth lag partly. Unfortunately also on the growth of bivalves the amount of available literature is limited. Therefore the Monte Carlo analysis will be done twice; for two different growth models. According to one growth model bivalves are not able to catch up a growth lag (safe assumption) and according to the other model the bivalves can catch up the growth lag partly.

POPULATION DYNAMICAL MODEL

As a mismatch only affects the growth of larvae, only one year class (all individuals that are born in the same year) of bivalves will be affected by a mismatch that occurs in one specific year. The total bivalve population in a certain year, consists of several year classes. Due to this, the population size depends on the number of births and the survival rates of bivalves during the current and previous years.

From measurements of the size of the bivalve population in the Voordelta, can be derived that these survival and birth rates show a large year-to-year variation in nature. Figure 7 shows the large variation of the population sizes.

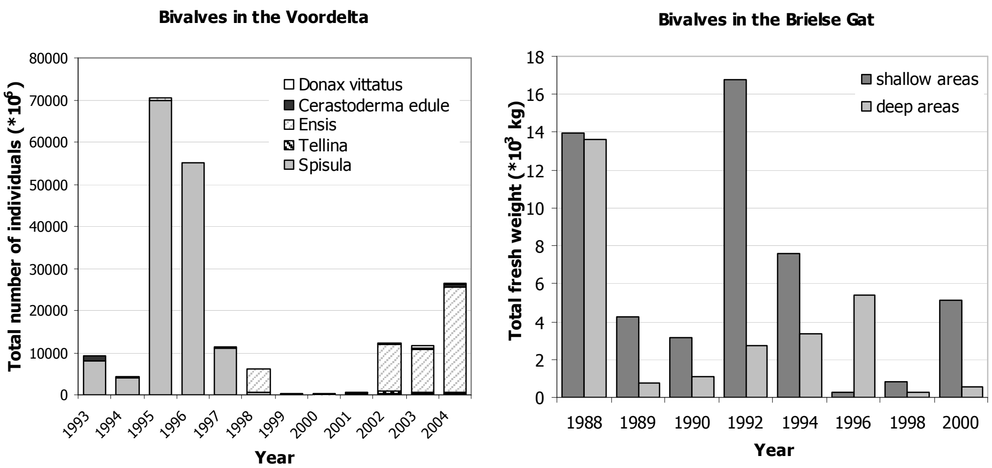


Figure 7 **Variation of total amount of bivalves in the Voordelta and Brielse Gat (northern part of Voordelta), left figure: data from KNAW-CEME, edited by F. Heinis (not published), right figure: data from HEINIS *et al.* (2002)**

Due to this large, unpredictable variation, the impact of a growth lag of a certain year class on the total population is uncertain. This is illustrated in figure 8. 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. The number of individual bivalves 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'. Due to this, the decrease of the total biomass of the population, given a certain growth lag, cannot be predicted accurately.

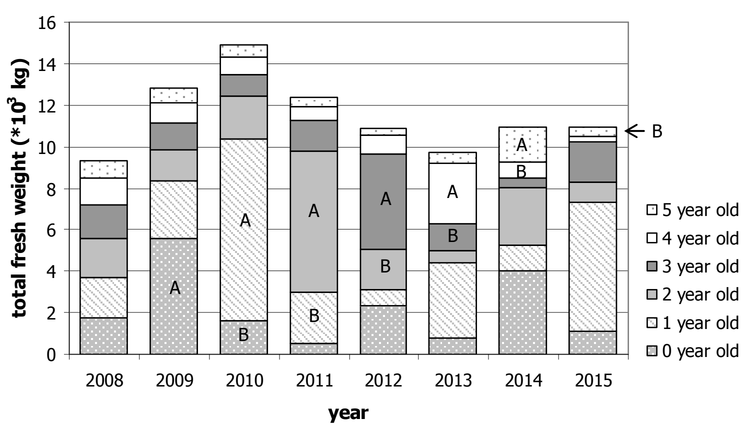


Figure 8 **Fictitious example of the variation of the bivalve population composition**

In a probabilistic approach it is possible to take into account the effect of the natural variation of the number of births and survival rates. On the basis of literature research and data of measurements, probability density functions for survival rates and the number of births have been derived. Both variables are not influenced by the sand mining activities. By using these probability density functions, the natural variation of the population size and composition can be simulated. In this way the unpredictable dynamics of nature can be incorporated into the model. This makes an important difference between a probabilistic and a deterministic approach. In a deterministic approach mostly constant values are used for survival and birth rates, which leads to the false suggestion that accurate predictions of ecological effects are possible. The large uncertainty margin of this prediction, which is a result of the stochasticity of nature, can be quantified in a probabilistic analysis.

