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Application of a validated primary production model (BLOOM) as a screening tool for marine, coastal and transitional waters

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Abstract

In order to manage aquatic systems, it is necessary to apply methods relating the environmental variables and system-state parameters with external factors that affect the system. External factors can be natural (i.e. the movement of water) or partly-anthropogenic (i.e. nutrient loads). In addition to the national authorities, who have been implementing environmental policies for several decades, the EU is presently implementing the Water Framework Directive (WFD) aimed at establishing a new set of standards for the ecological and water quality of water systems. Among these are the phytoplankton biomass and composition. Phytoplankton affects turbidity, oxygen depletion, total productivity of the system and the occurrence of (harmful) algal blooms. A range of methods is available to relate phytoplankton to the controlling environmental conditions. Among these are statistical relations for instance of the Vollenweider type as well as deterministic simulation models. At the end of the 1970s, a generic deterministic phytoplankton module called BLOOM was developed, which has since been applied to a wide range of fresh water and marine systems. Here we test the applicability of this model as a screening tool for coastal waters. We conclude that the model is able to reproduce observed chlorophyll levels adequately under a wide range of conditions. Subsequently the model is applied to demonstrate the potential impacts of reductions in nitrogen, phosphorus or both nutrients simultaneously. Depending on which factors are initially controlling, the impacts of these reductions vary considerably both between locations and during the season. While this type of application lacks explicit relations between nutrient concentrations and external loadings, it does consider a number of relevant conditions in a consistent way and requires remarkably little data and effort. It is therefore a valuable screening tool.
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Keywords: Phytoplankton modelling; Nutrient reduction; Coastal waters; Water Framework Directive; Chlorophyll-a

1. Introduction

In order to manage aquatic systems, it is necessary to apply methods relating the environmental variables and system-state parameters with external factors that affect the system. External factors can be natural (e.g. the movement of water) or partly-anthropogenic (e.g. nutrient loads). In addition to the national authorities, who have been implementing environmental policies for several decades, the EU is presently implementing the Water Framework Directive (WFD) (European Commission, 2000).

The WFD provides a framework for water management, with the aim of achieving a 'good chemical and

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ecological status' in fresh and near shore coastal waters throughout Europe. The implementation of the WFD involves a step-wise approach determining for each water body: (1) its status under undisturbed 'reference conditions', (2) its present status, (3) what could be considered as a 'good status' and finally (4) what should be done to achieve this status. With respect to the ecological status of transitional waters, the 'quality elements' of importance are phytoplankton, macrofauna and macrophytes. Fish are considered for fresh but not for the marine systems. To obtain a uniform implementation throughout Europe, all water bodies are classified according to the same principles, but this still leaves room for variations between water bodies in different countries or even within a country. It is also necessary to determine which part of the pressures are anthropogenic and which part can be considered as natural. By the year 2015, all aquatic systems should comply to these standards. While the WFD is restricted to a small part of the coastal zone, OSPAR (www.ospar.org) and the new Marine Strategy also consider offshore areas.

Hence the phytoplankton biomass and primary production are important indicators for managers of water systems. Phytoplankton affects turbidity, oxygen depletion, total productivity of the system and the occurrence of (harmful) algal blooms. When biomass levels are considered to be too high, nutrient reduction is a proven method to reduce levels in both marine and freshwater systems. However, it is not always obvious which nutrient should be reduced and sometimes results are disappointing. The effectiveness of nutrient reductions can be addressed by statistical data analysis; i.e. empirical relations between total P loadings and algae concentrations has been successfully done using the well known Vollenweider type relationships (Vollenweider, 1975). Because many more data are available on measured concentrations as compared to loadings, often empirical relationships directly relate algal biomass to P or N concentrations.

Alternatively, these questions can be addressed by deterministic modelling, where algae concentration and primary production can be calculated from measured or modelled nutrient concentrations. During the last decades, many simulation models for primary production have been developed with different characteristics, purposes and degree of validation (Di Toro et al., 1971, 1977; Baretta et al., 1995; Ebenhöh et al., 1997; Lancelot et al., 2000; Fulton et al., 2004; Janse, 2005) to mention just a few of them. At the end of the 1970s, a generic phytoplankton module called BLOOM was developed (Los et al., 1984; Los, 1991, 2005). Since then the model has been applied extensively both in hind

cast mode to explain what has happened in the past as well as in forecast mode to simulate the possible impacts of future conditions including management scenarios (Los and Brinkman, 1988; De Groodt et al., 1992; Van der Molen et al., 1994; Peeters et al., 1995; Los and Bokhorst, 1997; De Vries et al., 1998; Villars and DeVries, 1998; WL | Delft Hydraulics/MARE, 2001; Van Duin et al., 2001).

Different modes of complexity are possible with BLOOM ranging from a straightforward 0-D screening tool to a more detailed 3-D eco-hydrodynamic model. Applying models with different levels of complexity are valuable and each has various pros and cons. For a manager of a coastal water system it is sometimes necessary to obtain a rapid impression of the status of a particular water body and its sensitivity to certain pressures. How much phytoplankton biomass can be sustained? What factors seem to be controlling? In this paper, we present the results of the application of the BLOOM module for phytoplankton concentration and composition as a quick-scan tool. This is an example of a least complicated, 0-D application. As such BLOOM computes the total biomass, its division into major functional groups and limiting factors based on measured concentrations of nutrients, irradiance and temperature. Transport is not explicitly included, but it does affect the measured forcing by nutrients and background turbidity of the model. With this type of model, a first assessment of management measures can be made by varying the nutrient concentration levels, but there is no direct linkage to internal or external nutrient loadings or to anthropogenic or natural sources. An experienced user with a properly organised database can set up and apply this tool within a few hours. Many examples of this type of analysis have been reported by Los (1991). In this paper the reliability of the model results is tested by comparison against field observations for a variety of marine, coastal and transitional waters. Furthermore, model applications are shown to evaluate the effectiveness of nutrient reduction as a tool to decrease chlorophyll-a concentrations.

2. The model

Algal blooms usually consist of various species of phytoplankton belonging to different taxonomic or functional groups such as diatoms, flagellates, green algae and cyanobacteria, commonly referred to as blue-green algae. They have different requirements for resources (e.g. nutrients, light) and they have different ecological properties. Some species are considered to be harmful due to their effect on the turbidity of the water,

the formation of scums or the production of toxins. For example, *Oscillatoria* can achieve very high biomass levels in shallow lakes causing a very low transparency, *Microcystis* is notorious for the formation of scums and has been reported to produce toxins that are harmful to animals (e.g. cattle) and men. In the marine environment, *Phaeocystis* is probably responsible for foam on beaches (Lancelot et al.. 1987), and mass mortality of

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the formation of scums or the production of toxins. For example, *Oscillatoria* can achieve very high biomass levels in shallow lakes causing a very low transparency, *Microcystis* is notorious for the formation of scums and has been reported to produce toxins that are harmful to animals (e.g. cattle) and men. In the marine environment, *Phaeocystis* is probably responsible for foam on beaches (Lancelot et al., 1987), and mass mortality of shellfish due to the settlement of a bloom in sheltered areas and subsequent depletion of oxygen (Rogers and Lockwood, 1990). To deal with these phenomena, it is important to distinguish between different types of phytoplankton in a model. The phytoplankton module BLOOM is based upon the principle of resource competition between different species. Note that the use of the term species in this paper is a flexible term. Sometimes a model species is equivalent to a biological species, but the term species could also refer to a number of biological species, grouped in larger ecological units, which are supposed to have similar characteristics. For example the group of diatoms, which consist of various biological species is regarded as one model species or plankton functional type. Most biological species of phytoplankton adapt rapidly to changes in their external environment. Individuals of a single species can therefore display a significant range of variation. To incorporate this phenomenon, each species of BLOOM is represented by several (pheno-)types. A type represents the eco-physiological state of the species under various possible conditions of limitation. Typically different types are considered for nitrogen, phosphorus and light limitation respectively. Hence for example an N-type has the characteristics of a species grown under prolonged conditions of nitrogen limitation. In a similar way P and E-types are defined. Occasionally additional types such as colonies or nitrogen fixing cells are explicitly included in the model. Types are the basic variables of this module. The number of types and their characteristics are inputs, so they can be easily adjusted for different kinds of water systems. Since types differ with respect to all characteristics included in the model, a shift between types not only implies a shift in nutrient stochiometry, but also in other characteristics such as the growth, mortality, sedimentation and respiration rates and in the carbon to chlorophyll ratio.

