WQMCAL

Description of the CAL programme on Water Quality Modelling
Version 2
Basic river and lake water quality models
(with an outlook to "ecohydrological" applications)

Final report

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This written material is the "hard copy" of the text and equations of a Computer Aided Learning (CAL) programme). Most of the text therefore appears separately from the equations and this may make the reading through this "hard copy" a little cumbersome. On the screen, however, the presentation is better harmonised, as the author hopes. It is also hoped that lucidity and understanding will be even more enhanced by the graphs of the actual model runs, that the user can control

The author also wishes to emphasise that the software and the models are not intended for use in practical work (design, water pollution control planning, environmental impact assessment, etc) and serve solely for teaching purposes. The author therefore, also wishes to state that he does not assume any responsibility for failures, faults or damages caused by such non-intended use of the software.

This is a computer aided learning software (CAL) which has been prepared by

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for UNESCO in the framework of the IHP-V projects ("teaching" project 8.1 and “ecohydrology” projects 2.3 and 2.4), to aid university teachers and students in teaching respectively, and learning the basis of river and lake water quality modelling.

The authors wish to express herewith their gratitude towards UNESCO Venice Office, Regional Office for Science & Technology for Europe for financially supporting the development of this recent version of the software. They also wish to thank the support of the International Hydrological Programme of UNESCO for the publication of this document and the related software on CD-ROM.

The authors wish to thank herewith the support of their home institution, the Water Resources Research Centre VITUKI, Budapest, Hungary, where the knowledge needed for the preparation of this software has been gained in the framework of actual water quality modelling and other environmental and hydrological projects during many decades. Experiences gained by the first author during some 30 years of teaching subjects related to the "Environmental Hydrology" in various Hungarian and foreign universities and international courses have also been utilized to a great extent.

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Description of the CAL programme on Water Quality Modelling
Basic river and lake water quality models

Foreword

This programme is the second extended version of the former computer aided learning software (WQMCAL version 1.1, UNESCO series Technical Documents in Hydrology NO. 13, SC97/WS/80) which has been prepared by the same authors for UNESCO in the framework of the IHP-IV Project on the preparation of didactic materials in hydrology (CAL), to aid university teachers and students in teaching respectively, and learning the basis of river water quality modelling.
This present CAL version, which includes lake eutrophication models (with an outlook to "ecohydrological" applications) was made in such a way as to fit into the frames of UNESCO/IHP's "Ecohydrological" programme (Projects 2.3 and 2.4 of IHP-V).

The basis, or rather basics, of river and lake water quality modelling means for the purpose of this programme and software:

1. General theoretical background (Basic theory),
2. BOD-DO models; -the traditional "oxygen sag" curve and two more sophisticated versions
3. Dispersion-advection models: -a one dimensional pollutant-spill model version and a 2D transversal mixing model.
4. Lake (eutrophication) models: -spanning from simple experimental regression models to dynamic algae-phosphorus models, including a sub-model for input load calculation and a lake-water budget (regulation) model.

The authors wish to state that **no existing, commercially available river or lake water quality softwares have been utilized for writing this programme**. The authors have developed all model softwares presented below. This means, that the software is a genuine product, involving no copyright matters whatsoever and that all property rights of this material and software programme stay with the authors and UNESCO.

The authors also wish to emphasise that **the software and the models are not intended for use in practical work (design, water pollution control planning, environmental impact assessment, etc), neither in the present nor in any of the future forms, and serve solely for teaching purposes. Therefore the authors wish to state that they do not assume any responsibility for failures, faults or damages caused by such non-intended use of the softwares and the programme!! Moreover the authors will consider such use, when discovered, the violation of their respective rights as owners of design softwares that relay on the same or similar principles.**

This document and software is the second version of the earlier software by the same authors (Basic River Water Quality Models, WQMCAL version 1.1) expanded to deal also with the basics of lake water quality modelling, with special regard to plant nutrient budgets and eutrophication. This also means that all important features of version 1.1 are also included, although in an improved, modified way.

This CAL was made in such a way as to fit into the frames of UNESCO/IHP's "Ecohydrological" programme (Projects 2.3 and 2.4 of IHP-V). In the view of the author one of the basic tasks of ecohydrology is to trace the fate of pollutants and especially of plant nutrients through the water- (hydrological) and ecological systems. In doing so a major task is to describe, as quantitatively as possible, the input-response (nutrient input - trophic state response) relationships of lakes and standing water bodies. This means, with other words "eutrophication modelling", the basics of which is included in this software. Eutrophication models describing trophic state of standing waters in function of inflow, outflow, water level, water volume, with examples of analysing the likely outcome of management scenarios, will be the ecohydrological core of this CAL programme. In addition to this, a very simple catchment (watershed) model is also included in order to facilitate the calculation of input load (which drives the lake models) and the proportion of point-source and non-point source components of this load. This is also an important "ecohydrological" element of the software. Nevertheless, this watershed model is of the "wired-in" or fixed type, where the user cannot change thy hydrological and nutrient washoff parameters. The reason is, that in a later third stage of the software development the authors intend to include a relatively complex integrated catchment-modelling block, to add more flavours to the "ecohydrological" concept of this software.

It is to be noted that the ecohydrological objective will be fully met when this third part of the series is also made, since two of the main objectives of the ecohydrology programme of IHP are:

"i, To develop a methodological framework, through experimental research to describe and quantify flow paths of water, sediments, nutrients and pollutants through the surficial ecohydrological system of different temporal and spatial scales under different climatic and geographic conditions;

ii, To develop an integrated approach for managing the surficial eco-hydrological environment including the non-structural measures;"

and this actually means the description (integrated modelling) of the transport and transformation of pollutants (nutrients) in the catchment and stream network. That is a drainage basin modelling block of the CAL series should be also provided. This is the intended future third version of this software series.

Introduction

Water is life and thus the quality of water is an essential measure of the quality of life or rather the existence of life. Consequently water quality management is (or should be) one of the most important activities of mankind, so as to protect and save human life and the life of other living things, which latter is a precondition of human life as well.

The management of water quality, or the protection of the aquatic ecosystem in a broader sense, means the control of pollution. Water pollution originates from point and non-point (diffuse) sources (**Figure 1.)** and it is always due to human action (the author strongly believes that no such thing as "natural pollution" exists, as sometimes advocated by other people).

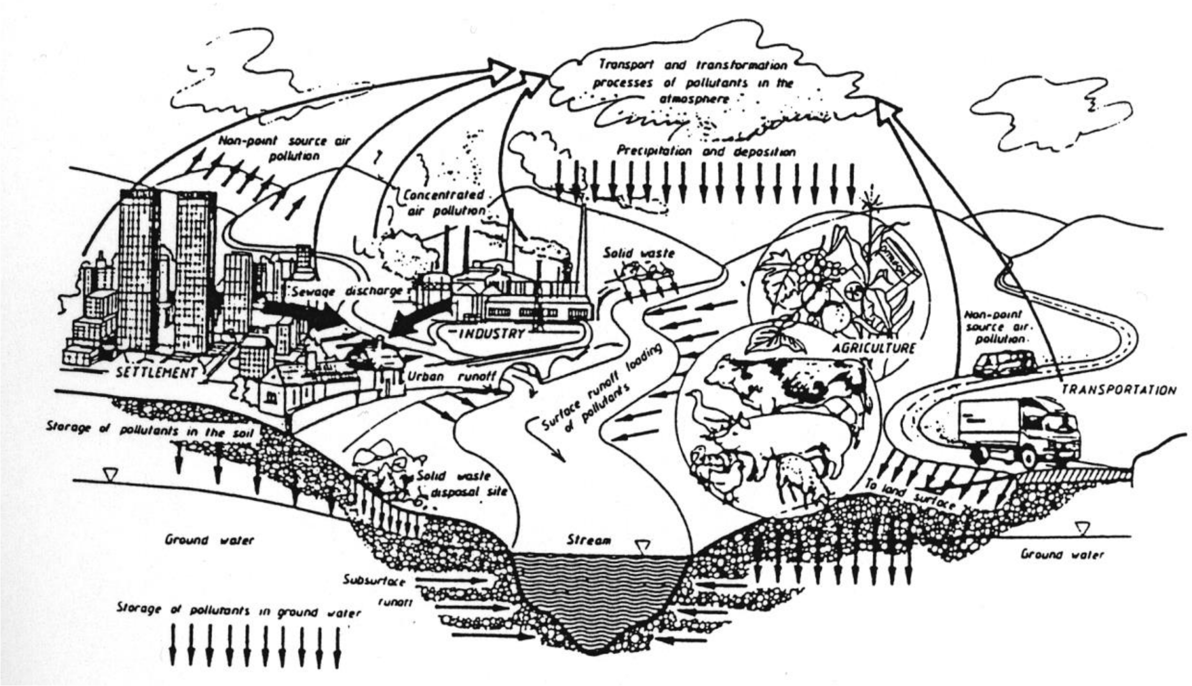


Figure 1.

The control of water pollution, the protection of aquatic systems, is thus the control of human activities that result in pollution. In addition to this man also should make efforts to enhance the capabilities of terrestrial and aquatic ecosystems in assimilating and reducing pollution. This is one of the basic notions of the novel "ecohydrological" concept of managing water quality (**Figure 2.**). This also means the understanding and enhancement of the evolutionarily established resistance and resilience of freshwater ecosystems to stress. This should be done, first of all, by understanding and quantifying the recursively interactive hydrological and ecological processes of aquatic ecosystems, in which the basics of lake eutrophication models can represent the essential very first step (from the environmental engineering point of view).

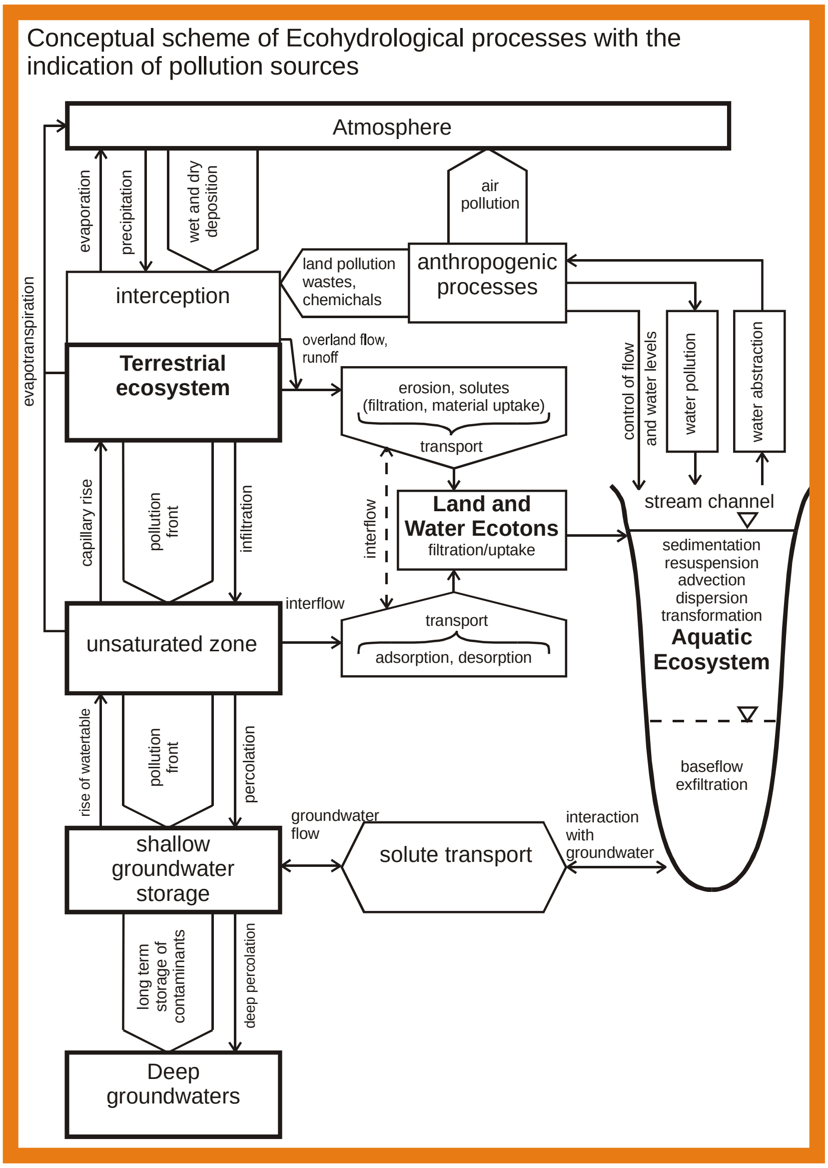


Figure 2.

One should also understand that the protection of the aquatic environment, and within this the control of pollution, is a profession and not an easy one. A profession like designing a house, a bridge, a road or just the making of a pair of shoes. This also means that no bridge designers (or hydraulic engineers) and no shoemakers and not even water chemists and aquatic ecologists can alone attempt the solving of water pollution control problems (although sometimes they think they can).

A crucial element in the series of complex activities of planning and implementing water pollution control actions is the quantitative determination and description of the cause-and-effect relationships between human activities and the state (the response) of the aquatic system, its quantity (the hydrological and hydraulic processes) and quality (the chemical and biological processes). These activities together can be termed the modelling of aquatic systems (hydrological, hydraulic and water quality modelling). These activities are aimed at calculating the joint effect (the impact) of natural and anthropogenic processes on the state of water systems (**Figure 3.**).

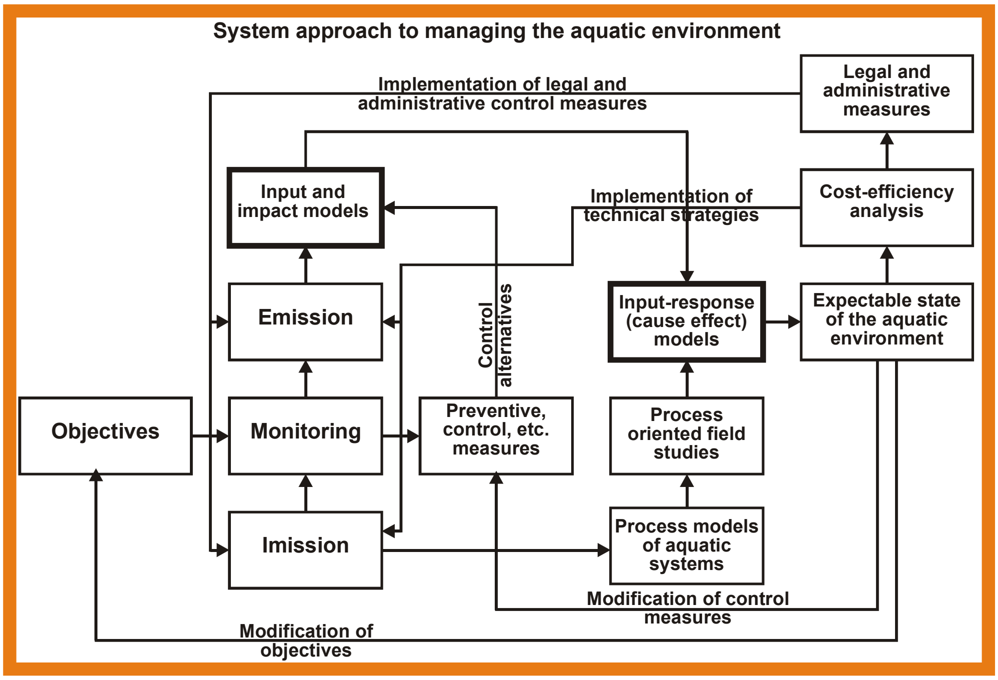


Figure 3.

The subject of this teaching aid is to introduce the basics of water quality modelling to the user. Although the qualitative and quantitative modelling of water systems (rivers, lakes and reservoirs) should be done simultaneously we will have to separate them for the purpose of this programme, always assuming that the quantitative state (the hydrological and hydraulic parameters) of the water system is known and sufficiently well described. With this we can focus on the quantitative, mathematical, description of processes that affect water quality (although the equations of flow modelling are also given in the Appendix, just for the shake of completeness, but they are not made use of in this programme).

Even within water quality modelling we are going to deal, in this second version of the software, with the most essential basics of river and lake modelling, with the hope that this CAL programme is only the second one in a series of similar softwares, which would deal with more details of river and lake modelling including the basics of modelling non-point source pollution, a crucial problem of ever growing importance of our era. This also means that the basic objectives of the "ecohydrological approach", the tracing of the fate of nutrients and other pollutants through the entire catchment and the aquatic ecosystem will only be achieved when the basics of integrated catchment modelling, the likely next part of the series, are also included in this software.

Basic theory of water quality models

General description

In logical order the teaching of this topic should have started with the description of both the quantitative and qualitative state of the water body. Nevertheless, the audience of such environmental engineering courses has, preferably, a strong background on hydrology and hydraulics, thus introduction to quantitative hydrodynamic modelling techniques is skipped here. The more so since even the basic flow modelling techniques would fill a separate curriculum in itself. Nevertheless the user can have an insight to the basic equations of fluid motion in Appendix I. The programme however, does not utilise these equations (see the respective equations in Appendix I.). Consequently in the following sections of this programme all hydraulic and hydrological river parameters (e.g. rate of flow, flow velocity, stream depth and width, etc) will be considered as given input data. In the lake modelling block, however, a simple hydrological catchment model and a lake water budget model are also included, to allow for the calculation of runoff and runoff-induced diffuse loads and for the regulation of the lake water level, both of which have an important bearing on the concentrations of substances in the lake-water.

Thus we will start with the introduction of the basic mass transport and transformation processes, relying on continuity and conservation of mass considerations.

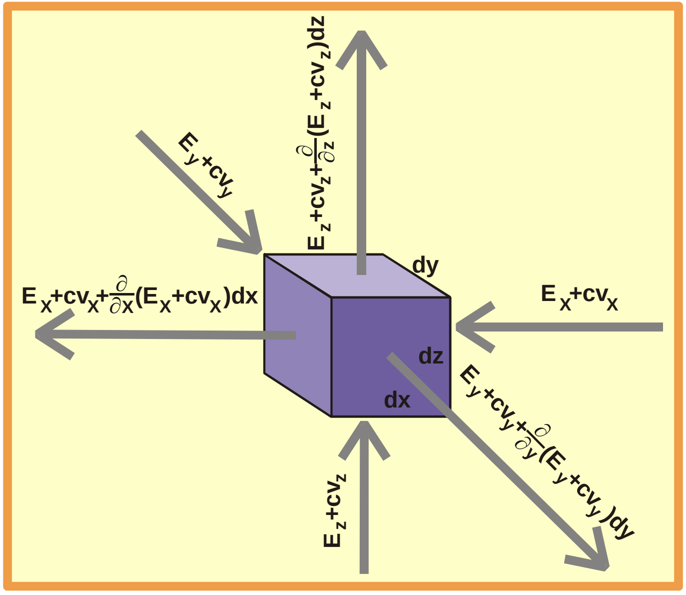


Figure 4.

Skipping again some of the details of deriving the basic equation (Jolánkai 1979, Jolánkai, 1992) let us consider an elementary water body, a cube of dx, dy and dz dimensions as shown in **Figure 4**. The quality of water within this elementary water body depends on the mass of a polluting substance present there. Water quality models then should describe the change of the mass of a polluting substance within this water body. The change of the mass of this substance is calculated as the difference between mass-flows (mass fluxes) entering and leaving this water body, considering also the effects of internal sources and sinks of the substance, if any. The mechanism of mass transfer into and out of this water body includes the following processes:

- Mass transported by the flow, by the v_x, v_z, and v_z components of the flow velocity vector. This process is termed the advective mass transfer. The transfer of mass, that is the mass flux (in mass per time, $M\ T^{-1}$, dimension) can be calculated in the direction x as $C*v_x*dy*dz$, where C is the concentration of the substance in the water (in mass per volume dimension, $M\ L^{-3}$), see also Equation 1.1.

- The other means of mass transfer is termed the dispersion or dispersive transport. Here one has to explain this term because there is usually considerable confusion with the terms diffusion and dispersion;-in short: dispersion is a term used for the combined effect of molecular diffusion and turbulent diffusion, and both of these latter processes is caused by pulsating motion, that is

  - by the "Brownian" thermally induced motion of the molecule (molecular diffusion), and
  - by the pulsation of the flow velocity around its mean value, caused by turbulence (called the turbulent diffusion).

The dispersive mass transfer (E_x, E_y, E_z) has the dimension of mass per time per area ($M\ T^{-1}\ L^{-2}$) and it is usually expressed by the law of Fick which states that the transport of the substance in a space direction is proportional to the gradient of the concentration of this substance in that direction the proportionality factor being the coefficient of dispersion, as shown in equation 1.1.

Mass transport terms for deriving the basic model

These equations describe the dispersive and advective transport of a polluting substance from the x direction into an elementary water body. The first term is actually the law of Fick which states that the diffusive (dispersive) transport of the substance in a space direction is proportional to the gradient of the concentration of this substance in that direction the proportionality factor being the coefficient of dispersion. The user finds more information on dispersion in the "general" part of this basic theory chapter and on the programme part on "dispersion river models". The second term is the advective transport term, which states that the specific (per unit area) transfer of mass to a spatial direction is the product of the concentration of a substance and the velocity of flow in that spatial direction. These are the terms used in writing the overall mass balance (that is Eq. 1.2) of an elementary water body as shown in Figure 4.

Eq. 1.1

$$E_x = D_x \frac{dC}{dx} \ ; \left[M\,L^{-2}\,T^{-1}\right]$$

$$ADV_x = C\,v_x \ ; \left[M\,L^{-2}\,T^{-1}\right]$$

Legend

E_x -	is the dispersive mass flux in the spatial direction x (in M L^{-2} T^{-1} dimension), with the assumption that the law of Fick holds for the joint effect of molecular diffusion and turbulent diffusion, that is for dispersion.
ADV_x-	is the advective mass flux in the spatial direction x (in M L^{-2} T^{-1} dimension)
C -	is the concentration, the mass of the quality constituent in a unit volume of water (mass per volume, M L^{-3});
D_x -	is the coefficient of dispersion in the direction of spatial co-ordinate x (in surface area per time, L^2T^{-1} units);
v_x -	is the component of the flow velocity in spatial directions x. (length per time, L T^{-1});

The mass-balance equation of an elementary water body

This equation was derived by writing a mass balance of in- and outflowing advective and dispersive mass fluxes of an elementary water body (see Figure 4. and see explanation of the terms at Eq. 1.1) and expressing the change of the mass of the substance with time. The terms for one spatial direction include the inflowing mass flux and the outflowing mass flux, which latter is the difference between inflowing flux and the change of the flux within the water body. For more details see the "General description of basic theory", the "mass transport terms for deriving the basic model" and the "General description of dispersion river models".

$$\text{Eq.1.2}$$

$$\begin{aligned}\frac{\partial C}{\partial t}\,dxdydz = &\left[(v_x C) + E_x\right]dydz + \left[(v_y C) + E_y\right]dxdz + \left[(V_z C) + E_z\right]dxdy \\ &-\left\{(v_x C) + E_x + \frac{\partial}{\partial x}\left[(v_x C) + E_x\right]dx\right\}dydz - \\ &-\left\{(v_y C)\,E_y + \frac{\partial}{\partial y}\left[(v_y C) + E_y\right]dy\right\}dxdy - \\ &-\left\{(v_z C) + E_z + \frac{\partial}{\partial z}\left[(v_z C) + E_z\right]dz\right\}dydx\end{aligned}$$

Legend

C-	is the concentration, the mass of the quality constituent in a unit volume of water (mass per volume, M L^{-3});
E_x,E_y,E_z -	are the dispersive mass fluxes in the spatial directions x, y, and z (in M L^{-2} T^{-1} dimension), with the assumption that the law of Fick holds for the joint effect of molecular diffusion and turbulent diffusion, that is for dispersion.
v_x,v_y,v_z -	are the components of the flow velocity in spatial directions x, y, and z, (length per time, L T^{-1});
dx,dy,dz -	are the side lengths of an elementary cube, an elementary water body, as shown in Figure 4.

The basic water quality model equation

This equation forms the basis of all water quality models. It was derived from Equations 1.1 and 1.2, by combining them, carrying out the operations, rearranging the result and dividing the equation by the elementary water volume dx*dy*dz and also by considering internal sources and sinks of the substance, as well as external sources. The basic equation describes the variation of the concentration of a quality constituent C with the time and space. Apart from the advective and dispersive transport terms that were discussed in relation to Equations 1.1 and 1.2 in this basic equation there is a general term, the internal source/sink term, or internal reaction term, that should be also discussed in somewhat more detail. They are also called the transformation processes with the meaning that the substance in concern is being transformed by various physical, chemical, biochemical and biological processes resulting in the change of the quantity of the substance in an elemental water body. This change is either a "loss" or sink term caused by processes such as settling, chemical-biochemical decomposition, uptake by living organisms or a "gain", a source term, such as scouring from the stream bed, product of chemical-biochemical reactions, biological growth, that is the "build-up " of the substance in concern on the expense of other substances present in the system. The actual form of these transformation processes will be presented in relation to concrete model equations such as the BOD-DO models, the models of the oxygen household and the plant nutrient (phosphorus) transformation processes of the lake models.

Eq. 1.3

$$\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} + v_y \frac{\partial C}{\partial y} + v_z \frac{\partial C}{\partial z} =$$

$$= \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z} \right) + S(x, y, z, t) \pm S_{internal}$$

Legend

C - is the concentration, the mass of the quality constituent in a unit volume of water (mass per volume, $M\,L^{-3}$);

D_x, D_y, D_z - are the coefficients of dispersion in the direction of spatial co-ordinates x, y, and z, (surface area per time, $L^2 T^{-1}$);

v_x, v_y, v_z - are the components of the flow velocity in spatial directions x, y, and z, (length per time, $L\,T^{-1}$);

t - is the time (T);

$S(x,y,z,t)$ - denotes external sources and sinks of the substance in concern that may vary in both time and space (mass per volume per time, $M\,L^{-3}\,T^{-1}$);

$S_{internal}$ - denotes the internal sources and sinks of the substance, ($M\,L^{-3}\,T^{-1}$);

Derivation of practical models from the basic model equation

The basic three-dimensional water quality model is seldom used in its original complex way (Eq. 1.3), mostly because three-dimensional problems occur rarely. For example river problems can be frequently reduced to one-dimensional (linear) or two-dimensional (longitudinal-transversal) problems, as it will be demonstrated in the programme. Another example is the "fully mixed reactor" type, or zero dimension, lake models of this programme, where no transport terms of the basic water quality models are included. Another reason of using simplified models is that transversal or vertical velocity measurement data are seldom available.

The internal source-sink terms, that were only denoted in Eq. 1.3 should be specified for each problem explicitly and they vary with the components considered.

Here it will be briefly demonstrated how can one derive the simple (river and lake) model versions of Eq.1.3, which can be used in the practice. In order to arrive to some of the simple water quality models presented below, we have to make first series of assumptions and approximations:

a, Neglect, for the time being, all terms accounting for dispersion. With this we assume that the system is fully mixed, which means that any external material input (load) to the river or lake will be instantaneously and fully mixed with the water. This is a very rough approximation and its consequences will be discussed in a subsequent sections dealing with dispersion and mixing problems. However, this approximation holds for long linear systems, e.g. in the case of smaller rivers with continuous steady input loads (waste water discharges).
It also holds, or must be assumed, for most of the lakes, since neither measurement data of lake currents nor the spatial distribution of water quality monitoring points, will (usually) allow the consideration of dispersion effects.

b, In the case of a river let us average flow and concentrations over the cross section. The only velocity component, which remains in the basic equation, is then v_x, the average longitudinal flow velocity.

c, In the case of a lake, a "standing" water body, neglect flow velocities and consider the water body fully mixed (the fully mixed reactor concept). In this case there remains only the internal source-sink term on the right hand side of the basic equation (Eq.1.3)

d, Consider one single water quality constituent with its concentration C and assume that it is subject to internal processes like decay, decomposition and settling. Assume that this process is proportional to the concentration of the constituent (the pollutant) and the coefficient of proportionality is K, the decay (decomposition, settling, etc.) rate coefficient. (Assumption of “first order” reaction kinetics)

When considering a river of steady state conditions (with flow of the river and input material loads into the river not varying in time) then we have arrived at the practically identical river and lake models of the form given in equations Eq.1.4 and Eq. 1.5. Note, that with these assumptions t=x/v, the time of travel, for the river, this making the two equations identical.