IMPACT ON EIDER DUCKS

The last part of the model is the relation between the number of eider ducks and the bivalve population in the Voordelta. Eider ducks mainly forage on two species of bivalves in the Voordelta: *Cerastoderma edule* (cockles) and *Ensis directus* (American razor shells). As only small razor shells are edible for eiders, the effect of a growth lag of these bivalves on the total amount of food for the eider ducks will be negligible. Besides, the amount of American razor shells has been much larger than the consumption by eider ducks since 1993.

As a worst-case assumption, the abundance of razor shells was neglected in the deterministic approach of the EIA. For the EIA was assumed that all eiders in the Voordelta depend on the size of a bivalve population that will be affected by a mismatch. The relation was assumed to be linear; for example a decrease of the total biomass of the bivalve population by 20%, will lead to a decrease of the number of eiders in the Voordelta by 20%.

Observations show that part of the eiders in the Voordelta feed on American razor shells [LEOPOLD *et al.* (2007)]. The other eiders mainly forage on cockles. Only the total biomass of edible cockles can be affected by a mismatch. Possibly all eiders can change their diet to razor shells in case of a shortage of cockles. However, as it is not possible to prove this by data, the Monte Carlo analysis is done for two different safe assumptions. One time the analysis is done for the very safe assumption that all eiders in the Voordelta are dependent on the amount of cockles. Secondly the analysis is done for the safe assumption that 40% of the eiders depend on the total biomass of cockles in the Voordelta.

In the probabilistic analysis the relation as shown in figure 9 is used. During years with a large population of cockles, a certain decrease of the total fresh weight will not lead to a decrease of the number of eiders. The total amount of food will still be sufficient.

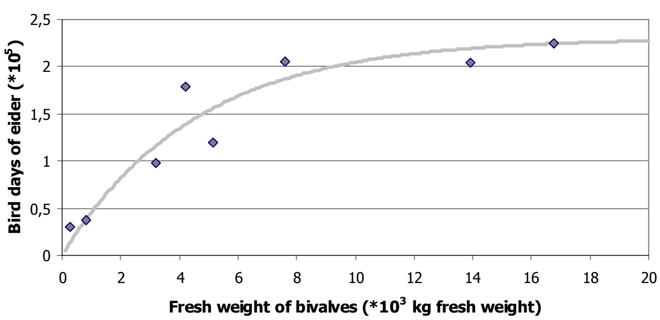


Figure 9 **Relation between eiders and bivalves for the measurements at the Brielse Gat [data from HEINIS *et al.* (2002)]**

MONTE CARLO ANALYSIS

For a period of 13 years after the start of the sand mining, the natural variation of the bivalve population size has been simulated by using values of birth and survival rates, which are chosen randomly from the determined probability density functions. The same simulated variation is used to model the number of eider ducks in the reference scenario as well as in the sand mining scenario. The only difference between these scenarios is the value of the delay of the algal bloom *D*; in the reference scenario *D=0*, while *D* is randomly chosen from the probability density functions in the sand mining scenario. For each year within the simulated periods of 13 years, the impact on the number of eider ducks is calculated as:

$$Impact = 1 - \frac{(Number\ of\ \ eiders)_{sandmining}}{(Number\ of\ \ eiders)_{reference}}$$ Equation 2

The Monte Carlo analysis was done several times, for different sand mining scenario's (see figure 5) and different assumptions on the probability density functions of A_{ref} and *H*, different growth models and different relations between the number of eiders and the bivalve population size (see table 1). The difference between the results for the different sand mining scenario's turned out to be negligible.

