Aquatic modelling in Finland – experiences and visions

Special lecture at Okayama University
13.5.2014
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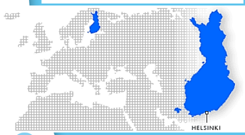
SYKE

Finland



- Total area: 338,144 km² square km 's, of which 10% is water and 69% forest; Europe's largest archipelago, including the semi-autonomous province of Aland.
- Distances: 1,160 km north to south, 540 km west to east Finland's land border with Russia (1,269 km) is the eastern border of the European Union.
- Climate: marked by cold winters and fairly warm summers. Temperatures of -20 Celsius are not uncommon in many areas. Finnish Lapland invariably has the lowest winter temperatures
- Population: 5.4 million, 71% live in towns or urban areas, 29% in rural areas
- GNP: In 2007, Finland's GNP per capita was 34,003 euros

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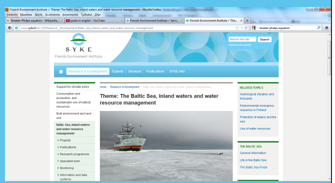
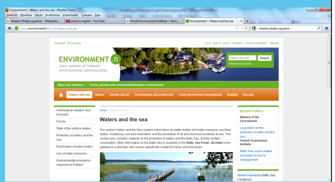
SYKE?

- One of 18 state research institutes http://www.research.fi/en/research_environments/state_research_institutes
- Web page www.syke.fi and www.environment.fi
- University of Jyvaskyla www.jyu.fi





CatchLake-hanke

17.5.2010

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Why water quality models

- New legislation in late 1960's forced point loaders (like industry and municipalities) to apply permission to lead purified waste waters to recipient waters (lakes, rivers, coastal areas etc..) from the Water Courts and
- During the Assesment Procedure ("Katselmustoimitus") the effects on the water quality was assessed and also the compensations were ordered
- Models were applied for
  - Determining the optimal loads
  - Determining the effected geographical areas
  - Dtermining the optimal locations for water water outlets
- Model applications from 1970's by Virtanen, Koponen and Sarkkula

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Later needs for modelling

- Problems with eutrophication and related diffuse loads increased the need of WQ assessment and modelling
- Effects of global change need to be assessed
- European wide approach: Water Framework Directive
- Fate and transport of harmfull substances (heavy metals, organic compounds etc..) is to be predicted since many recipient waters are also used for water supply
- Hydrological (water resources) modelling was fist needed for optimal regulation of our large lakes. Modelling started in early 1980's by Vehviläinen

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Presently many new needs

- Oil spill models
  - Operative models for oil combatting
- Habitat modelling for river restoration
- Socio-economical modelling
  - See CONPAT-project

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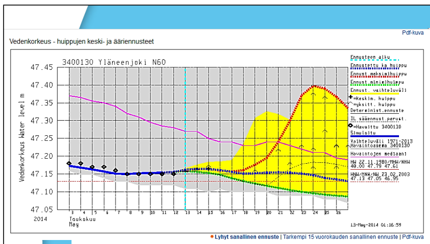
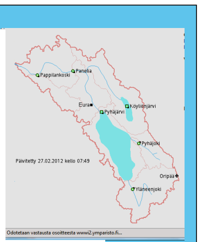
1. Catchment models

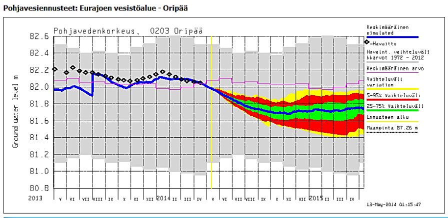
Hydrological simulation and forecast

- A country wide system (WSFS):
  - http://www.ymparisto.fi/en-US/Waters_and_sea/Hydrological_situation_and_forecasts/Hydrological_forecasts_and_maps/Hydrological_forecasts_and_maps%2826174%29
  - Used for operational forecasts
  - Used also for research
  - Based on water balance computation on watersheds (3rd division level)
- Dynamic links
  - Meteorological data forecasts (FMI)
  - Hydrological observations (water levels, river discharges, water temperature, ground water level)
  - Links to satellite automated imaging products (snow coverage, snow water equivalent)
- Automatic and tailored products



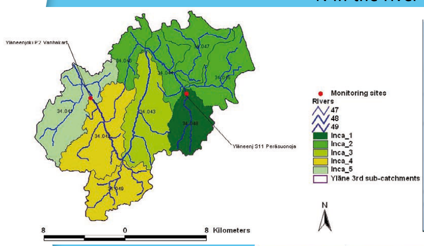


Pohjavesiennusteet: Eurajoen vesistöalue - Oripää



INCA-N

- process-based and semi-distributed model that integrates hydrology, catchment and river N processes to simulate daily concentrations of NO_3-N and NH_4-N in the river system

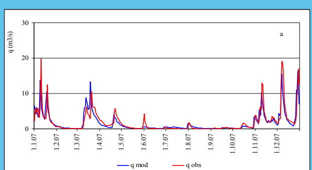


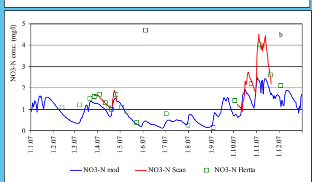
River Yläneenjoki catchement delineation for INCA-N application (Lepistö *et al.* 2008)

INCA-N SUB-CATCHMENTS	3rd LEVEL SUB-CATCHMENTS	AREA (Km²)	AGRICULTURAL AREA (%)
1	34.048	20.08	28
2	34.044–34.047	78.18	42
3	34.043	37.09	26
4	34.042, 34.049	61.59	27
5	34.041	36.10	19

INCA-N

- Calibration was successful
- The model was able to simulate annual dynamics of discharge and flow
- The NO_3 -N concentration peaks were sometimes slightly under- or overestimated
- No bigger problems were reported in CatchLake project report

