DHI Eutrophication Model 1 - Tropical Waters

MIKE ECO Lab Template

Scientific Description

DHI headquarters
Agern Allé 5
DK-2970 Hørsholm
Denmark

+45 4516 9200 Telephone
+45 4516 9333 Support
+45 4516 9292 Telefax

mike@dhigroup.com
www.mikepoweredbydhi.com

CONTENTS

DHI Eutrophication Model 1 – adjusted for Tropical Waters
MIKE ECO Lab Template
Scientific Description

1 Introduction 1

2 Applications 4

3 Mathematical Formulations 6
3.1 Phytoplankton Carbon (PC) 7
3.2 Production (PRPC) 8
3.3 Light Function 8
3.4 Temperature Function 9
3.5 Nutrient Dependence Function 9
3.6 Death of Phytoplankton (DEPC) 10
3.7 Sedimentation of Phytoplankton (SEPC) 10
3.8 Phytoplankton Nitrogen (PN) 11
3.9 Phytoplankton Phosphorus (PP) 12
3.10 Chlorophyll-a (CH) 13
3.11 Production (PRCH) 13
3.12 Zooplankton (ZC) 13
3.13 Detritus Carbon (DC) 16
3.14 Detritus Nitrogen (DN) 17
3.15 Detritus Phosphorus (DP) 18
3.16 Inorganic Nitrogen (IN) 19
3.17 Inorganic Phosphorus (IP) 21
3.18 Oxygen (DO) 23

4 Data Requirements 27

5 References 29

1 Introduction

MIKE ECO Lab is a numerical lab for Ecological Modelling. It is a generic and open tool for customising aquatic ecosystem models to describe for instance water quality and eutrophication. DHI's expertise and know how concerning ecological modelling has been collected in predefined ecosystem descriptions (MIKE ECO Lab templates) to be loaded and used in MIKE ECO Lab. So the MIKE ECO Lab templates describe physical, chemical and biological processes related to environmental problems and water pollution. The following is a description of the DHI Eutrophication Model 1 template adjusted for tropical waters.

Hence, the template is similar to the DHI Eutrophication Model 1 template on most processes and state variables, but with some adjustments to ensure at better description on:

- Lassiter temperature dependency for phytoplankton and macro algae growth
- Introduction of maps for higher sediment turnover and lower light in mangrove areas
- Introduction of maps for higher turnover due to mussel rafts
- Possibility to control the sediment interaction for a zero net-interaction

Besides these changes, all standard default rates and temperature coefficients have been adjusted for tropical conditions.

The DHI Eutrophication Model 1 template is used in investigations of eutrophication effects and as an instrument in environmental impact assessments. The eutrophication modelling can be applied in environmental impact assessments considering:

- Pollution sources, such as domestic and industrial sewage and agricultural run-off
- Cooling water outlets from power plants resulting in excess temperatures
- Physical conditions, such as sediment loads and change in bed topography affecting the benthic vegetation, in particular

The aim of using eutrophication modelling as an instrument in environmental impact assessment studies is to obtain, most efficiently in relation to economy and technology, the optimal solution with regards to ecology and the human environment.

The eutrophication model describes nutrient cycling, phytoplankton and zooplankton growth, growth and distribution of rooted vegetation and macroalgae in addition to simulating oxygen conditions.

The model results describe the concentrations of phytoplankton, chlorophyll-a, zooplankton, organic matter (detritus), organic and inorganic nutrients, oxygen and the area-based biomass of benthic vegetation over time. In addition to this, a number of derived variables are stored: primary production, total nitrogen and phosphorus concentrations, sediment oxygen demand and Secchi disc depth.

The eutrophication template is integrated with the advection-dispersion module, which describes the physical transport processes at each grid-point covering the area of interest. Other data required are concentrations at model boundaries, flow and concentrations from pollution sources, water temperature and influx of light, etc.

2 Applications

The eutrophication template can be applied in a range of tropical environmental investigations:

- Studies where the effects of alternative nutrient loading situations are compared and/or different waste water treatment strategies are evaluated
- Studies of oxygen depletion
- Studies of the effects of the discharge of cooling water
- Comparisons of the environmental consequences of different construction concepts for harbours, bridges etc.
- Evaluation of the environmental consequences of developing new urban and industrial areas

3 Mathematical Formulations

The MIKE 21/3 ECO Lab is coupled to the MIKE 21/3 AD module in order to simulate the simultaneous processes of transport, dispersion and biological/biochemical processes. The standard eutrophication model results in a system of 12 differential equations describing the variations for 12 components

The first 11 components or state variables (pelagic system) are moveable and treated in both the MIKE 21/3 AD and the MIKE 21/3 ECO Lab module. The additional components have a fixed nature belonging to the benthic system. The benthic vegetation is attached to the sea bed, stones or the like. It is, therefore, not subject to transport by water movements or to dispersion.

The simulated 12 components or the state variables of the model are:

1. Phytoplankton carbon (PC) (gC/m^3)
2. Phytoplankton nitrogen (PN) (gN/m^3)
3. Phytoplankton phosphorus (PP) (gP/m^3)
4. Chlorophyll-a (CH) (g/m^3)
5. Zooplankton (ZC) (gC/m^3)
6. Detritus carbon (DC) (gC/m^3)
7. Detritus nitrogen (DN) (gN/m^3)
8. Detritus phosphorus (DP) (gP/m^3)
9. Inorganic nitrogen (IN) (gN/m^3)
10. Inorganic phosphorus (IP) (gP/m^3)
11. Dissolved oxygen (DO) (g/m^3)
12. Benthic vegetation carbon (BC) (gC/m^2)

The processes and transfer of carbon, nitrogen and phosphorus in the Eutrophication model system is illustrated in Figure 3.1. Also included in the model is an oxygen balance.

The processes describing the variations of the components in time and space are dependent on external factors such as the salinity, water temperature, the light influx, and the discharges.

In addition to the 12 standard components, this template also includes two more components:

13. River suspended solids (RSS) (g/m^3).
14. Sum of PAR at sediment surface (SPARbw) (E/m^2).

The salinity and water temperature can be results of MIKE 21/3 AD simulations or be user specified values. The first possibility is especially relevant for cooling water investigations whereas the latter possibility often is used in areas where only natural variations in temperature are seen.