Once the model has computed the biomasses of the types, they are summed up to compute the biomass of each species. Often more than one type of a species is present at a particular moment in time, in theory all of the types of a species can be present simultaneously. The formulation of the model takes into account that adaptation occurs much more rapidly than succession between species.

The model considers the growth rate and the requirements for all potentially limiting environmental factors to determine the optimum combination of types using the linear programming method (Danzig, 1963). The nutrient and algae biomass concentrations at the beginning of the simulation period and the temperature and light intensity during the period are assumed known. The model must be solved for successive time periods in which the nutrient levels and initial biomass concentrations can be changed in accord with the solution of the previous time step. The optimization procedure distributes the available resources among all chosen algae types yielding a new composition of algae type biomass concentrations.

Typically, BLOOM considers between 3 and 10 representative algae species. For example, consider the following four (groups) of species: diatoms, microflagellates, dinoflagellates and *Phaeocystis*. These algae groups can be divided into three types based on their limiting nutrient or energy. Hence a total of 12 different algae types could be defined in this example.

Each distinct species subtype (from now on called type) is denoted by the index k. The BLOOM model identifies the concentration of biomass, B_k, of each algae type k that can be supported in the aquatic environment characterized by light conditions and nutrient concentrations. It can be demonstrated that finding the best adapted types at any moment in time is equivalent to maximizing the total rate of primary production given a number of environmental conditions (constraints). Defining the gross growth constant Pg_k (day^{-1}), the objective of the model thus is to

$$\text{Maximize} \sum_k Pg_k B_k \tag{1}$$

For each algae type, the requirements for nitrogen, phosphorus and silica (only used by diatoms) are specified by coefficients n_{ik}, the fraction of nutrient i per unit biomass concentration of algae type k.

The total readily available concentration, C_i (g m^{-3}) of each nutrient in the water column equals the amount in the total living biomass of algae, $\sum_k (n_{ik} B_k)$, plus the amount incorporated in dead algae, d_i, plus that dissolved in the water, w_i. These mass balance constraints apply for each nutrient i.

$$\sum_k (n_{ik} B_k) + d_i + w_i = C_i \tag{2}$$

The unknown concentration variables B_k, d_i, and w_i are non-negative. All nutrient concentrations C_i are the

measured or modeled total concentrations and are assumed to remain constant throughout the time period defined for the optimization model. The system is assumed to be in equilibrium over that period. The time step is an input to the model and may be chosen to vary during the simulation period to account for seasonal variations in characteristic time scales.

2.1. Nutrient recycling

A certain amount of each algae type k dies in each time step. This takes nutrients out of the live phytoplankton pool. A fraction remains in the detritus pool, and the remainder is directly available to grow new algae because the dead cells break apart (autolysis) and are dissolved in the water column. Detritus may be removed to the bottom or to the dissolved nutrient pools at rates in proportion to its concentration. Needed to model this is the mortality rate, M_k (day^{-1}), of algae type k, the fraction, f_p, of dead phytoplankton cells that is not immediately released when a cell dies, the remineralization rate constant, m_i (day^{-1}), of dead phytoplankton cells, the fraction, n_{ik}, of nutrient per unit biomass concentration of algae type k, and the settling rate constant, s (day^{-1}), of dead phytoplankton cells.

The rate of change in the nutrient concentration of the dead phytoplankton cells, dd_i/dt, in the water column equals the increase due to mortality less that which remineralizes and that which settles to the bottom.

$$dd_i/dt = \sum_k (f_p M_k n_{ik} B_k) - m_i d_i - s d_i \tag{3}$$

Both mortality and mineralization rate constants are temperature dependent. If the model is applied as a screening tool, Eq. (3) is solved under the assumption of a steady state which means its right-hand side equals 0. This gives an expression relating the amount of detritus to the algal biomasses. If BLOOM is applied as a dynamic simulation model, this equation is integrated numerically.

2.2. Energy limitation

Algae absorbs light for photosynthesis and growth. Energy becomes limiting through self-shading when the total light absorption consisting of a non-algal part and an algal part, exceeds the maximum at which growth is just balanced by respiration and mortality. For each algae type k there exists a specific extinction value K_k^{max} (m^{-1}) at which this is the case. The light intensity can also be too high, which means the total extinction is too low (photo-inhibition) for growth. This specific extinction value is K_k^{min}. The ranges between K_k^{min} and K_k^{max}

differ for different algal types k because each one of them is characterized by a different set of model coefficients. Among others a different light response curve for growth is used for each species in the model in the form of a table, through which a curve is fitted which is integrated numerically to account for diurnal variations in light intensities over depth due to mixing and in time. Letting K_k (m^3/m/g dry) represent the specific light absorbing extinction constant for living material of algae type k, the total extinction due to all living algae is

$$KL = \sum_k (K_k B_k) \tag{4}$$

Added to this must be the extinction caused by dead cells, KD and the contribution of all other fractions such as inorganic suspended matter and humic substances to the extinction of the water, KW (m^{-1}). Hence

$$K_k^{min} \leq KL + KD + KW \leq K_k^{max} \tag{5}$$

The extinction from dead cells is usually less than half of that from live cells. The amount of dead cells not yet mineralized is, from Eq. (3), $\sum_k (f_p M_k B_k)$. Assuming some fraction e_d (usually between 0.2 and 0.4) of the extinction rate of live cells,

$$KD = e_d \sum_k K_k f_p M_k B_k \tag{6}$$

If the total extinction is not within the range for an algae type k, its concentration B_k will be zero. To ensure that B_k is 0 if the total extinction is outside of its extinction range, a 0,1 binary (integer) unknown variable Z_k is needed for each algae type k. If Z_k is 1, B_k can be any non-negative value; if it is 0, B_k will be 0. This is modeled by adding three linear constraints for each algae type k.

$$KL + KD + KW \leq K_k^{max} + KM(1-Z_k) \tag{7}$$

$$KL + KD + KW \geq K_k^{min}(Z_k) \tag{8}$$

$$B_k \leq BMZ_k \tag{9}$$

where KM and BM are any large numbers no less than the largest possible value of the total extinction or biomass concentration, respectively. Since the objective of maximizing the sum of all $Pg_k B_k$ together with Eq. (9) wants to set each binary Z_k value equal to 1, only when the total extinction is outside of the extinction range K_k^{min} to K_k^{max} will the Z_k value be forced to 0. Eq. (9) then forces the corresponding B_k to 0. This means that beyond its feasible range of the extinction coefficient, a species cannot maintain a positive biomass.