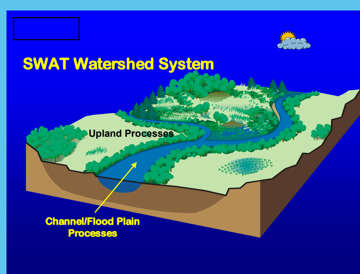




INCA-N results for year 2007 in Vanhakartano: (a) modelled vs. observed discharge, (b) modelled vs. observed NO_3-N concentration.
(Lepistö *et al.* 2008)

SWAT

- Continuous time model, operates on a daily time step at catchment scale
- Simulates suspended sediment & nutrient loading on catchment scale
- In European wide use
- Collaboration with Okayama University (Lake Kojima catchment)
- Has potential to include agricultural management actions



(See more in the the project report: http://www.ymparisto.fi/download.asp?contentid=85389&lan=fi)

SWAT

- According to CatchLake project report, the parameterization was again found challenging
- Sensitivity analysis and auto calibration tool were helpful
- Continuous turbidity data showed that model was not able to catch all the relevant erosion processes

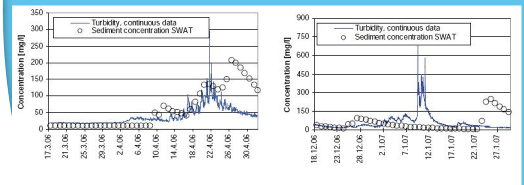


Fig. 27. Simulated sediment concentration and continuously measured turbidity at Vanhakartano during spring 2006 and winter 2007.

Lepistö A. et al. 2008

2. Simple mass balance models for lakes

Lake mass balance

$$\frac{dm}{dt} = I - O - S$$

- Where, m= total amount of phosphorus in a lake, I=total load of phosphorus entering to the lake, O=amount of phosphorus leaving the lake, S=retention (the amount of phosphorus (P) sediment to the lake)
- First applications by Piontelli and Tonolli (1969)
- In Vollenweiders (1969) solution the lake was considered as a continuously stirred tank (CSTR) and sedimentation of P was taken as following the first order kinetics with settling coefficient σ and phosphorus concentration (c) at the outlet was taken as mean concentration in the lake

Vollenweiders equation

$$\frac{dm}{dt} = I - Qc - \sigma m$$

$$\rho = \frac{Q}{V} \Rightarrow \frac{dc}{dt} = \frac{I}{V} - \rho c - \sigma c$$

- Where, Q= water discharge at the outlet and ρ= exchange coefficient, σ=settling coefficient
- It is expected here that the lake volume is constant (eq. an annual mean) and introduce
- In steady state we mark phosphorus concentration as c_{ss} it can be solved for time t

Solution for Vollenweider-equation

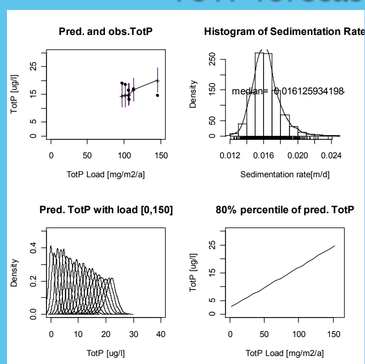
$$c = c_{ss} - (c_{ss} - c_0)e^{-(\rho+\sigma)(t-t_0)}$$

- Where c_0 is phosphorus concentration at time t_0
- Comments
  - Settling description with first order kinetics is too simple
  - Model can be used for studying the effects of loading options

ToTP forecasts

Järven ravinnepitoisuus vs. ravinnekuormitus. Lasketut ja havaitut arvot

Estimoitu sedimentaationopeuden jakauma



TotP-jakauman ennusteet kuormituksilla [0,10,20, … ,150] kg/d

TotP-ennusteiden 80% fraktiili (20% ylitystodennäköisyys) kuormituksen funktiona

3. River models

First models for flowing waters

$$\frac{dC}{dt} = K_2(C_s - C) = K_2 D$$

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

$$C = C_s - \frac{K_1 L_0}{K_2 - K_1}((e^{-K_1 t} - e^{-K_2 t}) + (C_s - C_0)e^{-K_2 t})$$

- Oxygen model by Streeter-Phelps (1925)
- Oxygen = f(advection by river waters, aeration and decomposition by bacteria), steady state
- In equation:
  - C=oxygen concentration (mg/l), C_0 =initial oxygen concentration in waters, C_s=saturation concentration of oxygen, D=oxygen deficit, K_2 = aeration coefficient (like 0,15 1/d), L=BOD value (mg(l), L_0= BOD- initial value , K_1 = decay coefficient of BOD (like 0,25 1/d), T=time (days)

Using Streeter-Phelps

- Water temperature and oxygen saturation concentration in that temperature have to be known.
- K_1 is temperature dependent. K_2 only slightly
- Several temperature correction equations available. Frisk and Nyholm (1980) mostly used in Finland
- Flow time has to be calculated for each river reach. In this way advection is taken into account

Dynamic flow models for rivers

$$Q = \frac{WY^{3/5}}{n}\left(S_0 - \frac{\partial Y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t}\right)^{1/2}$$

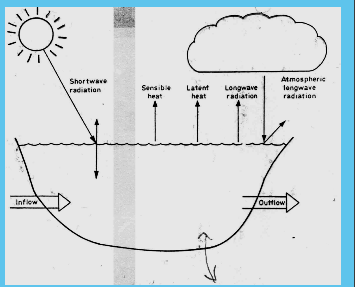
1 2 3 4 5

- St. Venant (1848) for river dynamics
- In equation
  - 1=discharge, 2=pressure gradient=bottom sloping term, 3=pressure gradient due to the surface slope, 4=advection due to the river flow, 5=local acceleration term
- For WQ -simulations
  - Streeter-Phelps type equation
  - Suspended solids like we look later in 3D models
  - Nutrients also similarly
- Presently we use SOBEK model from Deltares and HEC-RAS from US/EPA

