MIKE 1D Biological Processes

MIKE ECO Lab template

Scientific Documentation

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1   Introduction

This documentation describes a Biological Processes model (BP) implemented as a MIKE ECO Lab template for MIKE 1D. The main purpose of the template is to simulate the reaction processes in multi-compound systems. The BP module solves the system of differential equations describing physical and biological interactions involved in the survival of bacteria and oxygen conditions in sewers.

Organic matter is modelled either on the basis of BOD or COD input (which is optional for the user) and a global converting factor between BOD and COD. The BOD/COD - DO relations are described as aerobic processes only, and BOD/COD degradation is omitted in the model when simulating anaerobic conditions.

The processes and concentrations of the modelled components are influenced by modelled temperature, flow velocities, sedimentation and re-suspension rates. Therefore, the MIKE 1D BP template is integrated with both the AD module and the ST module. E.g., as a basis for the description of the water quality conditions, the AD module calculates the water temperature.

The following pollution components are possible to include in the module:

Dissolved oxygen	DO
Dissolved BOD/COD	BOD_{dis}
Suspended BOD/COD	BOD_{susp}
Faecale coli bacteria	$COLI_f$
Total coli bacteria	$COLI_t$
Streptocci bacteria	STREP
Dissolved ammonia	NH4
Dissolved phosphorus	PO4

When modelling BOD/COD as a PPC component, e.g. modelling of sediment-attached BOD based on the use of Pollutant Partitioning Coefficients, BOD_{susp} is divided into two fractions - fine and coarse. Both fractions are modelled as isolated suspended components using the same set of equations and parameters.

Dissolved ammonia and phosphorus are modelled as a conservative transport using the AD module only, e.g. no biological processes are included. NH4 and PO4 can be modelled as PPC's.

2 BOD/COD - DO Interactions

The interaction between organic matter and oxygen in sewers are based on following principle:

BOD/COD is degraded both in the water phase and in the biofilm attached to the sewer pipe using two different principles in the calculation of the BOD/COD reduction.

In the water phase, the heterotrophic biomass is generated by growth on readily biodegradable substrate and the process is normally described as:

$$BOD_{degra} = K_s \cdot \theta^{temp-20} \cdot (BOD)/(BOD + k_{m,BOD}) \cdot$$
$$(DO)/(DO + k_{m,DO}) \cdot B_x$$

(2.1)

where:

K_s	=	μ_{max}/Y_{max} (Max growth rate at 20°C / Max yield constant),
q	=	temperature constant,
$k_{m,BOD}$ =		half-saturation constant, BOD dissolved,
$k_{m,DO}$ =		half-saturation constant, DO,
B_x	=	biomass of active heterotrophic organisms.

The suspended heterotrophic organisms are responsible for the degradation of dissolved BOD/COD in the water phase. In order to use Equation **Error! Reference source not found.**, the biomass of the heterotrophic microorganisms B_x in the system must be known.

In MIKE 1D BP it is assumed that the heterotopic biomass constitutes a certain fixed fraction of the suspended BOD/COD (0.5-1.0). Consequently, the degradation of dissolved BOD/COD by this group of micro-organisms is modelled by using a fixed fraction of the suspended BOD/COD as the biomass and apply this estimated biomass to Equation **Error! Reference source not found.**.

For the biofilm, it is assumed that there exists a thick biofilm in the sewer pipe, and that oxygen is the limiting factor for the degradation of dissolved BOD/COD. This means that the diffusion rate of DO from the water phase into the biofilm determines the degradation rate of dissolved BOD/COD in the biofilm attached to the sediment and the pipe

Hydrolysis of suspended BOD/COD converts the suspended material into dissolved substrate. This process can be modelled as a temperature-dependent 1st order reaction (Henze et al. 1986). Suspended BOD/COD is produced in sewers due to the growth of heterotrophic organisms. This process can be modelled by applying a yield constant to the degradation rate for dissolved BOD/COD in the water phase. The model is shown is Conceptual diagram of the BOD/COD-DO model. Process A is de.
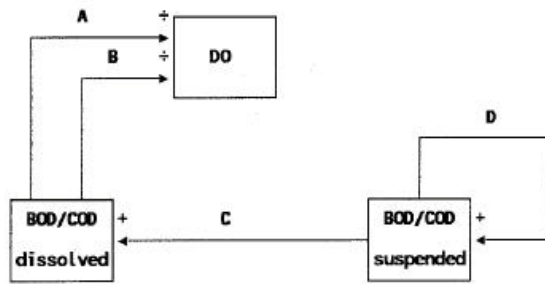
Figure 2.1   Conceptual diagram of the BOD/COD-DO model. Process A is de-gradation in biofilm, process B is degradation in water phase, process C is hydrolysis and process D is growth of heterotrophics