2.3. Growth limits

When the environmental conditions improve at a rate which is large relative to the potential biomass increase of a particular phytoplankton species, it may be impossible to achieve the level at which either light or some nutrient gets limiting within a single time-step of the model. To account for this situation, a constraint to delimit the maximum biomass increase within the time-interval is considered during the optimization procedure. Assuming that losses will be low during the exponential growth phase of a phytoplankton species, mortality is ignored in the computation of this growth constraint.

For all algae types k the maximum possible biomass concentration, B_k^{max} (g dry m^{-3}), at the end of the time interval Δt (days) depends on the initial biomass concentration, B_k^0, (g dry m^{-3}), the maximum gross production rate Pg_k^{max} (day^{-1}), the respiration rate constant, R_k (day^{-1}), and the time and depth averaged production efficiency factor, E_k. Using the net production rate constant, $Pn_k (=Pg_k^{max}E_k-R_k)$ (day^{-1}), for each algae type k:

$$B_k^{max} = B_k^0 \exp\{Pn_k\Delta t\} \tag{10}$$

If the initial biomass is smaller than a certain base level, this base level is used in stead. Empirically it was found that using a base level of 1% of the potential maximum generally results in realistic species shifts in the model.

2.4. Mortality limits

As in the case of growth, the mortality of each algae species is also constrained to prevent a complete removal within a single time-step when conditions get worse. The minimum biomass value of a species is obtained when there is no production, but only mortality. The minimum biomass, B_k^{min} (g dry m^{-3}), of type k at the end of time interval Δt depends on the initial biomass, B_k^0 (g dry m^{-3}), of type k and the specific mortality rate constant, M_k (day^{-1}) of type k.

$$B_k^{min} = B_k^0 \exp\{-M_k\Delta t\} \tag{11}$$

These minimum values are computed for each individual algae type. However the model sums each of these minimum values over all subtypes within each species and applies it to the total biomass of the species. This way the maximum possible mortality cannot be exceeded, but transitions between limit types remain possible.

As mortality is computed according to a negative exponential function, the minimum biomass level is always positive, in other words a species can never disappear completely. To prevent that insignificantly small biomass values are maintained in the model, the minimum value is replaced by zero once the value computed according to Eq. (11) drops below some base level. Empirically it was found that using a base level, which is 10 times smaller than the base level for the growth, generally results in realistic species shifts in the model.

The mortality constraint of a species (11) has precedence over its extinction constraint (9). Hence in case of a conflict when the mortality constraint demands a certain biomass level to be maintained which exceeds the maximum permitted by the available amount of light, the extinction constraint is dropped from the optimization procedure. Effectively this means that types disappear at the rate of M_k (day^{-1}) under unfavorable conditions and will not be completely removed in a single time step even though too little light is currently available to maintain a positive biomass level.

2.5. Competition between species

In biological terms the competition in the BLOOM model is governed according to the following principle. The algal types defined in the input compete with each other for all potentially limiting resources taking the existing biomass into account. The outcome of the competition for a potentially limiting resource is determined by the ratio between the gross growth rate constant and the requirement for that resource. Hence species with very high growth rates may outcompete more efficient, but slowly growing species, or very efficient species may outcompete species with a higher potential growth rate but a much higher requirement for that particular resource. In practice this means that opportunistic species with high growth rate usually dominate when total available nutrients are low and the average light intensity is high, whereas efficient species with lower potential growth rates and lower resource requirements dominate when total available nutrient levels are high and the average light intensity is low (high level of self-shading).

The principle of the model was briefly described in Los et al. (1984). An extensive description covering both the equations and underlying ecological assumptions is in Los (1991). A condensed version can be found in Los (2005). An overview of the model is shown in Fig. 1. Applied as a screening tool only phytoplankton, dissolved nutrients and the labile form of dead algae are explicitly taken into account. A number of additional compartments and fluxes are part of the model, but these were not considered here and are shown in grey.
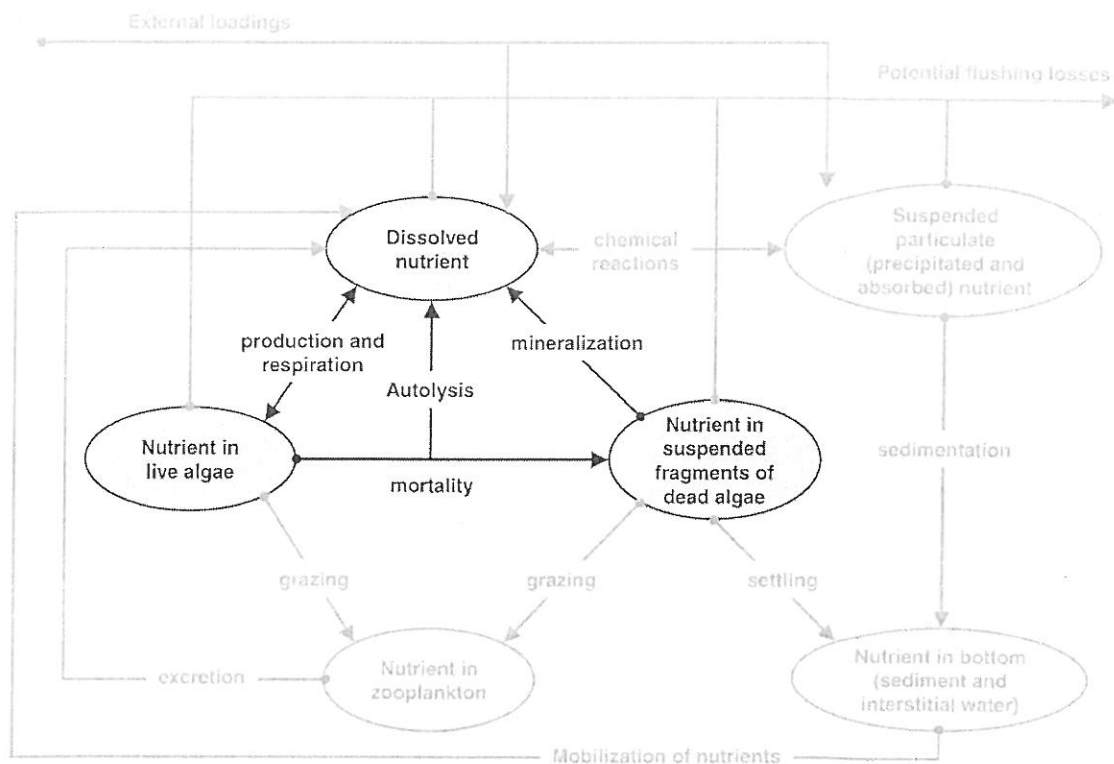
Fig. 1. Overview of the BLOOM phytoplankton model. Applied as a screening tool only dissolved nutrients, nutrients in phytoplankton and in suspended detritus are explicitly considered. Compartments and fluxes in grey can optionally be included but were not in the cases included in this paper.

The number and the characteristics of the phytoplankton species are inputs to the model. Data for about 20 different marine and fresh water species have been collected over the years based on literature, laboratory experiments (Zevenboom and Mur, 1981; Zevenboom et al., 1983; Zevenboom and Mur, 1984; Post et al., 1985; Riegman, 1996; Riegman et al., 1992; 1996; Riegman (unpublished results); Jahnke, 1989) and previous model applications. Depending on the problem, sometimes only major groups are included such as diatoms, greens and blue-greens, and sometimes individual species are modelled such as *Aphanizomenon* or *Phaeocystis*. In by far the majority of model applications, these characteristics are kept at their present default values. They are not tuned to improve the model fit because in so doing they could lose their generality.