4. Water temperature models

Heat balance components

- Components can be solved by quite well known equations
- Snow and ice form special challenges in Northern conditions
- Sometimes also heat from precipitation and sediment should be calculated



Equations in PROBE-model, F_s

$$F_s = (1-a)S_0 \cos z (T_r - A_w)\prod_{i=1}^{3}(1-N_i(-T_i))$$

$$A_w = 0.077(u \sec z)^{0.3}$$

$$T_r = 1.041 - 0.16(\sec z)^{0.5}$$

$$T_{low} = 0.35 - 0.015 \sec z$$

$$T_{middle} = 0.45 - 0.01 \sec z$$

$$T_{high} = 0.9 - 0.04 \sec z$$

$$\sec z = (\cos z)^{-1}$$

a=albedo

A_w= absorption by the water vapor

N_i= Ni is the amount of clouds of the different categories

(low, middle, high).

S_0=solar constant, 1395 Wm^{-2}

T_r= scattering-transmission function= f(z)

T_i= cloud function

u= amount water in the air mass

z=solar zenit angle

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Equations in PROBE-model, Long wave radiation F_l

$$F_l = F_l \uparrow - F_l \downarrow$$

$$F_l \uparrow = \varepsilon' \sigma T_s^4$$

$$F_l \downarrow = \sigma T_a^4 (c + b\sqrt{e_a})(1 + dN)$$

ε'= emissivity of the lake water =0.97

σ=Stefan-Bolzman constant=5.67*10^{-8} Wm^{-2} K^{-4}

T_s=lake water surface temperature (^{0}K)

T_a= air temperature (^{0}K)

e_a= water vapour pressure in air (mb)

N= cloudiness

c,b ja d = constant

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Equations in PROBE-model Sensitive heat flux, F_c

$$F_c \downarrow\uparrow = \rho_a C_p \overline{U}(C_{c1} - C_{c2}(T_s - T_a))$$

$$S_t = \overline{U}(T_s - T_a)$$

ρ=air temperature, kg m^{-3}, Cp=specific heat of water =4200 J kg^{-1} ,U= wind velocity m s^{-1} S_t= air stability, C_{c1}, C_{c2} = are sensible heat transfer, which depend on air stability

In stable conditions (S_t<0) C_{c1} = 0.0026 and C_{c2} =0.86E^{-3}

In unstable conditions (0<S_t<25), C_{c1} = 0.002 and C_{c2} =0.97E^{-3}

Very unstable conditions (25<S_t), C_{c1} = 0.0 and C_{c2} =1.46E^{-3}

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Equations in PROBE-model…

Latent heat flux, F_e

$$F_l \downarrow = L C_e \overline{U}(Q_w - Q_a)$$

Total heat flux

$$F_N = F_l + F_c + F_e$$

L=L is the latent heat of evaporation, Ce, is

the moisture transfer coefficient and Qw and Qa

are the water vapour densities close to the water

surface and in the atmosphere respectively.

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PROBE: Heat equation and vertical mixing

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\nu_T}{\sigma_T}\frac{\partial T}{\partial z}\right) + S_T$$

$$\nu_T = \frac{C_\nu \rho k^2}{\varepsilon}$$

Boundary condition at the upper boundary

$$\frac{\nu_T \partial T}{\sigma_T \partial z} = \frac{F_N}{\rho C_p}$$

ν_T= eddy diffusivity

σ_T=turbulent Prandtl number= ν/γ

ν=kinematic viscosity

γ=heat conductivity

k=kinetic turbulent energy

ε=dissipation of turbulent energy

C_ν=empirical constant

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Experiences about PROBE-model

- Case study: Huttula ym. 1994 Effects of Climate Change….pdf (see reference list below)
- Good results in scales from days…to years
- Water balance well calculated
- Ice formation and decay well calculated
- Heat exchange coefficients need to be calibrated for some lakes
- Hypolimnetic temperatures too low sometimes 🡐 vertical mixing too small in model
- Sheltering effects, effects of sediment quality and penetration of short wave radiation (extinction coefficients) need special attention

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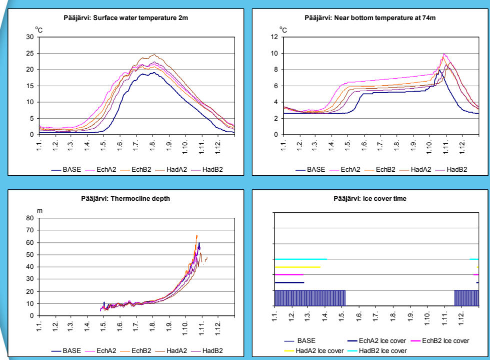
MyLake

- One dimensional vertical lake model
- Andersson and Saloranta 2000
- Ice model by Leppäranta (1991) and Saloranta (2000)
- The vertical diffusion coefficient from the stability frequency N^2 (Hondzo and Stefan, 1993)
- Utilises the MATLAB *Air-Sea Toolbox* (http://sea-mat.whoi.edu/air_sea-html/) for calclulation of radiative and turbulent heat fluxes, surface wind stress and astronomical variables
- Vertical mixing is based on the energy calculation between kinetic energy from wind and potential energy of layer(s) to be mixed
- **Model package with documentation available from TH**

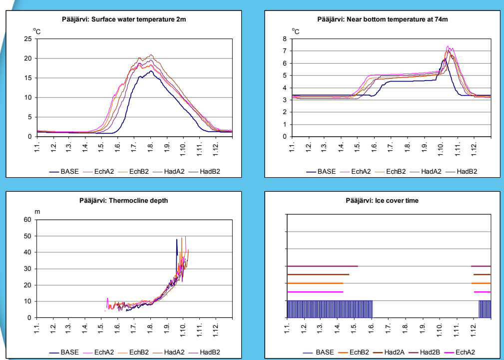
FINESSI-project

- Web tool for assessing the effects of global chage in Finland www.finessi.info/finessi
- Lake Pääjärvi (area= 13.5 km^2 , max depth= 87 m) and Halsjärvi (area= 0.5 km^2 , max depth= 6 m)
- Meteorological data from Jokioinen
- Calibration for Pääjärvi Link
- FINESSI uses 6 GCM-models Link
  - We Echam and Hadley Center