3 Oxygen Processes

A number of processes affect the oxygen concentration:

3.1 Re-aeration

Re-aeration is modelled in pipes only if they are not full flowing. The re-aeration equation is based on the difference between the actual and the saturation concentration of DO coupled to the hydraulic conditions /6/.

$$REAR = 24 * K2 * \Theta^{temp-20} * (C_s - DO) \tag{3.1}$$

$$K2 = \left(k1 * \left(1 + k2 * \frac{u^2}{g * d_m} \right) * (s * |u|)^{k3} * d_m^{-1} \right)$$

where:

$K2$	= re-aeration rate (m/h)
$k1, k2, k3$	= re-aeration parameters,
θ	= temperature coefficient,
u	= flow velocity (m/s),
g	= gravitation (m/s^2),
dm	= hydraulic mean depth (m),
Cs	= oxygen saturation concentration (g DO/m^3).

The oxygen saturation concentration C_s is temperature-dependent and is calculated by means of a standard equation:

$$C_s = 14.652 + T \cdot (-0.41022 + T \cdot (0.007991 - 0.000077774 \cdot T)) \tag{3.2}$$

where T is the water temperature (°C).

3.2 Degradation of BOD$_{dis}$ in Biofilm

The degradation of dissolved BOD/COD in biofilm is described as a standard ½-order reaction combined with a temperature-dependent oxygen diffusion and removal:

$$BOD_{degra, biofilm} = \theta^{temp-20} \cdot \sqrt{2D} \cdot k_{of} \cdot DO^{½} \cdot A_{biofilm} \big/ V \tag{3.3}$$

where:

θ	= temperature coefficient,
D	= diffusion coefficient of oxygen in water at 20°C (m^2/s),
k_{of}	= removal of oxygen in biofilm at 20°C (g DO/m^3·s),
$A_{biofilm}$	= area in pipe covered with biofilm (=water) (m^2),
V	= water volume (m^3).

The value of D is 20.0 (Jensen 1983, Gujer&Boller 1990) and k_{of} has been measured to 3.0 (Andreasen 1979, Arvin&Harremoës 1990).

Notice: Degradation of BOD_{dis} in biofilm is activated only if oxygen consumption in biofilm is modelled!

3.3 Degradation of BOD$_{dis}$ in Suspension

The degradation of dissolved BOD/COD carried out by suspended heterotrophics is described as:

$$BOD_{degra,\,susp} = K_s \cdot \Theta^{temp-20} \cdot BOD/(BOD + k_{m,\,BOD})$$
$$\cdot\, DO/(DO + k_{m,\,DO}) \cdot k_b \cdot BOD_{susp} \qquad (3.4)$$

where:

Ks	= μ_{max}/Y_{max} (day^{-1}) (Max growth rate at 20°C / Max yield constant),
θ	= temperature coefficient,
km,BOD	= half-saturation constant, BOD dissolved (g/m^3),
km,DO	= half-saturation constant, DO (g/m^3),
kb	= fraction of active heterotrophic organism in BOD$_{susp}$.

According to literature, μ_{max} varies from 3.0 to 13.2 day^{-1} and $Ymax$ varies from 0.6 to 0.7 kg VSS/kg BOD (Henze et al .1986). The values for Km,BOD and km,DO are by default set to 8 g BOD/m^3 and 2 g DO/m^3 , respectively (Henze et al .1986, Arvin & Harremoës 1990). kb varies from 0.5 to 1.0.

3.4 Hydrolysis of BOD$_{susp}$

Hydrolysis of suspended matter is described as a temperature-dependent 1st order reaction:

$$BOD_{hydro} = \Theta^{temp-20} \cdot k_{hl} \cdot BOD_{susp} \qquad (3.5)$$

where:

Θ	= temperature coefficient,
k_{hl}	= 1st order decay constant at 20°C (day^{-1}).

