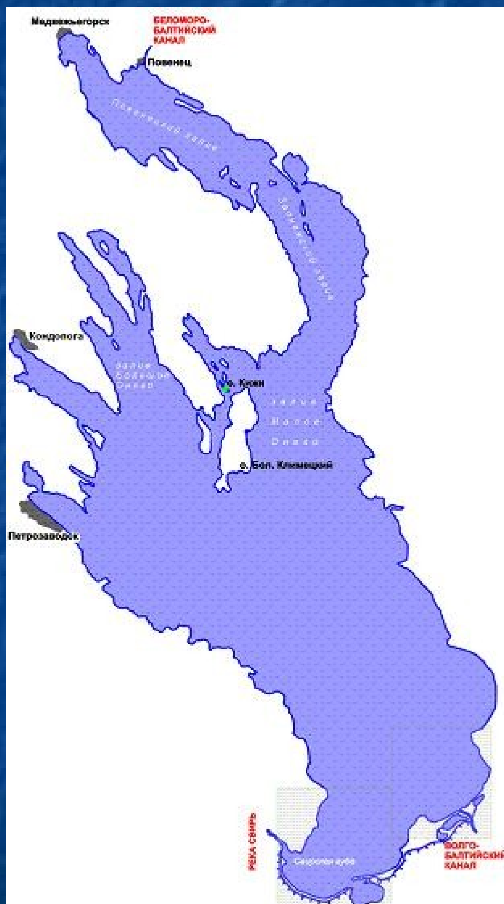
# Application of FLAKE model to lake water quality modelling studies

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P I R K A N M A A
R E G I O N A L E N V I R O N M E N T C E N T R E

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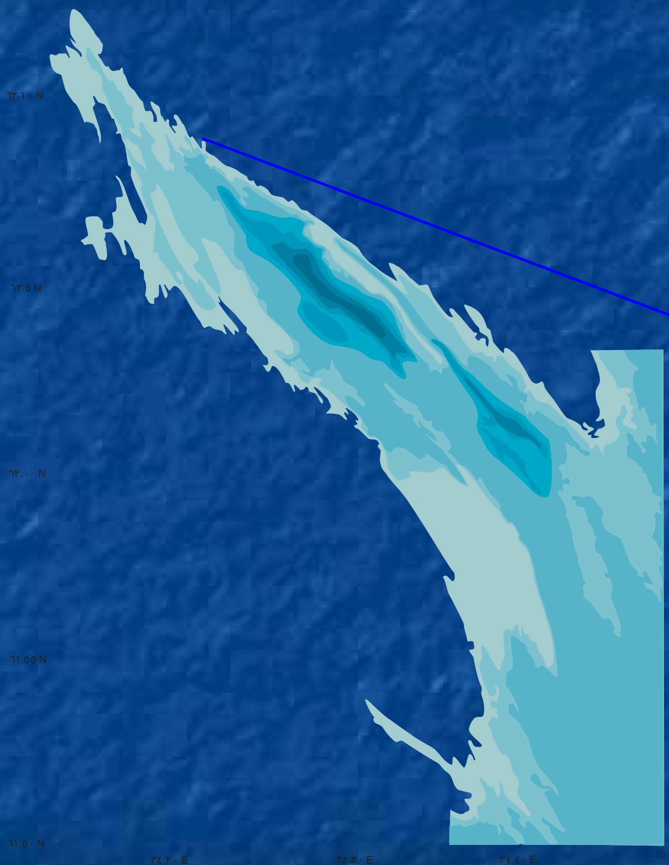
# Presentation outline

- I. Modelling dynamics of phosphorus P in Kondopoga bay – application of Danish P2 box model coupled with FLAKE
- II. Coupling of the simple ecological model with FLAKE model
  - Structure of the combined  modelling system
  - The ecological block of the model
  - Basic characteristics of the Petrozavodsk Bay, Lake Onega
  - Preliminary results of simulations
- Summary

| | Lake Onega | Lake Ladoga |
|---|---|---|
| Drainage area | 66 200 km$^2$ | 260 000 km$^2$ |
| Lake surface area | 9 900 km$^2$ | 17 200 km$^2$ |
| Water volume | 291 km$^3$ | 900 km$^3$ |
| Max depth | 120 m | 230 m |
| Mean depth | 30 m | 47 m |
| Retention time | 15 years | 11 years |

# Kondopoga Bay

Length 33 km
Surface area 243 km$^2$ (2.5% of the lake area)
Water volume 4.3 km$^3$ (1.5% of the lake volume)
Mean depth 21 m
Maximum depth 82 m



# The Danish model for P retention in lakes

- Two state variables:

$P_l$ – total phosphorus concentration in lake water and

$P_s$ – exchangeable total P in sediments

- Driving parameters in the model:

$P_i$ – inflow total P concentration,

Q – water discharge and

T – lake water temperature

# Governing equations – P2 model

$$\frac{dP_l}{dt} = \frac{Q}{V}\left(k \cdot P_i - P_l\right) - S + R,$$

$$\frac{dP_s}{dt} = \frac{Q}{V}\left((١ - k) \cdot P_i\right) + S - R,$$

$$k = \frac{١}{١ + \sqrt{\dfrac{V}{٣٦٥ \cdot Q}}},$$

$$S = a \cdot (١ + C_١)^{T-٢٠} \cdot \frac{P_l}{H},$$

$$R = b \cdot (١ + C_٢)^{T-٢٠} \cdot P_s$$

- V – lake volume, $m^3$
- Q – inflow discharge, $m^3$/day
- H – lake depth, m
- S – sedimentation
- R – release of TP from sediments to lake water
- a – sedimentation rate of TP, g P/ ($m^2$*day)
- $C_1$ – temperature correction for a
- b – release rate of TP, g P/ ($m^2$*day)
- $C_2$ – temperature correction for b

# Calibrated values of parameters on the basis of data from 16 lakes (HELCOM Report, 2004)

- Sedimentation rate a=0.047
- Temperature dependence of P-sedimentation $C_1 = 0.0$
- Sediment release rate b=0.000595
- Temperature dependence of P- release $C_2 = 0.08$

Introducing new parameters:

$A=Q/V+a/h$, $B=b(1+C_2)^{T-20}$, $C=Q/V*k*P_i$, $E=$ $C=Q/V*(1-k)*P_i$, the system of equations can be rewritten in matrix-vector form

$$P' = M \cdot P + \begin{Bmatrix} \dfrac{Qk}{V} \\ \dfrac{Q(1-k)}{V} \end{Bmatrix} \bullet P_i,$$

$$P = \begin{Bmatrix} P_l \\ P_s \end{Bmatrix},$$

$$M = \begin{bmatrix} -A & B \\ A - \dfrac{Q}{V} & -B \end{bmatrix}.$$

Characteristic equation:

$$\det(M - \lambda I) = \lambda^{ʳ} + (A+B)\lambda + \frac{Q}{V} B = \cdot$$

Eigenvalues:

$$\lambda_{1,2} = -\frac{A+B}{2} \pm \sqrt{\left(\frac{A+B}{2}\right)^2 - \frac{Q}{V} B}$$

# The stationary solution of the system has the following form:

$$P_l = P_i,$$

$$P_s = \frac{\left(\frac{Q}{V}\cdot(1-k)+\frac{a}{H}\right)}{b\cdot(1+C_2)^{T-20}}\cdot P_i$$

**Kondopoga bay**

Mean annual inflow (River Suna) 2.43 $km^3/a$ or $Q=44{,}3\ m^3/s$;

Income of TP with river water:

28 tons/a -> $P_{Suna}=0.0115\ g/m^3$;

**Kondopoga PPM**

Volume of sewage waters: 0.0529 $km^3/a$ (1992-1996, Filatov et al.1999)

Income of TP with sewage water:

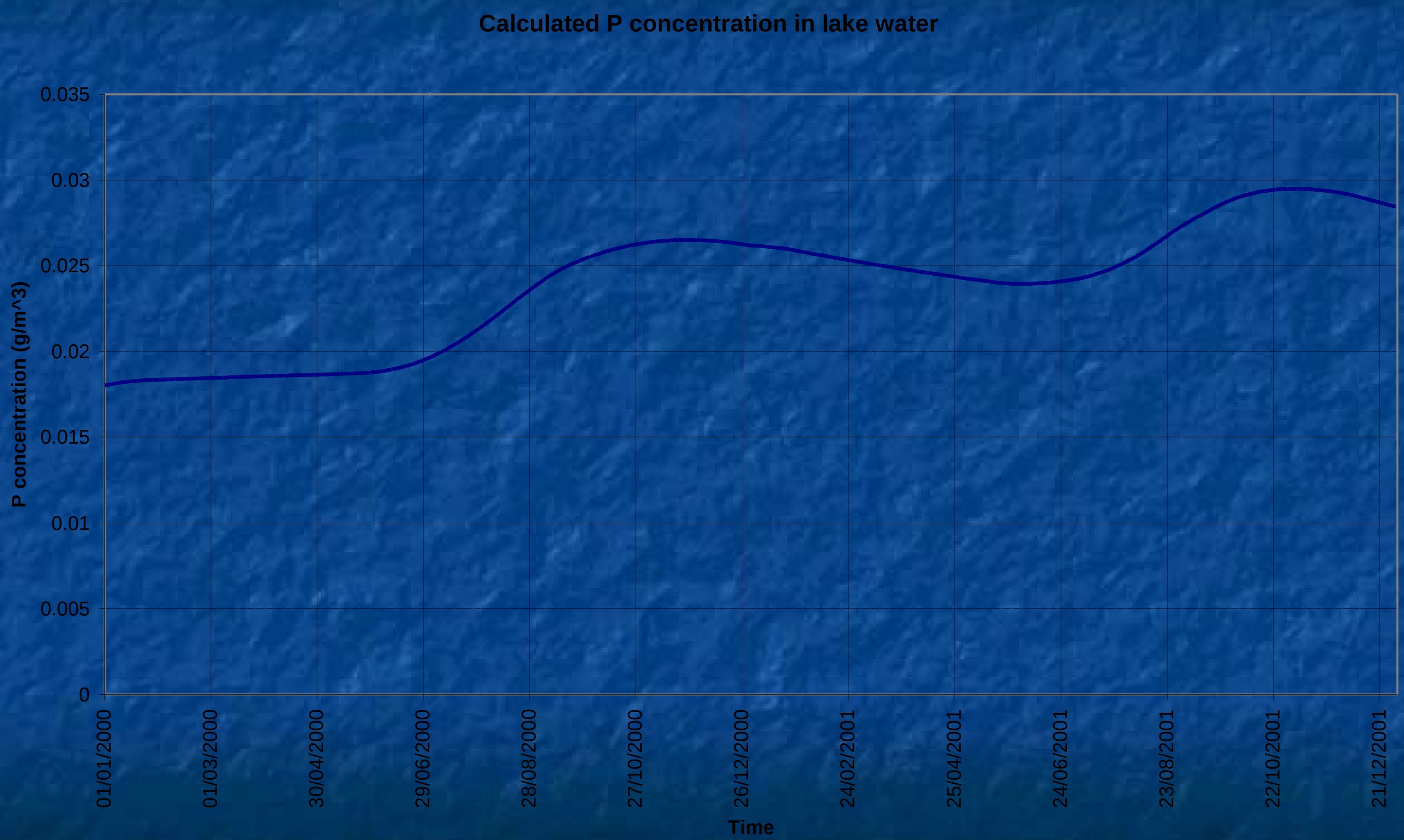
66.5 tons/a -> $P_{PPM}=1.2571\ g/m^3$

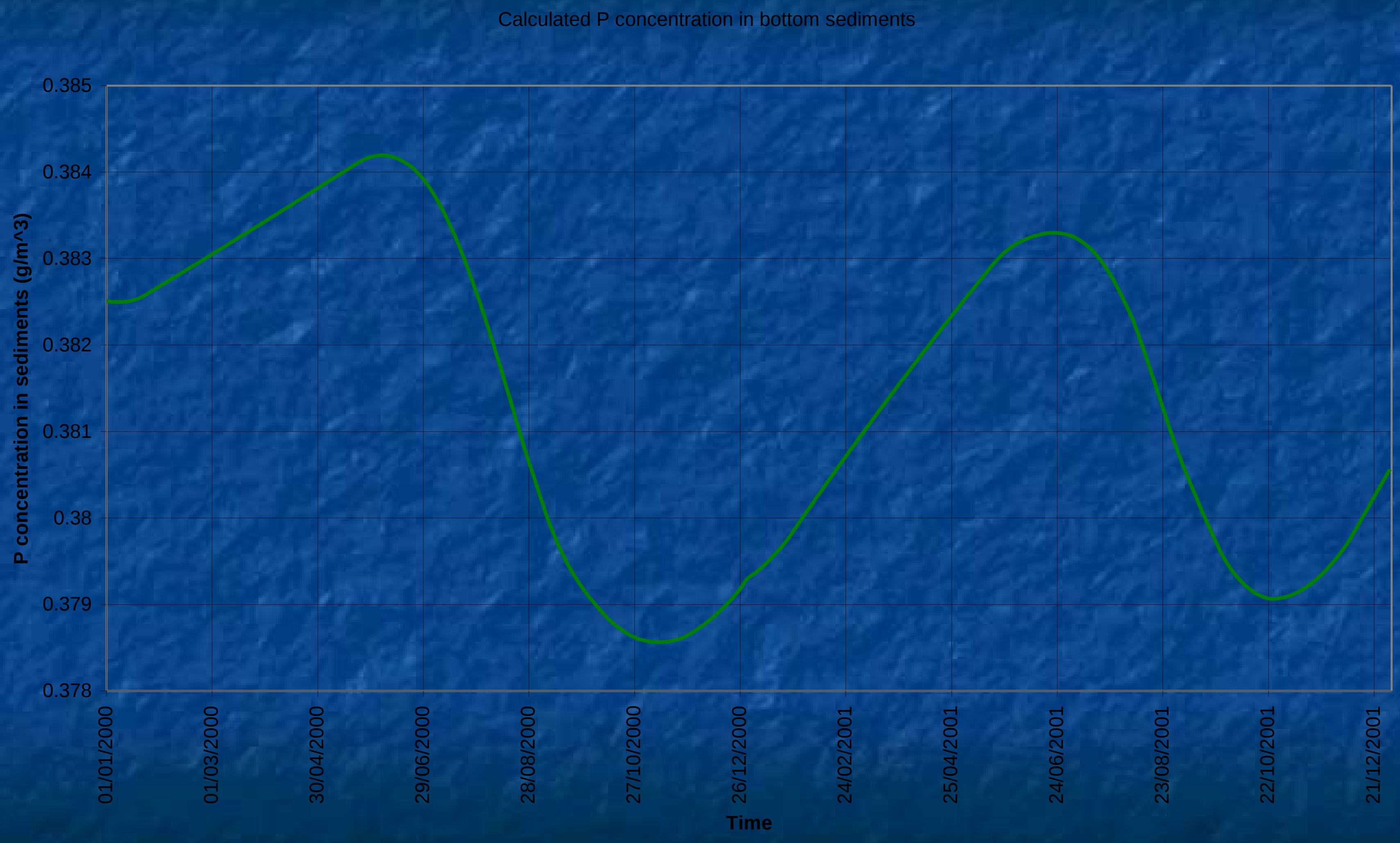
$P_i=(Q_{Suna}P_{Suna}+Q_{PPM}P_{PPM})/(Q_{Suna}+Q_{PPM})=$

$0.0381\ g/m^3$

$P_l=0.0381\ g/m^3$, $P_s=0.383\ g/m^3$ ($T_{water}=10^0\ C$)

# Dynamic calculations (T=f(time), calculated using FLAKE model:





Calculated P concentration in bottom sediments
P concentration in sediments (g/m^3)
0.385
0.384
0.383
0.382
0.381
0.38
0.379
0.378
01/01/2000
01/03/2000
30/04/2000
29/06/2000
28/08/2000
27/10/2000
26/12/2000
24/02/2001
25/04/2001
24/06/2001
23/08/2001
22/10/2001
21/12/2001
Time

# Models used in the study

Input:air temperature, humidity, wind speed, solar radiation and cloudiness

**FLAKE** – a bulk lake thermodynamic model (German Weather Service, NWPI, IGB– Mironov, Terzhevik, Kirillin,,2006)

Tributary inflows (LakeWeb catchment area sub-model by Håkanson & Buolion, 2002)

Lake water temperature time-series

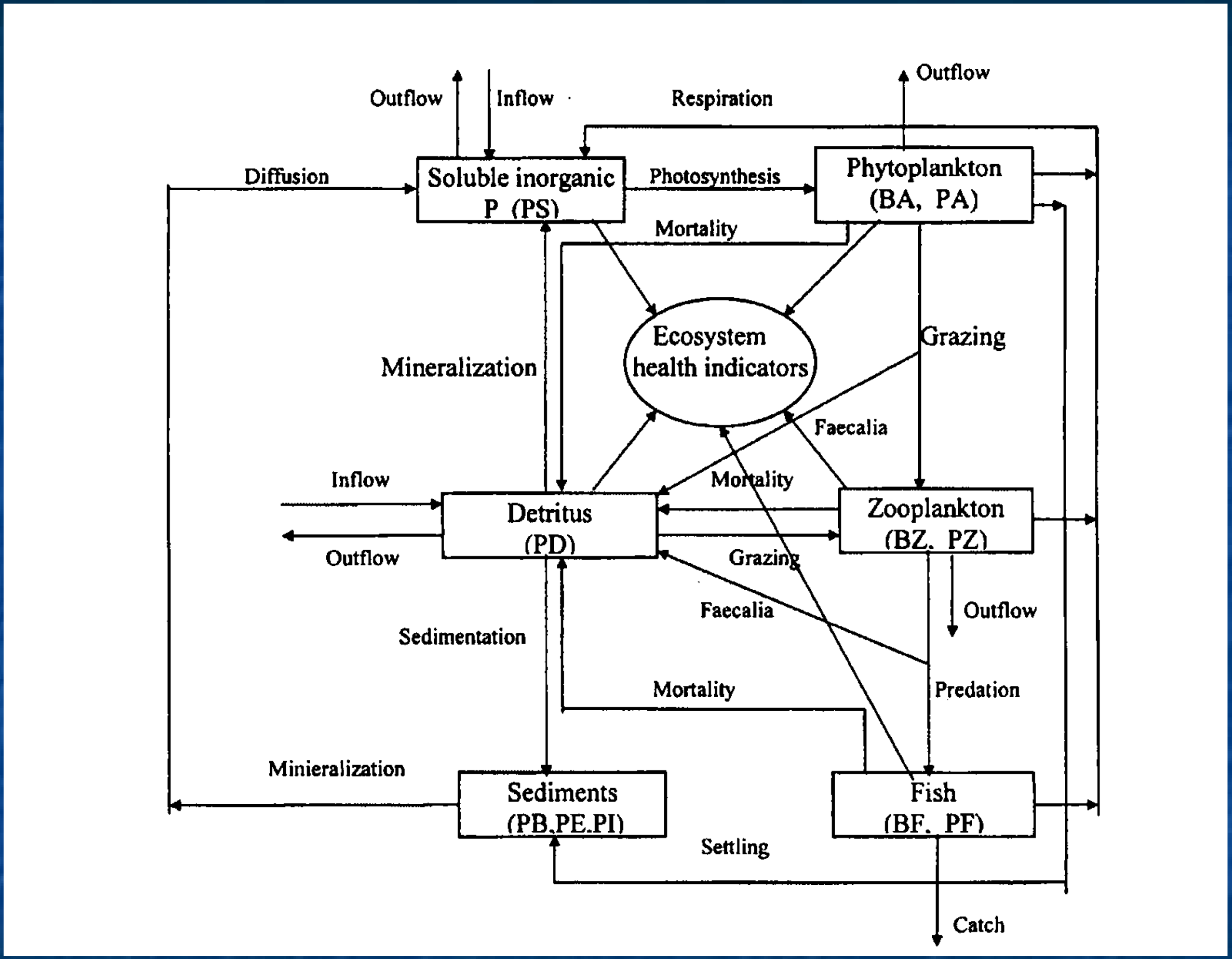
Lake ecological model (Fu-Liu Xu, Jørgensen, 2001)