The most simple water quality models

The most simple river model

$$v_x \frac{dC}{dx} = -KC$$

The most simple lake model

$$\frac{dC}{dt} = -KC$$

where

C - is the concentration, the mass of the quality constituent in a unit volume of water (mass per volume, M L^{-3});
v_x - is the mean flow velocity of a river reach investigated (L T^{-1})
K - is the reaction rate coefficient for first order kinetics (T^{-1})
t- is the time of travel interpreted as t=x/v
x - the distance downstream (L)

Practically all water quality model equations, used in the everyday practice, can be derived in a similar way: by adding one or more dispersion and advection terms and by coupling the reaction processes, when more than one interacting water quality constituents (pollutants) are concerned.

This latter "coupling of reactions" is the key action of constructing water quality models, and these techniques will be discussed when actually naming the parameters (such as BOD-DO, and plant nutrients-algae growth). which the user will find in the menu. A general remark, however, can also be added here: The result of the decomposition (decay, consumption or settling) of one constituent can be another one. Examples are:

i, The result of decomposition of biodegradable organic matter, expressed in terms of BOD (see more details in the menu block "BOD-DO models"), is the increase of oxygen deficit D in the water;
ii, Settling of a water quality constituent (such as like phosphorus) from the water phase, will result in the increase of the same component in the bottom sediment;
iii, The nitrification (oxidation) process, will turn organic nitrogen, into ammonium-nitrogen-then to nitrite nitrogen- then to nitrate nitrogen;
iv, Growth of algae will turn dissolved inorganic plant nutrients (phosphorus and nitrogen) of the water phase to organic matter (of the algal body), a process called primary production.

The most frequently used approach to the description (simulation) of these single and coupled reaction processes is the "first order" reaction kinetics. The principle of first order reaction kinetics states that the decay/decomposition/uptake/growth etc of a pollutant is proportional to the concentration of the pollutant and the factor of proportionality is K, the rate coefficient (T^{-1}).

Another important aspect in the derivation of water quality models is how to consider the external sources (of pollution) in the models. There are two basic ways:

1., Either as a point source, an initial condition, specifying the effect of the source (in given point of the space and at a given point of time) with an initial C_0 value. This C_0 value is calculated, usually, with the "dilution equation". Example of this will be given in the various "running" model blocks. (see the "river models" for more detail)

The general dilution equation

This is one of the most important tools in water quality "modelling", a simple mass balance equation, which is used when the pollution source is considered as an initial condition.

Considering a river and an effluent discharge of steady state conditions (with flows and concentrations not varying in time) and assuming instantaneous full cross-sectional mixing of the sewage water with the river water the initial concentration C_o downstream of an effluent outfall can be calculated by the dilution equation (Eq. 1.4), which stems from the balance equation of in- and outflowing fluxes written for the section of the discharge point (e.g. background river mass flux plus pollutant discharge mass flux equals the combined mass flow downstream of the point of discharge). This equation is used very frequently in simple analytical water quality models for calculating the initial concentration of pollutants

Eq. 1.4

$$C_0 = \frac{C_s q_s + C_b Q_b}{q_s + Q_b}$$

where

C_b - background concentration of the polluting substance in concern in the river, (ML^{-3});

C_s - concentration of the pollutant in the waste water, (ML^{-3});

Q_b - discharge (rate of flow) of the river upstream of the effluent outfall, ($L^3 T^{-1}$);

q_s - the effluent discharge, ($L^3 T^{-1}$);

2., Or, as a distributed source, by adding a constant or time and/or space varying input to each "elementary" water body. The most simple example is the input to the "fully mixed reactor" type lake models, where the input load is divided by the volume of the lake.

After these considerations one can define the following most frequently used river and lake model versions.

Table I. Basic river and lake model forms and their uses

Description	General equation	Use	Remark
3-D models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}+v_y\frac{\partial C}{\partial y}+v_z\frac{\partial C}{\partial z}=$ $=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)+S(x,\ y,z,t)\pm S_{internal}$	Oceans, seas, large lakes	not used in this form
2-D, horizontal river or lake models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}+\left(v_y\frac{\partial C}{\partial y}\right)=$ $=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+S(x,\ y,t)\pm S_{internal}$	Wind induced circulation (in lakes), transversal mixing (in rivers)	not used in this form
2-D river model	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}=\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial C}{\partial y}\right)+S(x,\ y,t)\pm S_{internal}$	Mixing of pollutant plume	See the "transversal mixing" model
2-D vertical plane lake models	$\frac{\partial C}{\partial t}+v_y\frac{\partial C}{\partial y}+v_z\frac{\partial C}{\partial z}=$ $=\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)+S(y,z,t)\pm S_{internal}$	Wind induced currents in deep lakes (in a cross section)	not used in this software
1-D river models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+S(x,\ t)\pm S_{internal}$	Longitudinal dispersion (pollutant spill) model	See in menu block "Accidental pollution wave" model
Quasi 1-D river model	$v_x\frac{dC}{dx}=+S(x)\pm S_{internal}$	Steady state river models	See the "BOD-DO" river models
0-D lake models	$\frac{dC}{dt}=S(t)\pm S_{internal}$	"fully mixed reactor" type lake models	See the lake models

BOD-DO River Models

General Description of BOD-DO river models

BOD-DO river models deal with the oxygen household conditions of the river, by considering some of the main processes that affect dissolved oxygen (DO) concentrations of the water. These models are of basic importance since aquatic life, and thus the existence of the aquatic ecosystem, depend on the presence of dissolved oxygen in the water.

All river water quality models, and thus the BOD-DO models, can be derived from the general basic water quality model equation (Eq.1.3). For some details of this derivation procedure see the Chapter on **Basic Theory** on water quality modelling, and on the Chapter on the **Derivation of simple practical models from the basic model equation.**

The main process that affect (deplete) the oxygen content of water is the oxygen consumption of micro-organisms, living in the water, while they decompose biodegradable organic matter. This means that the presence of biodegradable organic matter is the one that mostly affect the fate of oxygen in the water. There are internal and external sources of such biodegradable organic matter. Internal sources include organic matter that stem from the decay (death) of living organisms, aquatic plants and animals (also termed "detritus", or dead organic matter). Among external sources anthropogenic ones are of major concern and this includes wastewater (sewage) discharges and runoff induced non-point source or diffuse loads of organic matter.

In the models biodegradable organic matter is taken into consideration by a parameter termed **"Biochemical oxygen demand, BOD**". BOD is defined as the quantity (mass) of oxygen consumed from a unit volume of water by microorganisms, while they decompose organic matter, during a specified period of time. Thus BOD_5 is the five-day biochemical oxygen demand, that is the amount of oxygen that was used up by microorganisms in a unit volume of water during five days "incubation" time in the respective laboratory experiment. Thus the unit of BOD is mass per volume (e.g. gO_2/m^3, which equals mg O_2/litre).

Another main process in the oxygen household of streams is **the process of reaeration**, the uptake of oxygen across the water surface due to the turbulent motion of water and to molecular diffusion. This process reduces the "**oxygen deficit"** (D) of water, which is defined as the difference between saturation oxygen content and the actual dissolved oxygen level.
These two counteracting processes are considered in the traditional BOD-DO model (Streeter and Phelps, 1925) in the mathematical form that you can see in the "graph window" of the Chapter "The traditional BOD-DO model", the "Oxygen-sag curve"

The traditional BOD-DO model, the "oxygen-sag curve"

General description of the traditional oxygen sag curve

In this model the decomposition of biodegradable organic matter is expressed as the "first order" decay of BOD (termed here L) in function of the time (where time is the time of travel t=x/v) by Eq 2.1 and 2.2 (see also the basic theory chapter).

The oxygen line, the oxygen sag curve, is written for the oxygen deficit D is such a way that oxygen consumed by micro-organisms adds to the oxygen deficit, while the process of aeration (or reaeration; the uptake of oxygen across the water surface due to turbulence and molecular diffusion) reduces this deficit (Equations 2.3 and 2.4).

In these equations the initial conditions, e.g. $L = L_0$, and $D=D_0$ at $x=0$ ($t=t_0$) should be calculated using the **"Dilution equation"** (Eq 1.4). The substitution of waste water and river parameter values is relatively straight forward in the case of calculating L_0 (Eq. 2.5), while for calculating D_0 first the initial oxygen concentration should be calculated (Eq. 2.6) and the result of this should be subtracted from the saturation DO concentration to achieve D_0 (Eq. 2.7).

The saturation dissolved oxygen concentration of the water is temperature dependent, and the respective values can be obtained either from tables published in the relevant literature or from experimental expressions. In this teaching aid we will use the latter method in the form of Equation 2.8 (Wang et. al, ref. Gromiec, 1983):

The oxygen sag curve (which the user can see in the "window" when in the respective menu item) has a critical point where the dissolved oxygen content of water is the lowest, that is when the oxygen deficit is the highest. The time of travel (or the corresponding downstream distance) can be expressed by finding the minimum of the sag curve. It is obtained in the form of Eq. 2.9 for $t_{crit.}$, Eq. 2.10 for x_{crit}, and Eq. 2.11 for D_{crit}. Thus the critical dissolved oxygen concentration is obtained as the difference between saturation oxygen concentration and the critical oxygen deficit (Eq. 2.12).

For the practical use of the above simple model equations one should find, estimate, the values of the two model parameters K_1 and K_2.

There are two basic ways of estimating values of the reaction rate parameters:

1. If one has in-stream measurement data of DO and BOD then one can **calibrate** the model, by fitting the calculated curves to the measured ones. This can be easily done for BOD (for K_1), expressing K_1 from Eq. 2.2; but the value of reaeration coefficient K_2 can be found only by trial-error model simulations (or by using a respective fitting algorithm, built in models of practical use;- not included in the model used for this teaching aid)

2. If you do not have access to measurement data then you can **estimate model parameters** using formulae and tables published in the relevant literature.

The value of the reaeration coefficient K_2 depends, eventually, on the hydraulic parameters of the stream and a large number of experimental formulae have been presented in the literature along with reviews of these literature equations (Gromiec, 1983, Jolánkai 1979, 1992). These expressions deviate from each other, sometimes substantially. For the purpose of this CAL programme we have developed a special equation on the basis of a number of literature published equations that give the value of K_2 in function of flow velocity v and stream depth H, by simply averaging the coefficient values of different authors (when they were relatively close to each other). The thus obtained formula is Equation 2.13.

For the estimation of the value of K_1 the Table of Fair (ref. Jolánkai, 1979) can be used, when knowing the value of K_2, can be used. This Table expresses the ratio $f= K_2/K_1$ in function of the verbally described hydraulic condition of the stream as shown in **Table 2.**

Table 2 **Ratio $f=K_2/K_1$ in function of the verbally described hydraulic condition of the stream**

Description of the water body	range of $f=K_2/K_1$
Small reservoir or lake	0.5 - 1.0
Slow sluggish stream, large lake	1.0 - 2.0
Large slow river	1.5 - 2.0
Large river of medium flow velocity	2.0 - 3.0
Fast-flowing stream	3.0 - 5.0
Rapids and water falls	5.0 - and above

Both the reaeration coefficient K_2 and especially the decomposition rate coefficient K_1 depend on the ambient (water) temperature. For this latter the most widely accepted formula is Eq. 2.14

One should note that reported literature values of K_1 and K_2 vary over wide ranges of which, for this teaching aid programme, we will consider the following domain:

K_1 - 0.1 - 1.7 day^{-1}
K_2 - 0.2 - 1.2 day^{-1}

For this software we have discretised this domain at 0.1 day^{-1} steps and the user can adjust the variation of the ratio $f=K_2/K_1$, seeing also the corresponding description of the domain of river flow conditions. From this table (not shown here, but included in the programme) one cannot adopt values of f lower than 0.5 or higher than 5.0.

The BOD decay model

The BOD decay model describes the decomposition of biodegradable organic matter (termed here L) in function of the time (which is the time of travel along the stream, t=x/v).
In Equation 2.2 the initial conditions, e.g. $L=L_0$ at $x = 0$ ($t=t_0$) are calculated by the "Dilution equation".
For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.1

$$\frac{dL}{dt} = -K_1 L$$

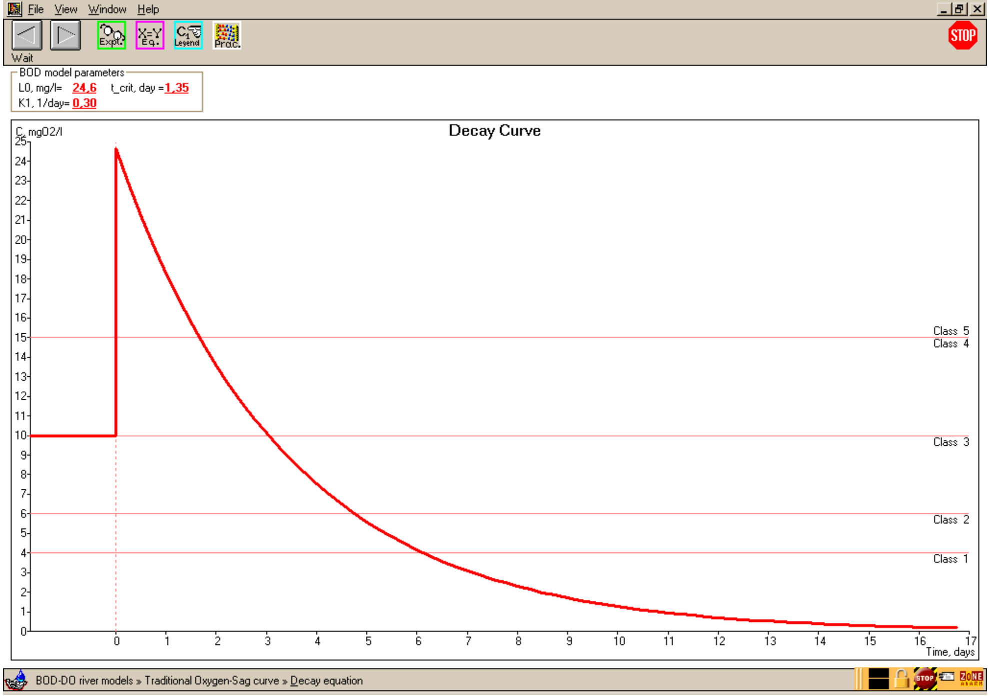
Eq. 2.2

$$L = L_0 e^{-K_1 t}$$

Legend

L-	BOD in the water (g O_2/m^3)
L_0-	initial BOD in the stream (below waste water discharge), see also Eq. 2.5
K_1-	is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})
t -	is the time, that is the time of travel in the river interpreted as t=x/v, where x is the distance downstream of the point of effluent discharge (T, given usually in days).

The BOD decay curve is shown in **Figure 5** (a screen outprint from the software).



BOD model parameters
L0, mg/l= 24,6 t_crit, day =1,35
K1, 1/day= 0,30

Figure 5.

The dissolved oxygen model

The traditional dissolved oxygen model describes the fate, the "sag", of the dissolved oxygen in the river as influenced by the decay of biodegradable organic matter and the reaeration process (across the water surface). For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.3

$$\frac{dD}{dt} = K_1 L - K_2 D$$

Legend

D - is the oxygen deficit of water (g $0_2/m^3$), see also equations 2.7 and 2.8.

L- BOD in the water (g O_2/m^3)

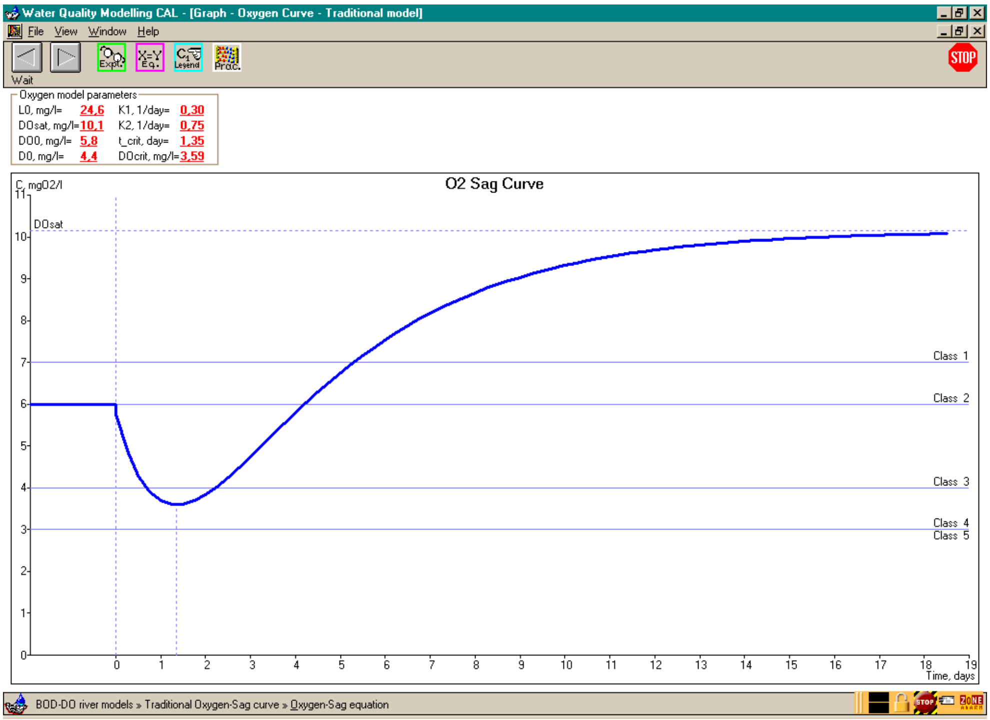
K_1- is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})

K_2 - is the reaeration rate coefficient (T^{-1})

t - is the time, that is the time of travel in the river interpreted as t=x/v, where x is the distance downstream of the point of effluent discharge

The "Oxygen Sag Curve" model

The traditional oxygen sag curve model describes the fate, the "sag", of the dissolved oxygen in the river as influenced by the decay of biodegradable organic matter and the reaeration process (across the water surface). For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve". The oxygen sag curve, a screen outprint of the software is shown in **Figure 6.**



Oxygen model parameters
L0, mg/l= 24,6
K1, 1/day= 0,30
DOsat, mg/l= 10,1
K2, 1/day= 0,75
DO0, mg/l= 5,8
t_crit, day= 1,35
D0, mg/l= 4,4
DOcrit, mg/l= 3,59

Figure 6.

Eq. 2.4

$$D = \frac{K_1 L_0}{K_2 - K_1}\left(e^{-K_1 t} - e^{-K_2 t}\right) + D_0 e^{-K_2 t}$$

Legend

D- is the oxygen deficit of water (g 0_2/m^3), see also equations 2.7 and 2.8.

D_0- is the initial oxygen deficit in the water (downstream of effluent outfall), see also equations 2.6 and 2.7

L_0- is the initial BOD concentration in the water (g O_2/m^3), (downstream of effluent discharge), see also Eq 2.5

K_1- is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})

K_2 - is the reaeration rate coefficient (T^{-1})

t - is the time, that is the time of travel in the river interpreted as t=x/v, where x is the distance downstream of the point of effluent discharge; and v - is the mean flow velocity of the river reach in concern. (L T^{-1})

The "dilution equation" for BOD

This dilution equation computes the initial concentration of BOD in the river downstream of a point source sewage discharge, with the assumption of instantaneous mixing. For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.5

$$L_0 = \frac{L_s q_s + L_b Q_b}{q + Q}$$

Legend

L_0- is the initial concentration of BOD in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l);

L_b- is the background concentration of BOD in the river, (ML^{-3}, e.g. mg O_2/l);

L_s- is the BOD content of the waste water, (ML^{-3});

Q - discharge (rate of flow) of the river upstream of the effluent outfall, (L^3 T^{-1});

q- the effluent discharge, (L^3 T^{-1});

The "dilution equation" for DO

This dilution equation computes the initial concentration of dissolved oxygen in the river downstream of a point source sewage discharge, with the assumption of instantaneous mixing. For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.6

$$DO_0 = \frac{DO_s q_s + DO_b Q}{Q + q}$$

Legend

DO_0- is the initial concentration of dissolved oxygen in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l);

DO_b- is the background concentration of dissolved oxygen in the river, (ML^{-3}, e.g. mg O_2/l);

DO_s- is the dissolved oxygen content of the waste water, (ML^{-3});

Q- discharge (rate of flow) of the river upstream of the effluent outfall, (L^3 T^{-1});

q- the effluent discharge, (L^3 T^{-1});

The initial oxygen deficit equation

This set of equations is used to calculate the initial oxygen deficit of the water downstream of a point source sewage discharge as compared to the saturation dissolved oxygen concentration, which latter is temperature dependent. For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.7

$$D_0 = DO_{sat} - DO_0 \text{ , } \quad [\text{mg}\, O_2/\text{litre}]$$

Eq. 2.8

$$DO_{sat} = 14.61996 - 0.4042\,T + 0.00842\,T^2 - 0.00009\,T^3$$

Legend

D_0- is the initial concentration of dissolved oxygen deficit in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l);

DO_0- is the initial concentration of dissolved oxygen in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l); see also Eq. 2.6

DO_{sat}- is the saturation oxygen concentration of water,

T- is the water temperature (^oC)

Critical values of the oxygen sag curve

This set of four equations is used to compute the lowest dissolved oxygen concentration (highest oxygen deficit) in the river water downstream of a single source of sewage water along with the corresponding time of travel and downstream distance. For more details see the "Basic theory", the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.9

$$t_{crit} = \frac{1}{K_2 - K_1} \ln \frac{K_2}{K_1}\left(1 - \frac{D_0\left(K_2 - K_1\right)}{L_0\, K_1}\right)$$

Eq. 2.10

$$x_{crit} = v\ t_{crit}$$

Eq. 2.11

$$D_{crit} = \frac{K_1}{K_2} L_0\, e^{-K_1 t_{crit}}$$

Eq.2.12

$$DO_{crit} = DO_{sat} - D_{crit}$$

Legend

t_{crit}- the critical time of travel (time during which the water particle arrives to the point of lowest DO concentration in the stream);

D_0- is the initial concentration of dissolved oxygen deficit in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l); see also equations 2.7 and 2.8

L_0- is the initial concentration of BOD in the river, downstream of the effluent discharge point (ML^{-3}, e.g. mg O_2/l); see also Equation 2.5;

K_1- is the rate coefficient of biochemical decomposition of organic matter, the BOD decay rate, (T^{-1}, usually day^{-1})

K_2 - is the reaeration rate coefficient, the rate at which oxygen enters the water from the atmosphere, (T^{-1})

x_{crit} - the critical distance downstream of the point of effluent discharge (the point of lowest DO concentration) (L);

v- is the average flow velocity of the river reach in concern ($L\ T^{-1}$);

D_{crit}- is the critical (highest) oxygen deficit in the water, along the river, (ML^{-3}, e.g. mg O_2/l)

DO_{crit}- is the critical (lowest) dissolved oxygen concentration of the water (ML^{-3}, e.g. mg O_2/l);

DO_{sat}- is the saturation oxygen content of water, see also equation 2.8.

Equation for estimating K_2

This equation is used for the estimation of the value of the reaeration rate coefficient K_2 in function of the flow velocity and flow depth. Note that this equation have been "generated" for the purpose of this programme and thus it differs from the many other formulas offered by the relevant literature. For more details see the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.13

$$K_2 = 2.148\, v^{0.878} H^{-1.48}$$

Legend

K_2 - is the reaeration rate coefficient, the rate at which oxygen enters the water from the atmosphere, (day^{-1})
v - is the average flow velocity in the river reach, (m/sec)
H - is the average depth of flow over the river reach, (m)

Temperature correction formula for K_1

This equation is used for the correction of the value of BOD decomposition rate coefficient K_1 in function of the water temperature. Note that this formula has been selected for this programme from among the many others offered by the relevant literature. Also note that in the computer programme there is a built in algorithm that guides the selection of the value of K_1, at 20 ^oC temperature in function of the type and size of the river and of the already calculated value of K_2. For more details see the, the "General description of BOD-DO river models" and the "General description of the traditional oxygen sag curve".

Eq. 2.14

$$K_{1(T)} = K_{1(20^oC)} 1.047^{(T-20)}$$

Legend

$K_{1(T)}$ - is the value of rate coefficient K_1 at water temperature T °C
$K_{1(20°C)}$- is the value of rate coefficient K_1 at water temperature T=20 °C

Expanded, modified, BOD-DO river models

General description of expanded models

The reader/user is kindly requested to get first acquainted with the "General introduction of BOD-DO" models and the "General introduction of the traditional oxygen sag equation".

In addition to the decay of organic matter and the process of reaeration, discussed under the above headings, there are many other processes in a stream which affect the fate (the sag) of the dissolved oxygen content. These processes are, without claiming completeness, as follows:

Physical processes:

- Effects of dispersion (mixing), spreading, mixing, diluting pollutants, thus reducing BOD (and increasing aeration, a process that is to be included in the reaeration rate coefficient K_2);
- Settling of particulate organic matter, that reduces in-stream BOD values;

Chemical, biological and biochemical processes:

- Effects of benthic deposits of organic matter (e.g. the diffuse source of BOD represented by the decay of organic matter that had settled out earlier onto the channel bottom);
- Sinks and sources of oxygen due to the respiration and photosynthesis of aquatic plants (macrophytes, phytoplankton (algae) and attached benthic algae;
- oxygen consumption by oxidising biochemical processes, such as nitrification.

Of the many modifications of the traditional oxygen sag curve we have selected two models for inclusion in this CAL programme. The criteria of selection was that the model should take many or most of the above processes into consideration (for the first model) and it should also consider longitudinally varying flow and with this non-point source external loads (for the second model). It is to be noted that we did not consider models that deal with dispersion and mixing, since such models will be separately discussed later on.

The first expanded BOD-DO model

General description of the 1st expanded BOD-DO model

This expanded BOD-DO model is the modification of the traditional oxygen sag curve model and therefore the user should get acquainted with the "General introduction of BOD-DO" models, the "General introduction of the traditional oxygen sag equation" and the "General introduction of the Expanded BOD-DO models".

The first expanded BOD-DO model, selected for this software, was developed by Camp (1963) and it involves the following processes in addition to the decay of organic matter (BOD decay) and reaeration:

- Sedimentation of biodegradable organic matter;
- Benthic oxygen demand (e.g. the diffuse source of BOD represented by the decay of organic matter that had settled out earlier onto the channel bottom);
- Internal oxygen source represented by the photosynthetic activity of aquatic plants. (In this case one should note that the term accounting for this process in the model is rather the balance between oxygen input via photosynthesis and oxygen consumption via the respiration of aquatic plants, since respiration is not represented by a separate term in this model).

It is also worthwhile to mention that due to the diurnal variation of light the variation of the photosynthetic oxygen source can be best represented by a periodical function of the time, as it is done in some other, more complex, models (not discussed here).

