

# DHI Eutrophication Model 1

## MIKE ECO Lab Template

### Scientific Description



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## 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.

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 especially the benthic vegetation.

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

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.

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.

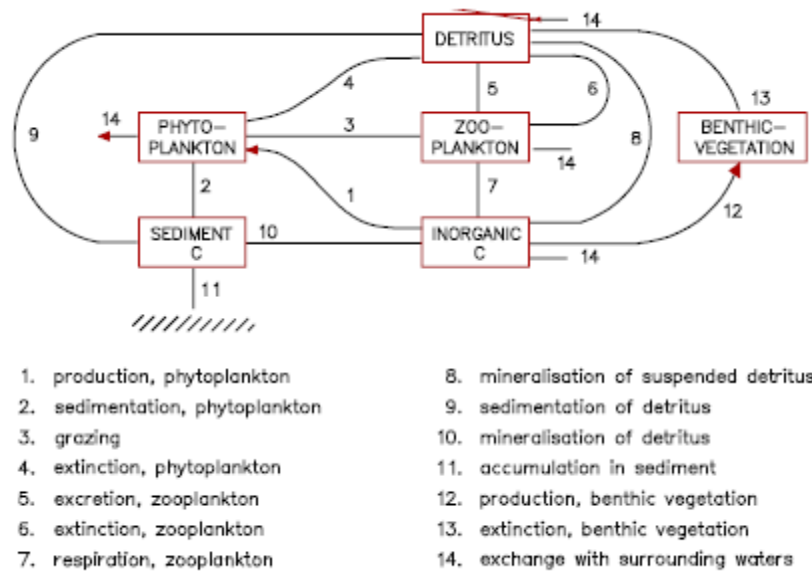


Figure 3.1 The simplified flow diagram of the fluxes of carbon, nitrogen and phosphorus in the eutrophication model

### 3.1 Phytoplankton Carbon (PC)

$$\frac{dPC}{dt} = \text{production} - \text{grazing} - \text{sedimentation} - \text{death} \quad (3.1)$$

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

Where

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

**NOTE:** Only relevant for MIKE 3.

## 2: Factors Affecting Primary Production

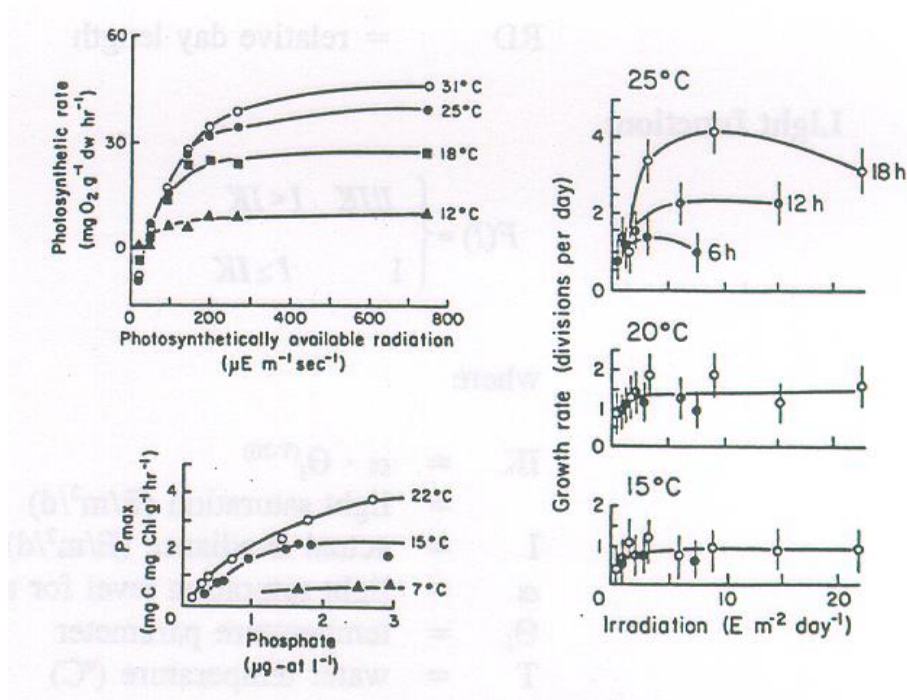


Figure 3.2 Interaction of temperature with light and nutrients. Top left: Photosynthetic rate of *Cladophora albida* under different levels of light intensity and temperatures in estuarine water. Adapted from Gordon et al. (1980). Right: Mean ( $\pm$  standard deviation) division rates during exponential 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.

$$PRPC = \mu \cdot F(I) \cdot F_I(T) \cdot F_I(N, P) \cdot FAC \cdot RD \quad (3.2)$$

Where

$\mu$	= maximum growth coefficient at 20°C (d <sup>-1</sup> )
FAC	= correction factor for dark reaction
RD	= relative day length

### 3.3 Light Function

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

Where

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

### 3.4 Temperature Function

$$F_I(T) = \theta_g^{(T-20)} \quad (3.4)$$

Where

$\Theta_g$	= temperature coefficient for growth
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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  $\mu_{Max}$  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.