Phytoplankton, zooplankton biomasses, fish, different fractions of phosphorus

# Ecological model

The model's state variables include:

- BA - phytoplankton biomass, g/m3
- BZ - zooplankton biomass, g/m3
- BF - fish biomass, g/m3
- PA - the amount of phosphorus in phytoplankton, g/m3
- FPZ - the proportion of phosphorus in zooplankton, kg P/kg BZ
- FPF - the proportion of phosphorus in fish, kg P/kg BF
- PD - the amount of phosphorus in detritus, g/m3
- PB - the amount of phosphorus in the biologically active sediment layer, g/m3
- PE - the amount of exchangeable phosphorus in sediments, g/m3
- PI - the amount of phosphorus in interstitial water, g/m3
- PS - the amount of soluble phosphorus in the lake's waters, g/m3




The conceptual diagram for the ecological model (from Fu-Lui Xu, 2001)

# Ecological model equations:

$$\frac{d}{dt}BA = (GA - MA - RA - SA - Gz/Y \cdot - Q/V) \cdot Ba$$

$$\frac{d}{dt}PA = AUP \cdot BA - (MA + RA + SA + GZ/Y \cdot + Q/V) \cdot PA$$

$$\frac{d}{dt}BZ = (MYZ - RZ - MZ - Q/V) \cdot BZ - (PRED\backslash/Y\backslash) \cdot BF$$

$$\frac{d}{dt}FPZ = MYZ \cdot (FPA - FPZ) = MYZ \cdot (PA/PB - FPZ)$$

$$\frac{d}{dt}BF = (GF - RF - MF - CATCH) \cdot BF$$

$$\frac{d}{dt}FPF = (PRED\backslash/Y\backslash) \cdot (FPZ - FPF)$$

$$\frac{d}{dt}PD = (\backslash/Y \cdot - \backslash) \cdot GZ \cdot PA - (\backslash/Y\backslash - \backslash) \cdot PRED\backslash \cdot PZ + MA \cdot PA + MZ \cdot PZ + MF \cdot PF + QPDIN - (KDP + SD + Q/V) \cdot PD$$

$$\frac{d}{dt}PB = ((QSED \cdot D/(DB \cdot DMU)) - QBIO - QDSORP$$

$$\frac{d}{dt}PE = (D \cdot (KEX \cdot (SA \cdot PS - QSED + SD \cdot PD))/(LUL \cdot DMU)) - KE \cdot PE$$

$$\frac{d}{dt}PI = (AE/AI) \cdot KE \cdot PE - (QDIFF/AI), whereAI = LUL \cdot (\backslash - DMU)/D$$

$$\frac{d}{dt}PS = RA \cdot PA + RZ \cdot PZ + RF \cdot PF + QPSIN + KDP \cdot PD + QDIFF + ((DB/D) \cdot DMU) \cdot (QBIO + QDSORP) - AUP \cdot BA - (Q/V) \cdot PS$$