There are three new parameters in this model, the sedimentation rate constant K_3, the benthic BOD B, and the photosynthetic input of DO P. Estimation of these parameters is rather difficult in the absence of measurement data. (measurement is also rather complicated: the white-black bottle method is used for measuring the net input of oxygen by photosynthesis; a bell-shaped device set into the bottom sediment is used for measuring the benthic oxygen demand; and sedimentation of biodegradable organic matter is indicated by the change of the slope of a straight line (in logarithmic paper) showing the longitudinal variation of in-stream BOD measurement data;- the user is advised to consult the literature for more details of these techniques, when so required).

Nevertheless for the purpose of this programme we will set pre-defined ranges of these model parameter values for the calculation example, and for that only. It will, however, indicate the way how such models are used in the practice, when no field measurement data on the parameter values are available;- e.g. they are used for trying to explain unaccounted differences between measured and calculated in-stream data. That is when an observed BOD-DO profile can not be simulated with reasonable parameter values of K_1 and K_2 then parameters B, P, and K_3 can be used to account for unknown internal sources or sinks in a trial-error manner.

The first expanded BOD model

These equations (the differential equation and its solution) describe the decomposition of organic matter (BOD decay), its sedimentation and the benthic source of it. See also: "General introduction of BOD-DO" models, the "General introduction of the traditional oxygen sag equation" and the "General introduction of the Expanded BOD-DO models".

Eq. 3.1

$$\frac{dL}{dt} = -\left(K_1 + K_3\right)L + B$$

Eq. 3.2

$$L = \left[L_0 - \frac{B}{\left(K_1 + K_3\right)}\right]\exp\left[-\left(K_1 + K_3\right)t\right] + \frac{B}{K_1 + K_3}$$

Legend

L- is BOD in the water (M L^{-3}, g O_2/m^3)

L_0- is the initial BOD in the stream (downstream of the waste water discharge), see also Eq. 2.5

K_1 - is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})

K_3 - is the rate constant for BOD removal by sedimentation (T^{-1}, usually day^{-1});

B - is the benthic oxygen demand, the rate of BOD addition to overlying water from the bottom sediment (M T^{-1} L^{-3}, usually $gO_2/m^3/day$)

t - is the time of travel (t= x/v) expressed in days

The 1st expanded oxygen model

The model describes the variation of the dissolved oxygen deficit of the water with the time of travel in function of the processes of reaeration, decomposition/decay of organic matter and oxygen production by photosynthesis. For more details see also the following topics: "General introduction of BOD-DO" models, the "General introduction of the traditional oxygen sag equation" and the "General introduction of the Expanded BOD-DO models", as well as equations 3.1 and 3.2

Eq. 3.3

$$\frac{dD}{dt} = -K_2 D + K_1 L - P$$

Eq. 3.4

$$D = \frac{K_1}{K_2 - (K_1 + K_3)} \left[L_0 - \frac{B}{(K_1 + K_3)} \right] \left\{ \exp\left[-(K_1 + K_3)t\right] - \exp(-K_2 t) \right\} +$$

$$+ \frac{K_1}{K_2} \left[\frac{B}{(K_1 + K_3)} - \frac{P}{K_1} \right] \left[1 - \exp(-K_2 t)\right] + D_0 \exp(-K_2 t)$$

Legend

D- is the oxygen deficit of water (M L^{-3}, e.g. gO_2/m^3), see also equations 2.7 and 2.8,

D_0- is the initial oxygen deficit of water (g O_2/m^3), downstream of the effluent discharge, see also equations 2.6 and 2.7

L- is BOD in the water (M L^{-3}, g O_2/m^3)

L_0- is the initial BOD in the stream (downstream of the waste water discharge), see also Eq. 2.5

K_1 - is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})

K_2 - is the reaeration rate coefficient (T^{-1}, usually day^{-1})

K_3 - is the rate constant for BOD removal by sedimentation (T^{-1}, usually day^{-1});

B - is the benthic oxygen demand, the rate of BOD addition to overlying water from the bottom sediment (M T^{-1} L^{-3}, usually gO_2/m^3/day)

P - is the rate of oxygen addition to water by the photosynthetic activity of aquatic plants (M T^{-1} L^{-3}, usually gO_2/m^3/day);

t - is the time of travel (t= x/v) expressed in days

The second expanded BOD-DO model

General description of 2^{nd} expanded BOD-DO model

The second expanded BOD-DO model selected for this software (programme) is that of the model system SENSMOD (Jolánkai, 1985), which has been developed by the authors of this CAL programme. Although in this model the basic modelling concept has also been changed slightly the reader/user is kindly requested to consult also the following topics: "General introduction of BOD-DO models", the "General introduction of the traditional oxygen sag equation", the "General introduction of the Expanded BOD-DO models" and the "General introduction of the first expanded BOD-DO models".

The main differences of this modelling concept are as follows:

1. Longitudinal variation of the mass flux (the product of flow and concentration) is expressed, instead of expressing the variation of concentration with the time (of travel), thus allowing for the consideration of longitudinally varying river flow.

2. The DO equation is written for the dissolved oxygen (termed here C_{ox}) instead of the oxygen deficit D.

3. Non-point source input loads are also considered in terms of concentrations of BOD and DO in the lateral inflow (here the term lateral inflow q ($L^2 T^{-1}$) refers to the increment of river flow Q ($L^3 T^{-1}$) over a unit downstream distance (L) of the river, assuming uniform q values over a given river reach.

4. Photosynthesis and respiration of aquatic plants are considered separately, that is rather with their difference, e.g. (P-R).

The **2nd expanded BOD-DO model**, selected for this programme/software has essentially the same parameters as the first expanded BOD-DO model and the same limitations refer to the possibilities of parameter estimation. The differences are:

a, the parameter q, the lateral inflow, that can be relatively easily obtained from the hydrological (longitudinal) profile. For a given river reach of length x it obtained as the flow increment over the reach divided by the length of the reach.

b, Concentrations of the constituents in the lateral inflow should be either estimated by another submodel (this is done in the SENSMOD model system, by the overland runoff-transport submodel, the NPS submodel) or a literature estimate of runoff concentration of the respective substance must be used.

c, Parameters of BOD decay rate K_1 and reaeration rate K_2 have slightly different values from those of the previous models (due to the difference in modelling concept and thus in the exponents of the model equations). A correction algorithm is built in the programme to facilitate conversion (not shown in the written material), so as to allow the use of the respective parameter estimation formulae and tables.

In the calculation example of this CAL programme we will use pre-defined ranges of parameter values, within which the user may select one, so as to see their effect on the final outcome of the model simulation.

The 2nd expanded BOD model

The model equations describe the longitudinal variation (profile) of BOD in function of the decomposition process of organic matter, non-point source inputs represented by lateral inflow and a benthic source of BOD. For more details see also the following topics: "General introduction of BOD-DO models", the "General introduction of the traditional oxygen sag equation", the "General introduction of the Expanded BOD-DO models", the "General introduction of the first expanded BOD-DO models" and the "General description of the 2nd expanded BOD-DO Model".

Eq. 3.5

$$\frac{d}{dx}\left[(Q+qx)\,L\right]=q\,L_d-K_1AL+B$$

Eq. 3.6

$$L(x)=L_0F^{\beta_1}+\frac{L_d+B\phi(x)}{\beta_1}\left[1-F^{\beta_1}\right]$$

where

$$F=\frac{Q_0}{Q_0+qx}\ ;\ \beta_1=1+K_1\phi(x)\ ;\ \phi(x)=\frac{\frac{Q_0}{q}+x}{v}$$

Legend

L- is BOD in the water (M L^{-3}, g O_2/m^3)

L_0- is the initial BOD in the stream (downstream of the wastewater discharge), see also Eq. 2.5

K_1 - is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})

L_d - is the concentration of BOD in the lateral inflow to the stream, (the diffuse load components, (M L^{-3}, g O_2/m^3)

Q - is the rate of flow in the river (L^3 T^{-1}, usually m^3/s)

Q_0- is the rate of flow at the beginning of the river reach, just upstream of the wastewater discharge (L^3, T^{-1}, usually m^3/s)

q - is the lateral, specific, inflow rate to the river (L^2 T^{-1}, usually m^2/s)

A - is the wetted cross-section area of the stream (L^2), defined as the rate of flow Q divided by the cross-sectional mean flow velocity v. (usually m^2)

B - is the benthic oxygen demand (M T^{-1} L^{-1}, here g O_2/m/day),

x - is the distance downstream along the river (L, usually in meters).

v - is the mean flow velocity along the river reach in concern (L T^{-1}, m/s),

The 2nd expanded dissolved oxygen model

The model describes the longitudinal variation of the dissolved oxygen content of the river as affected by point and non-point sources of biodegradable organic matter (BOD), the decomposition process of organic matter, the reaeration process and by the photosynthesis and respiration of aquatic plants.

For more details see also the following topics: "General introduction of BOD-DO models", the "General introduction of the traditional oxygen sag equation", the "General introduction of the

Expanded BOD-DO models", the "General introduction of the first expanded BOD-DO models" and the "General description of the 2nd expanded BOD-DO Model".

Eq. 3.7

$$\frac{d}{dx}\left[(Q+qx)\,C_{ox}\right]=q\,C_{ox_d}-K_1AL+K_2A\left(C_{ox_{sat}}-C_{ox}\right)+A(P-R)$$

Eq. 3.8

$$C_{ox}(x)=\left[\frac{L_d+B\phi(x)}{\beta_1}-L_0\right]\frac{K_1}{K_2-K_1}\left(F^{\beta_1}-F^{\beta_2}\right)+$$

$$+\left[C_{ox_{sat}}(\beta_2-1)-\frac{L_d+B\phi(x)}{\beta_1}(\beta_1-1)+\phi(x)(P-R)+C_{ox_d}\right]\frac{1-F^{\beta_2}}{\beta_2}+C_{ox_0}F^{\beta_2}$$

where

$$F=\frac{Q_0}{Q_0+qx}\,;\ \beta_1=1+K_1\phi(x)\,;\ \phi(x)=\frac{\frac{Q_0}{q}+x}{v}\,;\ \beta_2=1+K_2\phi(x)$$

Legend

C_{ox} -	is the dissolved oxygen concentration of water (referred to as DO in the former equations (M L^{-3}, gO_2/m^3),
$C_{ox,0}$ -	is the initial dissolved oxygen concentration downstream of the waste water discharge (see also Eq. 2.6)
$C_{ox,d}$ -	is the concentration of DO in the lateral inflow to the stream, (the diffuse load component, M L^{-3}, gO_2/m^3)
$C_{ox,sat}$ -	is the saturated dissolved oxygen concentration of water (termed before also as DO_{sat}, see also Eq. 2.8)
L_0-	is the initial BOD in the stream (downstream of the wastewater discharge), see also Eq. 2.5
K_1 -	is the rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})
K_2 -	is the reaeration rate coefficient (T^{-1}, usually day^{-1})
L_d -	is the concentration of BOD in the lateral inflow to the stream, (the diffuse load components, (M L^{-3}, g O_2/m^3)
Q -	is the rate of flow in the river (L^3 T^{-1}, usually m^3/s)
Q_0-	is the rate of flow at the beginning of the river reach, just upstream of the wastewater discharge (L^3, T^{-1}, usually m^3/s)
q -	is the lateral, specific, inflow rate to the river (L^2 T^{-1}, usually m^2/s)
A -	is the wetted cross-section area of the stream (L^2), defined as the rate of flow Q divided by the cross-sectional mean flow velocity v. (usually m^2)
B -	is the benthic oxygen demand (M T^{-1} L^{-1}, here g O_2/m/day),
x -	is the distance downstream along the river (L, usually in meters).
P-R -	is the net difference between oxygen production by the photosynthesis and oxygen consumption by the respiration of aquatic plants (M T^{-1} L^{-3}, gO_2/m^3/day).
v -	is the mean stream flow velocity in the river section investigated (L T^{-1}, m/s)

DISPERSION RIVER MODELS

General description of dispersion river models

Here the reader/user is kindly requested to consult also the **Basic theory** chapter of this material/programme, where a brief explanation of the term dispersion is given. Thus to summarise; dispersion is a transport process caused by the joint effect of molecular diffusion and turbulent diffusion. The traditional concept of modelling diffusion (and thus dispersion) relies on Fick's law, which states that the transport of the substance in a space direction is proportional to the gradient of the concentration of this substance in that direction the proportionality factor being the coefficient of diffusion/dispersion.

Writing a mass balance equation for an elementary water body of dx*dy*dz dimensions considering the above dispersive and the advective mass fluxes plus external sources and internal sources and sinks of the substance one obtains the **"basic equation" (Eq 1.3)** for the variation of the concentration of the substance with the time and space. (the reader/user is kindly requested to consult the relevant literature if he/she is interested in more details of the derivation of this basic equation).

In the practice many more or less simplified versions of this basic model equation are used for describing the fate of various substances within the rivers, when introduced (discharged) into the water from natural or anthropogenic sources within the river. Of these many possible applications we have selected for the purpose of this CAL programme two cases which represent probably the two most important applications of these dispersion models (sometimes termed also "mixing" models, because what actually happens is that the pollutant mixes with the water upon the above briefly described dispersive and advective transport processes). These two models are:

1. The one-dimensional **longitudinal dispersion model** and its probably most interesting use is when one wishes to study (describe, simulate) <u>downstream propagating "pollution waves"</u> upon accidental pollution events (instantaneous inputs of larger masses of pollutants).

2. The **transversal mixing model** when one wishes to determine the spreading of a pollutant plume, downstream of an effluent outfall, that is to determine the concentration distribution of the pollutant across the river at any cross-section downstream of the effluent outfall.

<u>The longitudinal dispersion model</u>

General description of longitudinal dispersion models

The reader/user is kindly requested first to consult the following topics "Basic theory" of modelling river water quality; and the "General description of dispersion river models".

The first is dispersion-advection river model selected for the purpose of this CAL programme is termed here the one-dimensional **longitudinal dispersion model** and its probably most interesting use is when one wishes to study (describe, simulate) <u>downstream propagating "pollution waves"</u> upon accidental pollution events (instantaneous inputs of larger masses of pollutants).

In constructing this model we consider the river as a linear system in which transversal and vertical transport processes are considered as instantaneously completed ones. With other words it means that the contaminant discharged into the stream from any external source is being instantaneously mixed with an elementary water body of A*dx volume. Here A is the wetted cross-section area of the river and dx is the elementary distance downstream. It means that the level of contamination of the stream by the pollutant at any point x, along the longitudinal profile, is represented by the cross-sectionally averaged concentration of that substance.

Using this assumption and considering a non-conservative contaminating substance which is subject to decay/decomposition as given in the "decay equation" (Eq 1.5) one can simplify Equation 1.3 to Equation 4.1. This one-dimensional dispersion/advection model of a non-conservative pollutant is solved for initial conditions of the input of pollutant mass M at x=0. The resultant solution describes the "flattening out" of time-concentration "pollutant waves" along the river. In this model the river flow is considered steady state, e.g. neither the flow nor the river depth and flow velocity changes with the time (or space).

Parameters of this model, apart from the hydraulic ones, are the reaction rate coefficient K and the longitudinal dispersion coefficient D_x.

Estimation of the reaction rate coefficient K depends on the pollutant concerned. Thus it can not be made for a general case. (for the calculation example of this CAL programme we have rather arbitrarily selected a range of K for a most common parameter , the COD).

For the estimation of D_x the literature offers a wide choice of experimental expressions that express D_x (sometimes termed also D_L, the L standing for the word "longitudinal") in function of the hydraulic parameters of the stream (the slope S, the hydraulic radius R, the flow Q, the shear velocity u_*, the stream depth h and the channel width B and combinations thereof), that affect turbulence, which in turn mostly determine the process of dispersion. Nevertheless when testing the available experimental expressions with real stream data the obtained values of D_x vary within an order of magnitude, or even more. This means that the only reliable method is to make field measurements (tracer studies and/or analysis of the data of actual pollution incidents), both being rather cost and labour intensive experiments.

For the purpose of this CAL programme we have selected a formula (the McQuivey-Keefer formula which yield D_x values in about the middle of the range over which the results of other expressions vary (Eq. 4.3).

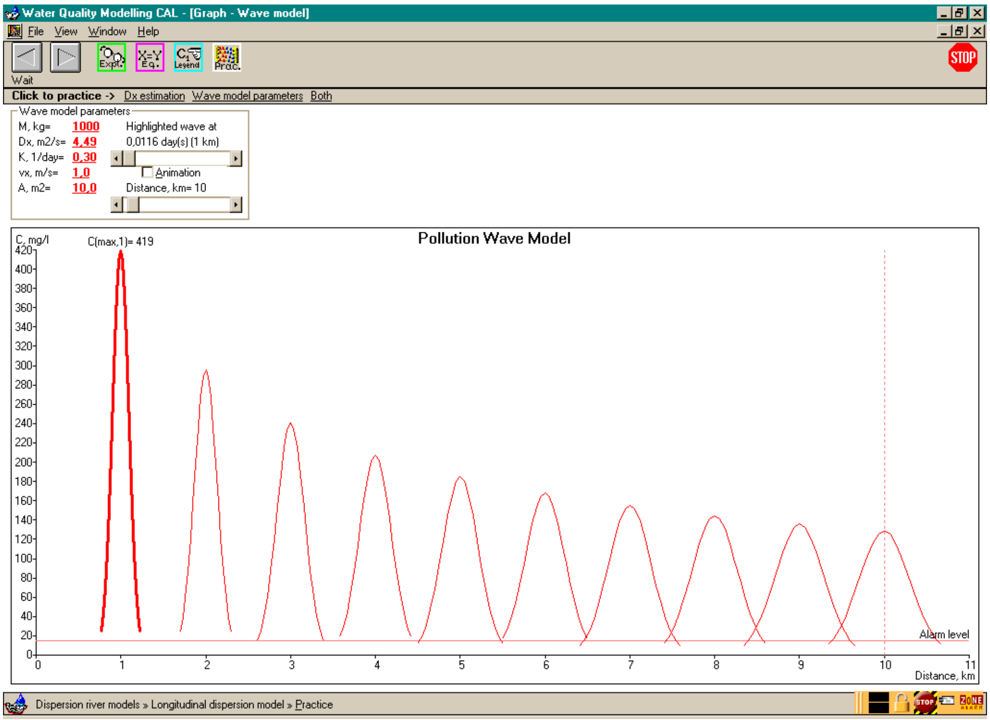
The accidental "pollution wave" model

This model, a special case of longitudinal dispersion models, describes the downstream propagation or "travel" of a pollution "wave", interpreted as a series of time vs. concentration curves in selected downstream sections of the river (at different distances x, downstream of an "accidental" point source of pollution represented by a pollutant mass M discharged instantaneously into the river. In constructing this model we consider the river as a linear system in which transversal and vertical transport processes are considered as instantaneously completed ones. With other words it means that the contaminant discharged into the stream from any external source is being instantaneously mixed with an elementary water body of A*dx volume. Here A is the wetted cross-section area of the river and dx is the elementary distance downstream. It means that the level of contamination of the stream by the pollutant at any point x, along the longitudinal profile, is represented by the cross-sectionally averaged concentration of that substance.

This model can be used for any non-conservative substances the decay (decomposition) of which can be approximated by first order reaction kinetics (see also Eqs. 1.5 and 1.6). For more details see the "the basic theory of water quality models", the "general description of dispersion river models" and the "general description of longitudinal dispersion models".

In the practice menu of this model you can set the length of the river reach to be modelled by the "Distance scroll bar", so as to be longer than the distance of a "monitoring station" or "water intake" where you want to know the actual value of the pollutant concentration with which the pollution "wave" arrives there. The software calculates 10 time-concentration distribution curves, splitting the above distance into equal parts.

This value can be seen in the graph when you set the "highlighted curve" to a position which equals (or is near to) the distance in concern. (see **Figure 7.**, a screen outprint of the software).



Wave model parameters
M, kg= 1000
Dx, m2/s= 4,49
K, 1/day= 0,30
vx, m/s= 1,0
A, m2= 10,0
Highlighted wave at
0,0116 day(s) (1 km)
☐ Animation
Distance, km= 10

Figure 7.

Eq.4.1

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - KC$$

Eq.4.2

$$C(x, t) = \frac{M}{A\sqrt{4\pi D_x t}} \exp - \left[\frac{(x - v_x t)^2}{4 D_x t} + Kt \right]$$

Legend

C - is the concentration of the pollutant in the stream (M L^{-3}, g/m^3)
M- is the mass of the pollutant discharged instantaneously into the stream (M, grams),
D_x- is the coefficient of longitudinal dispersion (L^2 T^{-1}, m^2/s)
K- is the reaction rate coefficient, assuming first order decay as the transformation process (T^{-1})
v_x - is the average flow velocity of the stream (L T^{-1}, m/s)
t - is the time (T),
A - is the wetted cross-section area (L^2), also defined as Q/v_x, where Q is the rate of flow in the river reach concerned.

Model for estimating dispersion coefficient D_x

This model estimates the value of the dispersion coefficient D_x in function of the rate of flow, the slope of the water surface, and the river width. The formula was chosen for the purpose of this CAL programme solely, from among the many other ones offered by the relevant literature.

Eq.4.3

$$D_x = 0.005394 \frac{Q}{S\,B} \quad ; \left[\frac{m^2}{sec} \right]$$

Legend

Q - is the stream flow, (m^3/s)
S - is the slope of the water surface (dimensionless, eg. in meter per meter)
B - is the width of the stream (m)

The transversal mixing model

General description of transversal mixing model

The reader/user is kindly requested first to consult the following topics "Basic theory" of modelling river water quality; and the "General description of dispersion river models"

One of the most frequently encountered practical use of dispersion (mixing) models is when one wishes to determine the spreading of a pollutant plume, downstream of an effluent outfall, that is to determine the concentration distribution of the pollutant across the river at any cross-section downstream of the effluent outfall.

It can usually be assumed that vertical mixing takes place immediately. It is also assumed in many cases that the transversal advective transport can be neglected (or rather its effect is incorporated in the value of the transversal mixing coefficient). This is needed mostly because there are no measurement data available for the transversal component of the flow velocity vector.

With this assumption the two dimensional, vertically averaged, longitudinal-transversal dispersion-advection model of a non-conservative pollutant can be derived from Eq 1.1. in the form of Equation 4.4

A further simplification can be applied by combining longitudinal and transversal dispersion effects into a single mixing term. Even further usual simplification is that the contaminant is considered a conservative one (this can be assumed in most of the practical cases, since the hydraulic transport/dilution effects will dominate the fate of the concentration within the plume until the transversal mixing is completed). With these further assumptions one obtains the simple transversal mixing model in the form of Equation 4.5

Although several analytical solutions of equations 4.4 and 4.5, and of several other model versions, are known from the relevant literature for various initial conditions (inlet, discharge, arrangements), the one we selected (Fisher, 1979) for the purpose of this CAL programme is probably one of the most practical one for cases when we want to investigate also the effect of the point of discharge of the pollutant within the cross section.

For an effluent discharge of C_o pollutant concentration and q_0 flow rate released into the stream at the discharge point (effluent outlet) of y_o m distance from the stream bank and at $x=x_o$ longitudinal distance the model formula of Equation 4.6 can be obtained.

Apart from the hydraulic and stream geometry parameters (that are input data for the model application) the value of the mixing coefficient ε_y should be estimated, either by fitting the model to measurement data (concentration distributions of the cross-sections) or by applying experimental expressions from the relevant literature. While it is always the best solution to use field measurement data for parameter estimation, in the case of the transversal mixing model the literature offers mostly the same type of equation and even the parameters of these experimental equations vary within relatively narrow ranges. For the purpose of this CAL programme we have selected Equation 4.7

In the relevant literature the value of the coefficient **d** varies between 0.1 and 0.9. Our own practical experience indicated that the effects of mixing are underestimated with the lower values of the domain of d. Thus we suggest the use of a higher value (for example **d=0.7**).

It should be mentioned that more precise model simulations can be achieved with models that are more complex than Eqs.4.2 and 4.3, with special regard to taking the distribution of flow velocity across the stream also into consideration, instead of considering the cross-sectionally averaged mean flow velocity v_x only.

A 2D dispersion-advection model

This model is just an example for a two-dimensional dispersion advection model for a non-conservative substance. For more details see the chapter on the "Basic theory", the "general description of dispersion models" and the "general description of transversal mixing models". Note that this model is not utilized in this CAL programme and serves for illustration only.

Eq.4.4

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} - KC$$

Legend

C - is the concentration of the pollutant in the stream (M L^{-3}, g/m^3)
D_x- is the coefficient of longitudinal dispersion (L^2 T^{-1}, m^2/s)
D_y- is the coefficient of lateral dispersion (L^2 T^{-1}, m^2/s)
K- is the reaction rate coefficient of a non-conservative substance, assuming first order decay as the transformation process (T^{-1})
v_x - is the average flow velocity of the stream (L T^{-1}, m/s)
t - is the time (T),

The transversal mixing model used in this programme

This model calculates the concentration distribution of a conservative substance across a river of a given width at various distances downstream of a single point source in function of the hydraulic parameters and channel geometry parameters. The distance of the point source from the river bank can also be varied. For more details see the chapter on the "Basic theory", the "general description of dispersion models" and the "general description of transversal mixing models".

In the practice menu of this model you can set the length of the river section to be modelled by the "Distance scroll bar". The software calculates 10 concentration distribution curves, splitting the above distance into equal parts. You can select then with the "Highlighted curve" scroll bar the one, where you wish to know the shape of the plume and the numerical concentration values at the river banks (Cl- concentration at the left bank; Cr- concentration at the right bank). Note that when you select a very small distance downstream of the source as the modelled reach the concentration distribution curves might become erratic. Also note that when you "pull out" the pipe from the river bed (y_o with negative values or larger than the river width B), the model can not be run and you hear and see warning signals. (see **Figures 8/a and 8/b** a schematic view of the pollutant plume and its computer realisation, the screen outprint of the software).