The mathematical formulations of the biological and chemical processes and transformations for each state variable are described one by one below. The differential equations are 1st order, ordinary and coupled.

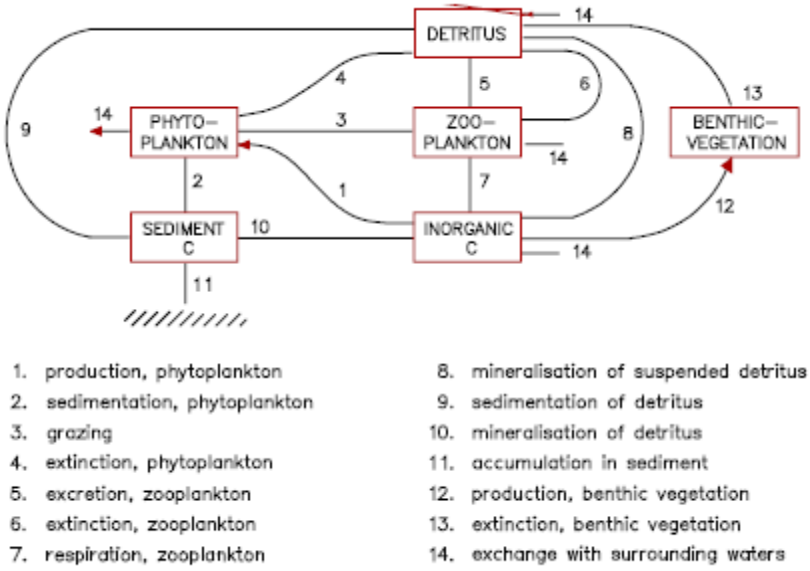

Figure 3.1 The simplified flow diagram of the fluxes of carbon, nitrogen and phosphorus in the eutrophication model.

3.1 Phytoplankton Carbon (PC)

$$\frac{dPC}{dt} = production - grazing - sedimentation - death \tag{3.1}$$

$$= PRPC - GRPC - SEPC + SEPC^{n-1} - DEPC$$

Where

n-1 denotes the input from the above layer (*n>1*)

Please note: Only relevant for MIKE 3.

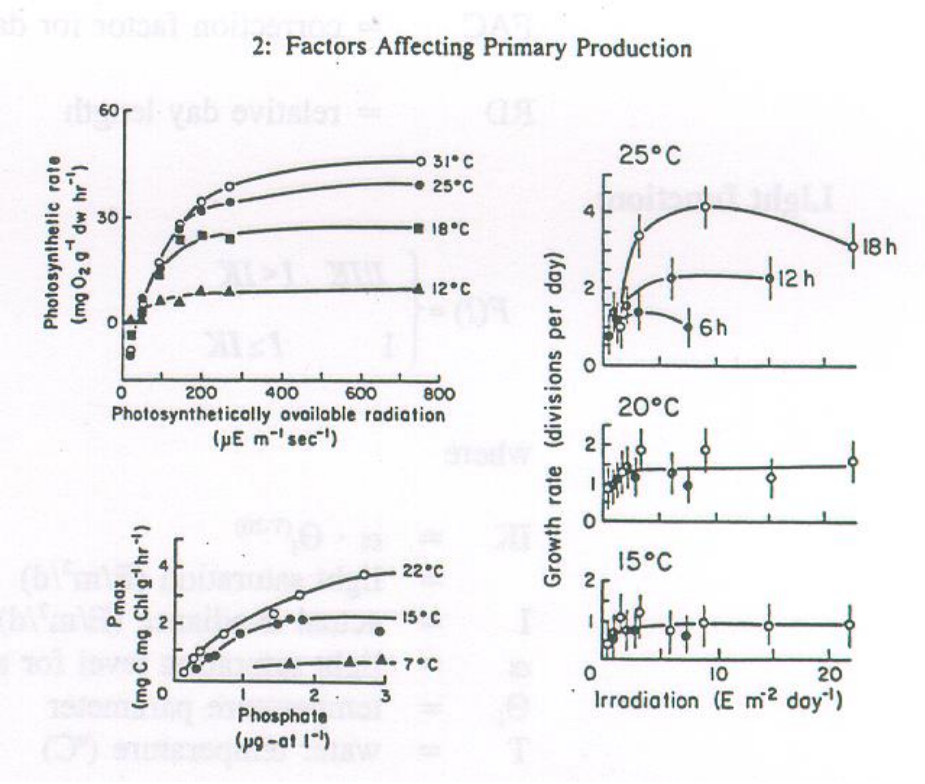

Figure 3.2 Interaction of temperature with light and nutrients. Top left: Photosynthetic rate of Cladophora albida under different levels of light intensity and temperatures in estuarine water. Adapted from Gordon et al. (1980). Right: Mean (± standard deviation) division rates during exponential phase of growth in Talassiosira fluviatilis at three temperatures and daylengths (18, 21, and 6 hrs). Adapted from Hobson (1974). © Canadian Journal of Aquatic and Fisheries Sciences. Bottom left: Maximum photosynthetic rate (P_{max}) of natural phytoplankton of Tokyo Bay under varying phosphate concentrations and temperatures. Adapted from Ichimura (1967). (from: Valiela, 1984)

3.2 Production (PRPC)

The net production of phytoplankton is light, temperature and nutrient dependent.

$$PRPC = \mu \bullet F(I) \bullet F_1(T) \bullet F_1(N,P) \bullet FAC \bullet RD \tag{3.2}$$

Where

μ	= maximum growth coefficient at 20°C (d^{-1})
FAC	= correction factor for dark reaction
RD	= relative day length

3.3 Light Function

$$F(I) = \begin{cases} I / IK & I < IK \\ 1 & I \geq IK \end{cases} \tag{3.3}$$

Where

IK	= $\alpha \cdot \Theta_i^{(T-20)}$ = light saturation (E/m^2/d)
I	= actual irradiance (E/m^2/d)
α	= light saturation level for algae at 20^{o}C (E/m^2/d)
Θ_i	= temperature parameter
T	= water temperature (^{o}C)

The irradiance at the surface (in $E \cdot m^2 \cdot d^{-1}$) is integrated analytically over depth until the depth of the actual layer, given the value of I in the light function. The light function then determines the relative light saturation level. In this model, the light saturation level may be made temperature-dependent, reflecting the observation that phytoplankton groups, such as dinoflagellates, that reach maximum abundance in late summer, have higher light saturation levels (Figure 3.2; cf. Valiela, 1984). In shallow, low-volume systems, where there is only a short lag between irradiance level and water temperature, a temperature dependency may be used to reflect physiological adaptation to ambient light intensity.