3. Implementation of the model

3.1. BLOOM application for screening

In order to test the applicability of the BLOOM model as a 0-D screening tool, it has been applied to six different locations in the Netherlands (Fig. 2, Table

1). The selected stations are located in different marine, coastal and transitional waters in the Netherlands ranging from station Dreischor in the salt water lake Grevelingen to Terschelling 235 (Doggerbank) in the central part of the North Sea. The model is run with a time step of 1 week. To apply the model the following forcing needs to be specified on a weekly basis: water depth, water temperature, surface irradiance, total available nutrient levels (N, P, Si), background extinction coefficient plus the extinction due to suspended matter and humic substances. Data on surface irradiance levels were obtained from the Royal Dutch Meteorological Institute. Each system was assumed to have a specific depth. The other data for all locations, have been extracted from the DONAR database that is available on the internet (www.waterbase.nl). The data have been sampled in the framework of the MWTL programme (Monitoring Programme of the National Water Systems) of the National Institute for Coastal and Marine Management (RIKZ). The year 1998 has been selected since a good data coverage was available for this year at all locations. Data were retrieved on the following parameters: NH_4, NO_2, NO_3, PO_4, SiO_2, Chl-*a*, suspended solids and salinity.
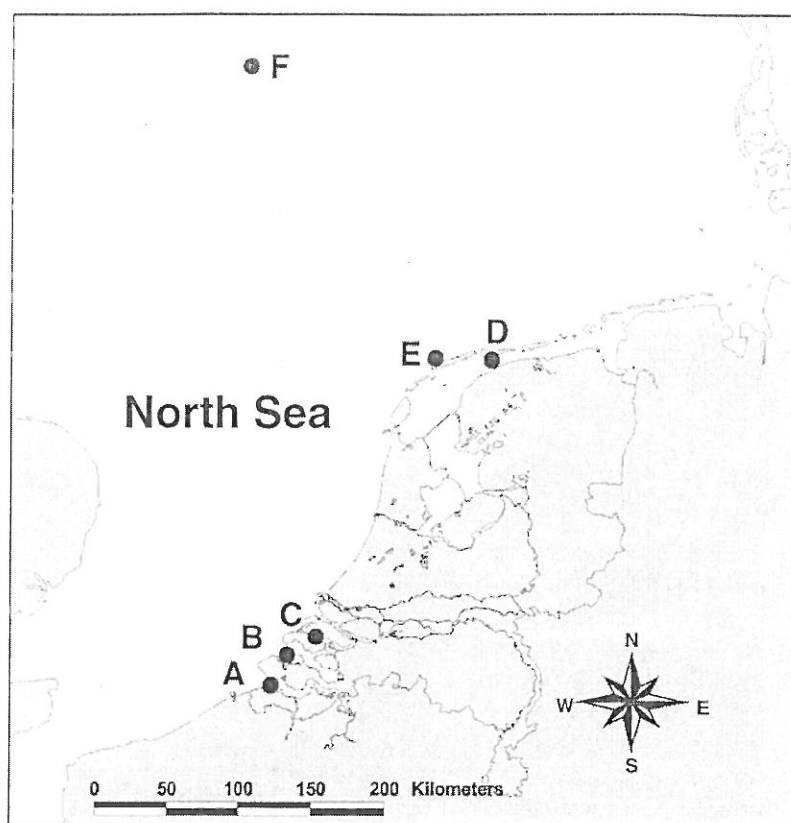
Fig. 2. Overview of the modelled locations. (A) Vlissingen; (B) Wissekerke; (C) Dreischor; (D) Dantziggat; (E) Terschelling 4; (F) Terschelling 235 (Doggerbank).

Estimation of the particulate organic nitrogen (PON) and phosphorus (POP) presents a problem since insufficient data are available for total nutrients. Moreover, measured levels of total nutrients include refractory components that are not readily available for phytoplankton growth and hence should not be included in the model's input. Since the purpose of the model application was to test its applicability as an easy to set-up screening tool, a uniform, simple assumption was used to estimate the amount in nutrients in phytoplankton and detritus based on the measured amount of chlorophyll. It is assumed that that 1 g chlorophyll-a corresponds to 7.5 g N and 0.75 g P in phytoplankton. This corresponds to a g C/

Chl-a ratio of 50 and N/C and P/C ratios of 0.15 and 0.015, respectively. In spite of a large range of variation, these ratios can be considered as typical for the species included in the model, which have been derived from the laboratory experiments described at the end of the previous chapter. Furthermore, it is assumed that for each g PON and POP in algae, also 1 g is present in the form of labile detritus. This 1-to-1 ratio is approximately the annual average computed by the model. No doubt an improved estimation is possible for individual locations, but for this model application the validity of this simple approach was tested and considered accurately enough. As a result, total for phytoplankton available N can be estimated using the following function:

$$TotN = NH_4 + NO_2 + NO_3 + 2 \cdot (7.5 \cdot Chl - a) \quad (12)$$

and total P is estimated as:

$$TotP = PO_4 + 2 \cdot (0.75 \cdot Chl - a) \quad (13)$$

For silicate, measured dissolved silicate levels have been used with a minimum concentration of 0.05 g l^{-1} throughout the year.

Table 1
Locations of the modelled monitoring stations in this paper

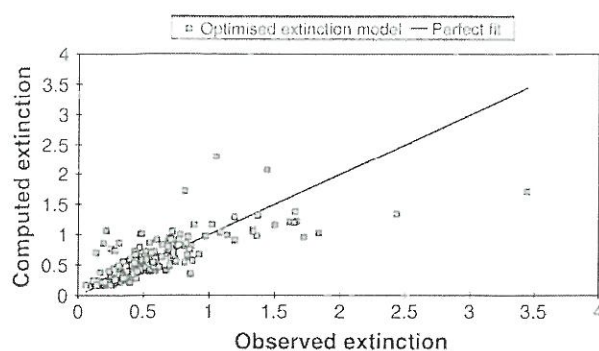|	Bassin	Latitude	Longitude
Vlissingen	Westerschelde	51°24′43.2″N	3°33′56.2″E
Wissekerke	Oosterschelde	51°36′05.7″N	3°43′14.0″E
Dreischor	Lake Grevelingen	51°42′52.6″N	3°59′57.6″E
Dantziggat	Wadden Sea	53°24′04.1″N	5°43′37.1″E
Terschelling 4	Coastal North Sea	53°24′50.9″N	5°09′00.6″E
Terschelling 235	Central North Sea	55°10′15.2″N	3°09′26.7″E

Fig. 3. Computed and measured extinction values (optimized extinction model). From van Gils and Tatman (2003).

Because primary production is strongly influenced by light availability and can even become limited if there is too little light, the calculation of the light conditions in the water is an important process. The availability of light is a function of the solar irradiation on the water surface of light within a certain wave length range (photosynthetically available radiation: PAR) and of the extinction due to absorption and scattering of the light inside the water column. The extinction of light in water is described by the Lambert–Beer model where the extinction coefficient can be related to the absorption and scattering properties of the water constituents. In this BLOOM application, the extinction coefficient is calculated according to an empirical model (Van Gils and Tatman, 2003), which compared to other previously reported relationships provided the best possible fit to the extinction measurements from all locations that are sampled by the RIKZ. The best model in terms of explaining the variability in the extinction

coefficient (Kd), is a four parameter model based on POC, salinity and two fractions of TSM ash weight (below and above 15 mg l^{-1}):

$$Kd = 0.067 + 0.081 \left(19.4 - \frac{S}{1.8} \right) + 0.30 \, POC$$
$$+ 0.036 \, SS_1 + 0.005 \, SS_2 \qquad (14)$$