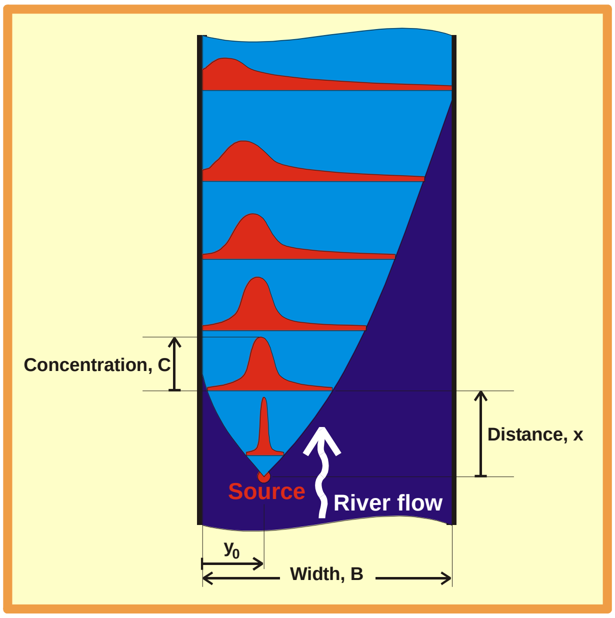
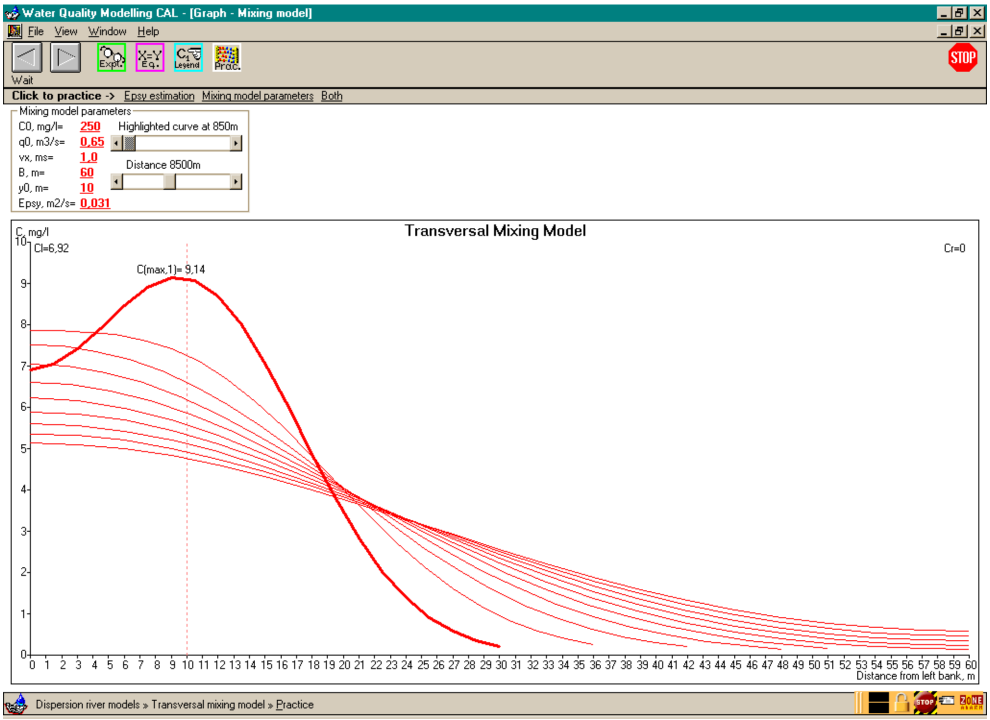


Figure 8/a



Mixing model parameters

C0, mg/l= 250

q0, m3/s= 0,65

vx, ms= 1,0

B, m= 60

y0, m= 10

Epsy, m2/s= 0,031

Highlighted curve at 850m

Distance 8500m

Cl=6,92

C(max,1)= 9,14

Cr=0

Figure 8/b

Eq.4.5

$$\frac{\partial C}{\partial t} = \varepsilon_y \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x}$$

Eq. 4.6

$$C(x,y) = \frac{C_{0,0}}{\sqrt{4\pi x'}} \sum_{n=0}^{\infty} \left(\exp\left[\frac{-(y' - 2n - y'_0)^2}{4x'} \right] + \exp\left[\frac{-(y' - 2n + y'_0)^2}{4x'} \right] \right)$$

Legend

C - is the concentration of the pollutant in the stream (M L^{-3}, g/m^3)

ε_y - is the transversal mixing coefficient (L^2 T^{-1}, m^2/s)

$C_{o,o}$= C_o q_o/v_x h B

C_o - is the concentration of the pollutant in the waste water discharge (M L^{-3}, g/m^3)

q_o - is the rate of flow of the waste water discharge (L^3 T^{-1}, m^3/s)

x - is the distance downstream of the source of pollution (m)

x' = x ε_y/v_x B^2

y' = y/B

y - is the distance from the river bank, across the river

y_o' = y_o/B

y_o - is the distance of the pollution source (pipe outlet) from the river bank (m)

B - is the width of the river (m)

Parameter estimation of the transversal mixing model

This equation estimates the value of the transversal mixing coefficient in function of the flow depth and the slope (the shear velocity). For more details see the chapter on the "Basic theory", the "general description of dispersion models" and the "general description of transversal mixing models".

Eq.4.7

$$\varepsilon_y = d\,h\,(hSg)^{\frac{1}{2}} \;;\; \left[\frac{m^2}{sec}\right]$$

Legend

g - is the acceleration of gravity (9.81 m/sec^2)

S - is the slope of the water surface (dimensionless, e.g. m/m)

h - is the average depth of flow (m)

d - is the experimental constant (the value suggested by the authors for the purpose of this study is 0.7)

LAKE MODELS

Introduction to basic lake ecosystem processes

As discussed under the "General theory of water quality models" all lake models included in this software are of the "fully mixed reactor" type. This means that no transport processes are considered. The main reason is, that the literature of lake modelling has proven that hydraulically based transport and transformation models cannot generally give significantly better or more realistic simulations of the water quality of lakes than those of the fully mixed reactor models, or the chain of such interconnected "fully mixed box" models (which latter can be used for simulating various interconnected basins or bays of the lakes or reservoirs). Nevertheless, the hydraulic equations of fluid motion are also given in **Appendix I.**, as general information, but they are not used in this programme. Another simplification was that this programme does not deal with deeper, thermally stratified lakes or reservoirs, but only with shallow lakes and reservoirs. The main reason to this approach was to avoid complications, which would result from the consideration of a high number of additional model parameters and coefficients.

In discussing the pollutant transformation processes of standing water bodies one eventually has to focus on the problem of eutrophication, as one of the most crucial environmental problems of our era.

The word eutrophy is generally taken to mean "nutrient rich" (Jörgensen, 1988), and is used sometimes as contrasted to dystrophic ("ill-nourished") (Baxter et al., 1992).

Eutrophication, known also as the natural ageing process of standing waters, has dramatically increased since the sixties, mostly in industrialized countries with intensified agriculture, due to the excessive anthropogenic input loads of plant nutrients phosphorus and nitrogen. Therefore, as contrasted to natural eutrophication, the recent problem is termed anthropogenic or man-made eutrophication. It is usually observed as the excessive growth of phytoplankton that turns standing waters and sluggish streams into green; known by the lay public as "algae bloom'" a term frequently used by scientists as well. It is frequently associated by the increased growth of attached algae or macrophytes.

Primary productivity, the growth of phytoplankton expressed as carbon produced per unit area of the lake per unit period of time (e.g. $gCm^{-2}\ yr^{-1}$), is high, leading to relatively high concentrations of dissolved organic matter DOM in the water. This supports a population of heterotrophic bacteria that decompose organic matter and deplete the dissolved oxygen content of water. In deep lakes, in the hypolimnion, this oxygen depletion might create anaerobic condition that gives rise to undesirable biological and chemical processes and may result in fish kills. Nevertheless, eutrophication is often associated with increased fish production but the species composition changes unfavourably.

Although about 16-20 elements are necessary for the growth of freshwater plants (among others; Carbon, Silicon, Calcium, Potassium. Magnesium, Iron, etc; -Jörgensen, 1988) anthropogenic eutrophication is almost exclusively due to the over enrichment of phosphorus and nitrogen, that is the result of increased external nutrient loads from a large variety of point and non-point sources (e.g. communal and industrial waste waters, agricultural runoff water, residential "urban" runoff waters, atmospheric fallouts onto the lake surface). From the view point of the sources this problem will be discussed in the 3rd version of the software, which will be dealing with hydrologically induced transport and transformation processes of pollutants. In natural lake ecosystems one or some of the plant nutrients -mostly phosphorus, sometimes nitrogen, and much more rarely silicon-, are present in so low concentrations that it/they limit the growth of phytoplankton, thus exercising control over the aquatic ecosystem as a whole. This "growth limiting factor" was, for the majority of lakes, phosphorus; or more precisely the bioavailable forms of phosphorus. The bioavailable form, the P form that algae can take up, is either taken as orthophosphate phosphorus PO_4-P, or termed the dissolved inorganic phosphorus DIP, or just the bioavailable phosphorus BAP, which is meant to include more than one phosphorus forms: DIP, a certain fraction of TP-DIP. Before discussing the quantification possibilities of the set of processes briefly discussed above the first task is to construct a scheme or flow diagram of the state variables and processes of lake ecosystems (as indicated in **Figure 9**.).

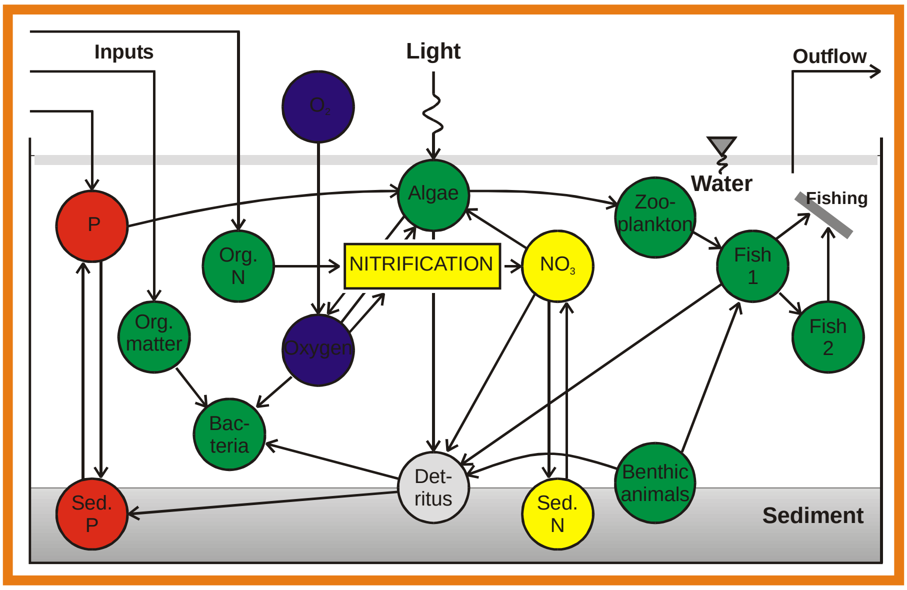


Figure 9.

Figure 9 is obviously a much simplified scheme, a model, of the actual processes, and focuses on two of the perhaps most important chains of processes.
These are

- the aquatic "food web", termed also the foodchain, and
- the main processes of the oxygen household

Verbally the main processes are as follows:

i. The growth of algae (phytoplankton) is governed mostly by the availability of the two main nutrients P, and N, plus light and temperature.

ii. Algae are consumed (grazed) by herbivorous or omnivorous zooplankton which is the food for carnivorous zooplankton and non-predatory fish, which latter is in turn the prey of predatory fish

iii. After death all living organisms contribute to the dead organic matter compartment, termed detritus, which forms the substratum for bacteria. Organic matter originates from external sources too.

iv. Decomposition of organic matter by bacteria includes a carbonaceous phase (CBOD) and a nitrogenous phase (NBOD). The latter is termed the nitrification process in which ammonia and amine compounds are oxidised to nitrite and then to nitrate by nitrifying bacteria (Nitrosomonas and Nitrobacter, respectively), thus recycling the "nitrogenous food" for algae (NO_3-N) from the dead organic matter.
There is some evidence that a fraction of the phosphorus content of particulate dead organic matter is also recycled by bacteria feeders into soluble and bioavailable form (Porter, 1975),

although it is generally claimed that there is a net loss of phosphorus from the water column to the lake bottom.

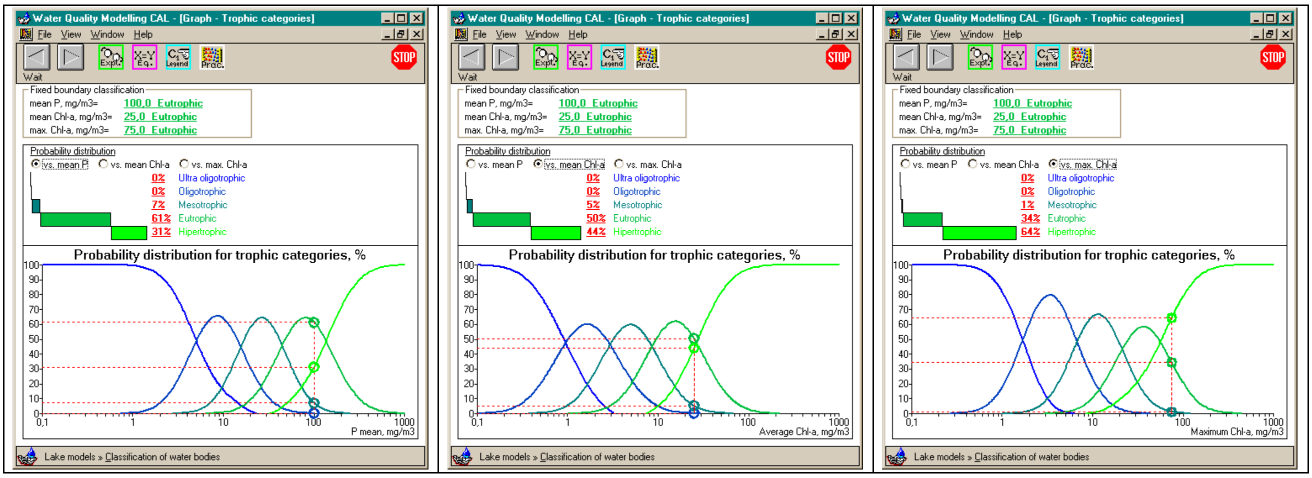
v. While the decomposition of organic matter depletes the dissolved oxygen content, aquatic plants (phytoplankton and macrophytes) contribute to it by their photosynthetic activity. However, out of the photoperiod -during the night- their respiration also depletes the oxygen content. Thus the net difference of photosynthetic oxygen production rate P and respiratory oxygen consumption rate R (e.g. P-R), will define the role of aquatic plants in the oxygen household process.

vi. There are external inputs to practically all compartments via point sources, inflowing water and atmospheric fallout, while losses via outflow (flushing), burial in the sediment, and via "harvesting" of fish and aquatic weeds provide the other arms of the mass balance.

vii. Several natural and man-influenced factors such as pH, water temperature, water depth, suspended solids (transparency), wind and/or temperature difference induced currents, wind induced turbulence etc affect the rates of the above briefly described processes.

There remains, however, a question to be answered and this is the classification of water bodies into classes of various trophic levels. Below two approaches will be briefly presented:

- In the eutrophication manual of OECD (OECD, 1982) the probability distribution of five trophic categories are given for a number of characteristic trophic parameters. This work has been based on the experimental data of a large number of lakes. A computer realisation of the slightly modified, adapted, distribution curves of this study , an outprint of the software's screen is shown in **Figures 10**. This is the result evaluating screen that appears in each lake model, showing the probabilities with which the lake in concern falls into a strophic state (in respect to mean P, Chlorophyll-a mean and maximum values).



Fixed boundary classification
mean P, mg/m3= 100,0 Eutrophic
mean Chl-a, mg/m3= 25,0 Eutrophic
max. Chl-a, mg/m3= 75,0 Eutrophic

Probability distribution
● vs. mean P ○ vs. mean Chl-a ○ vs. max. Chl-a
0% Ultra oligotrophic
0% Oligotrophic
7% Mesotrophic
61% Eutrophic
31% Hipertrophic

Probability distribution
○ vs. mean P ● vs. mean Chl-a ○ vs. max. Chl-a
0% Ultra oligotrophic
0% Oligotrophic
5% Mesotrophic
50% Eutrophic
44% Hipertrophic

Probability distribution
○ vs. mean P ○ vs. mean Chl-a ● vs. max. Chl-a
0% Ultra oligotrophic
0% Oligotrophic
1% Mesotrophic
34% Eutrophic
64% Hipertrophic

Figures 10.

The OECD study also presents a table, showing the fixed categories of eutrophication. The evaluation according to the fixed categories also appears in the heading of the trophic state evaluating screen (Figure 10 above).

Table 3. Fixed trophic state categories of the OECD study (1982)

Trophic categories	indices of trophic state (mg/m^3)		
	P_L	Chl_{mean}	Chl_{max}
Ultra-oligotrophic	< 4.0	<1.0	<2.5
Oligotrophic	<10.0	<2.5	<8.0
Mesotrophic	10-30	2.5-8.0	8.0-25
Eutrophic	35-100	8-25	25-75
Hypertrophic	>100	>25	>75

Where P_L-is the annual mean concentration of total phosphorus in the lake water
Chl_{mean}, Chl_{max}- are the mean and the maximum annual chlorophyll-a concentrations in the lake water (a measure of the phytoplankton, e.g. algae, concentration).

Felföldy (1987) presented a fairly detailed categorization of the trophic state on the basis of three parameters as shown in Table below:

Table 4: Trophic state categories, Hungarian guidelines (Felföldy, 1987)

Degree of trophity	Primary production gC/m^2.year	Algal count 10^6/litre	Chlorophyll-a mg/m^3
0 Autrophic	0	0	0
1 Ultra oligotrophic	<10	< 0.01	<1
2 Oligotrophic	11-50	0.01-0.05	1-3
3 Oligo-mesotrophic	26-50	0.05-0.10	4-10
4 Mesotrophic	51-100	0.1-0.5	11-20
5 Meso-eutrophic	101-175	0.5-1.0	21-50
6 Eutrophic	176-300	1-10	51-100
7 Eu-polytrophic	301-500	11-100	101-200
8 Polytrophic	501-800	101-500	201-800
9 Hypertrophic	>800	>500	>800

In the models of this software the evaluation of the results of any model run will be "automatically" made with the help of the probability curves of the OECD and also by the fixed categories of OECD.

General introduction to lake models

In terms of the general theory of modelling transport and transformation processes of water bodies (see the first "Basic theory" chapter), lakes offer the consideration of a large variety of transport and transformation models. For transport models (see Eqs 1.2 and 1.3) the outputs of hydraulic, or "circulation" models would be needed. As mentioned before this (hydraulic modelling of wind- and/or temperature-difference induced models) would need a teaching aid (a CAL Programme) of the magnitude of this present one. Consequently we skipped this modelling phase, but the user finds the relevant equations in **Appendix 1**. The developers have, actually, also skipped all kind of transport modelling and reduced the handling of the problem to the modelling of transformation processes. This means that of the lake modelling options shown in **Table 1.**, only the zero-dimensional, "fully mixed reactor" type models are discussed to a certain depth, to their "basics".

Table 5.: Basic categories of lake models

Type of model	Spatial dimension	Description
Simplified models	**0 –D**	**Fully mixed reactor**
	1-D	Vertical or longitudinal
Circulation models	2-D	Vertical plane, horizontal (single layer)
	3-D	Real 3-D multilayer, Ekman type

There are three basic reasons why we had to make this choice:

a, Results of the literature dealing with the comparison of hydraulically based lake eutrophication models with the fully mixed reactor type (chain of fully mixed reactor type) models indicated, that the latter gives fairly good approximation of the former (Paul, 1976; Shanahan and Harlemann, 1986). That is hydraulic transport models would not significantly improve the simulation and prediction capability of 0-D eutrophication models.

b, Usually available water quality monitoring (and flow pattern) data bases, do not allow real spatial differentiation of the processes. At the most one has information on the quality of various "bays" of larger lakes. This latter can be well approximated by a chain of fully mixed reactor models.

c, The transformation processes relevant to lake eutrophication are complex enough to form the subject of a teaching aid on the basics of lake modelling. Several options are available even for modelling the basics of nutrient budget and nutrient-algae-growth models, as will be indicated by the model blocks included in this software.

Important remark: In the lake models shown below, a built-in mechanism cares for all state variables reaching an equilibrium state. This mechanism kind of assumes that the models can be calibrated against long records of past measurement data. This means that parameter estimation sub-models are also built in into the software. Nevertheless the user will be allowed to change some of the parameters of this parameter-estimation submodels, like the assumed retention ratio parameters (see later). This was needed, in this software, to keep the models running (as a "free choice" of reaction rate parameters, would certainly result in the "blow up" of the models).

Quantification of transformation processes in standing waters

The quantification of lake processes described in the "general introduction of lake ecosystem processes" can be made in a large variety of ways; -starting with experimental and empirical relationships (Vollenveider, 1969; Chapra, 1975; OECD, 1982) and other simple nutrient -mostly phosphorus- budgeting type approaches (Lorenzen, 1975; Lewis and Nir, 1978; Chapra and Canale, 1991; Salas and Martino, 1991; Rossi and Premazzi, 1991), through various phosphorus-phytoplankton models (Thoman et al. 1974; Imboden and Gachter, 1975; Jolánkai and Szöllősi-Nagy, 1978; Larsen and Mercier, ref. Orlob, 1977; Jolánkai, 1991) and multiparameter dynamic lake ecosystem models (Jörgensen, 1976; Di Toro et al., 1977; Kelly and Spofford 1977; Kelly, 1973; Bierman et al. 1980; Di Toro and Conolly 1980; Kutas and Herodek 1986; Park et al, 1974), including the multilayered - epilymnion/hypolymnion - models of deep lakes (Lung et al. 1975; Niemi, 1978; Vincon-Leite and Tassin, 1990; Knoblauch, 1977; Jörgensen and Harlemann, 1977) some of them considering also vertical transport processes across the termocline. Stochastic approaches might be also applied or coupled with any of the conceptual and deterministic models (Canale and Effler, 1989). Some of the latest approaches claim the necessity of using the techniques of artificial intelligence for the interpretation and qualification of the complex hydroecological processes involved (Guerrin, 1991).

For any quantification, however, one has to deal first with the definition (or modelling) of inputs of flow and material to the lake. This will be done in a very simple model block (see "input load models"). A more detailed "integrated catchment modelling" block will replace this simplified block in the third, next" phase of the development of this software. Note that inputs will be calculated for phosphorus only, wit the assuming that the lake in concern is phosphorus limited. This was needed for keep the models within relatively easily manageable- controllable frames.

Next, a separate (or joint) "model" block is needed for the hydrology or the water budget of the lake, implying also the definition of the basic lake geometry parameters. This will be done in the "block" "Lake hydrology and regulation".

Input load model

(for eutrophication models)

Description

Input loads of phosphorus are calculated for the eutrophication models in two ways: 1. Either the data (annual mean flow and concentration and the point source load) are entered, or 2. The runoff and the non-point source load of the catchment basin is calculated by a very simple fixed model and the point source data are given. This model is a rough substitute of the future catchment model series, which shall be developed in the 3rd version of this software. Load reduction (treatment efficiency) options are also given: 10%-90% removal and 10%-60% removal for point and non-point sources, respectively.

Models

Model equations are not given in the software, only a choice for the above two options, then the respective scroll bars for the parameters to be entered plus a result field.

Options:

1. Data to be entered:

P_{in}-annual mean total P concentration in the inflow [mg/m^3]
Q_{in}-annual mean discharge of inflowing streams, [m^3/s]
L_{pt}= sum of point source loads of phosphorus [kg/day]

Non-point load estimate

$L_{nps}= 0.0864*P_{in}*Q_{in} - L_{pt}$, [kg/day]

2. Models:

A - area of the catchment basin [ha]

F -	fraction of forested land [0<F<1]
MP -	fraction of meadow-pasture, [0<MP<1]
Ag -	fraction of agricultural land, [0<Ag<1]
U -	fraction of urban land, [0<U<1]
	F+MP+Ag+U=1.00

PC - precipitation, [mm]
C_{pt} – Basin averaged concentration of phosphorus in the point source discharges [mg/m^3]
Q_{pt} – Total water discharge of point source dischargers [m^3/s]

Input load models:

Flow model

$Q = 0.0000003171*P*A*(0.05*F+0.1*MP+0.2*Ag+0.7*U)$, [m^3/s]

Non-point source load model

$L_{nps}=A*(0.01*F+0.2*MP+1.5*Ag+2.5*U)$, [kg/year]

Point source load calcualtion

$L_{pt} = 0.0864\ C_{pt}*\ Q_{pt}$ [kg/day]

Total load model

$L= 365*L_{pt} + L_{nps}$, [kg/year]

Calculation of P_{in}

$P_{in} = 0.03171*L/Q$, [mg/m^3]

3. Load reduction models

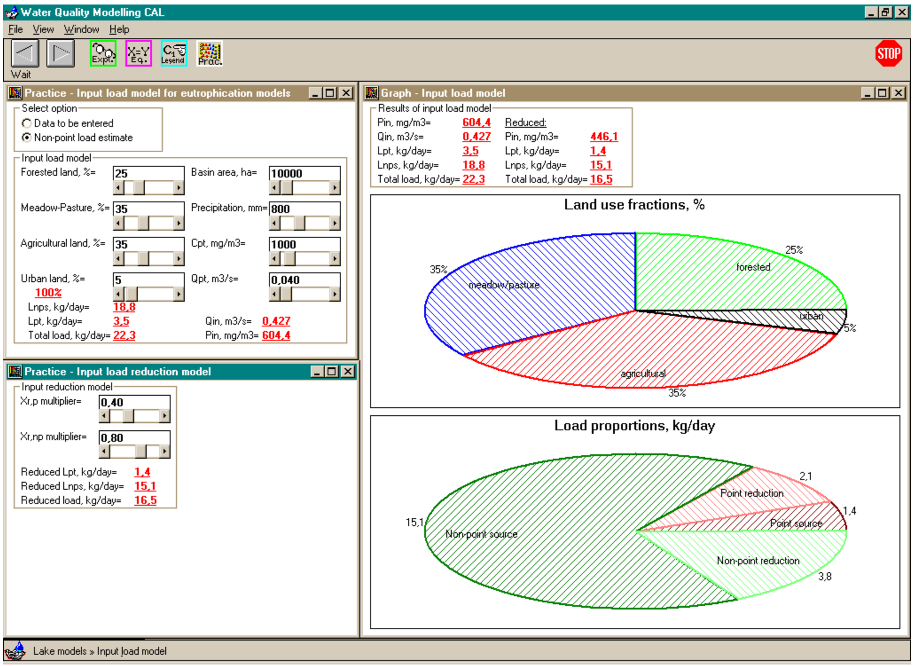
The user may enter load reduction (treatment factors) as follows:

10%-90% treatment efficiency for point sources (multipliers $X_{r,p}$= 0.9 -to- 0.1 of L_{pt} load)
10% - 60 % reduction efficiency for non-point sources ($X_{r,np}$= -0.9 -0.4)

The load reduction model

$L_{reduced}=X_{r,p}*365*L_{pt}+X_{r,np}*L_{nps}$, [kg/year]
$P_{in,r}=0.03171\ L_{reduced}\ /Q$

Figure 11. shows the results of the input load model, indicating also the effects of load reduction measures:



Practice - Input load model for eutrophication models

Select option
○ Data to be entered
● Non-point load estimate

Input load model
Forested land, %= 25
Basin area, ha= 10000
Meadow-Pasture, %= 35
Precipitation, mm= 800
Agricultural land, %= 35
Cpt, mg/m3= 1000
Urban land, %= 5
Qpt, m3/s= 0,040
100%
Lnps, kg/day= 18,8
Lpt, kg/day= 3,5
Qin, m3/s= 0,427
Total load, kg/day= 22,3
Pin, mg/m3= 604,4

Practice - Input load reduction model

Input reduction model
Xr,p multiplier= 0,40
Xr,np multiplier= 0,80
Reduced Lpt, kg/day= 1,4
Reduced Lnps, kg/day= 15,1
Reduced load, kg/day= 16,5

Graph - Input load model

Results of input load model
Pin, mg/m3= 604,4
Qin, m3/s= 0,427
Lpt, kg/day= 3,5
Lnps, kg/day= 18,8
Total load, kg/day= 22,3

Reduced:
Pin, mg/m3= 446,1
Lpt, kg/day= 1,4
Lnps, kg/day= 15,1
Total load, kg/day= 16,5

Figure 11.

Remark: In the final version of this CAL programme the input load will be calculated, for all lake- and where appropriate also for stream-models, with the help of a series of catchment modelling options. Of these the first model will be similar to that "wired in" (but not shown) into this CAL, using runoff coefficients and unit area loading rates for the various land use forms (as specified also in this model block). The most sophisticated one of these future models will be a kind of GIS based (digital raster map based) runoff and load calculation programme. This will be an important part of the 3rd version of this CAL as non-point sources tend to dominate the pollution processes of our era.