Jokioinen

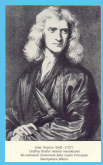


Sodankylä



5. Modelling currents in lakes and seas

Basic laws



- Conservation of momentum with Boussinesq approximation* and the assumption of vertical hydrostatic equilibrium**
- Continuity equation
- Conservation energy
- Equation of state

$$\frac{\partial u}{\partial t} + (u\cdot\nabla)u + 2\Omega\times u = -g + \rho^{-1}\nabla p + \nu\nabla^2 u + A_H\nabla_H{}^2 u + A_V\partial^2 u/\partial z^2$$

adv. *rotation* *gravity* *press.* *int.frict.* *turbulenceterms*

$$\nabla\cdot\bar{u} = 0 \Leftrightarrow \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} = 0 \qquad \rho = \rho_0 + \alpha(T-T_0) + \beta(S-S_0)$$

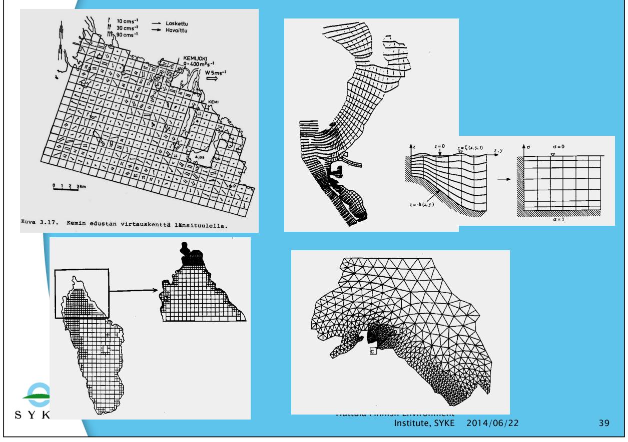
* It states that density differences are sufficiently small to be neglected, except where they appear in terms multiplied by *g*, the acceleration due to gravity

** The principle of hydrostatic equilibrium is that the pressure at any point in a fluid at rest is just due to the weight of the overlying fluid

Boundary conditions

- Boundary conditions
  - Surface: wind, solar radiation, net longwave heat balance ← meteorological data (IL)
  - Sides: river discharges, concentrations of ← hydrological and water quality data (SYKE)
  - Bottom: friction …← calibrated using bathymetric and vegation maps
  - Can be given
    - As fixed values, velocity=0 at bottom
    - As fluxes, sediment heat flux, about 1-3 W/m2
    - As sliding conditions (frictionless boundary), velocity on the side same as in the lake

S Y K E

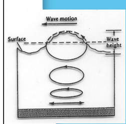


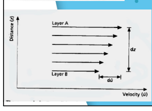
S Y K

Sedimentation of particulate matter

$$v_f = \frac{2(\rho_s-\rho)gr^2}{9\mu} = \frac{(\rho_s-\rho)gd^2}{18\mu}$$

- Settling velocity is solved from Stokes equation with some correction factor
- Material flux at both due to the erosive forces are calculated by using crtical shear approach
- Total shear (τ) on the lake bottom =
  - shear by orbital movements of waves = f(wind fetch over lake, lake mean depth, wind velocity and duration)
  - shear by currents
  - $\tau >$ critical shear (τ_{cr}), erosion happens with a rate $\propto$a*(excess shear)^b
  - τ_{cr}, a and b are experimental values, which we calibrate during model application
  - values for τ_{cr}: 0.008…1 Nm^{-2}, b=1..3, a = depends on sediment





6. Modelling water quality or hydrochemical and hydrobiological modelling

S Y K E

Application of WQ-models

- We include :
  - Advection
  - Dispersion
  - Settling on the bottom
- Bio- chemical processes
  - Decomposition, respiration, aeration, anaerobic release of P from the bottom
  - Select the most important variables concerning the problem
  - Oxygen, nutrients (like P,N), chlorophyll-a and some conservative substance (like Na)
  - Limiting factors (light, nutrients, …) must be included. Check!
  - Temperature corrections must be included. Check!

S Y K E

Concentration equation

$$\frac{\partial c}{\partial t} = \frac{\partial qL}{\partial n} - u\frac{\partial c}{\partial x} - v\frac{\partial c}{\partial y} - w\frac{\partial c}{\partial z}$$

$$+ \frac{\partial c}{\partial x}(D_x \frac{\partial c}{\partial x}) + \frac{\partial c}{\partial y}(D_y \frac{\partial c}{\partial y}) + \frac{\partial c}{\partial z}(D_z \frac{\partial c}{\partial z})$$

$$+ R(T, c...)$$

where,

- c = concentration of substance (nutrient, oxygen, metals, algae..) , qL= amount of loading release , n= length measure against release, u,v,w = advective velocities in x-, y- ja z- directions, D_x, D_y, D_z = dispersion coefficients, R(T,c) = biogeochemical changes affecting to the concentration of the substance
- Selection of the substance depends on the problem to be solved and available data

Oxygen model (Malve, Huttula and Lehtinen 1992)

Computation of dissolved oxygen Both abiotic and biotic factors affect the concentration of oxygen. The change of dissolved oxygen concentration as a function of time is described by the following equation':

$$\frac{dO_2}{dt} = K' \times \sqrt{W} \times (O_{2sat} - O_2) - K_1 \times BOD_7 \times BRAT + \mu \times \alpha_1 \times CH - r \times \alpha_2 \times CH - \frac{SOD \times AREA}{V} \quad (7)$$

K' = aeration constant = 2.0 • 10^{-4} cm/d, W = wind speed, z = layer thickness
O_{2sat} = dissolved oxygen saturation concentration at the surface layer temperature
O_2 = dissolved oxygen concentration at the surface layer temperature
K_1 = BOD decay rate = 0.1 l/d (function of temperature, f(T))
BOD, = BOD_7 concentration
BRAT = BOD/BOD_7 = 1.5
α_1, α_2 = stoichiometric coefficients for growth and respiration= 0.1903
μ = growth rate of algae
r = algal respiration coefficient = 0.065 1/d, (f(T))
CH = chlorophyll concentration
SOD = bottom sediment oxygen demand, (f(T))
AREA = area of the bottom sediment
V = volume of the water body

The first term on the right hand side describes aeration in the surface layer, the second one biological oxygen demand, the third and fourth ones phytoplankton growth and respiration, and the last one bottom sediment oxygen demand.