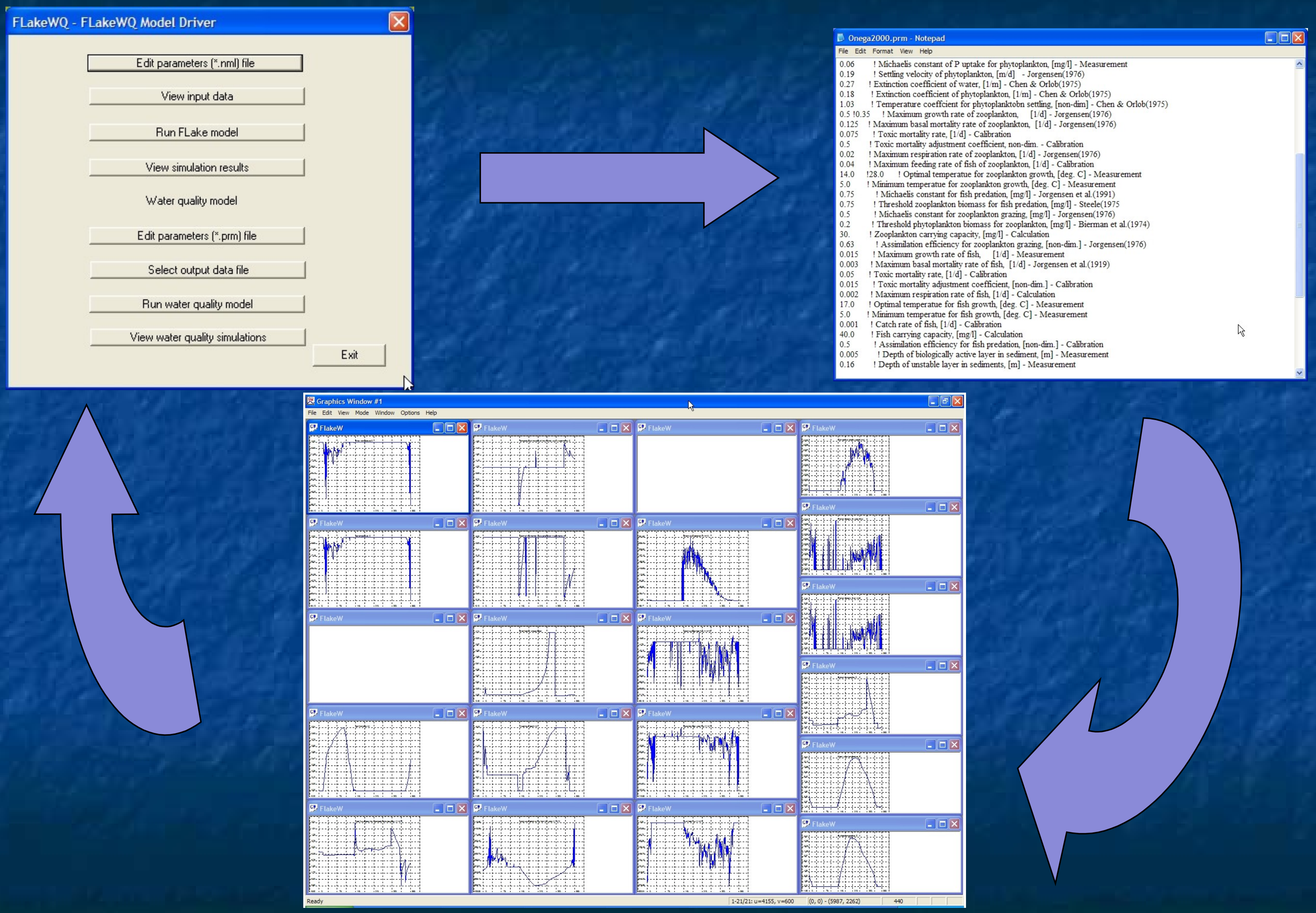
# Calibrated parameters: phytoplankton

| Symbol | Description | Unit | Literature range | Lake Chao case | Sources | Used value |
|---|---|---|---|---|---|---|
| GAmax | Maximum growth rate of phytoplankton | 1/d | 1 – 5 | 4.042 | Measurement | 0.35 |
| MAmax | Maximum mortality rate of phytoplankton | 1/d | | 0.96 | Measurement | |
| RAmax | Maximum respiration rate of phytoplankton | 1/d | 0.005–0.8 | 0.6 | Measurement | 0.4 |
| AUPmax | Maximum P uptake rate of phytoplankton | | 0.0014–0.01 | 0.003 | Calculation | 0.0014 |
| TAopt | Optimal temperature for phytoplankton growth | Cº | | 28 | Measurement | 20 |
| TAmin | Minimum temperature for phytoplankton growth | Cº | | 5 | Measurement | |
| FPAmax | Maximum kg P per kg phytoplankton biomass | - | 0.013–0.03 | 0.013 | J¯rgensen (1976) | |
| FPAmin | Minimum kg P per kg | - | 0.001–0.005 | 0.001 | J¯rgensen (1976) | |
| Phytoplankton biomass | | | | | | |
| KI | Michaelis constant for | kcal/m2 d | 173 –518 | 400 | J¯rgensen (1976) | |
| KPA | Michaelis constant of P uptake for phytoplankton | mg/l | 0.0005–0.08 | 0.06 | Measurement | |
| SVS | Settling velocity of phytoplankton | m/d | 0.1–0.8 | 0.19 | J¯rgensen (1976) | |
| $\alpha$ | Extinction coefficient of water | 1/m | | 0.27 | Chen & Orlob (1975) | |
| $\beta$ | Extinction coefficient of phytoplankton | 1/m | | 0.18 | Chen & Orlob (1975) | |
| $\theta$ | Temperature coefficient for phytoplankton settling | - | | | Chen & Orlob (1975) | |