If mangroves the light can be reduced according to a factor (mangrove light factor).

Furthermore, light available to phytoplankton growth can be corrected to account for the average light available above stratification. This feature is included to allow for more realistic phytoplankton growth estimation when applying a MIKE21 model (2D) model where stratification is not considered important for the hydrodynamic solution.

3.4 Temperature Function

$$F_1(T) = e^{Temp-optg}\left(\frac{intg - temp}{intg - optg}\right)^{lcg \cdot (intg-optg)} \tag{3.4}$$

Where

Lcg	= Lassiter temperature constant
Optg	= Optimun growth temperature (C)
Intg	= Inhibition temperature (C)
Temp	= water temperature (C)

Temperature for phytoplankton plays a major role as a covariate with other factors. Phytoplankton at low temperatures maintain greater concentrations of photosynthetic pigments, enzymes and carbon (Steemann, Nielsen & Jørgensen, 1968), enabling more efficient use of light. There are strong interactions between temperature and and *µMax* at any light intensity, with day length and production, and with nutrient uptake. In general, all rates increase with increasing temperatures and the irradiance level where maximum photosynthesis is reached is shifted to higher values with increasing temperatures.

However, as all specieses has an optimum and a limit of temperature the tropical template as included a Lassiter expression to allow for estimation of the optimal growth conditions with respect to temperatures.

3.5 Nutrient Dependence Function

Since phytoplankton growth depends essentially on the size of the internal nutrient pools, the nutrient-dependent growth limitation $F_1(N,P)$ is calculated from the relative saturation

of the internal N and P pools. Droop (1973, 1975) provides a theoretical basis for this approach which also has been incorporated in a theoretical model by Nyholm (1977) and in North Sea models by Mommaerts (1978), Tett et al. (1986) and Lancelot & Rousseau (1987).

$$F_1(N,P) = \frac{2}{\frac{1}{F(N)} + \frac{1}{F(P)}}$$

$$F(N) = \frac{PN/PC - PN_{\min}}{PN_{\max} - PP_{\min}} \tag{3.5}$$

$$F(P) = \frac{(PP/PC - PP_{\min}) \bullet (KC + PP_{\max} - PP_{\min})}{(PP_{\max} - PP_{\min}) \bullet (KC + PP/PC - PP_{\min})}$$

Where

PN_{min}, PN_{max}	= minimum and maximum internal nitrogen content in algae (gN/gC), respectively
PP_{min}, PP_{max}	= minimum and maximum phosphorus content in algae (gP/gC), respectively
KC	= half saturation constant for phosphorus in phytoplankton (gP/gC)

3.6 Death of Phytoplankton (DEPC)

Natural mortality of phytoplankton, or autolysis, has been shown to be a significant phenomenon in the marine ecosystem (Jassby & Goldman, 1974) and this decay of blooms is partly mineralised in the water column (Lancelot et al., 1987). In this model, the natural mortality of phytoplankton increases as the internal nutrient pools decrease.

The death rate is assumed to be proportional to the nutritional status of the phytoplankton

$$DEPC = \mu_d \bullet F_2(N,P) \bullet PC \tag{3.6}$$

Where

μ_d	= death rate under optimal nutrient conditions (d^{-1})
$F_2(N,P)$	= ½•{PN_{max}/(PN/PC) + PP_{max}/(PP/PC)}
$F_2(N,P)$	is a function with a minimum of 1. and a maximum when PN/PC and PP/PC ratios are at a minimum. The maximum value of F_2(N,P) depends on the specified PN_{mia} and PP_{mn} coefficients. The maximum value will typically be around 10.

3.7 Sedimentation of Phytoplankton (SEPC)

Nutrient-replete phytoplankton is able to adjust its buoyancy and hence, to minimise its sinking rate. Under conditions of nutrient-stress, with the internal nutrient pools at lower levels, sinking rates increase (Smayda, 1970, 1971).

At low water depth (h<2 m):

$$SEPC = \mu_s \bullet F_2(N,P) \bullet \text{mangrovefactor} \bullet PC \tag{3.7}$$

and at water depth h≥2 m:

$$SEPC = (U_s + musselfactor)/h \bullet F_2(N,P) \bullet \text{mangrovefactor} \bullet PC \tag{3.8}$$

Where

μ_s	= sedimentation rate parameter (d^{-1})
U_s	= sedimentation velocity (m/d)
h	= water depth (m)
mangrovefactor	= a factor for additional sediment turnover within mangroves
musselfactor	= a contribution for additional turnover due to mussel rafts (m/d).

The internal pools of phytoplankton nutrients in this model are state variables, because their uptake dynamics are decoupled from the phytoplankton carbon assimilation dynamics, resulting in time-varying PN/PC and PP/PC ratios. However, the nutrient pools being internal to the carbon-based phytoplankton, their source and sink terms are proportional to the corresponding phytoplankton carbon rates.

3.8 Phytoplankton Nitrogen (PN)

The mass balance for phytoplankton nitrogen reads:

$$\begin{aligned}\frac{dPN}{dt} &= uptake - grazing - sedimentation - death \\ &= UNPN - GRPN - SEPN + SEPN^{n-1} - DEPN\end{aligned} \tag{3.9}$$

Where

n-1	denotes the input from the above layer (*n>1*).

NOTE: Only relevant for MIKE 3.

The rates are similar to the ones for phytoplankton carbon:

Uptake (UNPN)

A description of the nitrogen uptake from phytoplankton can be found in section about the inorganic nitrogen.