Lake hydrology, regulation model

Explanation

In this model block the user defines the area A of the lake, assuming that it does not change with the depth. The initial water depth h_o (at the start of the simulation) is also given and the lake volume is calculated as V=A*h. The water release rate Q_{out} is specified (it shall be higher or lower than Q_{in}, when the operator wishes to rise or sink the lake's water level, respectively). The discharge capacity of the outflow structure ($Q_{out,max}$) shall also be given. Note that for the two simple lake models 1. and 2. $Q_{out}=Q_{in}$, where Q_{in} is the inflow rate as was calculated (or given) in the input load modelling block. For the rest of the models $Q_{out,max} > Q_{in}$, as regulation is only possible when the adjustable rate of outflow is higher than the inflow. Regulation water level options shall be confined by giving h_{max} and h_{min}, the range within which water level variation is allowed. With this conditions specified, the lake water budget model will run until one of the regulation limits are reached, then Q_{out} is automatically adjusted to be equal to $z+Q_{in}$. Where z is a correction element to counterbalance the difference between precipitation P and evaporation E. This means that Q_{out} is increased, when the precipitation onto the lake surface exceeds evaporation and the actual h equals h_{max} and decreased when it equals h_{min}. The opposite correction is applied when evaporation exceeds precipitation.

Model equations

Eq. 5.1

$$\frac{dh}{dt} = \frac{1}{A}\left[Q_{in} - Q_{out}\right] + P - E$$

$$Q_{out} = Q_{in} + z \quad \text{when} \quad h > h_{\max} \vee h < h_{\min}$$

$$z = (P - E) * A$$

Legend

h - is the lake depth, [m]

Q_{in}, Q_{out} - are the inflow and outflow rates of the lake, respectively, [m^3/year];

A - the average lake surface area, [m^2]

P and E - are the precipitation and evaporation onto/from the lake surface, respectively [m/year]

Experimental lake model. Lake model No.1

Explanation

These methods of predicting the nutrient concentrations and the associated trophic state of standing waters rely on the use of statistically defined empirical relationship between a state variable and one or more independent variables, characterising the lake's hydrological, hydraulic and input nutrient load conditions. Based on the original concept of Vollenveider (1969) the perhaps most well known set of tools have been published in a comprehensive study by the Organization for Economic Co-operation and Development (OECD, 1982), utilizing the data of a large number of lakes, also grouping these lakes into several categories (e.g. Alpine, Nordic, Shallow, etc). A sample relationship from this study was used for this CAL programme. Estimate of trophic state is given together with the probability of its occurrence, based on the same study. An important note is that parameters of the original model equations were slightly altered, in order to avoid copy right problems on one hand and not to allow the user to use this software for actual design purposes, but for the teaching/learning of the techniques only.

Experimental (OECD) lake model equations

Eq. 5.2

$$Chl_{mean} = 0.37\, X^{0.79}$$

$$Chl_{\max} = 0.74\, X^{0.89}$$

$$PP = 22.9\, X^{0.6} \quad or \quad PP = 589 \frac{X}{48.0 + X}$$

Eq. 5.3

$$X = \frac{P_{in}}{(1 + \sqrt{t_w})}$$

Legend

Chl_{mean}, Chl_{max} - are the average and maximum in-lake chlorophyll-a concentrations in mg/m^3

PP - is the primary production rate in the lake [gC/m^2 yr]

X - is the flushing corrected average inflow concentration of phosphorus

P_{in} - is the annual mean inflow concentration of total phosphorus, in mg/m^3 and

t_w - is the mean residence time of water in the lake, year

Note, that the primary production (PP) sub-model is not included in the software (to keep uniformity, as the rest of the models do not calculate this).

Further remarks:

Other empirical relationships of the OECD study included: nitrogen versus phosphorus; biomass and in-lake nutrient concentrations, transparency versus chlorophyll and versus nutrients, primary production versus P loading, primary production versus in-lake phosphorus and chlorophyll-a, etc.

In the relevant literature there were many attempts to modify, improve, or test the above models (Rechkow, 1979; Yeasted and Morel, 1978; Hoare, 1980; Golterman, 1980; Kerekes, 1983; Mahamat and Bhagat 1983; Salas and Martino, 1991) exercising sometimes strong criticism over them. One may, however, state that these empirical relationships are indispensable tools in assessing the fate of lake ecosystems, especially when quick answers to lake recovery problems are required on the basis of limited data, but they must be used with due concern to their limitations, perhaps together with parameter sensitivity and error analysis.

Dynamic nutrient budget model. Lake model No. 2

Description

Early lake eutrophication and nutrient budget models (Vollenveider, 1969; Lorenzen 1974; Sonzogni et al. 1976; Thoman et al. 1977) considered the phosphorus balance as the sum of external supply LP minus outflow and sedimentation, assuming that the lake (segment) is fully mixed and the lake volume is constant, while sedimentation is proportional to the P concentration of the lake. (see **Figure 12.**)

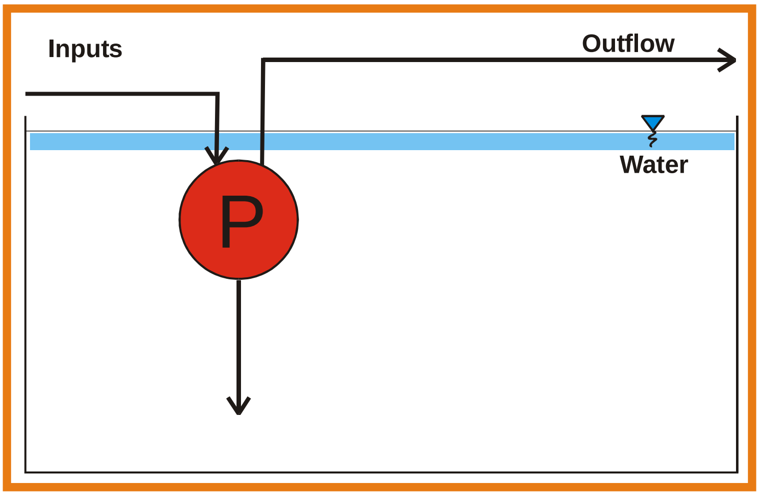


Figure 12.

For a given retention ratio "r"(0<r<1) of phosphorus, expressing the ratio of the lake equilibrium concentration P_{eq} to the inflow concentration P_{in}, the settling rate coefficient varies in function of the hydraulic washout rate q. This retention ratio is built into the software. Many modifications to this basic equation were developed and applied

Equations

Eq. 5.4

$$\frac{dP_L}{dt} = \frac{1}{A*h}\left[P_{in}Q_{in} - P_L Q_{out}\right] - K_{set} * P_L$$

$$P_L(t) = P_{L_0} e^{-(q+K_{set})t} + \frac{LP}{q+K_{set}}\left(1 - e^{-(q+K_{set})t}\right)$$

$$LP = \frac{Q_{in}P_{in}}{h*A} \wedge q = \frac{Q_{out}}{h*A}$$

Eq. 5.5

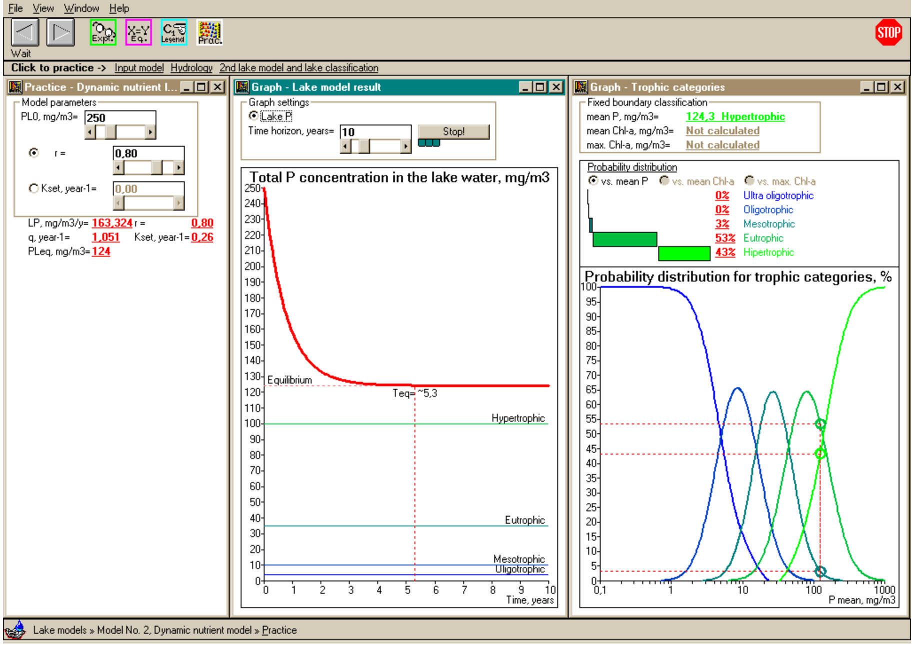
$$P_{L_{eq}} = \frac{LP}{q+K_{set}} \qquad r = \frac{P_{L_{eq}}}{P_{in}} \qquad K_{set} = q\left(\frac{1}{r} - 1\right)$$

Legend

P_L- is the total P concentration in the lake water $[ML^{-3}]$ $[mg/m^3]$
P_{L0} - is the initial total phosphorus concentration (at time t=0) of the lake
P_{Leq} - is the equilibrium concentration of the lake (for the given input load and settling rate),
P_{in}- is the mean inflow concentration of phosphorus,
Q_{in}- is the water inflow rate $[L^3\ T^{-1}]$, $(m^3/year)$

Q_{out}-	is the water outflow rate [L^3 T^{-1}], (m^3/year)
h-	is the average depth of the lake [L], (m)
A-	is the average surface area of the lake [L^2],(m^2)
LP-	is the volumnar P loading rate to the lake [ML^{-3} T^{-1}] (mg/m^3/year) to be obtained as the loading rate of P (MT^{-1}) divided by the lake volume V [L^3]
q-	is the hydraulic washout rate [T^{-1}], ($year^{-1}$), calculated as the water outflow rate [L^3 T^{-1}] divided by the lake volume V [L^3]
K_{set}-	is the sedimentation rate [T^{-1}], ($year^{-1}$)
r-	the retention ratio of phosphorus (0<r<1), expressing the ratio of the lake equilibrium concentration P_{Leq} to the inflow concentration P_{in}
t-	is the time [T]

Figure 13. shows a screen outprint of this model.



Click to practice -> Input model Hydrology 2nd lake model and lake classification

Model parameters
PL0, mg/m3= 250
● r = 0,80
○ Kset, year-1= 0,00

LP, mg/m3/y= 163,324 r = 0,80
q, year-1= 1,051 Kset, year-1= 0,26
PLeq, mg/m3= 124

Graph settings
● Lake P
Time horizon, years= 10

Fixed boundary classification
mean P, mg/m3= 124,3 Hypertrophic
mean Chl-a, mg/m3= Not calculated
max. Chl-a, mg/m3= Not calculated

Probability distribution
● vs. mean P ○ vs. mean Chl-a ○ vs. max. Chl-a
0% Ultra oligotrophic
0% Oligotrophic
3% Mesotrophic
53% Eutrophic
43% Hipertrophic

Lake models » Model No. 2, Dynamic nutrient model » Practice

Figure 13.

Note that in each model block the result evaluation field (Figure 10.) also appears. It is also to be noted that in each lake model block the option of directly entering the “input” model block and the “hydrological” model block is given. This facilitates the entering of new basic data (new lakes) or exercising certain clean-up strategies, load reductions or lake water level regulation.

P balance model with sediment interaction, Lake model No. 3

Explanation

One of the most widely used nutrient (phosphorus) budget models is the one where both the settling and resuspension of the nutrient is considered in the model. In this model block the water budget is also calculated, as it also has a strong bearing on the processes involved. In the sediment phosphorus budget a "burial" reaction is also considered to account for sediment phosphorus, which becomes non-exchangeable. This is a precondition if one wishes to consider the retention (loss) of phosphorus in the system. (**Figure 14.**). There are two ways of using the model: 1/ either the user enters the settling, scouring and burial rates of phosphorus, or 2/ the parameters are estimated by a sub model on the basis of de desired/measured equilibrium in-lake and sediment P concentrations and a retention ratio to be achieved.

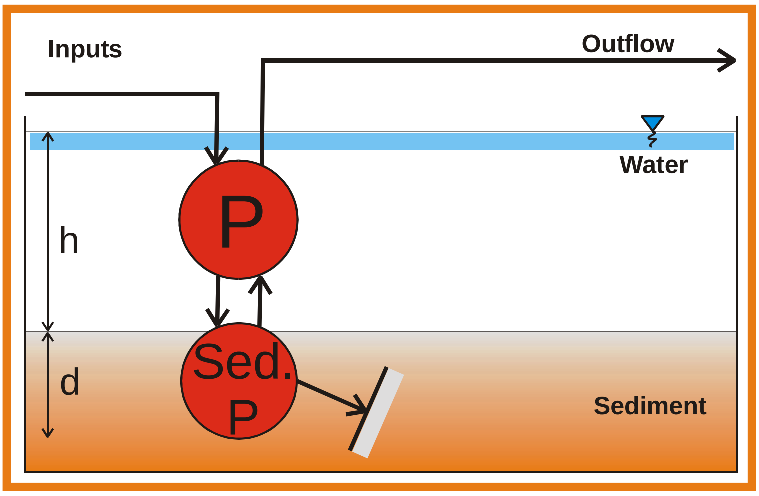


Figure 14.

Model equations

Eq. 5.6

$$\frac{dP_L}{dt} = \frac{1}{Ah}\left[P_{in}Q_{in} - P_L Q_{out}\right] - K_{set}P_L + K_{scu}P_s\frac{d}{h}$$

$$\frac{dP_s}{dt} = \frac{h}{d}K_{set}P_L - K_{scu}P_s - K_{bur}P_s$$

$$\frac{dh}{dt} = \frac{1}{A}\left[Q_{in} - Q_{out}\right] + P - E$$

Legend

P_L- is the in-lake P concentration, [mg/m^3]

P_s- is the P concentration in the sediment, [mg/m^3]

h - is the lake depth, [m]

d - is the depth of the (active, or interactive) sediment, [m]

Q_{in}, Q_{out} - are the inflow and outflow rates of the lake, respectively, [m^3/s];

P_{in} - is the P concentration in the inflow, [mg/m^3]

K_{set} - is the sedimentation (settling) rate constant of phosphorus [year^{-1}]

K_{scu} - is the phosphorus resuspension (scouring) rate constant, [year^{-1}]

K_{bur} - is the phosphorus "burial" coefficient [year^{-1}]

A - the average lake surface area, [km^{-1}]

P and E - are the precipitation and evaporation onto/from the lake surface, respectively, [m]

Parameter estimation sub-model

Description

If one has information on the actual (measured) or desired (planned) in-lake (equilibrium) phosphorus concentration and the actual or allowable (planned) equilibrium sediment P concentration (in the upper active layer of the sediment), then one can estimate first the burial rate, then the sedimentation (settling) rate K_{set} and scouring rate K_{scu}, that would be needed for achieving the actual/planned conditions by the submodels shown here (they can be derived from the basic balance equations).

sub-model equations

Eq. 5.7

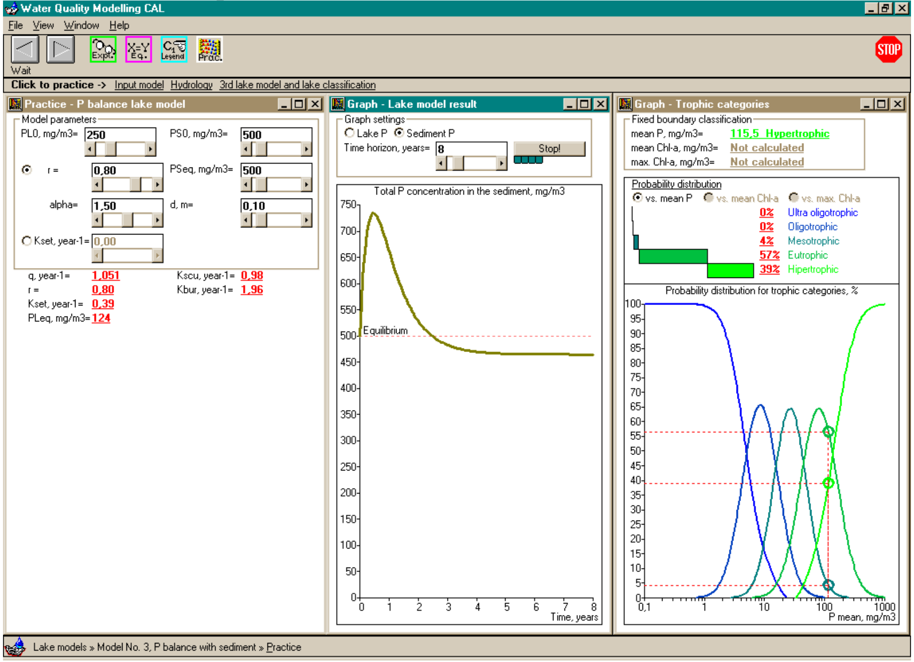
$$K_{bur} = \frac{q(1-r)P_{in}}{\frac{d}{h}P_{Seq}} \qquad K_{set} > q\left(\frac{1}{r}-1\right)$$

$$K_{scu} = \frac{K_{set} - q\left(\frac{1}{r}-1\right)}{\frac{P_{Seq}}{P_{Leq}}\frac{d}{h}} \qquad r = \frac{P_{Leq}}{P_{in}}$$

Legend

K_{set}- is the sedimentation (settling) rate constant of phosphorus [year^{-1}]
K_{scu} - is the phosphorus resuspension (scouring) rate constant, [year^{-1}]
K_{bur} - is the sediment phosphorus "burial" coefficient [year^{-1}]
q - is the hydraulic washout rate: inflow=outflow= Q divided by the lake volume V,[year^{-1}]
P_{Leq} - is the equilibrium phosphorus concentration in the lake water, [mg/m^3]
P_{in} - is the average P concentration in the inflow, [mg/m^3]
P_{seq} - is the equilibrium phosphorus concentration in the active sediment layer (of d m depth)
r- is the retention ratio of phosphorus in the lake

Figure 15. shows the screen outprint of the results of lake model No. 3:



Model parameters

PL0, mg/m3= 250
PS0, mg/m3= 500
● r = 0,80
PSeq, mg/m3= 500
alpha= 1,50
d, m= 0,10
○ Kset, year-1= 0,00

q, year-1= 1,051
r = 0,80
Kset, year-1= 0,39
PLeq, mg/m3= 124
Kscu, year-1= 0,98
Kbur, year-1= 1,96

Graph settings

○ Lake P ● Sediment P
Time horizon, years= 8

Fixed boundary classification

mean P, mg/m3= 115,5 Hypertrophic
mean Chl-a, mg/m3= Not calculated
max. Chl-a, mg/m3= Not calculated

Probability distribution

● vs. mean P ○ vs. mean Chl-a ○ vs. max. Chl-a

0%	Ultra oligotrophic
0%	Oligotrophic
4%	Mesotrophic
57%	Eutrophic
39%	Hipertrophic

Lake models » Model No. 3, P balance with sediment » Practice

Figure 15.

P budget model coupled with experimental eutrophication model, Lake-Model No.4

Description

One step forward in eutrophication modelling is when the nutrient budget model is coupled with an experimental regression model between the nutrient and an index of the trophic state (usually chlorophyll-a), as indicated by **Figure 16.**

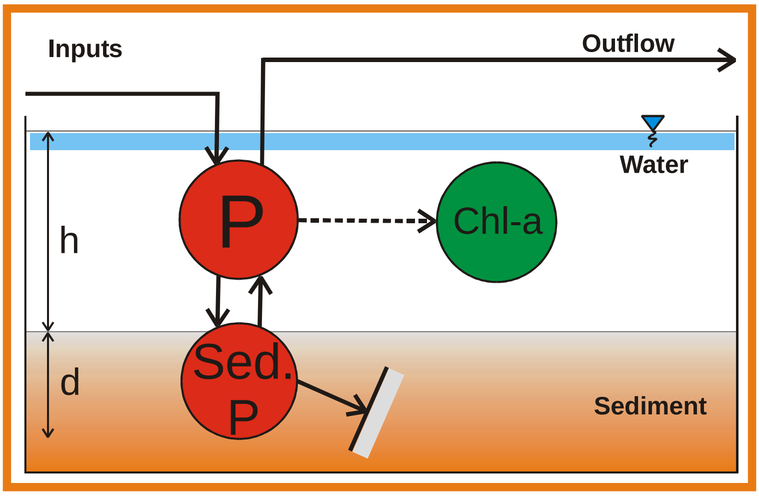


Figure 16.

The software programme is based on the following equations

Model equations

Eq. 5.8

$$\frac{dP_L}{dt} = \frac{1}{Ah}\left[P_{in}Q_{in} - P_L Q_{out}\right] - K_{set}P_L + K_{scu}P_s\frac{d}{h}$$

$$\frac{d\,P_s}{dt} = \frac{h}{d}K_{set}P_L - K_{scu}P_s - K_{bur}P_s$$

$$\frac{dh}{dt} = \frac{1}{A}\left[Q_{in} - Q_{out}\right] + P - E$$

and

Eq. 5.9

$$Chl_{mean} = 0.52\,P_L^{\,0.82}$$

$$Chl_{\max} = 0.74\,P_L^{\,0.96}$$

Legend

P_L- is the in-lake P concentration, [mg/m^3]

P_s- is the P concentration in the sediment, [mg/m^3]

h - is the lake depth, [m]

d - is the depth of the (active, or interactive) sediment, [m]

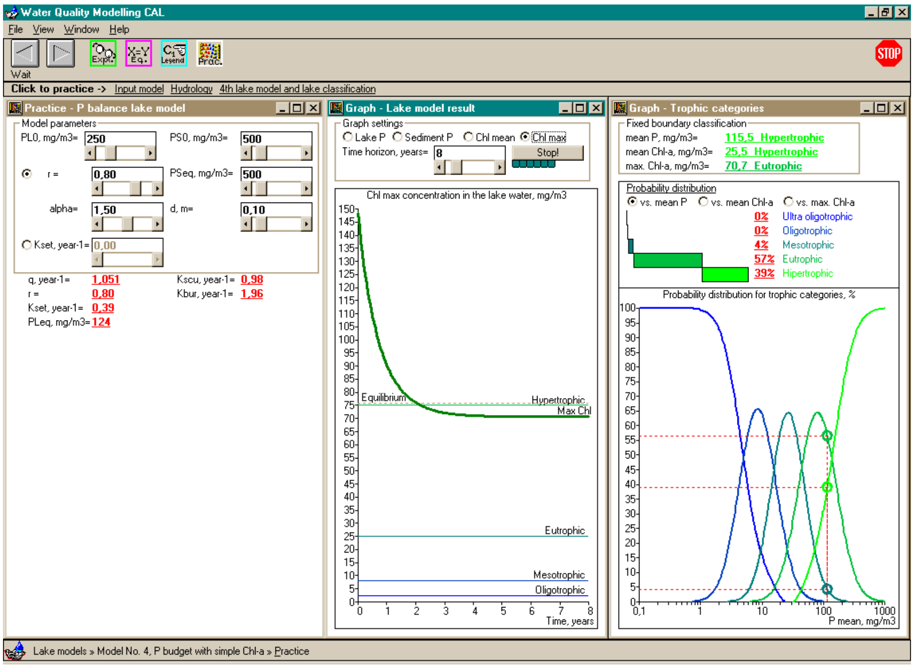
Q_{in}, Q_{out} - are the inflow and outflow rates of the lake, respectively, [m^3/s];

P_{in} - is the P concentration in the inflow, [mg/m^3]

K_{set} - is the sedimentation (settling) rate constant of phosphorus [year^{-1}]

K_{scu} - is the phosphorus resuspension (scouring) rate constant, [year^{-1}]
K_{bur} - is the phosphorus "burial" coefficient [year^{-1}]
A - the average lake surface area, [km^{-1}]
P and E - are the precipitation and evaporation onto/from the lake surface, respectively, [m]
Chl_{max}, Chl_{mean} - are the maximum and mean concentration of chlorophyll-a, respectively.

Figure 17. shows the result-screen of Lake model No.4:



Water Quality Modelling CAL

Click to practice -> Input model Hydrology 4th lake model and lake classification

Practice - P balance lake model

Model parameters
PL0, mg/m3= 250
PS0, mg/m3= 500
● r = 0,80
PSeq, mg/m3= 500
alpha= 1,50
d, m= 0,10
○ Kset, year-1= 0,00

q, year-1= 1,051
Kscu, year-1= 0,98
r = 0,80
Kbur, year-1= 1,96
Kset, year-1= 0,39
PLeq, mg/m3= 124

Graph - Lake model result

Graph settings
○ Lake P ○ Sediment P ○ Chl mean ● Chl max
Time horizon, years= 8

Graph - Trophic categories

Fixed boundary classification
mean P, mg/m3= 115,5 Hypertrophic
mean Chl-a, mg/m3= 25,5 Hypertrophic
max. Chl-a, mg/m3= 70,7 Eutrophic

Probability distribution
● vs. mean P ○ vs. mean Chl-a ○ vs. max. Chl-a
0% Ultra oligotrophic
0% Oligotrophic
4% Mesotrophic
57% Eutrophic
39% Hipertrophic

Lake models » Model No. 4, P budget with simple Chl-a » Practice

Figure 17.

Dynamic algae growth model, Lake model No.5

Explanation

In this model the dynamic phosphorus budget model (Lake model No.3) is coupled with an algae growth model. (**Figure 18**). Algae growth is assumed to be limited by phosphorus and temperature (Light limitation is assumed to be included in the temperature limiting function), and the limitation by other plant nutrients is neglected. This latter is usually a correct assumption for the nitrogen-fixing blue-green algae. This model is also driven by the results of the Input-load model and the lake water budget regulation model.

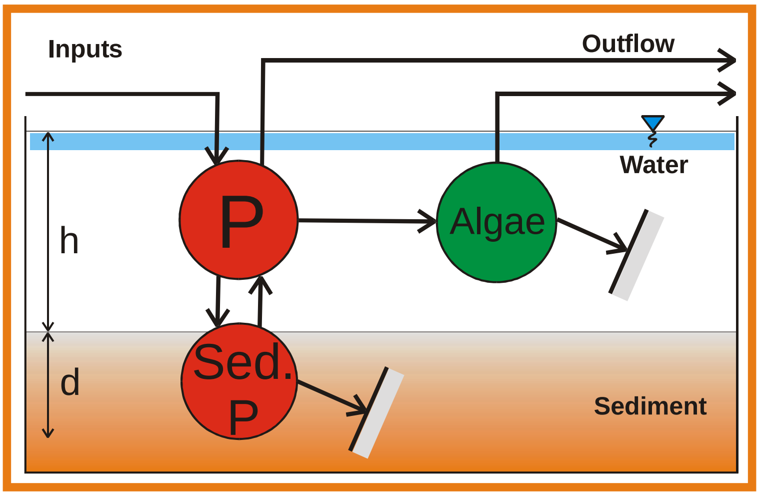


Figure 18.