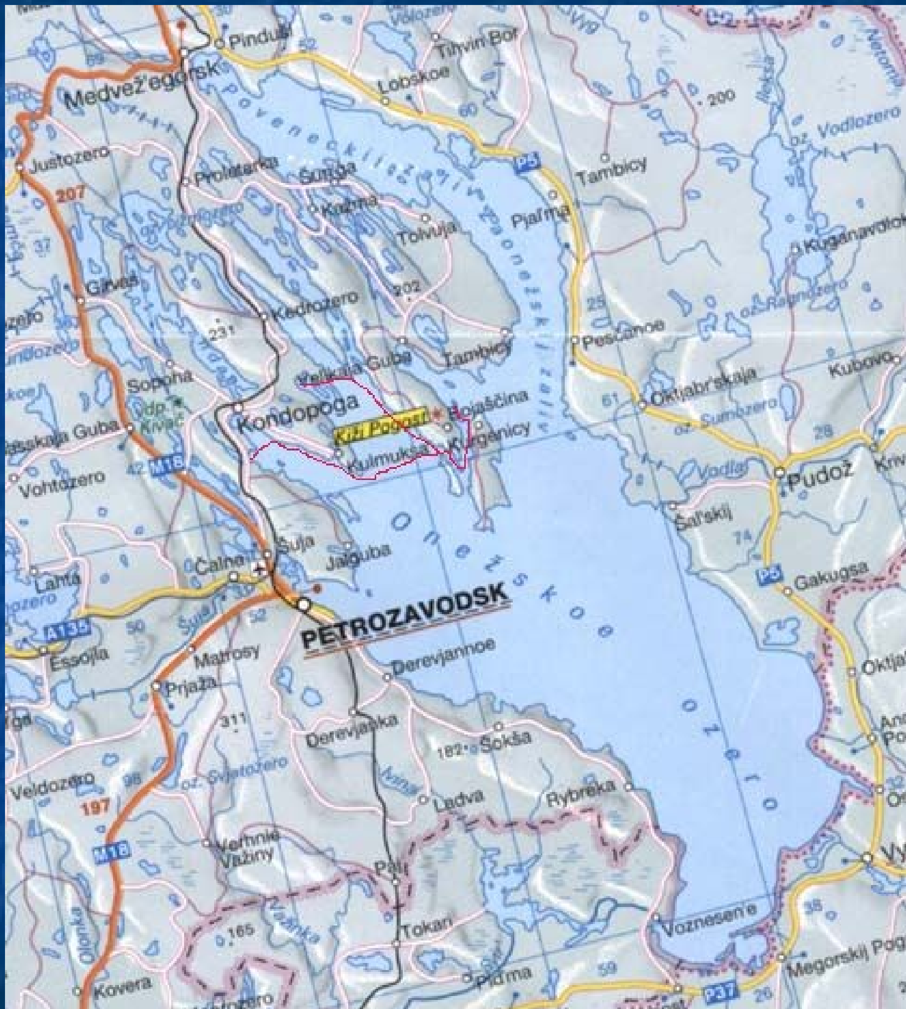
# Zooplankton

| Symbol | Description | Unit | Literature range | Lake Chao case | Sources | Used value |
|---|---|---|---|---|---|---|
| MYZmax | Maximum growth rate of zooplankton | 1/d | 0.1 – 0.8 | 0.35 | J¯rgensen (1976) | |
| MZmax | Maximum basal mortality rate of zooplankton | 1/d | 0.001–0.125 | | J¯rgensen (1976) | |
| TOXZ | Toxic mortality rate | 1/d | | 0.075 | Calibration | |
| Ktoxz | Toxic mortality adjustment coefficient | | | 0.5 | Calibration | |
| RZmax | Maximum respiration rate of zooplankton | 1/d | 0.001–0.36 | 0.02 | J¯rgensen (1976) | 0.03 |
| PRED1max | Maximum feeding rate of fish of zooplankton | 1/d | 0.012–0.06 | 0.04 | Calibration | |
| TZopt | Optimal temperature for zooplankton growth | C° | | 28 | Measurement | |
| TZmin | Minimum temperature for zooplankton growth | C° | | 5 | Measurement | |
| KZ | Michaelis constant for fish predation | mg/l | | 0.75 | J¯rgensen et al. (1991) | 0.5 |
| KSZ | Threshold zooplankton biomass for fish predation | mg/l | | 0.75 | Steele (1975) | |
| KA | Michaelis constant for zooplankton grazing | mg/l | 0.01–2 | 0.5 | J¯rgensen (1976) | |
| KSA | Threshold phytoplankton biomass for zooplankton | mg/l | 0.01–0.2 | 0.2 | Bierman et al. (1974) | 0.05 |
| KZCC | Zooplankton carrying capacity | mg/l | | 30 | Calculation | |
| Y0 | Assimilation efficiency for zooplankton grazing | - | 0.5–0.8 | 0.63 | J¯rgensen (1976) | |

# Calibration tool:



# Petrozavodsk Bay

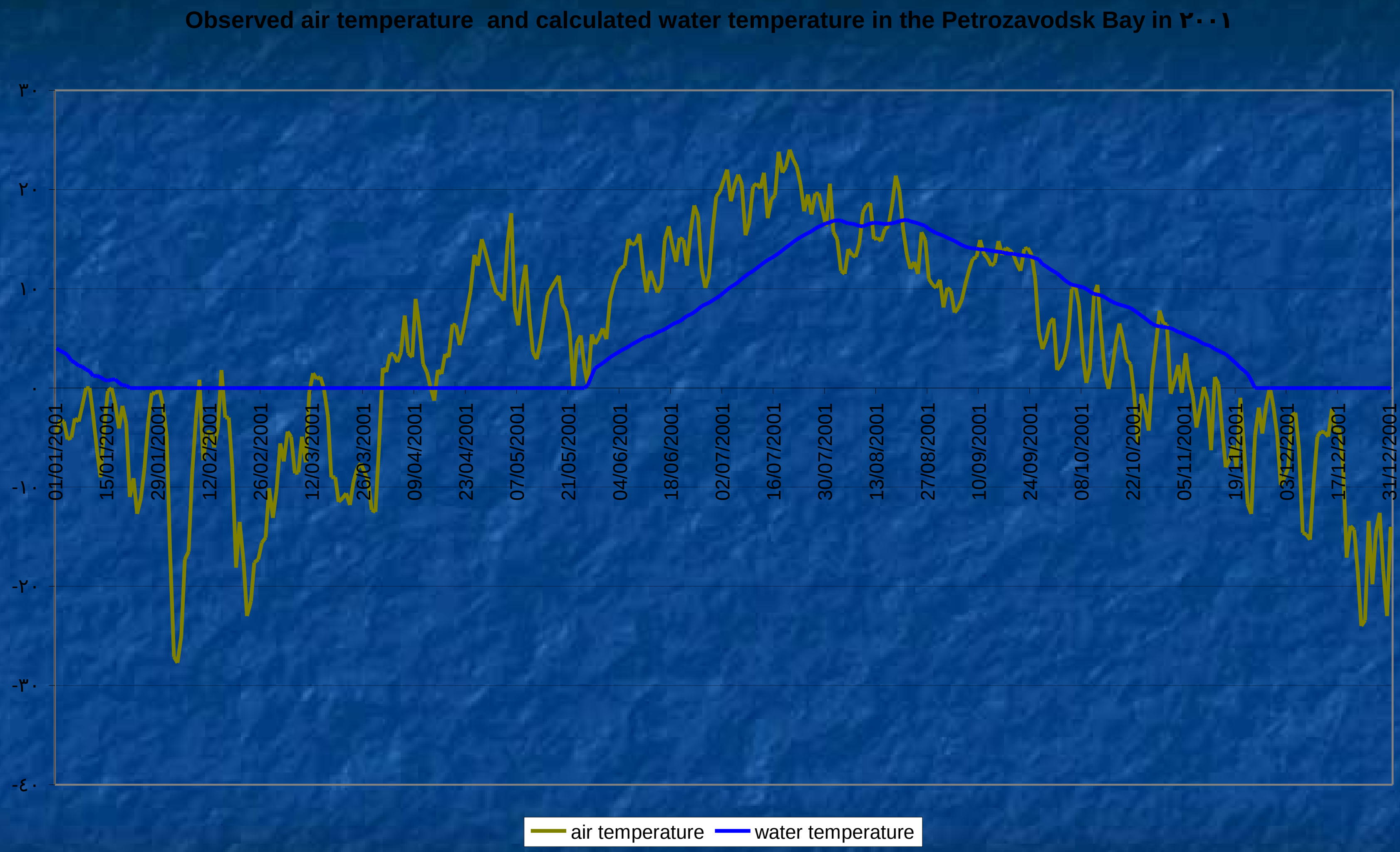



- Surface area - 73 km²
- Volume - 1,17 km³
- Mean depth - 16.0 m
- Water retention period – 0.35 year
- Tributary inflow - 3.4 km³/a