where S is the salinity of the water (–), POC is the measured particulate organic carbon concentration (mg C l^{-1}) and SS_1 and SS_2 are the concentration of small and large suspended sediment particles, respectively. It is assumed that the concentration of small sediment particles (SS_1) is 15 mg l^{-1} with a relative extinction coefficient of 0.036 $m^2 \, g^{-1}$ while the remainder of the total suspended sediment is considered as the coarse fraction with a specific extinction coefficient of 0.005 $m^2 \, g^{-1}$. The background extinction according to Eq. (14) equals 0.067 m^{-1}, the second term represents the extinction due to the dissolved humic substances. It is taken from the fraction of fresh water. This term vanishes when the salinity is 34.92. The fit of this extinction model to the data is shown in Fig. 3, which is taken from the original report by van Gils and Tatman (2003). To obtain the non-algal related part of the extinction coefficient, POC is put equal to 0 in Eq. (14). During the model simulation the contribution of live phytoplankton and labile detritus is computed by BLOOM. Weekly radiation data for 1998 were derived for location de Kooy, near Den Helder. Photosynthetic active radiation (PAR) was calculated from the total radiation by multiplication with a factor of 0.45. For all locations, the same radiation data were used. Missing values in time for a particular forcing function have been obtained by linear interpolation.

Table 2
Specific extinction coefficients and stochiometric ratios of types defined in BLOOM

Algal type	Specific extinction (m^2/g C)	N/C (mg/mg)	P/C (mg/mg)	Si/C (mg/mg)	Chla/C (mg/mg)	Dry/C (mg/mg)
Diatoms-E	0.24	0.255	0.0315	0.447	0.0533	3.0
Diatoms-N	0.21	0.070	0.0120	0.283	0.0100	3.0
Diatoms-P	0.21	0.105	0.0096	0.152	0.0100	3.0
Flagellate-E	0.25	0.200	0.0200	0.0	0.0228	2.5
Flagellate-N	0.225	0.078	0.0096	0.0	0.0067	2.5
Flagellate-P	0.225	0.113	0.0072	0.0	0.0067	2.5
Dinoflag-E	0.20	0.163	0.0168	0.0	0.0228	2.5
Dinoflag-N	0.175	0.064	0.0112	0.0	0.0067	2.5
Dinoflag-P	0.175	0.071	0.0096	0.0	0.0067	2.5
Phaeocyst-E	0.45	0.188	0.0225	0.0	0.0228	2.5
Phaeocyst-N	0.41	0.075	0.0136	0.0	0.0067	2.5
Phaeocyst-P	0.41	0.104	0.0106	0.0	0.0067	2.5

Original data based on laboratory experiments (references in main text). These were adjusted during previous validations of 2D and 3D North Sea model applications.

The model was applied to the selected locations in a 0-D mode. Species groups included in the model and its coefficients were adopted from previous 2- and 3-dimensional applications to the North Sea (Los and Bokhorst, 1997; Blauw et al., in press). They were kept the same here for each individual station, only the forcing functions of the nutrient concentrations, water depth and non-phytoplankton related contribution to the extinction were varied. The selected species groups are diatoms, microflagellates, dinoflagellates and *Phaeocystsis*. The main stochiometric coefficients used for this application are shown in Table 2. The time series of the calculated chlorophyll-*a* concentrations are compared with the observed chlorophyll-*a* concentrations.

3.2. Sensitivity analysis

The previously described BLOOM phytoplankton module was applied to establish the relations between phytoplankton biomass (e.g. chlorophyll-*a*) and physico-chemical quality elements and pressures (e.g. nutrients and light conditions) for the Dutch coastal waters. These relations are illustrated in the form of 'response curves', which depict the chlorophyll-*a* concentration as a function of different nutrient and/or light conditions (Fig. 4). By defining criteria for the desired phytoplankton biomass indicator level, to represent 'Good' (G) or 'Moderate' (M) status, the corresponding required pressure reduction in nutrients (e.g. R1 and R2) can be estimated from the response curve. Values for 'G' and 'M' have not yet been set for the Dutch coastal and transitional waters.

In general, the 'pressures' of relevance for phytoplankton are nitrogen, phosphorus, silicate and light availability (as proxies of nutrient loading/status and turbidity). Thus, separate response curves can be made for each of these factors. Although in reality the
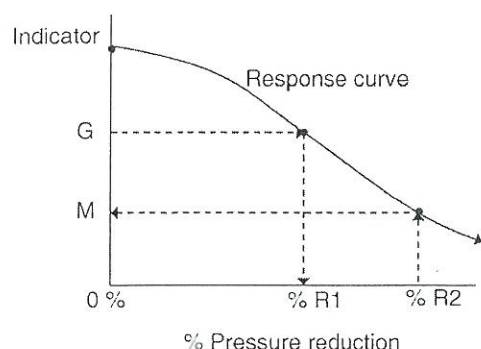

Fig. 4. Generic response curve illustrating the relation between the selected indicator (e.g. chlorophyll concentration) and % pressure reduction (e.g. nutrient concentration).

response of water bodies to changes in loadings will be complicated, as a first assessment response curves for nutrient concentrations are shown as percentage reductions with respect to a baseline concentration, ranging from 0% to 90% for N, for P and for N and P together. As such the response curves show how the phytoplankton will respond to a decrease in nutrients, which may correspond to a particular management strategy. All other model settings remained unchanged. For each simulation, the summer-averaged chlorophyll-*a* concentration was calculated where the summer was defined as 1 April–1 October.

4. Results

4.1. Model validation

The chlorophyll-*a* concentration is an important indicator for the state of eutrophication of marine systems. In the temperate North Sea system however, chlorophyll-*a* concentrations show large seasonal fluctuations throughout the year, with higher concentrations during spring and summer and lower concentrations during the winter. This is mainly because the light availability in winter is too low to support primary production in most areas. The onset of the spring bloom is determined by an increase in available light and varies considerably depending on the solar radiation, the depth and the non-algal part of the extinction such as the TSM concentration. The spring bloom is often limited by the available amount of phosphorus and/or silicate while the summer bloom in many stations is still nitrogen limited. Near shore, however, nitrogen limitation has become a rare phenomenon in Dutch waters since the end of the 1990s, due to the extremely high N/P ratio of the river loads. In autumn light becomes the main limitation again and biomasses decline to small values.

In this validation section, we compare the calculated chlorophyll-*a* concentrations with the observed values. The confidence in the model increases if there is a good agreement between model and observations in both the seasonal patterns and average concentrations.

In general, the seasonal variation and the absolute concentrations of chlorophyll-*a* are well described by the model at these locations (Fig. 5). Highest concentrations are observed at location Dantziggat, located in the Wadden Sea, with average concentrations during the summer half-year of 24 µg l^{-1} (Table 3) and a peak concentration of 57.6 µg l^{-1}, measured on April 21. Summer biomass levels are mainly controlled by

nitrogen and phosphorus at this location. Relatively high concentrations in winter are probably due to benthic rather than to pelagic primary productivity. Lowest concentrations are observed at Terschelling 235, at the Doggerbank in the central North Sea, with average chlorophyll-a concentrations of 1.5 μg l^{-1}. Nitrogen is the main limitation at this station, but summer phosphorus levels are also very low. The underestimation of the average chlorophyll-a concentrations at location Wissekerke is mainly due to the high peak concentration (35.2 μg l^{-1}) that is observed at the end of April, but not simulated by the model. Considering the size of this peak and the average light intensity at this station, it is unlikely that it could be produced locally, hence this peak is probably imported from adjacent parts

of the North Sea where the spring bloom starts earlier. At all locations, the winter concentrations of chlorophyll-a are underpredicted by the model. In most cases, the timing of the Spring phytoplankton peak is well modelled. Only at location Vlissingen, in the Westerschelde estuary, it appears that the increase in chlorophyll-a starts too late.