The value of k_{hl} is in the range of 0.05 - 0.10 day^{-1}.

3.5 Growth of Heterotrophics (BOD$_{susp}$)

The growth of heterotrophics is dependent of the BOD degradation in the water phase, and the equation reads:

$$BOD_{growth} = Y_{max} \cdot BOD_{degra,\,susp} \qquad (3.6)$$

3.6 Eroded Sediment Oxygen Demand

When modelling ST and BP simultaneously, eroded sediment will cause an immediate oxygen consumption. The oxygen decrease is depending of the amount of sediment eroded and its oxygen demand. The eroded sediment oxygen demand is described as:

$$SED_{oxdemand} = k_{sed} \cdot SED_{eroded} \cdot 1/(V \cdot dt) \qquad (3.7)$$

where:

ksed	= oxygen demand of sediment (g DO/ m^3 sediment),
SEDeroded	= amount of eroded sediment in timestep (m^3 sediment),
V	= water volumen (m^3),
dt	= timestep (days).

Notice: Eroded sediment oxygen demand is activated only when ST and BP are modelled simultaneously.

3.7   Oxygen Balance (DO)

The differential equation describing the effects of these processes on the dissolved oxygen concentration reads:

$$dDO/dt = REAR - BOD_{degra, biofilm} - BOD_{degra, susp} - SED_{oxdemand}$$ (3.8)

3.8   Dissolved BOD/COD Balance (BOD$_{dis}$)

The balance for BOD$_{dis}$ is:

$$dBOD_{dis}/dt = BOD_{hydro} - BOD_{degra, biofilm} - BOD_{degra, susp}$$ (3.9)

3.9   Suspended BOD/COD Balance (BOD$_{susp}$)

The differential equation for BOD$_{susp}$ reads:

$$dBOD_{susp}/dt = BOD_{growth} - BOD_{hydro}$$ (3.10)

4 Decay of Bacteria

Most pathogenic microorganisms are usually unable to multiply or survive for extensive periods in the aquatic environment. Eschericia coli (E. coli) is one of the dominant species in faeces from human and warm-blooded animals. The organism itself is normally considered non-pathogenic, but is very often used as indicator for faecal pollution and hence a potential for the presence of real pathogenic microorganisms.

In the MIKE 1D BP template, two methodologically defined groups of coliforms are distinguished: "Total coliform" and " Faecal coliform". The concept "Total coliform" may include a wide range of bacterial genera of which many are not specific of faecal contamination. Further more a third group of bacteria is included in the model - Streptocci bacteria.

The three groups of bacteria are modelled in the water phase with a temperature-dependent 1st order decay rate.

4.1 Decay Rate for Faecal Coliform (COLI$_{f,decay}$)

$$COLI_{f,\,decay} = \Theta^{temp-20} \cdot k_f \cdot COLI_f \tag{4.1}$$

where:

θ = temperature coefficient,
kf = 1st order decay constant at 20°C (day^{-1}).

The value of k_f is in the range of 0.6 - 0.8 day^{-1}.

4.2 Decay Rate for Total Coliform (COLI$_{t,decay}$)

$$COLI_{t,\,decay} = \Theta^{temp-20} \cdot k_t \cdot COLI_t \tag{4.2}$$

where:

θ = temperature coefficient,
kt = 1st order decay constant at 20°C (day^{-1}).

The value of kt is in the range of 0.7 - 0.9 day^{-1}.

4.3 Decay Rate for Streptoccoci (STREP$_{decay}$):

$$STREP_{decay} = \Theta^{temp-20} \cdot k_s \cdot STREP \tag{4.3}$$

where:

θ = temperature coefficient,
ks = 1st order decay constant at 20°C (day^{-1}).

The value of ks is in the range of 0.5 - 1.0 day^{-1}.

5 Pollutant Partitioning Concept (PPC)

The behaviour of sediments and sediment-attached pollutants is modelled in MIKE 1D by coupling the BP and the ST modules. This is achieved by attaching pollutants to two sediment fractions in terms of mass of pollutants per volume of sediment. The concept for modelling sediment-attached pollutants has been derived by Crabtree et al. (1993).