Phytoplankton biomass and ToTP

Computation of phytoplankton biomass Chlorophyll-a concentration is used as a relative measure of phytoplankton biomass. The rate of change of phytoplankton biomass is expressed as [8]

$$\frac{dCH}{dt} = \mu \times CH - r \times CH - \frac{SED}{h} \times CH \quad (8)$$

Phosphorus cycle Description of the phosphorus cycle is quite simple. Total phosphorus concentration in the lake is affected by external loading, phosphorus sedimentation and release of phosphorus under unaerobic conditions.
The change of total phosphorus concentration as a function of time is described by the following equation [8]

$$\frac{dTOTP}{dt} = -\frac{SEDP}{h} \times (TOTP)^2 + LOAD + \frac{RELEASE}{AREA \times h} \quad (11)$$

SEDP = net phosphorus sedimentation coeffkient = 0.002 (m/d)/(µg/l)
LOAD = external loading
RELEASE = rate of phosphorus release from the sediment under anaerobic conditions

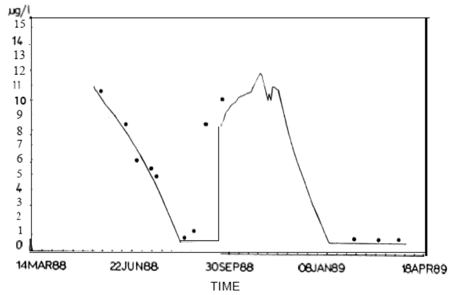


Figure 7. Observed (.) and calculated (-) oxygen concentrations in bottom layer (height 1 m). Calibration, summer 1988.

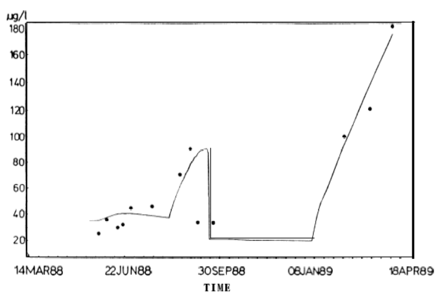


Figure 8. Observed (.) and calculated (-) total phosphorus concentrations in bottom layer (height 1 m). Calibration, summer 1988.

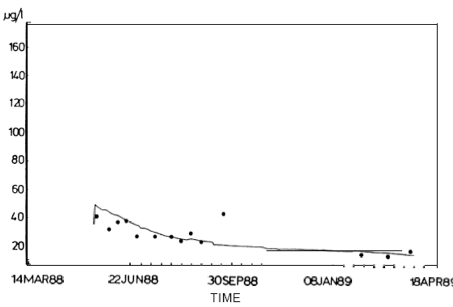


Figure 9. Observed (.) and calculated (-) total phosphorus concentrations in surface (0-1 m) layer. Calibration, summer 1988.

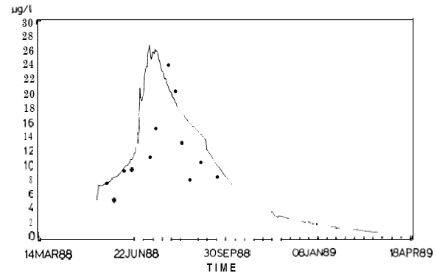


Figure 10. Observed (.) and calculated (–) chlorophyll-a concentrations in surface (0-1 m) layer. Calibration, summer 1988.

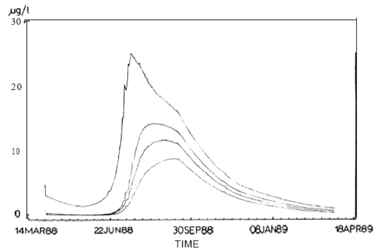


Fig. 11 Calculated chlorophyll-a concentration with loading levels 1 ▪ 4.

1. Present total phosphorus loading 55 697 kg/year

2. Fast obtainable loading level 47 469 kg/year
-reduction of the present loading 14.8%

3. Desirable loading level 37 483 kg/year
-reduction of the present loading 32.7%

4. Loading level with the best available protection measures 30 689 kg/year
-reduction of the present loading 44.9%

Interactions in EIA–SYKE–model

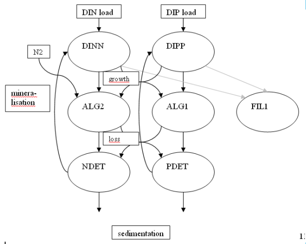


Table 1. Model variables.

symbol	definition	unit
c_C	Biomass of cyanobacteria (wet weight)	g m^{-2}
c_A	Biomass of the other algae (wet weight)	g m^{-2}
c_{DIN}	DIN concentration	mg m^{-3}
c_{DIP}	DIP concentration	mg m^{-3}
c_{Ndet}	Detritus nitrogen	mg m^{-3}
c_{Pdet}	Detritus phosphorus	mg m^{-3}
L_{DIN}	DIN load	mg m^{-3} d^{-1}
L_{DIP}	DIP load	mg m^{-3} d^{-1}
I	Total radiation	MJ m^{-2}d^{-1}
T	Temperature	°C
Ice	Ice-cover (0,1)	-
t	Time	d
h	Depth of grid cell	m