Grazing (GRPN)

$$GRPN = GRPC \bullet (PN/PC) \tag{3.10}$$

Sedimentation (SEPN)

$$SEPN = SEPC \bullet (PN/PC) \tag{3.11}$$

Death (DEPN)

$$DEPN = DEPC \bullet (PN/PC) \tag{3.12}$$

3.9 Phytoplankton Phosphorus (PP)

The mass balance for phytoplankton phosphorus reads:

$$\begin{aligned} \frac{dPP}{dt} &= uptake - grazing - sedimentation - death \\ &= UPPP - GRPP - SEPP + SEPP^{n-1} - DEPP \end{aligned} \tag{3.13}$$

Where

n-1 denotes the input from the above layer (*n>1*).

Please note: Only relevant for MIKE 3.

The rates are similar to the ones for phytoplankton carbon:

Uptake (UPPP)

A description of the phosphorus uptake from phytoplankton can be found in section about the inorganic phosphorus.

Grazing (GRPP):

$$GRPP = GRPC \bullet (PP/PC) \tag{3.14}$$

Sedimentation (SEPP):

$$SEPP = SEPC \bullet (PP/PC) \tag{3.15}$$

Death:

$$DEPP = DEPC \bullet (PP/PC) \tag{3.16}$$

3.10 Chlorophyll-a (CH)

The mass balance for chlorophyll-a reads:

$$\frac{dCH}{dt} = production - death - sedimentation$$
$$= PRCH - DECH - SECH + SECH^{n-1} \quad (3.17)$$

Where

n-1 denotes the input from the above layer (*n>1*).

Please note: Only relevant for MIKE 3.

3.11 Production (PRCH)

$$PRCH = (CH_{\min}/IK) \bullet \exp(F_3(N,P)) \bullet PRPC \quad (3.18)$$

Where

CH$_{min}$ = coefficient determining the minimum chlorophyll-a production ($E/m^2/d)^{-1}$

F$_3$(N) = $CH_{max} \cdot \{(PN/PC-PN_{min})/(PN_{max}-PN_{min})\}$

CH$_{max}$ = coefficient determining the maximum chlorophyll-a production (n.u.) in the absence of nutrient limitation.

Sedimentation (SECH)

$$SECH = SEPC \bullet (CH/PC) \quad (3.19)$$

Death (DECH)

$$DECH = (DEPC + GRPC) \bullet (CH/PC) \quad (3.20)$$

3.12 Zooplankton (ZC)

The mass balance for zooplankton reads:

$$\frac{dZC}{dt} = production - death$$
$$= PRZC - DEZC \quad (3.21)$$

Grazing (GRPC)

The grazing rate (GRPC) by zooplankton:

$$GRPC = \mu_z \bullet F_2(T) \bullet \frac{1}{F(PC)} \bullet F(DO) \bullet ZC \quad (3.22)$$

Where

μ_z = maximum grazing rate constant at 20°C (d^{-1})

As the density of prey items (phytoplankton in this case) increases, predators (zooplankton here) eat more prey. This functional response to prey density may take different forms: types I-III.

In the simplest, type I, response the predator population eats more in linear proportion to prey abundance until a satiation level is reached. This point is reached because the predator population is eating at capacity. Further increases in prey abundance have no effect on ingestion rates.

In a type II response the predator population increases consumption at decelerating rate as the density of prey increases until an asymptotis value is reached.

In this model a type III functional response has been formulated (see Valiela, 1984 for a review of the literature on types of functional response). Type III has a density-dependent portion where the rate of ingestion accelerates with increasing prey density. At higher prey densities the type III behaves much like the type II functional response, with the percentage mortality caused per predator becoming lower at increasing prey density down to an asymptotic value.

The parameters K_1 and K_2 determine the onset and the extent of the density-dependent portion of the functional response.

Temperature function

$$F_2(T) = \theta_z^{(T-20)} \quad (3.23)$$

Where

Θ_z = temperature coefficient for grazing rate

Phytoplankton dependence function

$$F(PC) = 1 + e^{(K_1 - K_2 \bullet PC)} \quad (3.24)$$

Where

K_1, K_2 = factors describing the grazing rate dependence on phytoplankton biomass (N.U. and m^3/g respectively)

Oxygen dependence function

$$F(DO) = \frac{DO^2}{DO^2 + MDO} \tag{3.25}$$

Where

MDO = oxygen concentration indicating depressed grazing rates due to oxygen depletion

Production (PRZC)

The production is coupled closely to the grazing of phytoplankton:

$$PRZC = V_C \bullet GRPC \tag{3.26}$$

Where

V_C = growth efficiency parameter for zooplankton (n.u.)

Respiration (REZC)

Respiration of zooplankton can be described as proportional to the grazing of phytoplankton by ignoring basic metabolism, since activity respiration dominates respiratory processes.

$$REZC = K_R \bullet GRPC \tag{3.27}$$

Where

K_R = proportionality constant

Death (DEZC)

Zooplankton mortality has a density-independent term as in Horwood (1974). The density-dependent term is a closure term, which is necessary in the model because zooplankton is the highest trophic level explicitly modelled. For a discussion of the closure problem, see Steele (1976).

The zooplankton decay is proportional to the zooplankton concentration, but at high densities the dependence is of second order resulting in:

$$DEZC = K_{d1} \bullet ZC + K_{d2} \bullet ZC^2 \tag{3.28}$$

Where

K_{d1} = rate constant (d^{-1}) especially important at concentrations below 1 g·m^{-3}

K_{d2} = rate constant important at high concentrations {d^{-1}·$(g/m^3)^{-1}$}

The zooplankton assimilation efficiency is not 100% resulting in an excretion (EKZC) of nutrients (C, N and P) being the difference between grazing, production and respiration:

$$EKZC = GRPC - PRZC - REZC \tag{3.29}$$

These excretion products are organic material entering the organic matter/detritus pool as outlined below in the detritus equations.

Detritus

Detritus is defined in the model as particles of dead organic material in the water. The detritus pool receives the dead primary producers and excreted material left after grazing. Sedimentation and mineralisation are the only processes draining the detritus pools.

There are three state variables: detritus carbon, nitrogen and phosphorus.