Model equations

Eq. 5.10

$$\frac{dP_L}{dt} = \frac{1}{Ah}\left[P_{in} Q_{in} - P_L Q_{out}\right] - K_{set} P_L + K_{scu} P_s \frac{d}{h}$$

$$\frac{dP_s}{dt} = \frac{h}{d} K_{set} P_L - K_{scu} P_s - K_{bur} P_s$$

$$\frac{dh}{dt} = \frac{1}{A}\left[Q_{in} - Q_{out}\right] + P - E$$

and

Eq. 5.11

$$\frac{dAB}{dt} = \frac{1}{Ah}\left[Q_{in} AB_{in} - AB\, Q_{out}\right] + \mu AB - K_a AB$$

$$\mu = \mu_{\max} \frac{P_L}{K_p + P_L} TEMPLIM$$

$$Chl - a = \alpha AB$$

and

Eq. 5.12

$$TEMPLIM = \frac{t_c - t}{t_c - t_o} \exp\left(1 - \frac{t_c - t}{t_c - t_o} \right) \; if \;\; t \leq t_c$$

$$0 \; if \;\; t > t_c$$

Legend

P_L- is the in-lake P concentration, [mg/m^3]
P_s- is the P concentration in the sediment, [mg/m^3]
h - is the lake depth, [m]
d - is the depth of the (active, or interactive) sediment, [m]
Q_{in}, Q_{out} - are the inflow and outflow rates of the lake, respectively, [m^3/s];
P_{in} - is the P concentration in the inflow, [mg/m^3]
K_{set} - is the sedimentation (settling) rate constant of phosphorus [year^{-1}]
K_{scu} - is the phosphorus resuspension (scouring) rate constant, [year^{-1}]
K_{bur} - is the phosphorus "burial" coefficient [year^{-1}]
A - the average lake surface area, [km^{-1}]
AB - is the concentration of algae biomass
AB_{in} - algae biomass concentration in the inflow
K_a - is the lumped algae loss rate constant (mortality and zooplankton grazing)
P and E - are the precipitation and evaporation onto/from the lake surface, respectively
μ - is the growth rate of algae
μ_{max} - is the maximum growth rate of algae
K_p- is the half-saturation constant for algae growth (P concentration at which the growth rate is half of the maximum)
TEMPLIM- is the temperature limiting function (1>TEMPLIM>0), a function of the water temperature
α - is a proportionality factor between algae biomass and chlorophyll-a (set for the model as that of the recent average of the Keszthely Bay of Lake Balaton, Hungary);
Chl-a; Chlorophyll-a concentration

Models of parameter estimation

Explanation

In order to keep the model parameters within realistic ranges, they are estimated on the basis of certain assumptions. The first assumption is that the model can be calibrated against measurement data of stabilised (equilibrium) state of the lake (or data of an assumed, planned state). For the estimation of the parameters of the phosphorus budget part of this model see there (lake models nos. 2-3). For the algae growth model the half-saturation parameter K_p is estimated with the assumption that at a very low phosphorus concentration (for which we suggest the use of the upper limit value of Class I. TP concentration and "wired in" the value of the Hungarian water quality standard), the growth rate will be one-tenth of the maximum growth rate, or lower. For the lumped algae loss rate coefficient K_a only a relationship with the maximum growth rate μ_{max} can be derived for the known or planned equilibrium state of the system (using retention ratios r of phosphorus, and r_a for algae).

Submodel equations

Eq. 5.13

$$K_p = \frac{P_{LCl.I}(1 - r_p)}{r_p} \qquad K_a = \mu_{\max}\frac{P_{Leq}}{K_p + P_{Leq}}\overline{TEMPLIM} + q(r_a - 1)$$

Legend

K_p- is the half-saturation constant for algae growth (in lake TP concentration at which the growth rate of algae is half of the maximum)

$P_{L,Cl.I}$ - is the upper limit value of water quality Class I (excellent) for total phosphorus in lake water

r_p - is the fraction (0.1>x>0), a reduction multiplier, of the maximum growth rate of algae (their product -e.g. $\mu_{low} = x*\mu_{max}$- is the assumed growth rate at Class I. TP concentration)

P_{Leq} - is the measured (or desired) new equilibrium annual mean total phosphorus concentration of the lake water ($P_{Leq} = r*P_{in}$)

r_a - is the ratio of the (desired) maximum in-lake algae biomass to the biomass in the in-flow: $r_a = AB_{in}/AB_{Leq,max}$

Figure 19/a and 19/b shows the results of algae-phosphorus lake model (No.5) for two situations, with slight changes only in the forest/agriculture land-use proportions. The dramatic effect of deforestation and increasing agricultural land is apparent in that the algae peaks does not seem to attenuate, after the unfavourable changes.

Results of input load model

Pin, mg/m3= 655,8
Qin, m3/s= 0,412
Lpt, kg/day= 0,0
Lnps, kg/day= 23,4
Total load, kg/day= 23,4

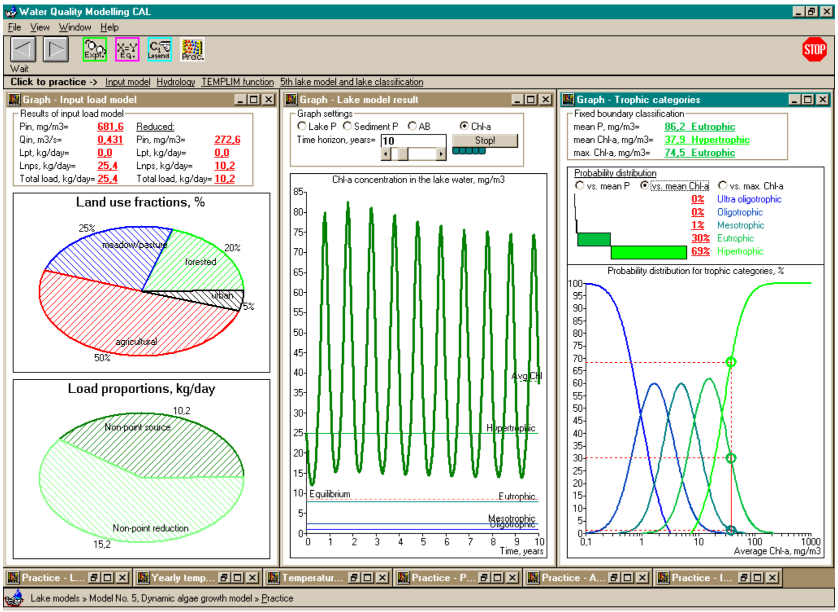
Reduced:
Pin, mg/m3= 262,3
Lpt, kg/day= 0,0
Lnps, kg/day= 9,3
Total load, kg/day= 9,3

Graph settings
○ Lake P ○ Sediment P ○ AB ● Chl-a
Time horizon, years= 10

Fixed boundary classification
mean P, mg/m3= 80,4 Eutrophic
mean Chl-a, mg/m3= 16,3 Eutrophic
max. Chl-a, mg/m3= 30,9 Eutrophic

Probability distribution
○ vs. mean P ● vs. mean Chl-a ○ vs. max. Chl-a
0% Ultra oligotrophic
1% Oligotrophic
16% Mesotrophic
62% Eutrophic
21% Hipertrophic

Figure 19/a



Results of input load model

		Reduced:	
Pin, mg/m3=	681,6	Pin, mg/m3=	272,6
Qin, m3/s=	0,431	Lpt, kg/day=	0,0
Lpt, kg/day=	0,0	Lnps, kg/day=	10,2
Lnps, kg/day=	25,4	Total load, kg/day=	10,2
Total load, kg/day=	25,4		

Graph settings

○ Lake P ○ Sediment P ○ AB ● Chl-a

Time horizon, years= 10

Fixed boundary classification

mean P, mg/m3= 86,2 Eutrophic
mean Chl-a, mg/m3= 37,9 Hypertrophic
max. Chl-a, mg/m3= 74,5 Eutrophic

Probability distribution

○ vs. mean P ● vs. mean Chl-a ○ vs. max. Chl-a

0%	Ultra oligotrophic
0%	Oligotrophic
1%	Mesotrophic
30%	Eutrophic
69%	Hipertrophic

Figure 19/b

Further remarks:

A very large variety of algae-growth models exist in the relevant literature. They also use a high variety of nutrient, temperature and light limitation functions.

Water quality limit values

Water quality limit values can be entered through the respective menu of the programme (WG limit values). For BOD_5 and DO the initial or default values of the programme those of the presently valid Hungarian surface water quality standard (as of 1994) are used. the user can enter the values of his/her respective home country standard, provided it consists also of five quality classes.

In the case of the longitudinal dispersion-advection model, the "pollution wave model" the user is kindly advised to consult the water quality standard of his/her home country in order to gain a realistic case, when a pollutant is named (the model can be used for any non-conservative substance, provided that the assumption of first order reaction kinetics holds).

In the case of the transversal mixing model the user can set a "critical value" for the pollutant investigated, the violation of which at a pre-selected downstream distance renders the situation (for example the installation of a water intake work) hazardous. The user is kindly advised again to consult the water quality standard (for drinking water intake, for example) of his/her home country in order to gain a realistic case, when a pollutant is named.

In the case of lake-eutrophication models the quality classes "wired-in" are those of the OECD report (OECD, 1982) and are not to be changed, since the probability distributions, which gives the "final evaluation", e.g. the probability of a value representing a given trophic category, also originate from this report.

Exercises for using the programme for teaching/learning

Below exercises (numerical examples) will be given for each of the main model blocks of the software, together with the solution and some explanation on how to reach the solution. These are to guide the teacher/student in creating similar examples for using this software.

Important note: The cases to be analysed include certain names of towns, rivers, etc. They are mostly fantasy names. The exception is the accidental pollutant spill case, where we used the real names of the recent (February, 2000) catastrophic cyanide spill of the Szamos-Tisza-Danube river system, as it certainly was of world wide interest at the time of developing this version of the software. Nevertheless**, the data and the simulation results presented below are of no scientific (and even less political) importance, as the methods presented in this software are highly simplified and serve only for teaching purposes**.

In this context the author wish to emphasise again that the software and the models are not intended for use in practical work (design, water pollution control planning, environmental impact assessment, etc) and serve solely for teaching purposes. This means that for the purpose of this CAL (for the purpose of ensuring fail-safe running of the models) many such approximations, simplifications and assumptions were made that would not be acceptable in the real life, in practical water quality modelling activities. Therefore ***the authors also wish to state that they do not assume any responsibility for failures, faults or damages caused by such non-intended use of the software and the programme.***

The user can generate and handle many more similar water pollution control or environmental management situations with the use of this software. Read more of the respective literature of water pollution control and of the management of aquatic ecosystems. However, be aware that you must not use this software for actual water pollution control calculations, as the models are oversimplified for the purpose of this programme and thus serve solely for teaching/learning purposes.

We wish you success in your teaching/learning programme.

Exercise 0. Design of sewage treatment efficiency (a task which can be solved without any environmental-engineering knowledge)

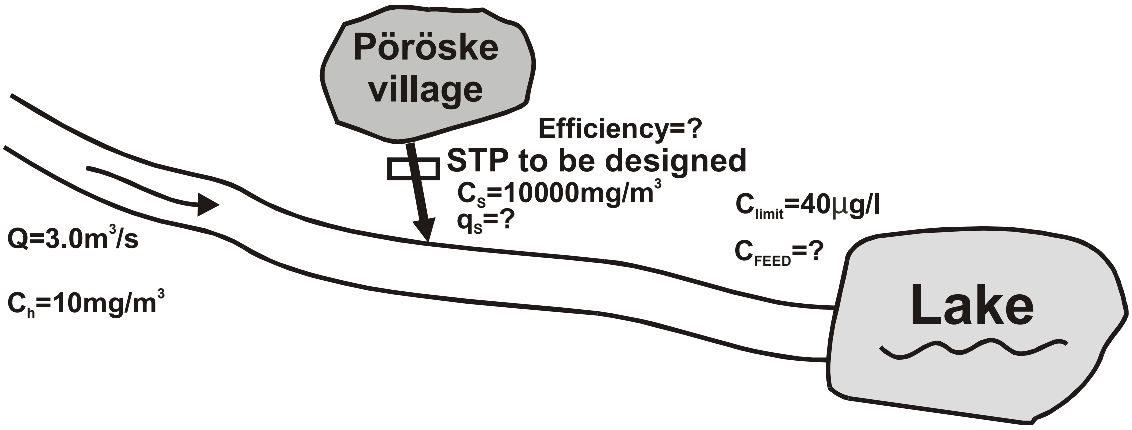
The village of Pöröske is in the valley of the River Abakoppány. The multiannual mean flow of the river is 3.0 m^3/s. Population of Pöröske is 6000. The daily average water consumption is 250 litre/capita/day. Water utilisation (the water spent for watering gardens, watering animals, etc) is 20%. Sewers are built in the village and they plan the construction of a sewage treatment plant. The local government also wishes to construct a small recreational reservoir downstream of the site of the planned effluent discharge. Licensing (getting the permit for constructions) is under way but the local authority has to prove that the aquatic environment of the to be reservoir will not be impaired by the sewage discharge. Thus the sewage treatment plant should be designed for phosphorus removal too, in order to avoid eutrophication. To achieve this the concentration of phosphorus in the inflow to the planned reservoir should meet the Class I water quality standard for phosphorus (total phosphorus concentration, TP-smaller than 40 mg/m^3).

We also know that the average TP of household sewage water is about 10 mg/l (C_s= 10000 mg/m^3) and the TP concentration of the unpolluted river, upstream of Pöröske, is C_b= 10 mg/m^3.

You are the designer and shall calculate the following:

- What TP concentration will characterize the water of the River Abakoppány, after having the sewage water discharged into it? (C_{feed}=........mg/m^3 ?);
- Does this value meet the Class I water quality?
- If not, what degree (level) of treatment should be secured for phosphorus (what is the required treatment efficiency is percentage)? [Note that the treatment efficiency is η=(1-X)*100, where X is the multiplier of the sewage load, a number between zero and one].

For the solution of this task you must only know (remembering the lectures) that the basis of all water quality management calculations is the making of mass balances, using mass-flux values. The mass-flux or load value is obtained as the product of water discharge (in volume per time dimension) and concentration (in mass per volume unit), yielding the load value in mass per time units. You have to the mass balance (mass-flux of the river background + mass-flux of the sewage discharge = resultant mass-flux downstream of the effluent discharge) and express the reservoir's feed water concentration C_{feed} from it.



Solution to Exercise 0

The background load of the river is = $Q * C_b = \underline{3.0 * 10.0= 30\ \text{mg/s}}$
The sewage discharge load is $q_s * C_s= \underline{0.01388 * 10\,000=138.8\ \text{mg/s}}$
(The sewage flow q_s was obtained by multiplying water consumption with the population and the water utilisation rate, converted to m^3/s.)

$$q_s= 250*0.8*6000:86400:1000= \underline{0.01388\ m^3/s}$$

On the basis of the conservation of mass, the following mass balance equation can be written

$$Q * C_b + q_s * C_s= C_{feed} * (Q+q_s)$$

from where

$$C_{feed} = (Q * C_b + q_s * C_s):(Q+q_s)= (30+138.8):3.01388= \underline{56.00\ mg/m^3}$$

Thus the feed water of the planned lake would be higher than the desired Class I. value, that is $\underline{40\ mg/m^3}$.

The desired treatment efficiency [$\eta= (1-X)*100$] is obtained as

$$C_{limit}= \underline{40\ mg/m^3}= (Q * C_b + X*q_s * C_s):(Q+q_s)\text{, from where}$$
$$X= \{(40*3.01388)-30\}:138.8= \underline{0.652}$$

This means that the minimum phosphorus removal efficiency should be **η=<u>35%.</u>**

Exercise 1. Analysis of a pollution case with the traditional BOD-DO model

1. The case

The town of Prettybrooks with a population of 65,000 wishes to build a sewage treatment plant (they did not have one till now). The local Environmental Authority demands an environmental impact assessment to be carried out for the project. The water quality targets to be met in the recipient stream, downstream of the to be sewage outfall are set for the oxygen household conditions as follows:

- Dissolved oxygen (DO) not less than 6 mg/l (Class II., good) in the critical low flow period of 80 per cent duration in the summer months, when the respective flow of the recipient river Little Lousy, upstream of the to be plant is Q= 12 m^3/s.

- BOD_5 less than 6 mgO_2/l (Class II., good)

Water consumption in Prettybrooks is 250 litre/cap./day in average and the estimated water losses of the system in the summer months (evaporation, gardening losses, leakage of the sewer system, etc) is 20%.

The environmental authority supplied the following background data for the river for this critical period:

Background BOD_5 concentration: L_b= 6 mg O_2/l
Background DO: 7 mg O_2/l
Estimated raw sewage strength BOD_5: 550 mg O_2/l,
DOs = 1.5 mg/l
Stream velocity= 0.4 m/s (a slowly flowing stream)
Mean depth of stream: 1.3 m
The river temperature in the summer months is 19 ^oC

Model calculations:

Calculate cross section area and stream width:
Calculate sewage quantity: 0.15 m^3/s

Use the Traditional BOD-DO model from the menu of the CAL programme:
Calculate the dilution equations
Enter the above data

You find L_o= 12.716 mg/l; DO_o= 6.937 mg/l
Check Saturation oxygen level:
You find DO_{sat}= 9.36 mg/l
Initial D (oxygen deficit)= 2.4 mg/l

Enter stream data and calculate K_2 (you find 0.65 day^{-1})

Consider Little Lousy river as a "large slow stream" for the calculation of K_1 by entering K_2/K_1 =1.8

You find K_1= 0.36 day^{-1}, correct for temperature $K_{1(T)}$ = 0.35 day^{-1}

Check the BOD decay curve and compare to limit values above. Calculate the length of river over which the quality criteria would be violated.

You find that it falls below Class II at about 2.2 days (time of travel) and this corresponds to 76 km. The conclusion is that requirements are not met.

Look at the oxygen sag curve. Compare to above criteria. Take note of critical time and DO concentration (1.47 days; 5.3 mg O_2/l)

You observe that DO criteria are also violated.

Design appropriate level of treatment. Note that a relatively good biological sewage treatment system will remove about 80% of the influent BOD. Enter the respective data, using the Practice menu of the traditional BOD-DO model (Date to be entered is 550*0.2= 110 mg/l for sewage BOD).

Observe the effects of this control measure.

You find that DO stay above Class II limit (6 mg/l) over the entire length below the outfall and BOD drops below Class II within short time as well. THUS THE CASE WAS SOLVED, YOUR FIRST EXPERIENCE WAS SUCCESSFUL.

Exercise 2. Analysis of a pollution case with an expanded BOD-DO model

1. The Case

The large city of Seven-Churches is about to build treatment plant and the regional government, the County Seat, is responsible for the larger area. Thus they will have to find a water pollution control solution for the entire catchment of the River Blue Rapids for its 150 km length, downstream of Seven-Churches, until it joins the River Grand Shore at Tricky Bridge. The local Environmental Authority demand an environmental impact assessment to be carried out for the sub-catchment in concern. The water quality targets to be meet over the entire 150 km length of the recipient stream, downstream of the planned sewage outfall are set for the oxygen household conditions as follows:

- Dissolved oxygen (DO) not less than 6 mg/l (Class II., good) in the critical low flow period (flow of 80% duration in the summer months).

- BOD_5 less than 6 mgO_2/l (Class II., good);

Data of the raw sewage of the city are as follows:

Background BOD_5 concentration : 6 mg O_2/l
Background DO: 7 mg O_2/l
Effluent discharge: 0.72 m^3/s
Estimated raw sewage strength BOD_5: 420 mg O_2/l
Oxygen content of the effluent: 1.5 mg/l
Stream velocity = 0.6 m/s (large river of medium flow velocity. Select f=2.0)
Mean depth of stream: 2.5 m
The river temperature in the summer months is 21 ^oC
Critical summer flow upstream of the city: 52 m^3/s

The river Blue Rapids has only several small, non-monitored, tributaries over this 150 km length downstream of Seven-Churches and you know from the hydrological flow profile data, from that of the hydrographic station at Tricky Bridge that the corresponding flow there is 68 m^3/s.
We do not have data on the pollution sources of the highly populated and agriculturally also cultivated watershed of Blue Rapids and consequently we must assume that they represent non-point source input to the river.

Use the 2nd Expanded BOD-DO model from the menu, which allows for NPS input loads:

Calculate lateral inflow q (68-(52+0.72)):150,000=0.000107 m^2/s.
Also calculate width of the river downstream of Seven Churches, because you will need it later: B=(52+0.72)/2.5/0.6=34.7 m.

Assume for non-point source BOD runoff strength 20 mg/l (a good average estimate for larger populated watersheds with mixed land use) and take its DO content as 4.0 mg/l.

Set for the time being both benthic oxygen demand and photosynthesis-respiration (source-sink) term to zero (note that P-R can not be set to zero, just near to zero, to avoid division by zero).

Make observations on the resulting model run. Can the water quality criteria be met without any control action?:

You observe that for BOD the desired Class II. water quality would be reached after about 6 days time of travel only, that corresponds to some 311 km river length, which means that the entire river reach in concern would be polluted. You also observe that the critical DO also falls below Class II (it is about 4.7 mg/l).

Design alternative cleanup measures for point and non-point source pollution:

1. Calculate the effect of 80% BOD removal at the effluent outfall of the city. Go back to the respective menu item (e.g. dilution equations) .You should enter 0.2x420=84 mg/l for BOD strength Ls. You will find that the critical DO is still below 6 mg/l and BOD remains also high over a longer reach of the river. Thus the task was not accomplished.

2. Assume point and non-point source control strategies to be introduced over the entire catchment basin. Assume 50% NPS BOD removal and only 25% improvement in the DO conditions (note that all these actions will appear as NPS reduction in your model; also note that overall catchment management measures can hardly exceed an efficiency of 50% reduction, not even at high costs). Enter 10 mg/l for L_d and 5 mg/l for C_d). Observe and make notes on the results.

   You find that DO sag curve remains just above the Class II. level and that BOD also drops below Class II over relatively short time/distance

3. Considering the fact that overall catchment management measures are very expensive and cumbersome to accomplish (although this must be the final solution) you may wish to investigate the effects of less efficient overall strategies. Consider 20% BOD removal only (You enter 0.8x20=16 mg/l for Ld) and you observe a small violation of DO targets).

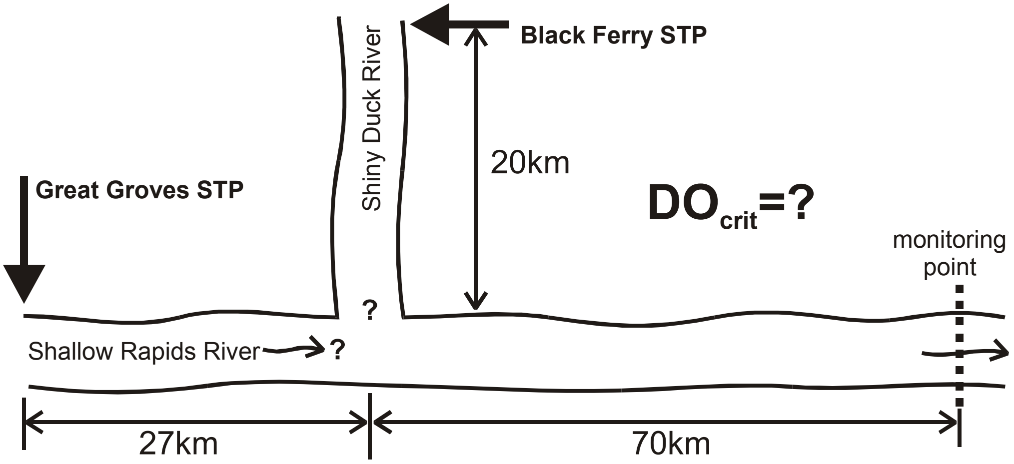
4. Try to think in terms of some stream aeration measures (there are many technical means for it) to improve the situation. (The P-R term of the model can be used for this). Calculate how much oxygen input you need to achieve WQ targets. You find that giving low values for P-R you will get good results, e.g. the model is very sensitive to this term. Calculate the amount of oxygen needed for 0.15 gO_2/m^3/day input. This is 52x86,400x0.15= 673.92 kg oxygen per day.

5. Try to consider some hydraulic river aeration means by assuming the increase of river flow velocity and the decrease of flow depth (turn back to the menu item "K_2 estimating”). Note that flow velocity and depth are interrelated through the discharge and the relatively unchanged river width ($Q=B \cdot h \cdot v$). Use "fast flowing stream" in estimating K_1. You will find that there is a considerable improvement in the BOD-DO conditions. You should also observe that the building of hydraulic structures is also a very expensive measure in larger rivers and it may be obstacled by the requirements of navigation and environmental protection.

Exercise 3. Analysis of a complex, multiple source, pollution situation with the simple BOD model

The Case

Consider a complex situation (more realistic), when there are 2 sources of pollution in the same river system. See the corresponding Figure.



The environmental authority requests the compliance with the following oxygen household limit values, over the entire river system:

Dissolved oxygen > 6.00 mg/l

Biochemical oxygen demand (BOD_5) < 6.00 mg/l

The upstream background conditions of the main river and the planned sewage discharge of the town Great-Groves are characterized by the following data:

Raw sewage strength (BOD),	L_{s1} = 420 (mg O_2/l)
Effluent discharge	q_{s1} = 0.72 (m^3/s)
Effluent DO	DO_{s1}= 2.00 (mg O_2/l)
River (design) flow	Q_{b1} = 52.0 (m^3/s)
Background BOD	L_{b1} = 6.0 (mg O_2/l)
Background DO	DO_{b1} = 7.0 (mg O_2/l)
River flow velocity	v_1 = 0.6 (m/s) (f=2.00)
Mean flow depth	h_1 = 2.5 m

Characteristic water temperature = 21 °C

Use the dilution equation and calculate the initial values:

L_0 =......11.654..mgO_2/l.. DO_0=.......6.925.mgO_2/l....D_0 (oxygen deficit):....2.1.mgO_2/l...

The other source, the town of Black Ferry, is located on the Shiny Duck river 20 km upstream from the confluence with the River Shallow Rapids, which is 27 km downstream from Great Groves. The population of Black Ferry is 65,000. The per capita water consumption rate is 250 litre/day and the water losses amount to 20% (drinking, bathing, watering, etc). The design discharge (August low flow) of Shiny Duck river is 12.0 m^3/s.

Other data are as follows:

Raw sewage strength (BOD), L_{s2} = 550 (mg O_2/l)

Effluent discharge	q_{s2} =..0.15......(calculate) (m^3/s)
Effluent DO	DO_{s2}= 2.5 (mgO_2/l)

River flow	Q_{b2} = 12.0 (m^3/s)
Background BOD	L_{b2} = 6.0 (mg O_2/l)

Background DO	DO_b= 7.0 (mg O_2/l)
River flow velocity	v_2 = 0.4 (m/s) (slow river, f= 1.5)
Average flow depth	h_2 = 1.3 m
Water temperature	21 ^oC

Use the dilution equation and calculate the initial values:
L_0 =......12.716. mgO_2/l... DO_0=.......6.944. mgO_2/l....D_0 (oxygen deficit):....2.07. mgO_2/l...

Downstream of the confluence with Shiny Duck, the River Shallow Rapids is characterized by the following data: flow velocity v_3= 0.5 m/s, water depth d_2= 2.0 m.

The task is to analyse the oxygen household conditions over the entire river system and design the treatment efficiencies, needed for meeting the limit values.

Make the following calculations:

1. Calculate (manually) the BOD and DO concentrations for the section of the River Shallow Rapids just upstream of its confluence with the river Shiny Duck (calculate values for the 27 km distance). Also calculate the critical DO levels and their locations, checking that whether they would occur within this 27 km or not. Use the CAL programme or calculate all parameters manually using the manual of the CAL programme (Equations 2.2 - 2.14).

K_{11} =..0.19..... day^{-1}
K_{21} =..0.35......day^{-1}
x_{1crit}=....144.6....km (t_{crit}=...2.79.....days, not falling into the reach)
DO_{1crit}=....5.37....mg O_2/l
BOD at 27 km=..10.54.......mg O_2/l
DO at 27 km=....6.27......mg O_2/l

2. Repeat the calculation with the data of Black Ferry, and Shiny Duck River, for the section upstream of the confluence (20 km)

K_{12} =...0.45.... day^{-1}
K_{22} =...0.65.....day^{-1}
x_{2crit}=..50.45......km (t_{crit}=...1.46.....days) not falling into the reach
DO_{2crit}=...4.44.....mg O_2/l
BOD at 20 km=..9.80.......mg O_2/l
DO at 20 km=...5.16.......mg O_2/l

3. Calculate the BOD-DO conditions of the Shallow Rapids river reach downstream of the confluence of the Shiny Duck river. Use again the dilution equation (*consider the Shiny Duck river as the "effluent"*) using the above calculated BOD and DO data.