MIKE 1D operates with three sediment types and two fractions: surface sediments, pipe sediments, and foul flow sediments, a fine and a coarse fraction.

Surface sediments and pipe sediments are considered to consist of two fractions, a coarse mineral fraction comprised of particles > 0.5 mm (D50 = 1 mm) and a fine mineral fraction comprised of particles < 0.5 (D50 = 0.1 mm). Both the fine and the coarse mineral fractions are assumed to have the same density which is 2650 kg/m^3.

Foul flow sediments are assumed to consist only of a fine sediment fraction which is primarily organic. The density of this fraction is approximately 1800 kg/m^3.

In MIKE 1D, pollutants are modelled both as dissolved and sediment-attached. The modelling of sediment attached pollutants is based on the Pollutant Partitioning Coefficients (PPCs) to associate pollutant concentrations to the two sediment fractions. The PPC concept assumes that pollutants in sediments do not accumulate under dry weather flows and that pollutants are only released when a sediment deposit is eroded. Any interactions between deposits and the flowing liquid are not considered.

The PPCs are used to relate sample results for real sediments to sediment fraction parameters for the model. The PPCs for each pollutant (BOD, COD and NH4) describe the distribution of pollutants in a volume of in situ sediment based on an estimate of the total pollution load *TP* for each sediment type.

The total pollutant load *TP* is expressed in units of mass of pollutants per litre of sediment with a specified bulk density. *TP* is partitioned into the following:

$$TP = DL + FL + CL$$

(5.1)

where:

DL	= dissolved load associated with interstitial liquid,
FL	= fine fraction load associated with particles < 0.5 mm,
CL	= coarse fraction load associated with particles > 0.5 mm.

DL, FL and *CL* (the PPCs) are expressed as a percentage of *TP*.

When sediments are eroded the PPCs are used to add the load of pollutants released to the flow in the dissolved *DL* phase, the fine fractions *FL* and the coarse fractions *CL*. No further partitioning occurs under the subsequent transport, but the specified decay rates will be applied. If sediment deposition occurs, the bed sediment pollutant load (*TP*) and the PPCs as originally specified for the system are resumed.

Foul flow sediments are partitioned into dissolved load and a fine load already as a boundary condition. When deposition and erosion of possibly deposited foul flow sediments occur, the PPCs values for the pipe sediments are used (i.e. only the *DL* and the *FL*).

Use of the PPC concept requires that the BP module runs in parallel with the ST morphological model.

The mass at a specific site in the system is calculated from the initial sediment volumes at the bed and the PPC values specified according to:

$$
\begin{aligned}
Mass_{init,j} &= TP \cdot BedSedimentVolume_{init,j} \\
Dissolved\ Mass_{init,j} &= Mass_{init,j} \cdot DL \\
Fine\ Fraction\ Mass_{init,j} &= Mass_{init,j} \cdot FL \\
Coarse\ Fraction\ Mass_{init,j} &= Mass_{init,j} \cdot CL
\end{aligned}
$$

(5.2)

The transport of the sediment-attached pollutants is directly coupled to the sediment transport computations. Hence pollutant concentrations are evaluated from the amount of sediment in suspension.

When erosion and deposition occur, and fine sediment-attached pollutants are considered, the concentration in the water phase at specific location in the system is calculated from Equation
:

$$
C_j = \frac{\frac{d\ Bedvolume}{dt} \cdot porosity \cdot FL + C_j \cdot V_j}{V_j}
$$

(5.3)

where V_j is volume of the water body.

When pollutants attached to coarse sediments are calculated, Equation is used:

$$
C_j = \frac{\frac{d\ Bedvolume}{dt} \cdot porosity \cdot CL + C_j \cdot V_j}{V_j}
$$

(5.4)

When erosion occurs, the interstitial liquid which is eroded is added to the corresponding pollutant component in the water phase. This is solved by including the eroded amount of dissolved pollutant (interstitial liquid) as a source term in the general Advection-Dispersion equation.

The *TP, DL, FL* and *CL* values are fixed in time and space. The amount of pollutant associated with the bed sediment is only dependent on the sediment transported in the system.

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