3.13 Detritus Carbon (DC)

The mass balance for detritus carbon reads:

$$\begin{aligned}\frac{dDC}{dt} &= generation - sedimentation - mineralization \\ &= (1 - VM) \bullet DEPC + EKZC + SLBC/h \\ &- SEDC + SEDC^{n-1} - REDC + DEZC\end{aligned} \tag{3.30}$$

Where

n-1	denotes the input from the above layer (*n>1*).

NOTE: Only relevant for MIKE 3.

Generation

The detritus generation is the sum of input from dead phytoplankton carbon (DEPC), dead zooplankton (DEZC), excretion of organic material from zooplankton (EKZC) and sloughing (or death) of benthic vegetation (SLBC).

Here

V_m	= fraction of dead phytoplankton, undergoing immediate mineralisation.

Sedimentation (SEDC)

The sedimentation of detritus is modelled similarly to the sedimentation of phytoplankton.

At low water depths (h<2m):

$$SEDC = \mu_d \bullet \text{mangsedfacon} \bullet DC \tag{3.31}$$

and at water depth h>2m:

$$SEDC = U_d/h \bullet \text{mangsedfacon} \bullet DC \tag{3.32}$$

Where

μ_d	= sedimentation parameter for detritus at low water depth (d^{-1})
U_d	= sedimentation rate parameter (velocity) for detritus (m/d)
mangrovefactor	= a factor for additional sediment turnover within mangroves

Mineralisation (REDC)

Bacterioplankton has been included implicitly in the model by giving the detritus a variable mineralisation rate, which is dependent on temperature and oxygen saturation. Thus, detritus causes both oxygen consumption and inorganic nutrient regeneration in the water column and in the benthic system. This implicit approach has the obvious advantage of saving one state variable, but the disadvantage of having to ignore dissolved organic carbon (DOC) as a potential substrate for bacterioplankton.

However, since the largest single source of DOC in aerobic situations is exudation by primary producers with in situ rates of around 10% of net phytoplankton production (Williams, 1975, Smith et al., 1977) this omission is felt to be justifiable.

Nutrient regeneration from the benthic system by mineralization processes is not dependent on the benthic detritus pool but on the sedimentation rate of pelagic detritus. Proportionality factors define the permanent loss of nutrients (adsorption, complexation, burial, denitrification) from the system.

$$REDC = \mu_m \bullet F_3(T) \bullet F_1(DO) \bullet DC \tag{3.33}$$

Where

μ_m	= maximum mineralisation rate at 20°C (d^{-1})
$F_3(T)$	= $\Theta_D^{(T-20)}$
Θ_D	= temperature coefficient for mineralisation of detritus
$F_1(DO)$	= $DO^2/(DO^2 + MDO)$

3.14 Detritus Nitrogen (DN)

The main balance for detritus nitrogen reads:

$$\frac{dDN}{dt} = generation - sedimentation - mineralization \tag{3.34}$$

$$= (1 - VM) \bullet DEPN + EKZN + DEZN + SLBN - SEDN + SEDN^{(n-1)} - REDN$$

Where
n-1 denotes the input from the above layer (*n>1*).

Please note: Only relevant for MIKE 3.

The rates are similar to the ones for detritus carbon.

Generation

Detritus nitrogen is the result of input from dead phytoplankton and excretion and death of zooplankton nitrogen. The excretion and death of zooplankton nitrogens are calculated from:

$$EKZN = VZN \bullet EKZC$$

$$DEZN = VZN \bullet DEZC \quad (3.35)$$

Where

VZN = *nitrogen content of zooplankton assumed to be constant* (gN/gC)

The rate for sloughing of benthic nitrogen is calculated from:

$$SLBN = PNB \bullet (SLBC/h) \quad (3.36)$$

Where

PNB = the nitrogen-carbon ratio in benthic vegetation assumed to be constant (gN/gC)

Sedimentation

$$SEDN = SEDC \bullet DN/DC \quad (3.37)$$

Mineralisation

$$REDN = REDC \bullet DN/DC \quad (3.38)$$

3.15 Detritus Phosphorus (DP)

The mass balance for detritus phosphorus reads:

$$\frac{dDP}{dt} = generation - sedimentation - mineralization$$

$$= (1 - VM) \bullet DEPP + EKZP + DEZP + SLBP - SEDP + SEDP^{(n-1)} - REDP \quad (3.39)$$

Where

n-1 denotes the input from the above layer (*n>1*).

Please note: Only relevant for MIKE 3.

The rates for phosphorus are similar to the detritus carbon rates.

Generation

This is the sum of phosphorus from dead phytoplankton, excretion and death of zooplankton phosphorus and sloughing of benthic vegetation phosphorus.

The excretion and death of zooplankton phosphorus and the sloughing of benthic phosphorus are expressed as:

$$EKZP = VZP \bullet EKZC$$

$$DEZP = VZP \bullet DEZC \quad (3.40)$$

$$SLBP = PPB \bullet (SLBC/h)$$

Where

VZP	= the constant phosphorus content of zooplankton (gP/gC)
PPB	= the constant phosphorus content of benthic vegetation (gP/gC)

3.16 Inorganic Nitrogen (IN)

The inorganic nitrogen is here modelled as the sum of ammonia, nitrate and nitrite. The main balance for inorganic nitrogen includes as a sink the uptake by the primary producers: phytoplankton (UNPN) and benthic vegetation (UNBN) and as a source the mineralisation of organic nitrogen (detritus) (REDN), zooplankton (REZN) and sedimented phytoplankton and detritus (RESN).

$$\frac{dIN}{dt} = input\ \ from\ mineralization - uptake \quad (3.41)$$

$$= REDN + REZN + RESN^{*} + VM \bullet DEPN - UNPN - UNBN$$

Pleae note: For MIKE 3 only relevant for the bottom layer.

Input from mineralisation

The mineralisation rates for detritus and zooplankton are described above. The mineralisation of sediment, which is only relevant for the bottom layer, is described by:

$$RESN = K_{SN} \bullet F_5(T) \bullet F_2(DO) \bullet (SEDN + SEPN) \quad (3.42)$$

Where

K_{SN}	= proportionality factor at 20°C
$F_5(T)$	= $\Theta_M^{(T-20)}$
$F_2(DO)$	= DO/(DO+MDO)
Θ_M	= temperature coefficient for mineralisation of sediment

The mineralisation is expressed as a fraction of the sedimentation of organic matter.