Table 2. Model parameters

Symbol	definition	reference	value	unit
N_{inC}	Nitrogen in cyanobacteria	Redfield, 1958	0.0193	-
P_{inC}	Phosphorus in cyanobacteria	Redfield, 1958	0.00268	-
N_{inA}	Nitrogen in the other algae	Redfield, 1958	0.0193	-
P_{inA}	Phosphorus in the other algae	Redfield, 1958	0.00268	-
μ_{Cmax}	Maximal growth rate of cyanobacteria	calibration	0.5	d^{-1}
μ_{Amax}	Maximal growth rate of the other algae	Olli *et al.*, 1996	0.7	d^{-1}
R_{Cmax}	Maximum loss rate of cyanobacteria	calibration	0.1	d^{-1}
R_{Amax}	Maximum loss rate of the other algae	calibration	0.15	d^{-1}
K_{NC}	Half-saturation coefficient of DIN for cyanobacteria	Tyrrell, 1999	0	mg m^{-3}
K_{PC}	Half-saturation coefficient of DIP for cyanobacteria	Kononen & Leppänen, 1997	2	mg m^{-3}
K_{NA}	Half-saturation coefficient of DIN for the other algae	calibration	7	mg m^{-3}
K_{PA}	Half-saturation coefficient of DIP for the other algae	calibration	1	mg m^{-3}
K_{IC}	Half saturation coefficient of radiation for cyanobacteria	calibration	20	MJ m^{-2} d^{-1}
K_{IA}	Half saturation coefficient of radiation for the other algae	calibration	15	MJ m^{-2} d^{-1}
C_{min}	Minimum biomass of cyanobacteria	calibration	0.5	g m^{-2}
A_{min}	Minimum biomass of the other algae	calibration	0.01	g m^{-2}
A_{max}	Maximum total biomass of algae	calibration	300	g m^{-2}
β_0	Maximal detritus nitrogen mineralisation rate	Garber, 1984	0.018	d^{-1}
γ_0	Maximal detritus phosphorus mineralisation rate	Garber, 1984	0.043	d^{-1}
ν_{Ndet}	Settling rate of detritus nitrogen	Heiskanen & Tallberg, 1999	1	m d^{-1}

ν_{Ndet}	Settling rate of detritus nitrogen	Heiskanen & Tallberg, 1999	1	m d^{-1}
ν_{Pdet}	Settling rate of detritus phosphorus	Heiskanen & Tallberg, 1999	1	m d^{-1}
S_{Ndet}	Sedimentation rate of detritus nitrogen	calibration	0.16	m d^{-1}
S_{Pdet}	Sedimentation rate of detritus phosphorus	Lehtoranta, 1998	0.00	m d^{-1}
T_{opt}	Optimal temperature			
	for the growth of cyanobacteria	Kononen & Leppänen, 1997	25	°C
	for the growth of the other algae	calibration	15	°C
	for losses	calibration	25	°C
	for detritus nitrogen mineralisation	Garber, 1984	18	°C
	for detritus phosphorus mineralisation	Garber, 1984	18	°C
a_T	Coefficient for temperature limiting factor			
	for the growth of cyanobacteria	calibration	1.14	-
	for the growth of the other algae	calibration	1.001	-
	for losses	calibration	1.05	-
	for detritus nitrogen mineralisation	Garber, 1984	1.31	-
	for detritus phosphorus mineralisation	Garber, 1984	1.60	-
I_{red}	Radiation attenuation by ice	calibration	0.5	-
h_{mix}	Depth of mixing layer	calibration	20	m

Table 3. Model equations, rates and limiting factors.

Equations

$$\frac{\partial c_C}{\partial t} = (\mu_C - R_C)c_C \quad (1)$$

$$\frac{\partial c_A}{\partial t} = (\mu_A - R_A)c_A \quad (2)$$

$$\frac{\partial c_{DIN}}{\partial t} = \beta\, c_{NDet} - \mu_A N_{inA} c_A h_{mix}^{-1} - \mu_C N_{inC} c_C h_{mix}^{-1} + L_{DIN} \quad (3)$$

$$\frac{\partial c_{DIP}}{\partial t} = \gamma\, c_{Pdet} - \mu_A P_{inA} c_A h_{mix}^{-1} - \mu_C P_{inC} c_C h_{mix}^{-1} + L_{DIP} \quad (4)$$

$$\frac{\partial c_{Ndet}}{\partial t} = N_{inA}\, R_A c_A h_{mix}^{-1} + N_{inC}\, R_C c_C h_{mix}^{-1} - \beta c_{Ndet} - \nu_{Ndet} c_{Ndet} h^{-1} - S_{Ndet} c_{Ndet} h^{-1} \quad (5)$$

$$\frac{\partial c_{Pdet}}{\partial t} = P_{inA}\, R_A c_A h_{mix}^{-1} + P_{inC}\, R_C c_C h_{mix}^{-1} - \gamma c_{Pdet} - \nu_{Pdet} c_{Pdet} h^{-1} - S_{Pdet} c_{Pdet} h^{-1} \quad (6)$$