### 3.5 Nutrient Dependence Function

Since phytoplankton growth depends essentially on the size of the internal nutrient pools, the nutrient-dependent growth limitation  $F_I(N,P)$  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).

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

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

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

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

$$DEPC = \mu_d \cdot F_2(N, P) \cdot PC \quad (3.6)$$

Where

$\mu_d$  = death rate under optimal nutrient conditions ( $d^{-1}$ )

$F_2(N, P)$  =  $\frac{1}{2} \cdot \{PN_{\max}/(PN/PC) + PP_{\max}/(PP/PC)\}$

$F_2(N, P)$  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  $PN_{\min}$  and  $PP_{\min}$  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):

$$SEPC = \mu_s \cdot F_2(N, P) \cdot PC \quad (3.7)$$

and at water depth  $h \geq 2$  m:

$$SEPC = U_s / h \bullet F_2(N, P) \bullet PC \quad (3.8)$$

Where

$\mu_s$	= sedimentation rate parameter ( $d^{-1}$ )
$U_s$	= sedimentation velocity (m/d)
$h$	= water depth (m)

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:

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

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)

$$GRPN = GRPC \bullet (PN/PC) \quad (3.10)$$

#### Sedimentation (SEPN)

$$SEPN = SEPC \bullet (PN/PC) \quad (3.11)$$

#### Death (DEPN)

$$DEPN = DEPC \bullet (PN/PC) \quad (3.12)$$

### 3.9 Phytoplankton Phosphorus (PP)

The mass balance for phytoplankton phosphorus reads:

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

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 (UPPP)

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

#### Grazing (GRPP):

$$GRPP = GRPC \bullet (PP/PC) \quad (3.14)$$

#### Sedimentation (SEPP):

$$SEPP = SEPC \bullet (PP/PC) \quad (3.15)$$

#### Death:

$$DEPP = DEPC \bullet (PP/PC) \quad (3.16)$$

### 3.10 Chlorophyll-a (CH)

The mass balance for chlorophyll-a reads:

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

Where

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

**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 ( $E/m^2/d$ )<sup>-1</sup>

$F_3(N)$  =  $CH_{\max} \cdot \{(PN/PC - PN_{\min}) / (PN_{\max} - PN_{\min})\}$

$CH_{\max}$  = 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:

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

### Grazing (GRPC)

The grazing rate (GRPC) by zooplankton:

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

Where

$\mu_z$  = 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 asymptotic 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

$\theta_z$  = temperature coefficient for grazing rate

### Phytoplankton dependence function

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

Where

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

### Oxygen dependence function

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

Where

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

## Production (PRZC)

The production is coupled closely to the grazing of phytoplankton:

$$PRZC = V_C \bullet GRPC \quad (3.26)$$

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.

$$REZC = K_R \bullet GRPC \quad (3.27)$$

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:

$$DEZC = K_{d1} \bullet ZC + K_{d2} \bullet ZC^2 \quad (3.28)$$

Where

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

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

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:

$$EKZC = GRPC - PRZC - REZC \quad (3.29)$$

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:

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

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 ( $h < 2m$ ):

$$SEDC = \mu_d \bullet DC \quad (3.31)$$

and at water depth  $h > 2m$ :

$$SEDC = U_d / h \bullet DC \quad (3.32)$$

Where

$\mu_d$  = sedimentation parameter for detritus at low

water depth ( $d^{-1}$ )

$U_d$  = sedimentation rate parameter (velocity) for detritus (m/d)

#### 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.

$$REDC = \mu_m \cdot F_3(T) \cdot F_1(DO) \cdot DC \quad (3.33)$$

Where

$\mu_m$	= maximum mineralisation rate at 20°C (d <sup>-1</sup> )
$F_3(T)$	= $\Theta_D^{(T-20)}$
$\Theta_D$	= 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:

$$\frac{dDN}{dt} = \text{generation} - \text{sedimentation} - \text{mineralization} \quad (3.34)$$

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

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 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:

$$EKZN = VZN \cdot EKZC \quad (3.35)$$

$$DEZN = VZN \cdot DEZC$$

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:

$$\frac{dDP}{dt} = \text{generation} - \text{sedimentation} - \text{mineralization} \quad (3.39)$$

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

Where

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

**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).

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

$$= REDN + REZN + RESN + VM \cdot DEPN - UNPN - UNBN$$

**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:

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

Where

$K_{SN}$	= proportionality factor at 20°C
$F_5(T)$	= $\Theta_M^{(T-20)}$
$F_2(DO)$	= $DO/(DO+MDO)$
$\Theta_M$	= 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:

$$As \ DO < MDO \quad (3.43)$$

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

Where

$N_{REL}$  = release rate under anoxic conditions (g/m<sup>2</sup>/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:

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

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:

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

Where

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

$$UNBN = PNB \cdot (PRBC/h) \quad (3.46)$$

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:

$$\frac{dIP}{dt} = \text{input from mineralization} - \text{uptake} \quad (3.47)$$

$$= REDP + REZP + RESP^* + VM \cdot DEPP - UPPP - UPBP$$

**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:

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

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:

$$RESP = P_{REL} / h \quad (3.49)$$

Where

$P_{REL}$  = constant release rate (g/m<sup>2</sup>/d)

#### Uptake

Uptake by phytoplankton is described similarly to the nitrogen uptake.

Under non-limiting conditions:



$$UPPP = \min \left[ \begin{array}{l} V_{kp} \cdot \frac{IP}{IP + KPP} \cdot PC \\ PRPC \cdot PP_{\max} \end{array} \right] \quad (3.50)$$

and under limiting conditions:

$$UPPP = \min \left[ \begin{array}{l} \max \left[ \begin{array}{l} V_{kp} \cdot \frac{IP}{IP + KPP} \cdot PC \\ Mineralization + external supply \end{array} \right] \\ PRPC \cdot PP_{\max} \end{array} \right] \quad (3.51)$$

Where

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

The uptake by benthic vegetation:

$$UPBP = PPB \cdot (PRBC/h) \quad (3.52)$$

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:

$$\begin{aligned} \frac{dDO}{dt} &= production - consumption + reaeration \\ &= ODPC + ODBC - ODZC - ODDC - ODSC - \\ &\quad Vm \cdot Vo \cdot DEPC + REAR \end{aligned} \quad (3.53)$$

## 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

$$\begin{aligned} ODPC &= V_o \bullet PRPC \\ ODBC &= V_o \bullet (PRBC/h) \end{aligned} \quad (3.54)$$

Where

$V_o$  = oxygen to carbon ratio at production ( $\text{gO}_2/\text{gC}$ )

## 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.

$$\begin{aligned} ODDC &= V_o \bullet REDC \\ ODZC &= V_o \bullet REZC \end{aligned} \quad (3.55)$$

Mineralisation of dead phytoplankton:

$$V_o \bullet V_m \bullet DEPC \quad (3.56)$$

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  
 $F_5(T)$  =  $\Theta_M^{(T-20)}$   
 $\Theta_M$  = temperature coefficient for mineralisation  
 $F_2(DO)$  =  $DO/(DO+MDO)$

The oxygen consumption is then found from:

$$ODSC = V_o \bullet RESC \quad (3.58)$$

## Reaeration

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

$$REAR = K_{RA} \bullet (C_s - DO) \quad (3.59)$$

Where

$K_{RA}$  = reaeration rate ( $\text{d}^{-1}$ )  
 $C_s$  = oxygen saturation concentration ( $\text{g}/\text{m}^3$ )  
 $C_s = 14.652 - 0.0841 \cdot S + T \cdot \{0.00256 \cdot S - 0.41022 + T \cdot (0.007991 - 0.0000374 \cdot S - 0.000077774 \cdot T)\}$

$T$  = water temperature (°C)  
 $S$  = 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:

$$\frac{dBC}{dt} = \text{production} - \text{loss} = PRBC - SLBC \quad (3.60)$$

### Production (PRBC)

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

Where

$\mu_B$  = net specific growth rate at 20°C

$RD$  = relative day length

$F_6(T)$  =  $\Theta_B^{(T-20)}$

$\Theta_B$  = temperature coefficient for benthic vegetation growth

$F_2(I) = \begin{cases} I_B / I_{KB}, & I_B < I_{KB} \\ 1, & I_B \geq I_{KB} \end{cases}$

$I_B$  = light intensity at bottom (E/m<sup>2</sup>/d)

$I_{KB}$  = light saturation intensity for the benthic vegetation (E/m<sup>2</sup>/d)

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

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

$KBN$  = Half saturation constant for the nitrogen limitation function (g/m<sup>3</sup>)

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

$KBP$  = half saturation constant for the phosphorus limitation function (g/m<sup>3</sup>)

## Loss/sloughing (SLBC)

$$SLBC = \mu_s \bullet F_7(T) \bullet (BC - BABC) \quad (3.62)$$

Where

$\mu_s$

= sloughing or loss rate at 20°C (d<sup>-1</sup>)

$F_7(T)$

=  $\Theta_s^{(T-20)}$

$\Theta_s$

= temperature coefficient for loss

$BABC$

= minimum area based biomass of benthic vegetation (g/m<sup>2</sup>)

## 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.



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