Under anoxic conditions, the release of nutrients is not only a result of recently sedimented material, but also a zero order function where large amounts of nutrient buried in the sediment will be released. This is described by a constant release rate per areal unit:

$$As\ DO < MDO$$

(3.43)

$$RESN = N_{REL}/h$$

Where

N_{REL} = release rate under anoxic conditions (g/m^2/d)

Uptake

The "uptake" is both uptake by phytoplankton (UNPN) and by benthic vegetation (UNBN).

Uptake by phytoplankton (UNPN)

The model for phytoplankton includes modelling of nutrient limited growth determined by intracellular concentrations. The uptake is then different for limited and non-limited conditions. Under limiting conditions where PN<PN$_{max}$ the uptake rate of nitrogen is chosen from three expressions in the following way:

$$UNPN = \min \left[\begin{array}{l} \max \left[\begin{array}{l} V_{kn} \cdot \dfrac{IN}{IN + KPN} \cdot PC \\ Mineralization + external\ supply \end{array} \right. \\ \\ PRPC \cdot PN_{\max} \end{array} \right. \quad (3.44)$$

This scheme states that under limiting conditions the uptake is determined either by the extracellular concentration (IN) or by the release of nutrients by biological and chemical decomposition processes and external supply. The highest value of these two is chosen. This shall of course not exceed the uptake as determined by the production and maximum nitrogen content. The latter is also true for the non-limiting condition where a choice of the minimum of the following values is made:

$$UNPN = \min \left[\begin{array}{l} V_{kn} \cdot \dfrac{IN}{IN + KPN} \cdot PC \\ \\ PRPC \cdot PN_{\max} \end{array} \right. \quad (3.45)$$

Where

V_{kn} = the uptake rate constant for nitrogen (d^{-1}·(mg/l)$^{-1}$)

KPN = Halfsaturation concentration for N uptake(mg N/l)

Uptake by benthic vegetation (UNBN)

The model for the benthic vegetation does not include a nutrient limited growth as a function of intracellular concentration but a slightly more simple approach in which the extracellular nutrient concentration may be growth limiting. The nutrient uptake is then proportional to the net production.

$$UNBN = PNB \bullet (PRBC/h) \tag{3.46}$$

Where

PNB	= nitrogen to carbon ratio (gN/gC)
PRBC	= production of benthic carbon (see later for the benthic vegetation mass balance)

The growth limitation function is described together with the production of benthic vegetation below.

3.17 Inorganic Phosphorus (IP)

The main balance for inorganic phosphorus (e.g. phosphate) reads:

$$\frac{dIP}{dt} = input\ \ from\ mineralization - uptake$$

$$= REDP + REZP + RESP^{*} + VM \bullet DEPP - UPPP - UPBP \tag{3.47}$$

Please note: For MIKE 3 only relevant for the bottom layer.

The rates are very similar to the rates for nitrogen.

Input from mineralisation

The input from mineralisation is the sum of mineralisation of detritus, zooplankton and phytoplankton phosphorus and the release from the sediment.

Release from the sediment, which is only relevant for the bottom layer, is expressed as:

$$RESP = K_{SP} \bullet F_5(T) \bullet F_2(DO) \bullet (SEDP + SEPP) \tag{3.48}$$

Where

K_{SP}	= proportionality factor at 20°C

The remainder of the terms in this equation have been explained above.

Under anoxic conditions (DO<MDO) a constant release rate is modelled:

$$RESP = P_{REL}/h \tag{3.49}$$

Where

P_{REL}	= constant release rate (g/m^2/d)

Uptake

Uptake by phytoplankton is described similarly to the nitrogen uptake.

Under non-limiting conditions:

$$UPPP = \min \left[\begin{array}{l} V_{kp} \bullet \frac{IP}{IP + KPP} \bullet PC \\ \\ PRPC \bullet PP_{\max} \end{array} \right. \tag{3.50}$$

and under limiting conditions:

$$UPPP = \min \left[\begin{array}{l} \max \left[\begin{array}{l} V_{kp} \bullet \frac{IP}{IP + KPP} \bullet PC \\ \\ Mineralization + external\,supply \end{array} \right. \\ \\ \\ \\ \\ \\ PRPC \bullet PP_{\max} \end{array} \right. \tag{3.51}$$

Where

V_{kp}	= uptake rate for phosphorus (d^{-1}•(mg P/l)$^{-1}$)
KPP	= halfsaturation concentration for P uptake(mg P/l)

The uptake by benthic vegetation:

$$UPBP = PPB \bullet (PRBC/h) \tag{3.52}$$

Where

PPB	= the phosphorus to carbon content (gP/gC)
PRBC	= production of benthic vegetation explained later

3.18 Oxygen (DO)

The oxygen balance includes the oxygen production of the primary producers, the oxygen consumption by mineralisation and respiration and also the reaeration, e.g. the oxygen exchange between water and air. The mass balance then reads:

$$\frac{dDO}{dt} = production - consumption + reaeration$$

$$= ODPC + ODBC - ODZC - ODDC - ODSC - \quad (3.53)$$

$$Vm \bullet Vo \bullet DEPC + REAR$$

Production

Oxygen is produced during the production of phytoplankton and benthic vegetation. A specific amount of oxygen is produced per gram of carbon, according to the basic

$$ODPC = Vo \bullet PRPC$$

$$ODBC = Vo \bullet (PRBC/h) \quad (3.54)$$

Where

Vo	= oxygen to carbon ratio at production (gO_2/gC)

Consumption

The oxygen consumption is due to mineralisation of organic matter in water and sediment, to respiration of zooplankton and to mineralisation of the part of the phytoplankton, which is mineralised immediately without entering the detritus pool.

$$ODDC = Vo \bullet REDC$$

$$ODZC = Vo \bullet REZC \quad (3.55)$$

Mineralisation of dead phytoplankton:

$$Vo \bullet Vm \bullet DEPC \quad (3.56)$$

The sediment oxygen demand is related to the carbon mineralisation in the sediment which again is related to the sedimentation of organic matter (detritus and phytoplankton).