Rates

$$\mu_C = \mu_{Cmax} f_{CN}(c_{DIN}, c_{DIP})\; f_{CI}(I)\; f(T) f_{AC}(c_A, c_C) \quad (7)$$

$$\mu_A = \mu_{Amax} f_{AN}(c_{DIN}, c_{DIP})\; f_{AI}(I)\; f(T) f_{AC}(c_A, c_C) \quad (8)$$

$$R_C = R_{Cmax} f(T)(c_C - C_{min})/c_C \quad (9)$$

$$R_A = R_{Amax} f(T)(c_A - A_{min})/c_A \quad (10)$$

$$\beta = \beta_0 f(T) \quad (11)$$

$$\gamma = \gamma_0 f(T) \quad (12)$$

Limiting factors

$$f_{CN}(c_{DIN}, c_{DIP}) = \frac{c_{DIN}}{c_{DIN} + K_{NC}} \frac{c_{DIP}}{c_{DIP} + K_{PC}} \quad (13)$$

$$f_{AN}(c_{DIN}, c_{DIP}) = \frac{c_{DIN}}{c_{DIN} + K_{NA}} \frac{c_{DIP}}{c_{DIP} + K_{PA}} \quad (14)$$

$$f(T) = \exp\left[\int_{T_{opt}}^{T} \ln \theta dT\right], \text{ where } \theta = a_T + (1 - a_T)T/T_{opt} \quad (15)$$

$$f_{CI}(I) = \frac{I(1 - Icel_{red})}{I(1 - Icel_{red}) + K_{IC}} \quad (16)$$

$$f_{AI}(I) = \frac{I(1 - Icel_{red})}{I(1 - Icel_{red}) + K_{IA}} \quad (17)$$

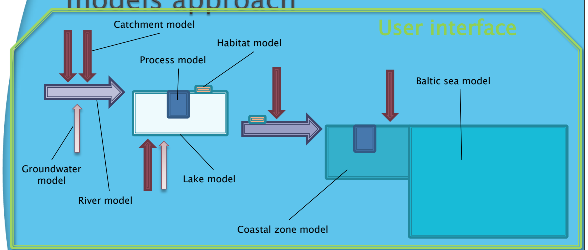
$$f_{AC}(c_A, c_C) = 1 - \frac{c_A + c_C}{A_{max}} \quad (18)$$

SYKE

7. Some visions and lessons

SYKE

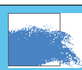
Modelling philosophy: the chain of models approach



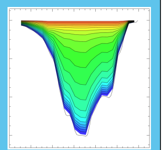
- Water flows through the different models and tracers flow along with the water. Process models can act on the tracers, or calculate small scale flow, and e.g. habitat models depend on the other models
- **Catchment model**: WSFS-Vemala, INCA, SWAT, SOBEK
- **River model**: SOBEK, River2D, **COHERENS**
- **Habitat model**: Delft HABITAT, River2D
- **Lake model**: COHERENS, MyLake
- **Process models**: biological models, sediment models, Elmer
- **Coastal zone model**: COHERENS
- **Baltic sea model**: COHERENS

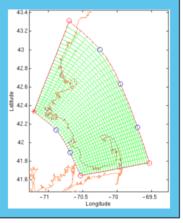
SYKE

COHERENS modelling tool



museum



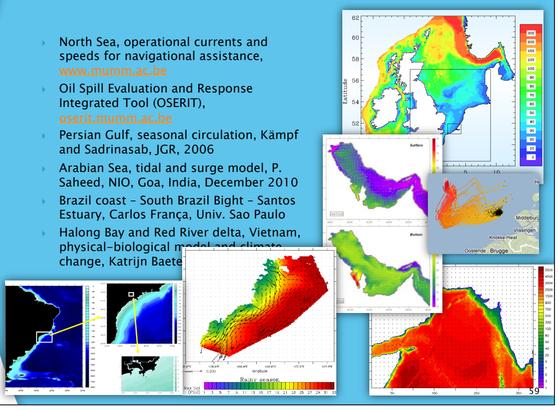


- **CO**upled **H**ydrodynamical **E**cological model for **REgioN**al **S**helf seas, RBINS-MUMM, Belgium
- 3D finite difference, s-layer, multi-platform numerical model designed for application in coastal and shelf seas, estuaries, lakes and reservoirs
- Open source, available to the public since 2000
- Multi-platform, extremely good documentation (1500+ pages)
- Modular design
  - Physical core
    - selectable simulation modes, dimensions, numerical schemes
  - Flexible and expandable
    - Biological/ecological module
    - Sedimentation module
    - Wave modules
    - Tracers
    - Processes
- Actively developed, constantly evolving (latest version V2.5.1 available since August/2013)

SYKE

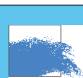
COHERENS around the world

- North Sea, operational currents and speeds for navigational assistance, www.mumm.ac.be
- Oil Spill Evaluation and Response Integrated Tool (OSERIT), oserit.mumm.ac.be
- Persian Gulf, seasonal circulation, Kämpf and Sadrinasab, JGR, 2006
- Arabian Sea, tidal and surge model, P. Saheed, NIO, Goa, India, December 2010
- Brazil coast - South Brazil Bight - Santos Estuary, Carlos França, Univ. Sao Paulo
- Halong Bay and Red River delta, Vietnam, physical-biological model and climate change, Katrijn Baete...



SYKE

COHERENS at SYKE

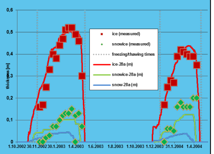


- COHERENS was selected as SYKE's marine and lake modelling tool of choice
  - Performance as multi-purpose modelling tool - adaptability to both lake and marine environment
  - Open source code & excellent documentation
  - Modularity
  - Active development
- COHERENS performed well in model inter-comparison study in the Gulf of Finland (Myrberg et al, 2010)
- Development resources can be concentrated to improving a single modelling tool
  - The goal of module development work at SYKE is to improve the applicability of the COHERENS model in low-salinity Baltic region applications for multi-year (incl. winter) simulations
  - Modules have been developed for eg. tracers, sediments and ice formation/melting
- V1 code used since 2006, from 2012 all new projects use V2

SYKE

Ongoing, near-future and proposed COHERENS developments at SYKE 1/4

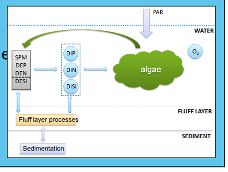
- Adapting model heat balance to boreal lake environment
  - Shallow lake thermodynamics not completely correctly modelled
- Ice and snow model
  - Important for multi-year simulations and climate change scenarios
  - Measurements
  - Calibrate and validate the developed code
  - Add simple advection
- Fully utilise the advances in COHERENS V2 code
  - Nesting
  - Sediment model
  - Flooding and drying schemes
  - etc
- Coupling COHERENS to other models
  - River models, catchment models, WSFS-VEMALA, groundwater flows
  - "Chain of models"