K_{13} =...0.29.... day^{-1}
K_{23} =...0.42.....day^{-1}
x_{3crit}=...76.....km (t_{crit}=...1.76.....days)
DO_{3crit}=...4.72.....mg O_2/l

4. Calculate the effect of 80% BOD removal at both treatment plants on the BOD-DO conditions of the river system. Consider DO_s= 5.0 mg O_2/l for the treated effluent.

5. Compose a "treatment model" for the overall case, expressing the resultant BOD concentration of the monitoring point, 70 km downstream of the confluence of the two rivers, in function of the treatment efficiencies of the two plants in the form of

$L_{monitoring\ point} = a\ \eta_1 + b\eta_2\ + d$

where

$\eta_{1.,2}$- are the treatment factors of the respective treatment plants (fraction of BOD load remaining after treatment (e.g. 80% efficiency corresponds to $\eta=0.2$).

Write the dilution equations and use the BOD decay equation in formulating the model. Determine model coefficients a, b, and c. Use the model for checking various control (removal) options and variations.

Solution

The BOD in Shallow Rapids upstream of the confluence with Shiny Duck river is obtained as:

$L_{1v} = [(L_{s1}*q_{s1}*\exp\text{-}K_{11}t_1):(Q_{b1}+q_{s1})]*\eta_1 +[(Q_{b1}*L_{b1}*\exp\text{-}K_{11}t_1):(Q_{b1}+q_{s1})] = A*\eta_1+B$

where: $A=[(L_{s1}*q_{s1}*\exp\text{-}K_{11}t_1):(Q_{b1}+q_{s1})]=(420*0.72*0.906):(52+0.72)=5.2$ and

$B=(Q_{b1}*L_{b1}*\exp\text{-}K_{11}t_1):(Q_{b1}+q_{s1})=(52*6.0*0.906):52.72=5.36$

Similarly the BOD of Shiny Duck river upstream of the confluence with Shallow Rapids river will be:

$L_{2v} = [(L_{s2}*q_{s2}*\exp\text{-}K_{12}t_2):(Q_{b2}+q_{s2})]*\eta_2 +[(Q_{b2}*L_{b2}*\exp\text{-}K_{12}t_2):(Q_{b2}+q_{s2})]= C\eta_2+D$

where: $C=(L_{s2}*q_{s2}*\exp\text{-}K_{12}t_2):(Q_{b2}+q_{s2})=(550*0.15*0.771):(12+0.15)=5.23$ and

$D=(Q_{b2}*L_{b2}*\exp\text{-}K_{12}t_2):(Q_{b2}+q_{s2})=(12*6*0.771):12.15=4.57$

Note that the times of travel are:

$t_1 = 27000:0.6:86400=0.521$ days and $\exp(-K_{11}t_1) = 0.906$

$t_2 = 20000:0.4:86400=0.578$ days and $\exp(-K_{12}t_2) = 0.771$

$t_3 = 70000:0.5:86400=1.62$ days and $\exp(-K_{13}t_3) = 0.625$

Next, the BOD concentration of the river Shallow Rapids at the end of the reach examined (control point) is calculated as:

$L_{monitoring}=[(A*\eta_1+B)*(Q_{b1}+q_{s1}) + (C\eta_2+D)*(Q_{b2}+q_{s2})]*\exp\text{-}K_{13}t_3 : (Q_{b1}+q_{s1} + Q_{b2}+q_{s2})$

Combining the three equations you obtain:

$L_{monitoring}=[(5.2*\eta_1+ 5.36)*52.72) +(5.23*\eta_2+4.57)*12.15]*0.625 : (52.72+12.15)=$
$=2.64*\eta_1 + 0.612*\eta_2+3.25$

Thus for example 80% treatment at both plants would result in the following BOD concentration in the monitoring station 70 km downstream of the confluence of the two rivers

$L_{80\%treatment} = 2.64*0.2 +0.612*0.2 +3.25= 3.9$ mg O_2/l

Note that due to the higher multiplier of η_1 the same BOD removal rate at the larger source will be more efficient in cleaning up the river than at the smaller source (an evident result).

Exercise 4. Analysis of an accidental pollution case

The Case

An oil transporter lorry has fallen into a river from over the bridge. Its load of 2 tonnes of mineral oil has been instantaneously discharged into the river.

Use the "longitudinal dispersion model " of the CAL programme

The river data are as follows:
River flow Q = 300 m^3/s
Channel slope, S = 20 cm/km
River width, B= 60 m
Flow velocity, v= 0.7 m/s

Set alarm concentration to 300 µg/l.
Consider zero decay of the oil (K=0)
Calculate flow depth and cross-section area. H=...7.14.m, A=....428.57.m^2.
What is the value of the dispersion coefficient D_L =….134.85.m^2/s.
Find the place where the concentration decreases below alarm level (exactly at 100 km downstream of the source).

There is a drinking water intake at 40 km downstream of the accident.
Hand-calculate maximum concentration value of the pollution wave at 40 km, downstream of the site of the accident. (…0.474….mg/l).

When does the pollution peak arrive to this section?...........15.87........hours,

How much will be the pollutant concentration at the section of the water intake two hours earlier: $C_{40km,\ 13.87\ h}$=...........197..........µg/l (t=…49932.. s)

How much lead time the operators of this waterworks have for action until the above calculated (not yet critical) concentration arrives (your work, as an experienced modelling specialist has taken 1.0 h and you were informed about the accident in half an hour)

$T_{lead\ time\ for\ action}$=......13.87-1.5 = 12.37......................h

After the event has passed you were given recorded data. You certainly wish to process these data in order you update the knowledge on river parameters (e.g. obtain correct values for the dispersion coefficient). The reported measurement data are as follows:

At a station 10 km downstream $C_{1\ max}$= 1.0 mg/l, while at another one at 25 km distance it was $C_{2\ max}$ =0.6 mg/l. Find the appropriate formula in the lecture notes.

Calculate D_L = ….113.78 …. m^2/s
Correct your prediction for the site where the alarm level is not exceeded. Change only average stream width. (B= 71 m, D_L= 113.96, alarm level is reached at 120 km)

Exercise 4a. Analysis of another accidental pollution event

The Case

You are to evaluate the likely near-source circumstances of the catastrophic cyanide pollution spill, which occurred at 22:00 p.m. on the 30th of January, 2000 at the tailings pond of a gold-mining company of Baia Mare (Nagybánya), Romania, due to the failure of the dam of the pond. The pollutant spill then flowed into the river Lapus in Romania, then entered the River Somes/Szamos which crosses the border to Hungary, then enters the River Tisza, which flows into the Danube and then the Black Sea.

The peak of the concentration wave arrived to Csenger station, at the Hungarian/Rumanian border, with a cyanide (CN) concentration of C_{max}=32.6 mg/l at 20:30 p.m., on the 1st of February 2000. Csenger is located approximately 100 km downstream of the site of the spill.
The flow of the river Szamos at Csenger was Q= 160 m^3/s.
Cyanide is a relatively conservative substance not subject to decay (K=0).
Evaluating teams processing the stream measurement data of the entire river system estimated that the quantity of the pollutant spilled was about 100 tons of cyanide.

Estimate the longitudinal dispersion coefficient from these above data:

Model calculations

(Use the pollutant spill model equation and note that the maximum concentration of a pollutant wave is when $x=v_x t$)
What is the time until the peak concentration arrived: t = 46.5 h=167,400 sec
What is the average flow velocity v_x = 0.6 m/sec (=x/t), A=266.67 m^2
D_x = 62.93 m^2/s $D_L=M^2/(A^2 C_{max}^2 * 4 * \pi * t)$

Choose the "Accidental pollution wave model" from the menu and enter the data (Note: that the maximum pollutant mass that can be entered is 10 tons, because the programme was not designed to events of such magnitude, and thus you will have to multiply all results by 10). Vary channel geometry parameters flow depth (h), channel width (B) and slope (S), within realistic ranges, until you achieve the above calculated value D_x. (D_L=62.54 at S=19.9 cm/km and B=69 m)
Use the model for answering the following questions:

What was the likely CN maximum concentration near (10km) to the source: 103 mg/l.
What could have been the CN maximum concentration at Cicirlua/Nagysikárló (20 km from the source): 73.1 mg/l
What was the CN maximum concentration at Caraseu/Szamoskrassó (approximately 40 km from the source): 51.7 mg/l
What was the likely CN maximum concentration at Satu Mare/Szatmárnémeti (approximately 80 km from the source): 36.5 mg/l

Can it be a correct value if the local authorities reported 7.8 mg/l maximum concentration for Satu Mare: Yes, but they must have certainly missed the peak, by several hours, unless the Csenger value was wrong. Calculate, what could have been the corresponding sampling time, the time-lag, when missing the peak (Setting alarm level to 0.78 mg/l, you find that it intersects the curve of 80 km distance at about 7 km earlier, which corresponds to about 3.2 h time lag).

How the measurement date of the Hungarian authorities at Tunyogmatolcs (approximately 120 km from the source), when they reported a maximum concentration of 30 mg/l, can be confirmed by this calibrated model: very much, the simulated value is 29.8 mg/l.

How the measurement date of the Hungarian authorities at Olcsvaapáti (approximately 145 km from the source), when they reported 25 mg/l maximum concentration, can be confirmed by this calibrated model: It is likely that they slightly missed the peak, because the simulated value is 27.1 mg/l.

Finally note that cyanide is a highly toxic compound. The international limit value is 0.1 mg/l in streams used for drinking water production.

Exercise 5. Analysis of transversal mixing cases

A large industrial discharger seeks to have license from the environmental authorities. It is characterized by the following data:

q_o= 0.85 m^3/s
C_o= 656 mg/l (COD_{cr})

The case is very special since there are water intakes just 1500 m downstream of the planned source. Thus the water quality limit value should be set to Class I (12 mg COD/l).
Data of the recipient river are:

h= 2 m, B= 160 m, v= 0.7 m/s, S= 40 cm/km (do not alter the value of "d" in the programme)

Analyse the case with the transversal mixing model
Note that this model calculates in-stream concentrations, which are due to the given source (e.g. background concentration is considered zero).

1. Analyse the case when the discharge is at the river bank $C_{COD,\ at\ bank}$=……13.8.......mg/l;

2. Determine, how far the source has to be moved towards the main streamline to meet the limit value (Y_{source}=.........approximately. .....12...m)

3. You have to be cautious with your proposal for the discharge permit. Calculate the effluent COD and the required treatment efficiency for allowing discharge at the river bank: C_o=......579…..........mg/l, η=.….12.65……....%

4. To be on the safe side prescribe a distance from the bank, which corresponds to zero concentration (increase) at the riverbank 1500 m downstream.
$Y_{source,0\ increase}$=..100………....m

Investigate a case when the given effluent would be discharged into a river of about ten times less flow (Q= 25 m^3/s). (Leave depth h, velocity v and slope S unchanged, enter the width B that corresponds to the new Q). B=…17.85 (18)………m
Consider that COD value must not exceed the Class II limit value (22 mg/l) after full mixing.

5. How much is the COD concentration increase due to this source after full mixing: $COD_{full,mix}$=..…21.57……...mg/l

6. What level of treatment is needed to meet the Class I limit value at 1500 m downstream, at the river bank, when the discharge point is y_0= 5 m
C_o=.......444.....mg/l, η=......32.3......%

Exercise 6. Analysis of lake eutrophication with experimental regression models (based on the OECD study)

A lake of 10 km^2 area and 5 meters average depth has a drainage area of 100 km^2. The multiannual average runoff is 94.6 mm).

Calculate inflow to the lake: $Q = 0.3\ m^3/s$

Scarce data indicate that the multiannual average inflowing phosphorus concentration is very high, P_{mean}= 800 μg/l

Use the following experimental equations:

Mean chlorophyll-a concentration [mg/m^3]:

$$\text{Chl-a}_{mean} = 0.37\ X^{0.79}$$

Maximum Chl-a concentration [μg/l]:

$$\text{Chl-a}_{max} = 0.74\ X^{0.89}$$

Primary production (gC/m^2 year):

$$PP = 22.9\ X^{0.6} \text{ or}$$

$$PP = 589X/(48+X)$$

where: $X = P_{inflow}/(1 + t_w^{0.5})$, and

P_{inflow}= average concentration of phosphorus in the inflow (mg/m^3)

t_w= mean residence time of water in the lake (in years); average lake volume per average inflow

Calculate the values:

t_w=......5.28......................year

X=...........242.5.............. mg/m^3

Chl-a_{mean}=.......28.3.............mg/m^3

Chl-a_{max}=............98.1.........mg/m^3

PP =...617.5 ; 491.7....................gC/m^2/year

Compare results with the following categories:

Table 1. Fixed trophic state categories of the OECD study (1)

Trophic categories	Indices of trophic state (mg/m^3)		
	P_L	Chl_{mean}	Chl_{max}
Ultra-oligotrophic	< 4.0	<1.0	<2.5
Oligotrophic	<10.0	<2.5	<8.0
Mesotrophic	10-30	2.5-8.0	8.0-25
Eutrophic	35-100	8-25	25-75
Hypertrophic	>100	>25	>75

Trophic state categories, Hungarian guidelines (Felföldy, 1987)

Degree of trophity	Primary production gC/m^2.year	Algal count 10^6/litre	Chlorophyll-a mg/m^3
0 Autrophic	0	0	0
1 Ultra oligotrophic	<10	< 0.01	<1
2 Oligotrophic	11-50	0.01-0.05	1-3
3 Oligo-mesotrophic	26-50	0.05-0.10	4-10
4 Mesotrophic	51-100	0.1-0.5	11-20
5 Meso-eutrophic	101-175	0.5-1.0	21-50
6 Eutrophic	176-300	1-10	51-100
7 Eu-polytrophic	301-500	11-100	101-200
8 Polytrophic	501-800	101-500	201-800
9 Hypertrophic	>800	>500	>800

This means that the expectable state is hypertrophic or eu-polytrophic-polytrophic for primary production.

Calculate the reduction of P load required for meeting the following criteria:

$\text{Chl-a}_{max} < 25\ mg/m^3$

$\text{Chl-a}_{mean} < 8\ mg/m^3$

$PP < 176\ gC/m^2$ /year

P_{inflow}, for Chl-a_{max} <25 mg/m^3: ...172.12......... µg/l
P_{inflow}, for Chl_{mean} <8 mg/m^3: …161.42......... µg/l
P_{inflow}, for PP <176 gC/m^2 /year: ...98.71.......... µg/l (using the first formula)

The original load (how much? ....7568.6.........kg/year) was assumed to include 15% direct point sources and 10% indirect point sources (non-sewered settlements), while the rest was coming via the runoff-load (non-point source input).

Do the calculations for the following situation: 80% P reduction of direct point sources, 60% of indirect point sources and 40% of non-point sources.

How much is the feasibly reduced load?
$L_{reduced}$=..0.24*0.15*0.2 +0.24*0.1*0.4 + 0.24*0.75*0.6= 0.1248 g/s = 3935.7 ..kg/year

Calculate the conditions achievable by this reduced load:
What is the mean P concentration of the inflow?
$P_{inflow,r}$=....0.1248:0.3*1,000=416............... (mg/m^3)
Trophic values achievable by the load reduction:
$X_{improved}$=…126.13.. mg/m^3
Chl-a_{mean}=....16.9................mg/m^3, eutrophic
Chl-a_{max}=.....54.8................mg/m^3, eutrophic
PP =....417.2 ; 426.6..........gC/m^2/year, eu-polytrophic
Compare the results with the categories:

The lake remains eutrophic, although the highly dangerous hypertrophic conditions were relieved. Further improvement is only achievable by drastic measures (forestation, banning certain agricultural practices, declaration of nature conservation areas, etc.). This situation is unfortunately a very realistic one in agricultural catchments

Check whether this "feasible" solution is able to achieve the desired load.

How much is the desired load?
for Chl$_{max}$:......1628.4.........(kg/year)
Chl-a$_{mean}$:..1527.2.........(kg/year)
PP:..........933.9.........(kg/year)

Exercise 6a. Analysis of lake eutrophication with experimental regression models (based on the OECD study) Lake Model No. 1

A lake of 90 km^2 area and 5 meters average depth has a drainage area of 1000 km^2. The multiannual average runoff is 120 mm).

Calculate inflow to the lake: Q = 3.8 m^3/s.
Enter the "hydrology" sub-model, set evaporation equalling precipitation, $Q_{out}=Q_{in}=Q_{out,max}$, $h_{min}=h_{max}=h=$ 5.0 m.
Enter the "input load" menu.
Scarce data indicate that the multiannual average inflowing phosphorus concentration is very high, $P_{mean}=$ 600 µg/l
The point source input is roughly about 25% , how much? (3.8*0.6*86.4*.25=49.2 kg/day). Enter 50 kg/day for the point source.

Check the trophic state, both by the fixed boundary and by the probability distribution (You obtain hypertrophic conditions, with the exception of mean Chl-a, for which both classification shows eutrophic conditions).

Make a "clean up". Use realistic removal rates: 80% for point sources (X,rp=0.2) and 40% for non-point sources (X,rnp=0.6).

Check the trophic state, both by the fixed boundary and by the probability distribution (You obtain eutrophic conditions, with the exception of mean P for the fixed boundaries (101.8 hypertrophic), and eutrophic conditions for the probabilistic classification. Thus you have improved the trophic state by about one category).

Check whether the theoretically achievable best technology (90% point source and 60% non-point source reduction) could help. (You still remain in the eutrophic range).

Note that, unfortunately, it is a realistic scene, and eutrophic conditions remain even after a major cleanup, in cultivated agricultural land.

Switch over to the "non-point source estimate" programme in the input model block (the "catchment model" which calculates -on the basis of fixed literature ranges- runoff load on the basis of land use data to be entered). Set up a realistic land use distribution: e.g. 30% forest, 50% agriculture, 15% meadow and 5% urban land. Try to achieve the same inflow (3.8 m^3/s), by adjusting precipitation. Do not forget to enter the data for the catchment area. Keep the point source load value (50 kg/day) unchanged, by entering concentration (Cpt) and flow (Qpt) data for the point source. (Note that the

phosphorus concentration value of municipal point sources is several thousand μg/l). Vary precipitation in such a way as to obtain the same inflow (Qin) (Cpt= 2000 μg/l, Qpt= 0.290 m3/s, Lpt=50.1 kg/day, Prec=670 mm, Qin 3.796 m3/s).
Set back cleanup factors to 1.00. Go back to the Lake model No.1 and look at the results. Try to change land use proportions for cleanup, cleaning also up the point source.

What do you observe?: (You find that the catchment model yields even more pessimistic conditions.)
Note that the current "built-in" catchment model is very rough and unrealistic and will be replaced by a complete set of sub-models in the 3rd version of this CAL software.

Go back to the input load menu item (for the "data to be entered" alternative). Change the P_{in} to 300 mg/m^3. Set point source input to 20 kg/day.

Set back cleanup factors to 1.00
Check the trophic state, both by the fixed category and by the probability distribution (You still obtain eutrophic conditions).
Try the realistic and the possible maximum cleanup measures, as above. What do you find?
The realistic cleanup still leaves you with eutrophic conditions, but the maximum cleanup results in mesotrophic ones.

Exercise 7. Analysis of lake eutrophication with a simple lake model (manual calculation).

Consider the lake of the previous example.
A lake of 10 km^2 area and 5 m average depth has a drainage area of 100 km^2. The multiannual average runoff is 94.6 mm.

Calculate the inflow to the lake: Q = 0.3 m^3/s

Scarce data indicate that the multiannual average inflowing phosphorus concentration is very high, P_{mean}= 800 µg/l

Use the following simple lake model:

$$\frac{dP}{dt} = LP - (q + K)P \qquad (5)$$

where

P- is the P concentration of water in the reservoir [ML^{-3}]

LP- is the volumnar P loading rate to the lake [$ML^{-3}\,T^{-1}$], to be obtained as the loading rate of P (MT^{-1}) divided by the lake volume V [L^3]

q- is the hydraulic washout rate [T^{-1}], calculated as the water outflow rate [$L^3\,T^{-1}$] divided by the lake volume V [L^3]

K- is the sedimentation rate [T^{-1}]

t- is the time [T]

Solution of Eq. 5 for initial conditions P=P_o at t=0 is obtained as

$$P(t) = P_0 e^{-(q+K)t} + \frac{LP}{q+K}\left(1 - e^{-(q+K)t}\right) \qquad (6)$$

The equilibrium concentration corresponding to a new LP load is thus obtained as

$$P_{eq} = \frac{LP}{q+K} \qquad (7)$$

Calculate volumnar loading rate LP =0.1519 g/m^3.year
Calculate washout rate q =0.18922 year^{-1}

Consider sedimentation rate K=0.1 year^{-1} and calculate the expectable P concentration in the lake.
P=.........0.522.................g/m^3
Determine the corresponding trophic state from the OECD table (.....hypertrophic................)

Try different K (sedimentation rate) values and check how the equilibrium lake concentration varies with different assumptions.

Calculate how much sedimentation rate would correspond to achieving class II (200 mgP/m^3) water quality. K=…..0.5673 yr^{-1}

Use a much smaller sedimentation rate (as you can not expect a lake to act as a permanent sink of this magnitude).

Try to derive a "feasible or plausible" sedimentation (retention) rate coefficient by assuming that 20% of the incoming load is retained in the lake. Try to derive the necessary formula by writing the mass balance equations for a fully mixed lake where inflow equals outflow and only concentrations vary. In the mass balance use $r=P_{eq}/P_{in}$ (the retention ratio of phosphorus, that is r=0.8 for 20% retention), while in the second one use K (the retention rate coefficient with time^{-1} dimension). Combine the two equations and derive the K= f(q,r) relationship. *This relatively difficult task is for you to check whether you fully understood the mass-balance concept and the meaning of the retention rate.* The formula that relates washout rate q to the retention ratio r (0.8 in the assumed case) is derived as

$Q/V*P_{in} - K*P_{eq} = Q/V*P_{eq}$

dividing the equation by P_{in}

$q – rK = rq$

from where

$K = (q-rq)/r$ or $K=q/r * (1-r)$

for the given case

K= f(q,r)=..................formula

$K_{20\%}$=...(0.189 – 0.189*0.8)/0.8= 0.047..................year^{-1}

Calculate the load reduction efficiency that would be required for achieving the above defined water quality class (with the new, reduced retention rate $K_{20\%}$).

$LP_{Class\ II.}$<.0.2*(0.1892 + 0.047) = 0.047......................g/m^3.year

What overall load reduction efficiency would be required to achieve this load?

η=.........70......%. The required load reduction is X*0.152=0.047, X=0.31 and this corresponds to about 70% reduction of the load from the catchment.

Calculate the feasibly achievable load subject to the following considerations:

Assume that 15% and 10% of the total load originated from direct and indirect point sources, respectively, while the rest is non-point source runoff load. Check whether the overall removal rate can be achieved or not if your feasible management strategies allow 80%, 60% and 40% removal efficiencies for direct point sources, indirect point sources and non-point sources, respectively.

$LP_{reduced}$=......LP*(0.15*0.2 + 0.1*0.4 + 0.75*0.6) = 0.52*LP=0.0785 ....g/m^3.year.

η= ....(1-0.52)*100= 48.................%

Thus the problem cannot be solved with the available technologies, although the result is better than what was obtained by the OECD regressions models. You will have to look for additional treatment techniques, such as the construction of pre-treatment reservoirs (filter ponds) at the river inflow sections.

Calculate and plot the lake response curve (in-P lake concentration) with and without load reduction for the following parameters:

P_o= 0.3 mg/l

K = 0.05 year^{-1}

Compose similar examples if you have more time left for this exercise.

Exercise 7a. Analysis of lake eutrophication with the simple dynamic P budget model. Lake Model No. 2.

A lake of 90 km^2 area and 5 meters average depth has a drainage area of 1000 km^2. The multiannual average runoff is 120 mm).

Calculate the inflow to the lake: Q = 3.8 m^3/s
Enter the "hydrology" sub-model, set evaporation equalling precipitation, $Q_{out}=Q_{in}=Q_{out,max}$, $h_{min}=h_{max}=h=$ 5.0 m.
Enter the "input load" menu.
Scarce data indicate that the multiannual average inflowing phosphorus concentration is $P_{mean}=$ 300 µg/l.
The point source input is 20 kg/day.

Set the phosphorus retention capacity of the lake to 30% (a realistic value): r=0.7
Set PL_0 to 90 mg/m^3. Simulate 15 years (time horizon).
Run the model, what do you observe?
Fixed boundary evaluation: PL= 210 µg/l, hypertrophic;
Probabilistic evaluation (highest probability): hypertrophic with 74% probability.

Make a "clean up". Use realistic removal rates: 80% for point sources (X,rp=0.2) and 40% for non-point sources (X,rnp=0.6).

Fixed boundary evaluation: PL= 108.9 µg/l, hypertrophic;
Probabilistic evaluation (highest probability): eutrophic with 59% probability

Check whether the theoretically achievable best technology (90% point source and 60% non-point source reduction) could help.

Fixed boundary evaluation: PL= 71.2 µg/l, eutrophic;
Probabilistic evaluation (highest probability): eutrophic with 63% probability

Thus you have highly improved the conditions, but the lake still remains eutrophic.

Check whether the ever-reported best phosphorus retention (70%) could improve the situation (this is the lowest "wired-in" limit value for r, r=0.3):
Fixed boundary evaluation: PL= 30.5 µg/l, mesotrophic;
Probabilistic evaluation (highest probability): mesotrophic with 63% probability

Check what retention value would be sufficient for staying in the mesotrophic range: r=0.34

You may repeat the same example with the 3rd lake model (with sediment interaction), you shall achieve the same results.

Exercise 8. Lake eutrophication analysis with the dynamic algae-P lake model of the CAL programme (Lake model No.5)

Note that in this model the number of parameters is already so high that you might not be able to fully reconstruct the example given below.

A lake of 90 km^2 area and 5 m average depth has a drainage area of 1000 km^2. The multiannual average runoff is 120 mm.

Calculate the inflow to the lake: $Q=3.8\ m^3/s$
Enter the "hydrology" sub-model, set evaporation equalling precipitation, $Q_{out}=Q_{in}$; $Q_{out,max}$,=5 m^3/s $h_{min}=h_{max}=h=$ 5.0 m.
Enter the "input load" menu.
Scarce data indicate that the multiannual average inflowing phosphorus concentration is $P_{mean}=$ 300 μg/l.
The point source input is 20 kg/day.

Set the phosphorus reduction capacity of the lake to 30% (a realistic value): r=0.7
Set PL_0 to 90 mg/m^3. Set $P_{s0}=P_{seq0}=$500 μg/l. Set ra=0.7, r=0.7, rp= 0.1. Set AB0=ABin= 830 μg/l
Simulate 15 years (time horizon).

Set reduction factors to 1.0 in the input submodel block.
Important: Stop the model, while you are entering new data, because it takes time for running the model and the programme may be "blown up", when data are entered while the model is running.

Run the model by adjusting step by step the maximum growth rate μmax (mumax) until you achieve similar values than what you had for the same example with the use of earlier lake models (hypertrophic-eutrophic conditions)
At mumax = 0.29 day^{-1} you will have the following results:

Fixed boundary evaluation: PL= 209.5 μg/l, hypertrophic; Chl-a, mean: 44 μg/l hypertrophic; Chl-a,max: 124.4 μg/l, hypertrophic.
Probabilistic evaluation (highest probability): hypertrophic with 74% probability for PL; 76% hypertrophic for Chl-a, mean; 87% hypertrophic for Chl-a,max.