Table 1 Different assumptions for Monte Carlo analyses

Analysis	Percentage of eiders possibly affected	Bivalves catch up a growth lag?	PDF* of timing of algal bloom A_{ref}		PDF* of timing of hatching *H*		Sand mining scenario
			μ [day]	σ [day]	μ [day]	σ [day]	
A	100%	No	April 15th	15	May 18th	8	s1a
B	40%	No	April 15th	15	May 18th	8	s1a
C	100%	Partly	April 15th	15	May 18th	8	s1a
D	100%	No	April 9th	14	May 25th	8	s1a

*the mean value *μ* and standard deviation *σ* of the normal probability density functions of A_{ref} and *H* are given

The results of the different Monte Carlo analyses are shown in figure 10. The horizontal axis shows the possible, maximum impact *X* (see equation 2) that occurs during a period of 13 years after the start of the sand mining. The vertical axis shows the probability that the maximum impact, which will actually occur, is larger than *X* (horizontal axis).

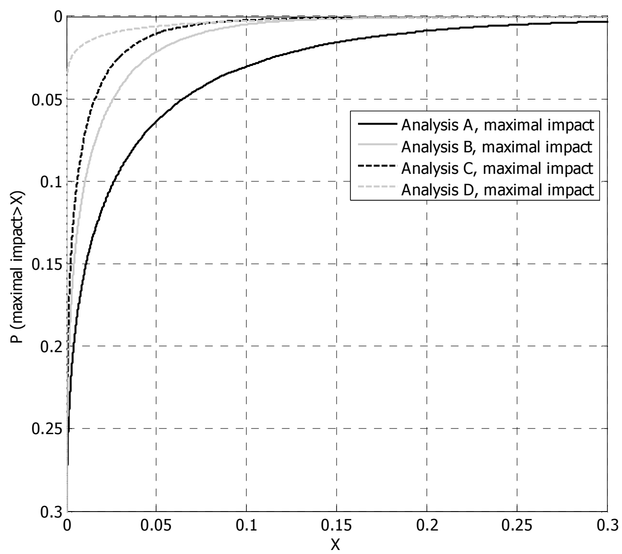


Figure 10 **Monte Carlo-results: probability distribution for the maximal relative impact *X* analyses A, B, C and D**

CONCLUSIONS

Impact of sand mining on eider ducks

For the ecological effect of the sand mining for Maasvlakte 2 can be concluded that the probability that the sand mining has a significant effect on eiders in the Voordelta is very small and can be considered negligible.

From figure 10 can be derived that, even in case of safe assumptions (analysis A, see table 1), the probability that the sand mining leads to a relative decrease of the number of eiders larger than 10% is only 0.03. 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 results also show a large probability that the sand mining activities do not have an impact at all on eiders in the Voordelta; larger than 0.7.

The results of the Monte Carlo analyses for the less safe assumptions (analyses B, C and D, see table 1) show that the probability on a decrease larger than 10% is even smaller than $5*10^{-3}$. It is very likely that the assumptions for analyses B, C and D correspond better with reality than analysis A. Though, proving this conclusively on the basis of data is not possible.

Difference between probabilistic approach and EIA

The difference between the result of the deterministic approach of the EIA and the result 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.

Predicting ecological effects

The impact of sand mining activities on eiders in the Voordelta, depends on a large number of factors that show large variation 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 variation.

DISCUSSION

Advantages of a probabilistic approach

By using a probabilistic approach to quantify ecological impacts, insight is given into 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 only on the basis of the results of a deterministic approach, may lead to the decision that measures should be taken, while the probability on significant effects might be very small or even negligible. Because of this, a probabilistic analysis will be very useful when a deterministic, worst-case approach leads to the prediction of significant effects.

Applicability of a probabilistic analysis for EIA's

This study showed that applying a probabilistic analysis for the quantification of the impact on sea ducks of the sand mining for Maasvlakte 2 is possible. Although not all uncertainties could be incorporated into the probabilistic analysis and still some safe assumptions had to be made, it could be proven that the probability of occurrence of significant effects is very small.

It is expected that also for the quantification of ecological impacts of other projects, part of the relevant uncertainties can be taken into account in a probabilistic calculation. If worst-case assumptions can be prevented in this way, applying a probabilistic approach will be useful.

Assessment framework

After the quantification of the magnitude of ecological effects and the accompanying probability of occurrence, the following questions remain:

- Which effects are considered meaningful for a population and which are not?
- Which probability that significant effects occur is unacceptable?

As official guidelines for the assessment of predicted ecological effects do not exist, 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?

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