SYKE

Ongoing, near-future and proposed COHERENS developments 2/4

- Increase understanding of shallow area flows
  - Fetch
  - Local wind effects on the same horisontal scale as lake model itself
  - Hydraulic effects of bottom macrophytes
- Wave modelling
  - Coupling to external models
- Ecological/nutrient model with particle-bound nutrient transport
- Transport and evolution of harmful substances
  - Organic tin compounds (TbTs)
  - Bacteria, viruses
  - Artifical sweeteners, medicines
- Coupling to external biological models
  - BFM
  - PyWQM



SYKE

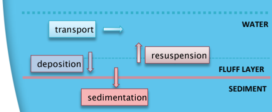
Ongoing, near-future and proposed COHERENS developments 3/4

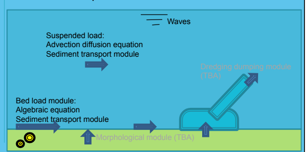
- Age tracers and automatic fraction calculations (2013-2014)
- Automatic sanity checking mid-simulation
- Improving data output usability
  - Looking at results while simulation is running
  - Importing/exporting NetCDF to other software
  - Visualisation improvements
- Seto inland sea, Japan (Okayama U.)
  - Complex morphology
  - Tidal interactions
  - Power generation
- Data assimilation and automatic calibration (collaboration with Okayama U.)
  - Initial values and loads from satellite imagery
  - Particle filtering method
  - Ensemble Kalman filtering

SYKE

COHERENS sediment models

- COHERENS V1
  - Very simple model
  - Single fraction
  - Simple wave-current interaction
  - Temporary deposition in 'fluff layer', resuspension and permanent sedimentation
  - Based on Jones et al. (1995)[1]
  - Area of applicability on ocean floors
- COHERENS V2.5
  - State-of-the-art model
  - Cohesive and non-cohesive sediment
    - Multiple fractions
    - Hiding effects and flocculation
  - Multiple ways to calculate bed-current-wave interactions
  - Two-way coupled with hydrodynamics
    - Density driven sediment flows
    - Turbulence damping
  - Bed slope effects
  - Developed at IMDC & RBINS[2]



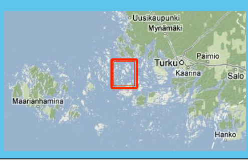


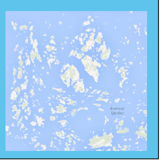
1) Jones S.E., Jago C.F. and Simpson J.H., 1995. Modelling suspended sediment dynamics in tidally mixed and periodically stratified waters : progress and pitfalls. In : C.B. Pattiaratchi (Editor), Mixing Processes in Estuaries and Coastal Seas. Coastal and Estuarine Studies, Vol. 41, American Geophysical Union, 315-338.
2) Breugem, W.A., Decrop, B., Frederix, K., Delecluyse, K., v .Holland, G., Luyten, P., Hyde, P., Development of a sediment transport model in Coherens,

SYKE

Ongoing, near-future and proposed COHERENS developments 4/4

- Archipelago Sea model
  - Commission from the Ministry of Environment
  - The goal is to produce an intuitive graphical tool to help decision-making in controlling loading to the Archipelago Sea area
  - Nested marine model on the Baltic, coupled to WQ models
    - Full Baltic Sea coarse resolution + fine resolution archipelago sea model
    - River/agricultural loading (WSFS-VEMALA)
    - Eutrophication & water quality (PyWQM/SEABED project)
  - Joint project with SYKE's Freshwater and Marine Centers with partners from FMI, regional authorities, Åbo Akademi, KTH (Sweden)





SYKE

COHERENS applicability

- From large sea areas with high salinity down to small lakes (~ 1 km^2) with zero salinity
- Physical modelling in three dimensions
  - Currents, temperature, salinity
  - Tidal effects
  - Flooding
  - Morphology changes
- Ecological modelling
  - Nutrient fluxes, biology, sedimentation, resuspension
- Fate of substances
  - Transport, drifting, spreading, diffusion
  - Process modelling
- Climate change scenarios
  - Multi-year modelling

SYKE

Basic lessons

- Solution orientation ➔
  - Model to be applied has to solve the problem at hand
  - As simple model as possible
  - We should have good understanding what happens in nature
- Model (=Tool) known and at hand
  - Well documented
  - Open source code
  - Possibility to modify the model
  - Collective experience and team work
- Data collection
  - Calibration
  - Validation

SYKE

Related literature

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2. Huttula T., Peltonen A., Bilaletdin Ä., Saura M., 1992: The effects of climatic change on lake ice and water temperature. Aqua Fennica Vol. 22,2.
3. Myrberg, K., Ryabchenko, V., Isaev, A., Vankevich, R., Andrejev, O., Bendtsen, J., Erichsen, A., Funkquist L., Inkala A., Neelov I., Rasmus K., Rodriquez Medina M., Raudsepp U., Passenko J., Söderkvist J., Sokolov A., Kuosa H., Anderson T. R., Lehmann A. & Skogen M. D. 2010: Validation of three-dimensional hydrodynamic models of the Gulf of Finland. Boreal Env. Res. vol. 15, nº5, pp. 453-479
4. Huttula T., Pulkkanen M., Arkhipov B., Leppäranta M., Solbakov V., Shirasawa K., and Salonen K., 2010: Circulation in an ice covered lake. Estonian Journal of Earth Sciences, 2010, 59, 4, 298-309.
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6. Veijalainen, N., Lotsari E., Alho, P., Vehviläinen, B., Käyhkö, J. 2010. National scale assessment of climate change impacts on flooding in Finland. Journal of Hydrology 391: 333-350.
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SYKE