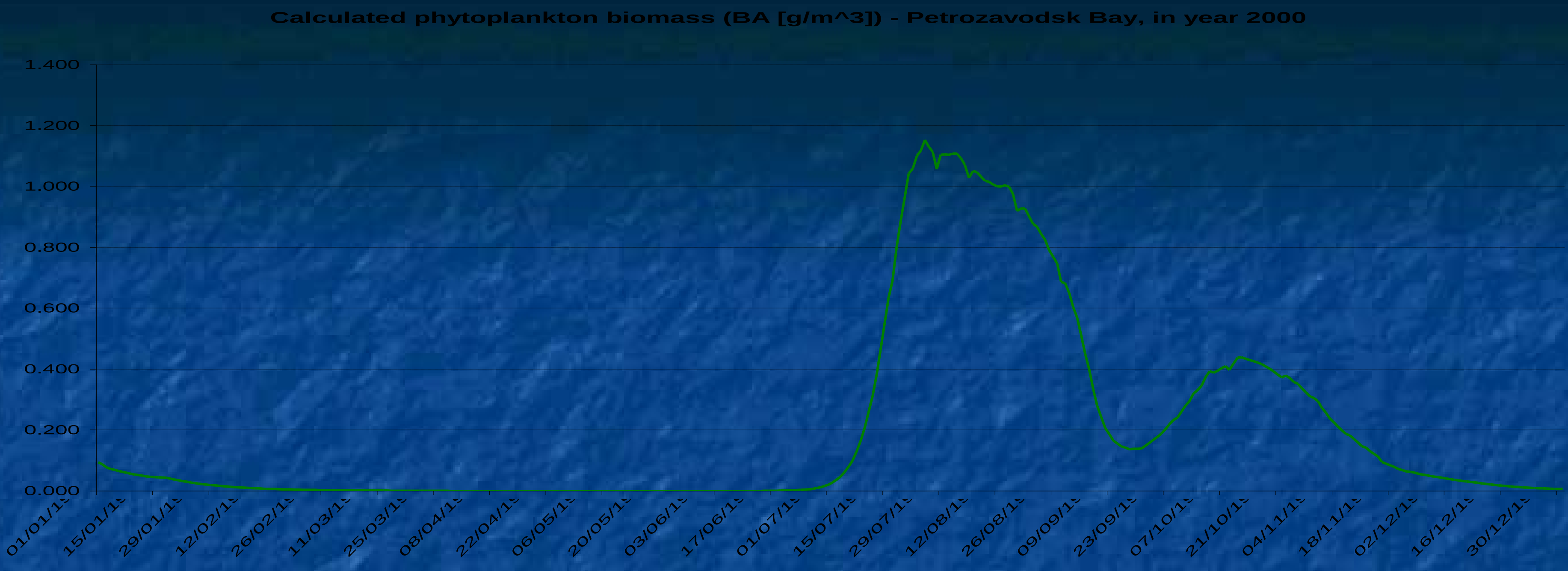
  Total $P_{inflow}$ - 184 tons/a
- Waste waters-49.3*10⁶ m³/a

Total $P_{waste\ waters}$-122 tons/a

(Filatov et al., 1999, 2004)




Example of FLAKE model simulations


Calculated phytoplankton biomass (BA [g/m^3]) - Petrozavodsk Bay, in year 2000
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
01/01/19
15/01/19
29/01/19
12/02/19
26/02/19
11/03/19
25/03/19
08/04/19
22/04/19
06/05/19
20/05/19
03/06/19
17/06/19
01/07/19
15/07/19
29/07/19
12/08/19
26/08/19
09/09/19
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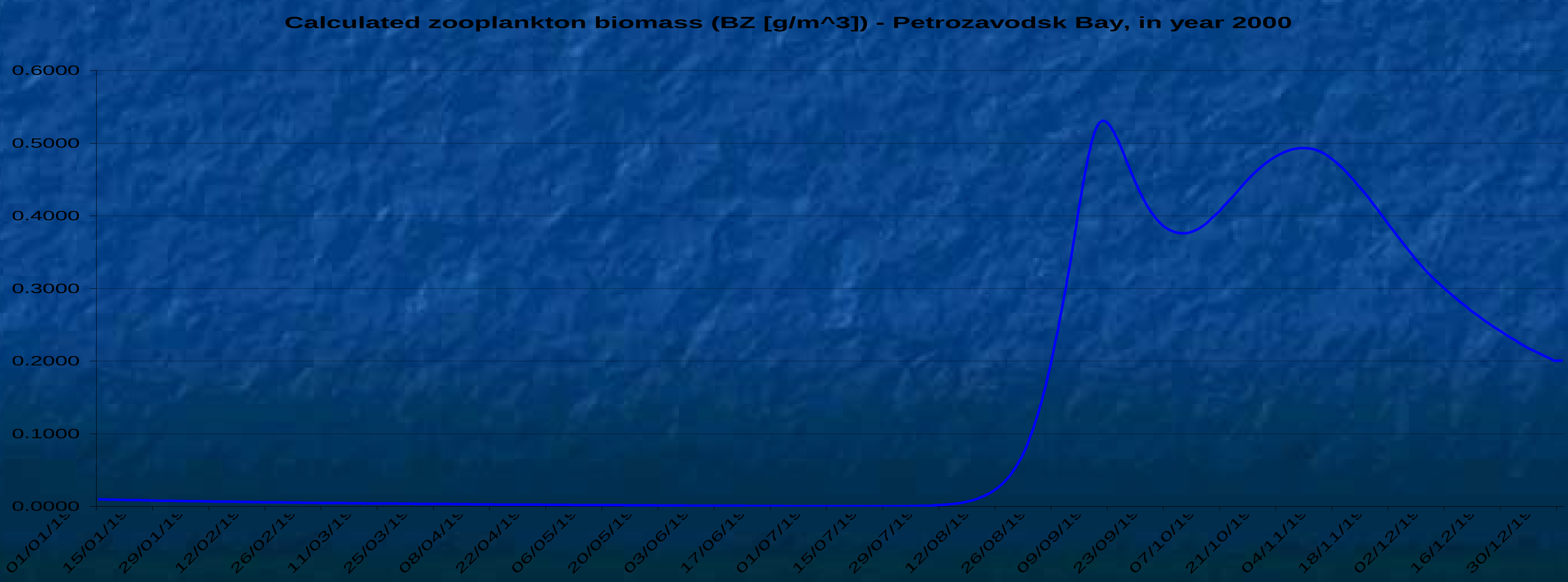
02/12/19
16/12/19
30/12/19