An example of the simulation results for individual species at the location Dreischor is given in Fig. 6. Diatoms dominate in spring and autumn, flagellates dominate in early summer, dinoflagellates during late summer. Simulated *Phaeocystis* levels are consistently low at this location. This pattern is controlled by the seasonal variation in limiting factors and the characteristics of the model species with respect to these factors.
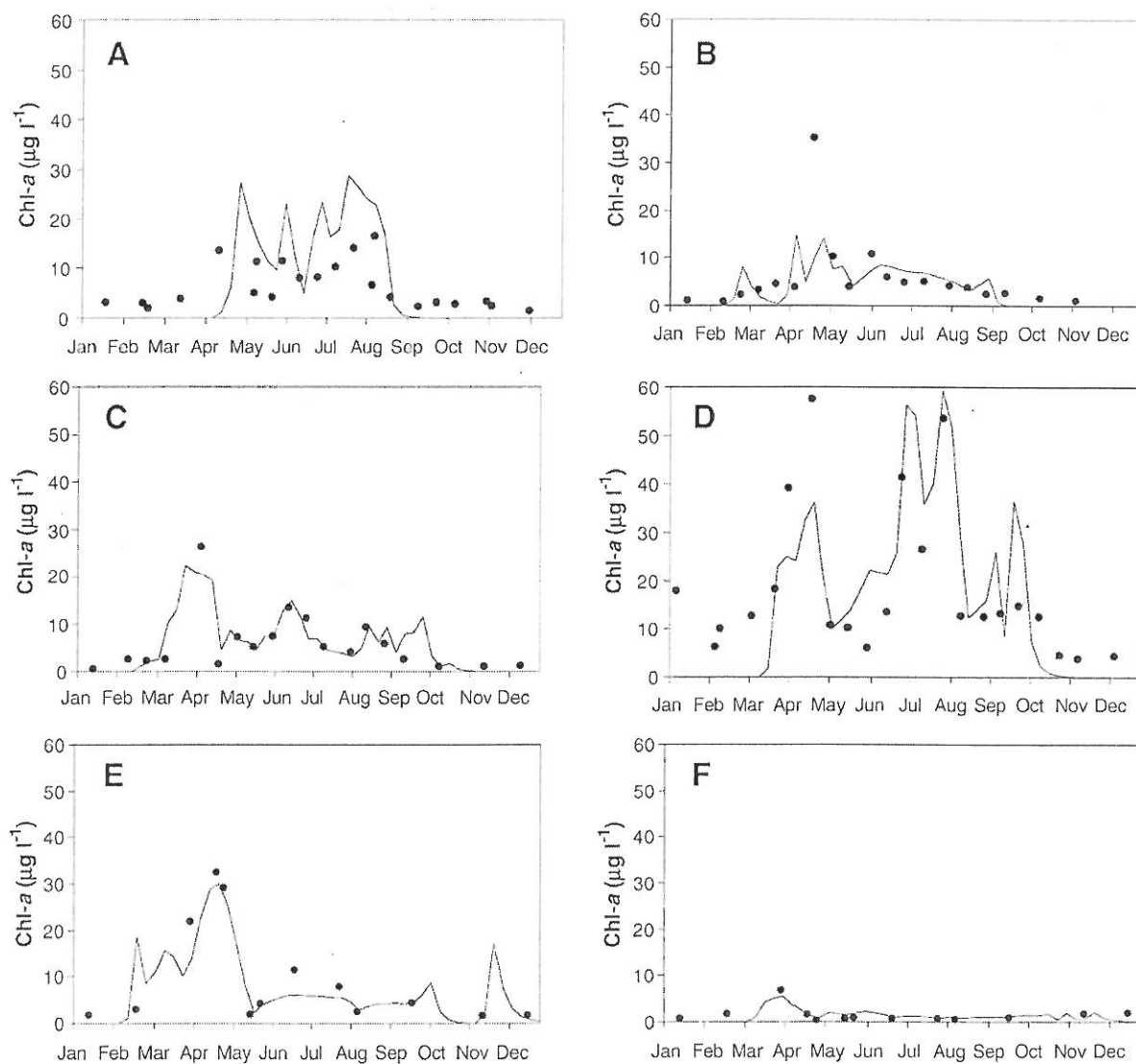

Fig. 5. Modelled (solid lines) and observed (dots) chlorophyll-a concentrations (μg l^{-1}) at the locations Vlissingen (A), Wissekerke (B), Dreischor (C), Dantziggat (D), Terschelling 4 (E) and Terschelling 235 (F).

Measurements for a direct comparison are lacking, but the general succession of species seems reasonable.

4.2. Sensitivity analysis: effect of nutrient reduction

Response curves for the nutrient reductions are shown in Fig. 7. In the coastal location Terschelling 4 the response curve shows a fairly linear relation between decreased chlorophyll concentration and phosphorus reduction (Fig. 7E). With low levels of N reduction (0–30% reduction), there is a limited response in chlorophyll concentration. This indicates that phosphorus rather than nitrogen is the main limiting factor to the phytoplankton growth at this location. The same is true for many other Dutch coastal stations (not shown here).

Of the selected stations representing estuaries, marine lakes and Wadden Sea, location Dreischor in Lake Grevelingen shows a limited response for P reduction in the range of 0–50%. This indicates that Phosphorus is not the limiting factor in the phytoplankton growth at these locations (Fig. 7C). A 50% reduction of the N concentration is much more effective in this system, resulting in a decrease in summer averaged chlorophyll-a of more than 30%. At location Vlissingen on the other hand, a reduction of P concentrations seems to be more effective than reduction of N, indicating that phytoplankton growth at this location during the summer is more limited by P than by N. At the locations Wissekerke, Dantziggat and Terschelling 235, the response curves for N and P are comparable, implying that both nutrients limit the average algal biomass to the same extent. It should be pointed out that even if the response in chlorophyll appears to be linear, the reduction percentage is usually considerably smaller than the corresponding reduction in the affected nutrient. This demonstrates that the model is adjusting
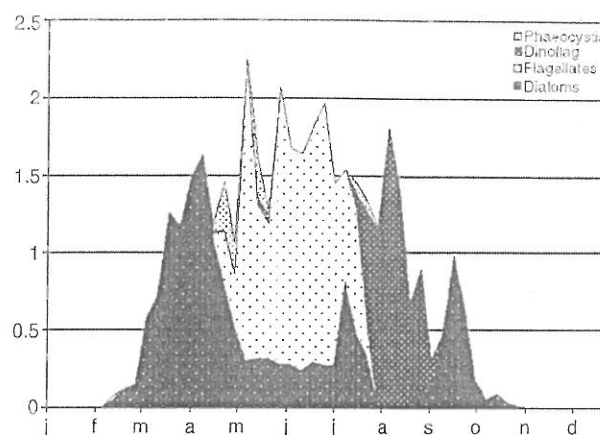

Fig. 6. Simulated species composition (mg C l^{-1}) at location Dreischor (Lake Grevelingen).

its nutrient to chlorophyll ratio by shifting among the simulated phytoplankton types. This kind of response is maintained until the most efficient phytoplankton type has been selected and only one nutrient is constantly limiting. This usually occurs with a reduction in the order of 70%. From there on the simulated reduction in chlorophyll is similar to the reduction of this nutrient.