$$RESC = K_{MSC} \bullet F_5(T) \bullet F_2(DO) \bullet (SEPC + SEDC) \quad (3.57)$$

Where

K_{MSC}	= proportionality factor at 20°C and oxidised condition
$F_5(T)$	= $\Theta_M^{(T-20)}$
Θ_M	= temperature coefficient for mineralisation
$F_2(DO)$	= DO/(DO+MDO)

The oxygen consumption is then found from:

$$ODSC = Vo \bullet RESC \tag{3.58}$$

Reaeration

The reaeration is found from the oxygen saturation concentration and a reaeration rate:

$$REAR = K_{RA} \bullet (C_S - DO) \tag{3.59}$$

Where

K_{RA}	= reaeration rate (d^{-1})
C_S	= oxygen saturation concentration (g/m^3)
	= 14.652-0.0841·S+T·{0.00256·S-0.41022+ T·(0.007991-0.0000374·S-0.000077774·T)}
T	= water temperature (^oC)
S	= Salinity (o/oo)

Benthic Vegetation (BC)

The benthic vegetation is assumed to be rooted and/or attached to stones etc. Fixed nitrogen to carbon and phosphorus to carbon ratios are assumed. The mass balance for the benthic vegetation is:

$$\frac{dBC}{dt} = production - loss = PRBC - SLBC \tag{3.60}$$

Production (PRBC)

$$PRBC = \mu_B \bullet F_6(T) \bullet F_3(I) \bullet F_4(N,P) \bullet RD \bullet BC \tag{3.61}$$

Where

μ_B	= net specific growth rate at 20^{o}C
RD	= relative day length
$F_6(T)$	$= e^{Temp-optg}\left(\frac{intg-temp}{intg-optg}\right)^{lcg\bullet(intg-optg)}$
Θ_B	= temperature coefficient for benthic vegetation growth
$F_2(I)$	$= \begin{cases} I_B / I_{KB}, I_B < I_{KB} \\ 1 \quad\quad , I_B \geq I_{KB} \end{cases}$
I_B	= light intensity at bottom ($E/m^2/d$)
I_{KB}	= light saturation intensity for the benthic vegetation ($E/m^2/d$)

$F_4(N,P)$ $= \dfrac{2}{\left(\dfrac{1}{F_2(N)} + \dfrac{1}{F_2(P)}\right)}$

$F_2(N)$ $= \dfrac{IN}{IN + KBN}$

KBN = Half saturation constant for the nitrogen limitation function (g/m^3)

$F_2(P)$ $= \dfrac{IP}{IP + KBP}$

KBP = half saturation constant for the phosphorus limitation function (g/m^3)

Loss/sloughing (SLBC)

$$SLBC = \mu_S \bullet F_7(T) \bullet (BC - BABC) \tag{3.62}$$

Where

μ_S = sloughing or loss rate at 20°C (d^{-1})

$F_7(T)$ = $\Theta_S^{(T-20)}$

Θ_S = temperature coefficient for loss

BABC = minimum area based biomass of benthic vegetation (g/m^2)

4 Data Requirements

- Basic Model Parameters
  - Model grid size and extent
  - Time step and length of simulation
  - Type of output required and its frequency
- Bathymetry and Hydrodynamic Input
- Combined Advection-Dispersion Model
  - Dispersion coefficients
- Initial Conditions
  - Concentration of parameters
- Boundary Conditions
  - Concentration of parameters
- Pollution Sources
  - Discharge magnitudes and concentration of parameters
- Process Rates
  - Size of coefficients governing the process rates. Some of these coefficients can be determined by calibration. Others will be based on literature values or found from actual measurements and laboratory tests.
- Forcings
  - Data sets of photosynthetic active light (PAR) ($E/m^2/day$)

5 References

Bach, H.K., D. Orhon, O.K. Jensen & I.S. Hansen. Environmental Model studies for the Istanbul Master Plan. Part II: Water Quality and Eutrophication. Wat.Sci.Tech. Vol. 32, No. 2, pp 149-158, 1995.

Bach, H., A. Malmgren-Hansen and J. Birklund. Modelling of Eutrophication Effects on Coastal Ecosystems with Eel¬grass as the Dominating Macrophyte. Presented at the Int. Conf. on Marine Coastal Eutrophication, Bologna, 21-23 March 1990.

Baker, E.T. and J.W. Lavelle. The Effect of Particle Size on the Light Attenuation Coefficient of Natural Suspensions. J. of Geophysical Reas. Vol. 89, No. C5, pp 8197-8203, Sept. 1984.

Blackburn T.H., Henriksen K. Nitogen cycling in different types of sediments from Danish Waters Limnol. Oceanogr. 28(3), pp. 477-493.

Bocci M., Coffaro G., Bendoricchio G. Modelling biomass and nutrient dynamics in eelgrass (Zostera marina): applications to Lagoon of Venice (Italy) and Øresund (Denmark) Ecol. Model. 102, pp 67-80, 1997.

Canale, R.P. and Martin T. Aues. Ecological Studies and Mathematical Modelling of Cladophora in Lake Huron: 5. Model Development and Calibration. J. Great Lakes Res. 8(1), pp 112-125, 1982.

Coffaro G., Bocci M. 1997. Resources competition between Ulva rigida and Zostera marina: a quantitative approach applied to the Lagoon of Venice. Ecol. Model. 102 PP 81-95, 1997

Dahl-Madsen, K.I. Mathematical Modelling of Eutrophied Coastal Areas. Prog. Wat. Tech., Vol. 10, Nos. 5/6, pp 217-235, 1978.

Droop, M.R. Some thoughts on nutrient limitation in algae. J. Phycol. 9: 264-272, 1973.

Droop, M.R. The nutrient status of algal cells in batch cul¬tures. J. Mar. Biol. Ass. U.K. 55: 541-555, 1975.

Goldman, Joel C. Outdoor Algal Mass Cultures- II Photosyn-thetic Yield Limitations. Water Research, Vol. 13, pp 119-136, 1979.

Gordon, D.M., P.B. Birch and A.J. McComb. The effect of light, temperature, and salinity on photosynthetic rates of an estuarine Cladophora. Bot. Mar. 23: 749-755, 1980.