Make a "clean up". Use realistic removal rates: 80% for point sources (X,rp=0.2) and 40% for non-point sources (X,rnp=0.6). (Go back to the input load menu!)

Fixed boundary evaluation: PL= 108.9 μg/l, hypertrophic; Chl-a, mean: 26.4 μg/l hypertrophic; Chl-a,max: 56.6 μg/l, eutrophic.
Probabilistic evaluation (highest probability): eutrophic with 59% probability for PL; 48% eutrophic for Chl-a, mean; 48%-48% hypertrophic and eutrophic for Chl-a,max.
Thus, the algae-phosphorus model yields (at this given parameter set) a similar answer, than the other more simple lake models.

Note again, that with slight changes of the input values and model parameters you might have very different results. (The more simple models are usually more realistic, because they reflect earlier statistics, while this model is highly sensitive to a larger number of model parameters)

Exercise 8a Analysis of a small lake with various lake models

Consider a small lake of 10 km^2 area and 2.0 m average depth, draining a catchment basin of 90 km^2. The population in the area (10000 inhabitants) has no sewage treatment, and their sewage water is assumed to reach the recipient streams with approximately 8 mg/l TP concentration. The daily water consumption is 250 litre/capita/day. The assumed water loss (via garden watering and evaporation, infiltration etc) is 20%. Calculate the point source load: Qpt=0.023 m^3/s, Cpt=8000 mg/m^3, Lpt= 15.9 kg/day. (Note that you can only enter 0.022 m^3/s for Qpt and thus you obtain 15.2 kg/day for the point source load.)

Use the input model and select "non-point load" calculation. Enter the following data for land use proportions: 41% forest, 25% meadow, 30% agriculture, 4% urban land. The multiannual precipitation of the area is 800 mm. Take note of the total calculated inflow (0.327 m^3/s).

Enter the "hydrology" sub-model, set outflow=inflow, set ho=hmin=hmax= 2.0 m, E=P. Set Q_{out} to 0.3 m^3/s and Qoutmax to 1.0 m^3/s

Run the Lake Model No.1

Fixed boundary evaluation: PL= 425.5 µg/l, hypertrophic; Chl-a, mean: 41.6 µg/l hypertrophic; Chl-a,max: 171.9 µg/l, hypertrophic.

Probabilistic evaluation (highest probability): hypertrophic with 96% probability for PL; 73% hypertrophic for Chl-a, mean; 95% hypertrophic for Chl-a,max.

Make the realistic cleanup ($X_{r,p}$=0.2, $X_{r,np}$=0.6). What is the result?:

Fixed boundary evaluation: PL= 167.5 µg/l, hypertrophic; Chl-a, mean: 20.1 µg/l eutrophic; Chl-a,max: 74.3 µg/l, hypertrophic.

Probabilistic evaluation (highest probability): hypertrophic with 61% probability for PL; 58% eutrophic for Chl-a, mean; 64% hypertrophic for Chl-a,max.

Try additional forestation measures, go back to input sub-model, set the following land use proportions: Forest: 50%, Meadow: 23%, Agriculture: 23%, Urban land: 4%. How much improvement can you achieve?

Fixed boundary evaluation: PL= 157.5 µg/l, hypertrophic; Chl-a, mean: 19.2 µg/l eutrophic; Chl-a,max: 70.3 µg/l, eutrophic.

Run the lake model No.2

Do not forget to reset original land use proportions and reduction values (to 1.00). Set r=0.7 PL_0=250. Simulate 15 years.

Fixed boundary evaluation: 731.0 µg/l, hypertrophic

Probabilistic evaluation: 99%, hypertrophic

Make the realistic cleanup. What is the result?

Fixed boundary evaluation: 287.8 µg/l, hypertrophic

Probabilistic evaluation: 87%, hypertrophic

Run the lake model No. 3

Reset original loads. Set P_{s0}=100, P_{seq}=500, r=0.7

Fixed boundary evaluation: 749.4 µg/l, hypertrophic

Probabilistic evaluation: 100%, hypertrophic

Make the realistic cleanup. What is the result?

Fixed boundary evaluation: 295.1 µg/l, hypertrophic

Probabilistic evaluation: 88%, hypertrophic

Try "highest possible" reduction (r=0.3, $X_{r,p}$=0.1, $X_{r,np}$=0.4)

Fixed boundary evaluation: 81.5 µg/l, eutrophic

Probabilistic evaluation: 64%, eutrophic

Run the lake model No.4

Reset original loads and reduction factors, reset r to 0.7

Fixed boundary evaluation: PL= 749.4 µg/l, hypertrophic; Chl-a, mean: 118.4 µg/l hypertrophic; Chl-a,max: 425.6 µg/l, hypertrophic

Probabilistic evaluation (highest probability): hypertrophic with 100% probability for PL; 98% hypertrophic for Chl-a, mean; 100% hypertrophic for Chl-a,max

Make the realistic cleanup ($X_{r,p}$=0.2, $X_{r,np}$=0.6). What is the result?:

Fixed boundary evaluation: PL= 295.1 µg/l, hypertrophic; Chl-a, mean: 55.1 µg/l hypertrophic; Chl-a,max: 173.9 µg/l, hypertrophic

Probabilistic evaluation (highest probability): hypertrophic with 88% probability for PL; 85% hypertrophic for Chl-a, mean; 95% hypertrophic for Chl-a,max

Try "highest possible" reduction (r=0.3, $X_{r,p}$=0.1, $X_{r,np}$=0.4)

Fixed boundary evaluation: PL= 81.5 µg/l, eutrophic; Chl-a, mean: 19.2 µg/l eutrophic; Chl-a,max: 50.6 µg/l, eutrophic.

Try additional forestation measures, go back to input sub-model, set the following land use proportions: Forest: 50%, Meadow: 23%, Agriculture: 23%,

Fixed boundary evaluation: PL= 71.6 µg/l, eutrophic; Chl-a, mean: 17.3 µg/l eutrophic; Chl-a,max: 44.6 µg/l, eutrophic.

Run Lake model No.5

Set $AB_{in}=AB_0$=830, r_a=0.7, r_p=0.1, r=0.7. Set back reduction factors X to 1.00 in the input model. Set back original land use proportions. Simulate 15 years. Do not change other parameters.

Gradually change maximum growth rate mumax until you achieve concentrations and trophic categories similar to those of the 4th model run. What do you observe?:

At maximum growth rate mumax=0.18 day^{-1} you obtain:

Fixed boundary evaluation: PL= 749.4 µg/l, hypertrophic; Chl-a, mean: 134.9 µg/l Hypertrophic; Chl-a,max: 412.2 µg/l, hypertrophic.

Probabilistic evaluation (highest probability): hypertrophic with 100% probability for PL; 99% hypertrophic for Chl-a, mean; 100% hypertrophic for Chl-a,max.

Make the realistic cleanup ($X_{r,p}$=0.2, $X_{r,np}$=0.6). What is the result:

Fixed boundary evaluation: PL= 295.1 µg/l, hypertrophic; Chl-a, mean: 4.5 µg/l mesotrophic; Chl-a,max: 9.7 µg/l, Mesotrophic.

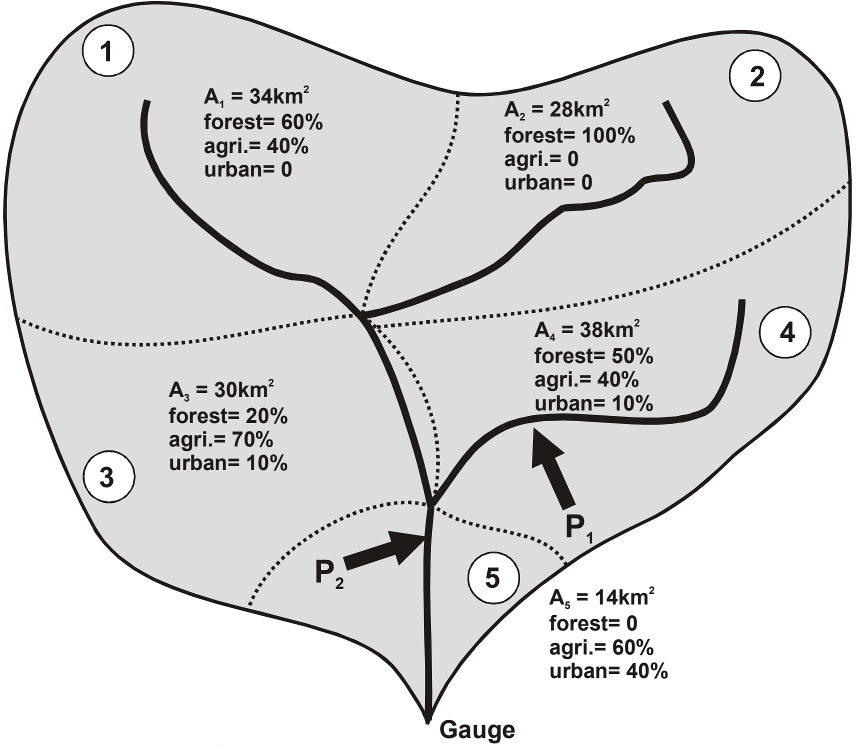
Compare and evaluate the five model runs:

The five models give more or less the same results: The small lake would be hypertrophic without cleanup measures. Realistic cleanup measures reduces hypertrophy to eutrophy only by the forecast of lake model no.1 Lake model No.5 gives the best response to cleanup measures. Highest possible reduction and cleanup would still result in eutrophic state.

Note that the oversimplified "wired-in" catchment model (the non-point load estimate according to land use proportions) might be responsible for these unrealistically bad conditions. This will be improved in the 3rd version of this software, when realistic, detailed catchment models will be included.

Exercise 9. Analysis of the nutrient budget of a drainage basin

The task is to calculate (estimate) the total phosphorus load leaving the catchment, shown below, and calculate the effect of management alternatives:



Total catchment area: A= 144 km^2
Annual mean runoff: R = 60 mm
Calculate the mean flow: Q = .0.274......m^3/s
Calculate the annual loads of the two point sources:
P_1, discharge: q1 = 0,006 m^3/s; TP concentration: C_{p1} = 5 mg/l; load: L_{p1}=...946….kg/year
P_2; discharge: q2 = 0,022 m^3/s; TP concentration: C_{p2}= 2 mg/l; load: L_{p1}=...1387….kg/year

Use the following model for calculating the total P load:

$$L = \sum_i P_i + \sum_j \sum_k UAL_k A_j r_{jk} \text{ where}$$

L= total annual load leaving the area (kg/year)
P_i= annual load of the i-th point source (kg/year)

UAL_k -the "Unit Area Loading rate" of the k-th land use form, for which the following estimates were offered by relevant literature:

UAL_{forest} = 0,05 kgP/ha.yr
UAL_{agri}= 0,5 kgP/ha.yr
UAL_{urban}= 2.0 kgP/ha.yr

A_j- The area of the j-th subcatchment (ha)

r_{jk} - ratio of the k-th landuse form in the j-th subcatchment (fraction, 0-1)

L= 946 + 1387 + 0.6*3400*0.05 + 0.4*0,5*3400 + 2800*0,05 + 0,5*3800*0,05 +

0,4*3800*0,5 + 0,1*3800*2,0 + 0,2*3000*0,05 + 0,7*3000*0,5 + 0,1*3000*2,0 +0,4*1400*2,0 + 0,6*1400*0,5= 8090

L=......8090...........(kg/year)

Calculate the total flow (including the point source discharges) and the annual mean concentration of TP in the stream water
Q_{out} =...0.302.....m^3/s
TP_{mean}= ....0.849....mg/l

Compare this value with that of the water quality classes for waters to be impounded or discharged into a lake (Hungarian Standards) (TP Class I 0.04 mg/l; Class II 0.2 mg/l; Class III 0,4 mg/l; Class IV 1,0 mg/l). What do you conclude?
Class IV water quality, indicating hypertrophic conditions.

Consider the following management strategies and calculate the achievable load reduction:
Effluent concentration after P removal: 1.0 mg/l.
Efficiency of non-point source management strategies for agricultural areas = 40% P reduction.
Efficiency of non-point source management strategies for urban areas = 60% P reduction.

$L_{reduced}$ = 189 + 694 + 0.6*3400*0.05 + 0.6*0.4*0,5*3400 + 2800*0,05 + 0,5*3800*0,05 + 0.6*0,4*3800*0,5 + 0.4*0,1*3800*2,0 + 0,2*3000*0,05 + 0.6*0,7*3000*0,5 + 0.4*0,1*3000*2,0 + 0,4*0,4*1400*2,0 + 0.6*0,6*1400*0,5= 3988

$L_{reduced}$=.............3,988...............kg/year
$TP_{reduced}$ =...........0.418...............mg/l

It still falls slightly into Class IV.

Continuation of exercise 9.

In the reality washoff loads depend highly on the runoff, while runoff changes substantially with the landuse.

Calculate weighed runoff values for the different landuse forms (agriculture, urban land, forest) with the help of the following runoff coefficients (attention, the total runoff volume must remain the same; $V_{measured}$ =.8,640,000......m^3/year).

α_{forest}= 0.05
α_{agri}= 0.15
α_{urban}= 0.4

$V_{measured}$= (A*R)= 8640000 m^3/year
R_{forest}=....24.8......mm/year
R_{agri}=...74.65......mm/year
R_{urban}=...199.1......mm/year

Calculate unit area loading rates (UAL) in function of the runoff, using the following formulas (Jolánkai, 1999)

For forest:

$$UAL_{forest} = \frac{1}{1 + \exp(5.92 - 0.1R)}$$

For agricultural land:

$$UAL_{agri} = \frac{8}{1 + \exp(4.4 - 0.018R)}$$

For urban land:

$$UAL_{urb} = \frac{6}{1 + \exp(2.15 - 0.0053R)}$$

UAL_{forest} =....0.031...........kg/ha.year
UAL_{agri} =.......0.36..........kg/ha.year
UAL_{urb}=..........1.50..........kg/ha.year

Repeat the load assessment with the new UAL values
L=..........6518.......(kg/year)

Calculate total flow (including the point source discharges) and the annual mean concentration of TP in the stream water
Q_{out} =...0.302.....m^3/s
TP_{mean}= ....0.684...mg/l

Compare this value with that of the water quality classes for waters to be impounded or discharged into a lake (Hungarian Standards) (TP Class I 0.04 mg/l; Class II 0.2 mg/l; Class III 0,4 mg/l; Class IV 1,0 mg/l). What do you conclude?

Calculate again the achievable load reduction:
$L_{reduced}$=.................3108..........kg/year
$TP_{reduced}$ =................0.326........mg/l

What is the final conclusion? The runoff based, more accurate, model yields a little more favourable results, because the estimated annual runoff was very low (even in Hungarian conditions).

Calculate the runoff and the TP load for each of the five subcatchments:
Q_1=...0.048......m^3/s, L_1 =.....0.0175......g/s C1=0.365 mg/l
Q_2=...0.022......m^3/s, L_2 =...0.00275........g/s
Q_3=....0.073.....m^3/s, L_3 =.....0.0388......g/s
Q_4=....0.081.....m^3/s, L_4 =......0.0673.....g/s
Q_5=.....0.077....m^3/s, L_5 =...0.0802........g/s

Draw the hydrological profile for the main stream (between 1- and-Gauge) considering the following subsequent section lengths from upstream to downstream: 5 km, 6 km and 4 km. Do not forget, that subcatchments 3. and 5. are direct watersheds to the main stream, and thus their flow occurs as lateral inflow (as the slope of the flow profile).

Draw also the longitudinal load profile (showing the calculated values), showing also the point source "steps". Attention: the direct catchment loads appear again as slopes of the load profile, as non-point source inflow.

Draw also the phosphorus concentration profile (showing the above calculated values). This will indicate whether there are sections upstream, where a fishpond could be created, without the danger of eutrophication. Do not forget to use the "dilution equation" in calculating the concentrations downstream of junctions.

What other tasks might be performed to improve the overall catchment-management analysis done above?...
(Development and inclusion of transformation submodels, for accounting the retention/delivery of phosphorus along the transportation routes.)

* * *

Testing your knowledge

1. What is the time of travel?

a, it is the time period elapsed between the points of time of taking two samples in a river during a longitudinal profile measurement study.

b, it is the average period of time of the movement of water/pollutant particles between two selected cross-sections of the river.

c, it is the distance between two selected river cross-sections divided by the cross-sectionally and longitudinally averaged flow velocity of the river reach in concern, that is t=x/v.

correct answers: (use the "Test" menu)

2. What does the term "mass flux" mean?

a, it is the concentration of a pollutant divided by time of travel.

b, it is the concentration of a pollutant multiplied by the rate of flow (e.g mass flux=QXC, frequently termed also as "load")

c, Its is the rate of mass flow in a specified direction or across a given surface area; the movement of mass during a unit period of time (e.g $M T^{-1}$, g/sec, kg/day, etc)

correct answers: (use the "Test" menu)

3. What is dispersion?

a, dispersion is a transport process caused by the joint effect of molecular diffusion and turbulent diffusion.

b, Dispersion is a transport process in which the pollutant particles are moved by the pulsating motion of the flow velocity vector and by a similar thermally induced pulsating motion of the molecule.

c, Dispersion is a transport process when contaminant particles are moved jointly by hydraulic and wind forces.

d, Dispersion is the joint effect of wave and flow velocity induced motion.

correct answers: (use the "Test" menu)

4. What is Biochemical Oxygen Demand (BOD)?

a, It is the amount of oxygen produced by biological and chemical processes taking place in the water.

b, It is a measure of the biodegradable organic matter content of water.

c, BOD is defined as the quantity (mass) of oxygen consumed from a unit volume of water by microorganisms, while they decompose organic matter, during a specified period of time.

d, BOD is the amount of oxygen excreted by microorganisms into a unit volume of water during the decomposition of organic matter during a selected period of time.

correct answers: (use the "Test" menu)

5. What the term "oxygen deficit" (D) means?

a, It is the rate of oxygen consumption by the respiration of aquatic plants.

b, It is the loss of oxygen from water, caused by molecular diffusion across the water surface.

c, It is the difference between the saturation dissolved oxygen content and the actual dissolved oxygen content of water.

correct answer: (use the "Test" menu)

6. How would you calculate the initial concentration of a pollutant in the river downstream of a pollution discharge outlet for the steady state BOD-DO models presented in this programme?

a, As the sum of pollutant mass fluxes of the river and the effluent discharge, divided by the sum of river flow and waste water flow.

b, As the sum of the concentrations of the pollutant in the river and that in the waste water (e.g C_s+C_b).

c, Expressing the concentration C_0 from a mass balance equation written for the selected (downstream) cross-section (e.g. by the "dilution equation").

d, As the sum of background river mass flux of the pollutant plus the pollutant concentration in the sewage water.

correct answers:(use the "Test" menu)

7. What are the main source and sink terms of oxygen in the BOD-DO process models?

a, Sources: aeration (reaeration) caused by aerating devices such as aerator rotors and motorboat propellers. Sinks: photosynthesis by aquatic plants and the BOD decomposition.

b, Sources: Reaeration across the water surface and the photosynthesis of aquatic plants. Sinks: Oxygen uptake by micro-organisms while they decompose organic matter, benthic oxygen demand, and the respiration of aquatic plants.

c, Sources:turbulence and wave motion plus molecular diffusion plus photosynthesis. Sinks: BOD decay process plus respiration of aquatic plants, plus benthic oxygen demand.

correct answers: (use the "Test" menu)

8. What are the best ways of estimating model parameters, such as K_1, K_2, D_L, D_m etc?

a, Selection of the most reliable experimental expression from the relevant literature.

b, Calibration of the respective model, by fitting it to series of field measurement data. Measurements should cover most changes of ambient conditions (e.g, ranges of flow, velocity and water depth, temperature, etc variations).

c, Using literature defined ranges (tabulated values) of the respective parameters.

correct answer: (use the "Test" menu)

9. What is simulated/described by the Longitudinal dispersion model presented in this programme?

a, Concentration vs. time curves in different cross-sections of the river downstream of an instantaneous pollution source of pollutant mass M.

b, The longitudinal concentration profile of a pollutant upon the effect of an accidental input of pollutant mass M.

c, Pollutant concentration distribution curves across the river, downstream of a source of accidental mass input.

correct answer: (use the "Test" menu)

10. What is simulated/described by the Transversal Mixing Model presented in this programme?

a, Transversal and vertical concentration distributions of a pollutant downstream of a continuous source of that pollutant.

b, Depth averaged transversal concentration distribution curves of a pollutant downstream of its continuous point source.

c, The distance where full transversal mixing of the pollutant with the stream takes place.

correct answer: (use the "Test" menu)

11. What is the process of eutrophication?

a, Excessive growth of aquatic vegetation due to increased input loads of organic matter.
b, Processes due to the enrichment of water in plant nutrients
c, Excessive growth of aquatic vegetation due to increased input loads of inorganic plant nutrients.
d, Processes due to increased temperature, increased organic load, and increased irradiation
correct answers: (use the "Test" menu)

12. What can control, limit, the growth of algae?

a, Concentrations of organic matter, phosphorus and other nutrients
b, Either phosphorus or nitrogen
c, Phosphorus, nitrogen, light and temperature
d, Phosphorus, nitrogen, light, temperature and long list of other elements (which latter are usually, but not exclusively, abundant)
correct answers: (use the "Test" menu)

13. What is the major process of phosphorus retention in lakes and reservoirs?

a, Sedimentation and subsequent "burial" (when the deposited P becomes non-exchangeable with the overlying water)
b, Uptake by aquatic macrophytes
c, Uptake by algae, then zooplankton, then fish and the removal by fishing.
correct answers: (use the "Test" menu)

14 What is a possible "ecohydrological" eutrophication control option in reservoirs?

a, Rising of water levels and diluting the concentrations
b, Excessive use of motor boats to provide oxygen input by the propellers, which helps decomposing dead organic matter
c, Provision of appropriate water level for the spawning of predator fish like pike-perch, which will predate on zooplankton-feeding fish, decreasing their number, thus increasing zooplankton, which latter will feed on algae, thus reducing eutrophication
d, Introduction of herbivorous fish, which will eat macrophytes, thus removing plant nutrients and organic matter
correct answers: (use the "Test" menu)

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Appendix I Pollutant transport processes in lakes

In lakes and reservoirs the transport processes of particulate and dissolved constituents of water are related to water motion, to currents, that are induced by one or more of the following forces and phenomena;

- currents caused by inflow to and outlet from the standing water body
- wind induced currents, including wave motion and the pulsating turbulent motion caused by seiche (wind setup)
- density currents (in deep thermally stratified lakes) While inflow and outlet induced throughflow currents are of significance mostly in river impoundments, and density difference dependent currents might be of interest in deep stratified lakes, wind induced currents dominate the flow pattern in many or most of the lakes.

The transport of pollutants in lakes and reservoirs can be only described along with the description of the motion of fluid as caused by the above effects.

The conservation of momentum equation expressing the acceleration of fluid in a three dimensional space is written as:

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}+\frac{1}{\rho}\frac{\partial P}{\partial x}-\Omega v_y=\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial v_x}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{xy}\frac{\partial v_x}{\partial v_y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_{xz}\frac{\partial v_x}{\partial z}\right)+F_{sx}-F_{bx} \tag{1/a}$$

$$\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}+\frac{1}{\rho}\frac{\partial P}{\partial y}-\Omega v_x=\frac{\partial}{\partial x}\left(\varepsilon_{yx}\frac{\partial v_y}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{yy}\frac{\partial v_y}{\partial v_y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_{yz}\frac{\partial v_y}{\partial z}\right)+F_{sy}-F_{by} \tag{1/b}$$

$$\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}+\frac{1}{\rho}\frac{\partial P}{\partial z}+\frac{1}{\rho}g\frac{\partial(\partial z)}{\partial z}=\frac{\partial}{\partial x}\left(\varepsilon_{zx}\frac{\partial v_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{zy}\frac{\partial v_z}{\partial v_y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_{zz}\frac{\partial v_z}{\partial z}\right)-F_{bz} \tag{1/c}$$

The corresponding equation of continuity for an incompressible fluid is

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \tag{2}$$

Next, the transport process can be described by the conservation of mass equation (similarly to Eq.1.3.)

$$\begin{gathered}\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}+v_y\frac{\partial C}{\partial y}+v_z\frac{\partial C}{\partial z}=\\=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)+S(x,y,z,t)+\_\,S_{internal}\end{gathered} \tag{3}$$

When temperature dependent process kinetics should be also considered then the changes of temperature can be also described by the heat conservation equation as

$$\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z} \right) + \frac{M}{\rho c} \tag{4}$$

In equations 1. through 4. the following notations were used

v_x,v_y,v_z - components of flow velocity in x, y, and z coordinate directions, respectively [LT^{-1}]
ρ - the density of fluid [ML^{-3} or $FT^2 L^{-4}$]
P - pressure [FL^{-2}]
ε_{xx}, ε_{xy},... - turbulent eddy diffusivity coefficients [L^2T^{-1}]
Ω - the Coriolis parameter [T^{-1}]
F_{sx}, F_{sy} - surface (wind) friction forces [FL^{-3}]
F_{bx}, F_{by}, F_{bz} - bottom friction forces [FL^{-3}]
C - is the concentration of the pollutant [ML^{-3}]
D_x, D_y, D_z - are coefficients of dispersion [L^2 T^{-1}]
T - is the water temperature [temperature unit, e.g^o C, ^{o}F]
K_x, K_y, K_z - combined heat exchange coefficients (due to turbulent eddy diffusivity and molecular heat conductivity) [L^2 T^{-1}]
M - inputs of heat at a given point [thermal unit*L T]
c - specific heat [thermal unit*M^{-1}* temperature unit^{-1}]

Terms in the above equations 1 a-c have the following meanings:

First left-hand side term:
    local inertia;- instantaneous local acceleration of fluid at a point;
Second -to- fourth left-hand-side terms
    convective inertia;- acceleration of fluid when transported from one point to another one
Fifth left-hand-side term:
    acceleration caused by pressure forces
Sixth left-hand side terms (Equations 1/a and 1/b):
    acceleration caused by the Coriolis force (due to the rotation of Earth)
First-to-third right-hand side terms:
    acceleration of fluid caused by the combined effects of viscosus friction forces and turbulent fluctuation forces (with the assumption that the Boussinesq approximation of Reynold's stress terms is valid)
Sixth left-hand-side term (Eq. 1/c):
    vertical acceleration of fluid caused by gravity force

(terms of the mass balance equation -Eq.3.- have been explained previously, see Eq. 3. in the main text).

For more details of the derivation of the above equations the reader is advised to consult the respective literatures (Orlob, 1977; Harleman et. al., 1972; Bengtsson,1978; Clements and Schnelle, 1969).

Although the above equations provide a fairly general description of the temporal and spatial variations of fluid properties, there exist more general approaches;- for example when the variations of fluid density $\rho = f(x,y,z,t)$ are also considered.

In actual practical applications the choice of the lake circulation and material transport model depends on the problem to be solved and on the physical, chemical and biological characteristics of the water body concerned. The range of possible models to be developed on the basis of the above general approach can be well illustrated by classifying according to spatial representation, as shown below after Shanahan et.al.(1986).

Type of model	**Spatial dimension**	**Description**
Simplified models	0 -D	Fully mixed reactor
	1-D	Vertical or longitudinal
Circulation models	2-D	Vertical plane, horizontal (single layer)
	3-D	Real 3-D multilayer, Ekman type