5. Discussion

In Introduction it was pointed out that assessing the present status and its response to changes in external pressures are important elements of the implementation of the WFD. The purpose of this model application is to demonstrate that it is possible to obtain an acceptable first impression of these aspects for coastal water systems by applying the BLOOM model as a screening tool for a single box. To that purpose the simulated chlorophyll-a concentrations by the standard version of the model were compared to the measurements at a number of stations where conditions in terms of nutrients and light vary considerably. Most forcing conditions could be directly obtained from measurements, other required some assumptions. To keep these assumptions as generic as possible we used the same method to estimate the forcings everywhere thus preferring robustness of the approach over tuning to local conditions.

The results presented here demonstrate that it is indeed possible to obtain an acceptable overall agreement between simulated and observed chlorophyll-a levels particularly during the summer half year. Some deviations occur in the Wadden Sea (station Danziggat), for which winter levels are obviously underpredicted. This is most probably due to the lack of microphytobenthos in the model, which according to De Jonge

Table 3
Overview of the modelled and observed chlorophyll-a concentrations (μg l^{-1})

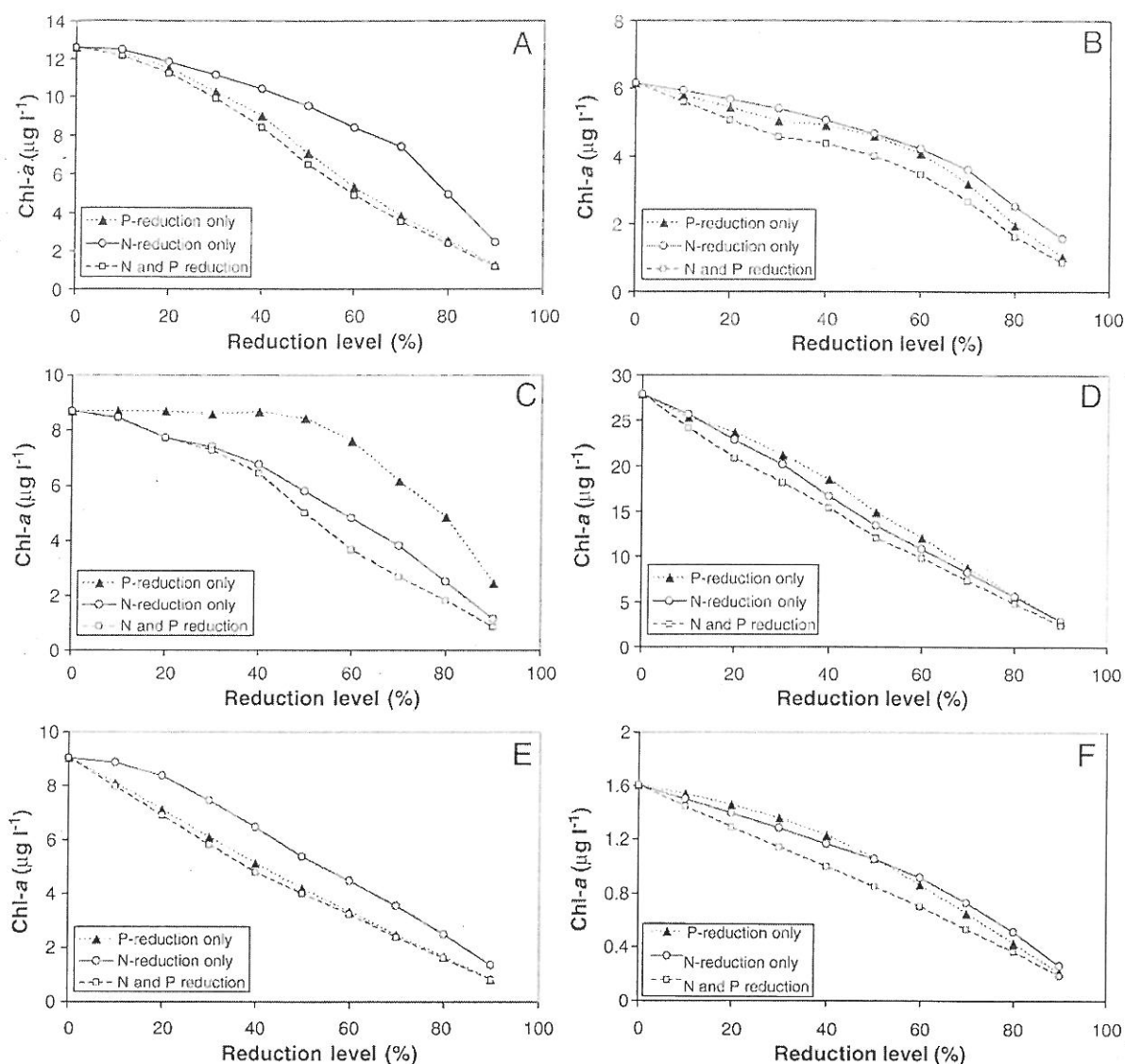|	Yearly averaged chlorophyll-a concentrations (μg l^{-1})		Summer averaged chlorophyll-a concentrations (μg l^{-1})	
	Modelled	Observed	Modelled	Observed
Vlissingen	6.3	6.4	12.6	8.4
Wissekerke	3.4	5.7	6.1	7.7
Dreischor	5.7	5.9	8.7	8.3
Dantziggat	15.1	18.3	27.8	24.0
Terschelling 4	7.0	9.5	9.0	12.8
Terschelling 235	1.2	1.5	1.6	1.4

The summer is defined from 1st April to 1st October.

Fig. 7. Predicted summer averaged chlorophyll-*a* concentrations (μg l^{-1}) resulting from P-reduction (dotted lines), N-reduction (solid lines) and both N- and P-reduction (broken lines) for the locations Vlissingen (A), Wissekerke (B), Dreischor (C), Dantziggat (D), Terschelling 4 (E) and Terschelling 235 (F). Note the different scaling on the *y*-axis.

(1992) is a major source of chlorophyll-*a* in the Wadden Sea.

Other factors responsible for some deviations between simulations and observations are (1) the absence of advective transport processes in the 0-D model, (2) the assumption of complete vertical mixing under all conditions, (3) the estimation method for available nutrients and background turbidity and (4) the absence of grazers in the model. It is important to note that the model simulations presented here already cover a wide range of conditions in which the highest and lowest average chlorophyll-*a* values vary by a factor of 20 (Table 3). This increases the credibility of the simulation results for nutrient reductions.

Considering that BLOOM was applied in 0-D mode, the resemblance between simulated and measured chlorophyll levels may look surprising because most of these stations are affected by the tide and by other horizontal transport processes. The reason why the model results do not suffer heavily from a lack of advective transport is that its main forcings are periodically updated based on in situ measurements. Hence if the nutrient, salinity or TSM levels have changed due to some event which is not explicitly included in the 0-D box model, these new levels are used to generate the input conditions for the next model time step. As long as the potential net growth rates of the phytoplankton types in the model are in the same order
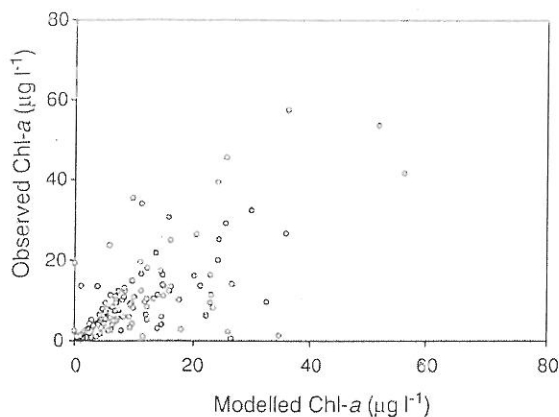
Fig. 8. Observed and modelled summer chlorophyll-*a* concentrations ($\mu g \; l^{-1}$) at for all stations. The line indicates the 1:1 relation between observed and modelled chlorophyll levels. The R^2 of this relation is 0.40.

of magnitude as the observed rate of change in forcing, the model will be able to adjust to the new conditions rapidly enough to track the observed changes in chlorophyll levels.