Gundresen K.J., Glud R.N., Jørgensen B.B. Havbundens Iltomsætning. Havforskning fra Miljøstyrelsen, nr. 57. 1995

Hobson, L.A. Effects of interaction of irradiance, daylength, and temperature on division rates of three species of marine unicellular algae J. Fish. Res. Bd. Canada 31: 391-395, 1974.

Horwood, J.W. A model of primary and secondary produc¬tion. ICES C.M. 1974/L 19:1-10, 1974.

Ichimura, S. Environmental gradient and its relation to primary productivity in Tokyo Bay. Records Oceanogr. Works (Japan) 9: 115-128, 1967.

Iziumi H., Hattori A.. Growth and organic production of eelgrass (Zostera marina) in temperate waters of the pacific coast of Japan. III The kinetics of nitrogen uptake. Aquat. Bot. 12, pp. 245-256, 1982.

Jacobsen O.S. Sorption, adsorption and chemosorption of phosphate by Danish lake sediments Vatten nr. 4, PP 230-241, 1978

Jacobsen O.S. Sorption of phosphate by Danish Lake Sediments Vatten nr. 3, PP 290-298, 1977.

Jassby, A.D. and C.R. Goldman. Loss rates from a lake phytoplankton community. Limnol. Oceanogr. 21: 540-547, 1974.

Jensen H.S., Mortensen P.B., Andersen F.Ø, Rasmussen E.K., A. Jensen, 1995. Phosphorus cycling in cosatal marine sediment. Limnol. Oceanogr. 40(5), PP 908-917.1995.

Lancelot, C. and V. Rousseau. ICES intercalibration exercise on the 14C method for estimating phytoplankton primary production. Phase 2: experiments conducted on board of RV DANA. Preliminary report, 35 pp, 1987.

Lancelot, C, G. Billen, A. Sourina, T. Weisse, F. Colijn, M.J.W. Veldhuis, A. Davies and P. Wassman. Phaeocystis blooms and nutrient enrichment in the continental coastal zones of the North Sea. Ambio 16: 38-46, 1987.

Lomstein, Bente et al. Omsætning af organisk kvælstof i marine sedimenter. Havforskning fra Miljøstyrelsen nr. 58. 1995

Mommaerts, J.P. Systeembenadering van en gesloten mariene milieu, met de nadruk op de rol van het fytoplankton. Doc¬toral thesis. Vrije Universiteit Brussel: 1-335, 1978.

Mortensen P.B., Jensen H.S., Rasmussen E.K., Østergaard Andersen P. Fosforomsætning i sedimentet i Århus Bugt. Havforskning fra Miljøstyrelsen, nr. 17. 1992.

Nyholm, Niels. A Mathematical Model for the Growth of Phytoplankton. Presented at the Int. Symp. on Experimental Use of Algal Cultures in Limnology, Sandefjord, Norway, Oct. 26-28 1976.

Nyholm, N. Kinetics of phosphate-limited algal growth. Biotechn. Bioengineering 19: 467-492, 1977.

Nyholm, Niels. A Simulation Model for Phytoplankton Growth Cycling in Eutrophic Shallow Lakes. Ecological Modelling, Vol. 4, pp 279-310, 1978.

Nyholm, Niels. The Use of Management Models for Lakes at the Water Quality Institute, Denmark. State-of-the-art in Ecological Modelling, Vol. 7, pp 561-577, 1979.

Press, W.H., B.P. Flannery, S.A. Teukolsky and W.T. Vetterling. Numerical Recipes. Cambridge University Press (1986). Press.

Ruadij P., W.Van Raaphorst, 1995 Benthic nutrient regeneration in the ERSEM ecosystem model of the North SeaNetherlands Journal of Sea Research, 33 (3/4) PP 453-483, 1995

Scavia, Donald. Examination of Phosphorus Cycling and Control of Phytoplankton Dynamics in Lake Ontario with an Ecological Model. J. Fish. Res. Board Can., Vol. 36, pp 1336-1346, 1979.

Schnorr, J.L. and D.M. Di Toro. Differential Phytoplankton Sinking- and Growth Rates: an Eigenvalue Analysis. Ecologi¬cal Modelling, Vol. 9, pp 233-245, 1979.

Smayda, T.J. The suspension and sinking of phytoplankton in the sea. Oceanogr. Mar. Biol. Ann. Rev. 8: 357-414, 1970.

Steele, J.H. The role of predation in ecosystem models. Marin. Biol. 35: 9-11, 1976.

Steemann Nielsen, E. and E.G. Jørgensen. The adaptation of plankton algae. III. With special consideration of the impor-tance in nature. Physiol. Plant. 21: 647-654, 1968.

Swartzman, Gordon L., and Richard Bentley. A Review and Comparison of Plankton Simulation Models. ISEM Journal 1, Nos. 1-2, pp 30-81, 1979.

Sweerts et all. Similarity of whole-sediment molecular diffusion coefficients in fresh water sediments of low and high porosity. Limnol. Oceanogr. 36 (2), pp. 336-341, 1991.

Tett, P., A. Edwards and K. Jones. A model for the growth of shelf-sea phytoplankton in summer. Estuar. Coast. Shelf Sci. 23: 641-672, 1986.

Valiela, I.Marine ecological processes. ISBN 3-540-90929-X, Springer-Verlag, New York, 1984.

Wetzel, R.L., R.F. van Tine and P.A. Penhale. Light and Submerged Macrophyte Communities in Chesapeake Bay: A Scientific Summary. Report of the Chesapeak Bay Pro¬gramme, Virginia Institute of Marine Science, 1981.

Sundby Bjørn, Gobeil C., Silverberg N. The Phosphorus cycle in coastal marine sediments.Limnol. Oceanogr. 37 (6), pp. 1129-1145. 1992.

Williams, P.J. LEB. Aspects of dissolved organic material in sea water. In: J.P. Riley & G. Skirrow. Chemical Oceano-graphy. Academic Press, New York: 301-363, 1975.

Windolf J, Jeppesen E., Jensen J.P. Kristensen P.1996. Modelling of seasonal variation in nitrogen retention and in-lake concentration: A four-year mass balance study in 16 shallow Danish Lakes. Biogeochemistery 33, PP 25-44.1996.