Inhomogeneous vertical mixing is sometimes observed, but this is only a temporary, not a dominant phenomenon at any of the stations reported here. Hence it seems that this source of error is of minor importance to the locations considered here.

In Eqs. (12) and (13) the term which estimates the organic part of the available nutrients is obviously a simplification of reality, ignoring temporal and spatial variations in stochiometric coefficients and seasonal variations in the ratio between labile detritus and live phytoplankton. No attempt was made to adjust these estimations to local conditions or to vary them seasonally because applying the same equation everywhere is considered to be more attractive from a management point of view. For the same reason Eq. (14), which was used to estimate the non-algal part of the extinction coefficient, was uniformly applied. Considering the overall results of the model, errors in the estimation of nutrients and turbidity in general seem to be acceptable.

Lack of grazing is another potential source of error. Unfortunately little quantitative information is available on the grazing rates of filter feeders in Dutch marine waters. Obviously at some locations, notably in the Wadden Sea filtration by mussels is important, but the importance of this source of error cannot be quantified.

It should be noted that most deviations between model and observations occur in the winter season. The present application is, however, focused on the

summer half year so the performance during that part of the year is most important. As a further illustration the summer half year simulation results and measurements are plotted against each other in Fig. 8. In spite of some deviations particularly in the range between 20 and 40 $\mu g \; l^{-1}$ of chlorophyll, there are no systematic errors in the model results, which confirms that the overall fit is acceptable for its application as a screening tool.

The definition of the summer half year period taken as a basis for the assessment of the model output is to some extent arbitrary. It may be argued that this period starts too late considering that the spring bloom occurs earlier at some but not at all locations. To test the sensitivity of the conclusions we have redrawn Fig. 8 and recomputed the response curves for the period March 1 till September 1. Although the results are not identical, the differences are insignificant.

As an additional form of validation BLOOM has been applied in a similar way to a number of sites from Italian and Portuguese coastal waters as part of the Rebecca project. The same methodology was applied to estimate the model forcings (Eqs. (12)–(14)), but day length and irradiance data were adapted to comply with local conditions. The result for the oligotrophic station Miramare in the Northern part of the Adriatic Sea is shown in Fig. 9 as an example. Observed and simulated chlorophyll-*a* levels at this location are in the order of 1 $\mu g \; l^{-1}$, which is similar to the values simulated with extreme nutrient reductions for most of the Dutch stations. In particular the summer half year values are well reproduced, hence the model presented here still holds when nutrient levels are far below the present values in Dutch coastal and transitional waters. So the model is valid even at these low nutrient concentrations.

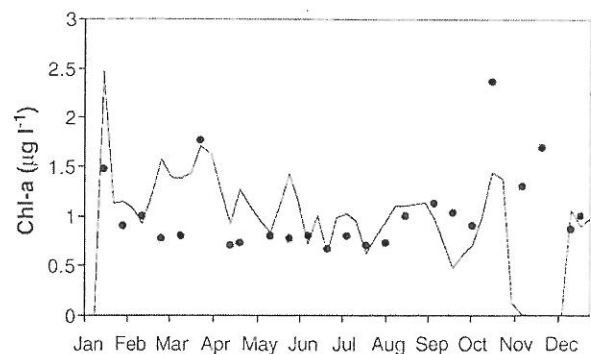In comparison to statistical methods, the application of BLOOM as a screening tool has several advantages.

Fig. 9. Modelled (line) and observed (dots) chlorophyll-*a* concentrations ($\mu g \; l^{-1}$) at Miramare in the Northern part of the Adriatic sea.

The model concept and its coefficient are generic and do not have to be adapted for local conditions of European waters. The model contains explicit formulations on the relationship between the effect variables (e.g. chlorophyll-*a*, composition of the phytoplankton community) and many relevant environmental conditions. These include not only the pressure proxies (i.e. nutrient levels) but also other factors, which may not be controlled, such as the light intensity or water temperature. Also, because simulations are performed on a weekly basis, seasonal variations in controlling factors are explicitly taken into account. In most of the computations, at least two different factors become limiting in different parts of the year. For instance at location Dreischor, the spring bloom in March and at the beginning of April is limited by P (Fig. 10). As a result, N reduction by 50% has no effect on the size of the spring bloom. During the summer however, the primary production becomes limited by N, resulting in lower chlorophyll-*a* concentrations for the 50% N-reduction scenarios. A 50% P-reduction even results in slightly higher chlorophyll-*a* concentrations in June, which is due to a change in simulated phytoplankton composition.

For the Dutch coastal zone, a 2-D/3-D primary production model is operational: the GEM model, which is a rather detailed eco-hydrodynamic model which includes the BLOOM module (Blauw et al., in press). The validation result of the screening version of BLOOM has been compared to GEM (Fig. 11). The resemblance in results of the two models is apparent. This is reassuring as it indicates that the same conclusions on the status of a water system can be drawn regardless whether the screening or a detailed model version is applied. A choice for either model
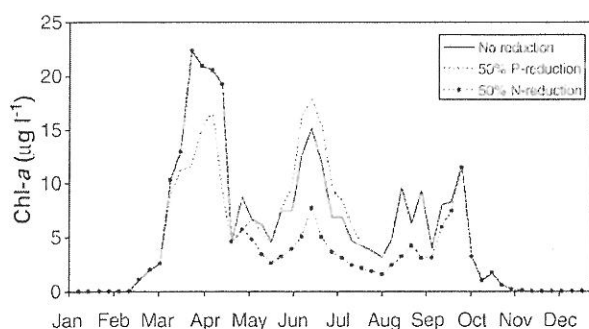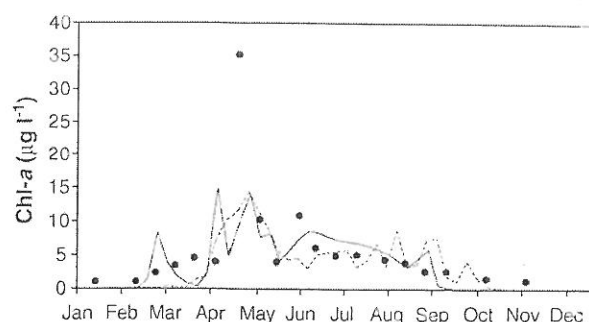

Fig. 11. Comparison of the calculated chlorophyll-*a* concentrations resulting from the 0-D BLOOM model (solid line) and the 2-D GEM model (broken line) for the location Wissekerke in the Oosterschelde. Dots indicate the observations.

version can thus be made based upon the purpose and the availability of data.

In general it is recommended to apply a screening model as described here during an initial phase to assess the present conditions and the sensitivity to different pressures. Occasionally this analysis may even be sufficient for instance in water bodies where light remains controlling even if nutrient concentrations are reduced down to the maximum attainable level. Whenever additional information on individual sources or an enhanced level of detail on physical or biological processes is considered to be of importance, it is recommended to set-up a 2- or 3-D eco-hydrodynamic model.

Acknowledgements

Fig. 10. Predicted chlorophyll-*a* concentrations ($\mu g\ l^{-1}$) at the location Dreischor. The solid line represents actual situation for 1998 without nutrient reduction. The broken line represent the predictions with 50% P-reduction and the broken line with dots are for 50% N-reduction compared to the actual situation.

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