Calculated zooplankton biomass (BZ [g/m^3]) - Petrozavodsk Bay, in year 2000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
01/01/19
15/01/19
29/01/19
12/02/19
26/02/19
11/03/19
25/03/19
08/04/19
22/04/19
06/05/19
20/05/19
03/06/19
17/06/19
01/07/19
15/07/19
29/07/19
12/08/19
26/08/19
09/09/19
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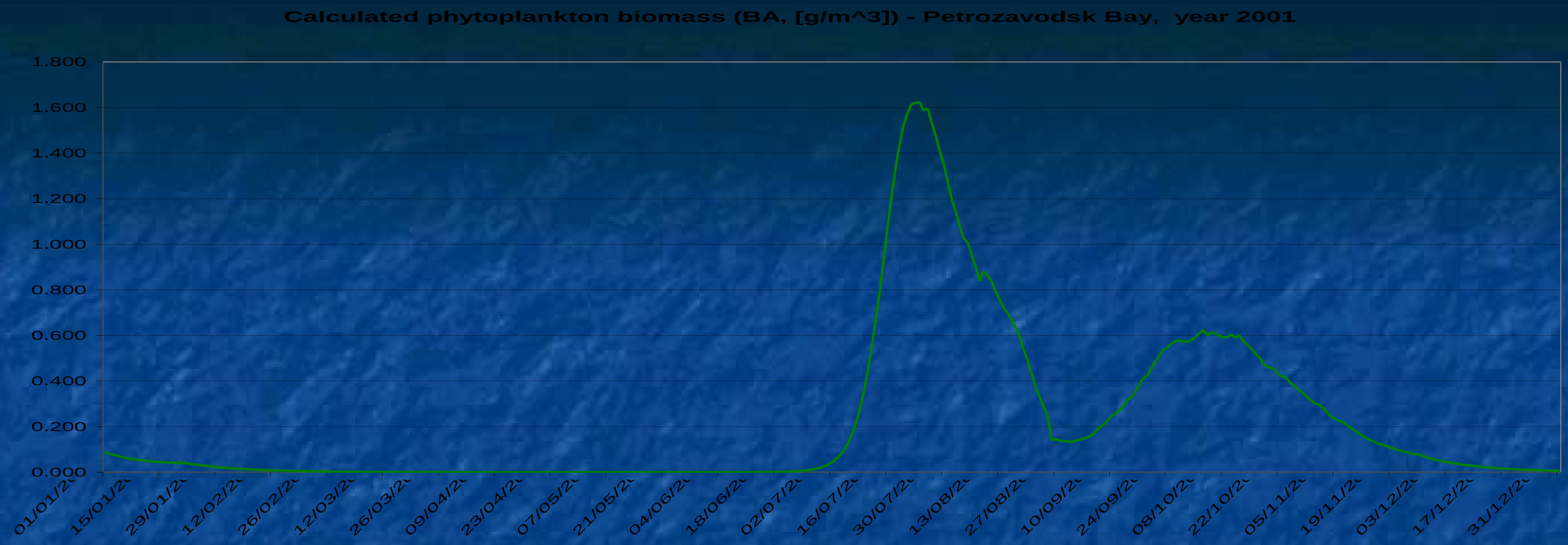
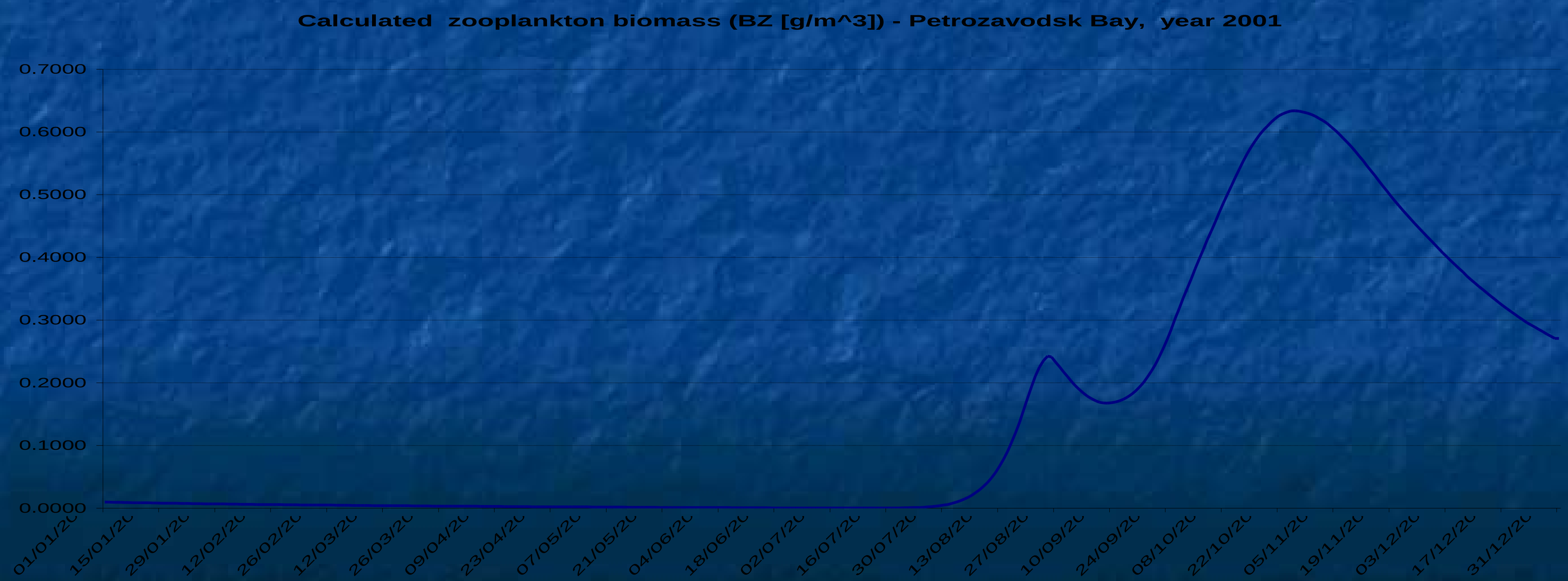
18/11/19
02/12/19
16/12/19
30/12/19


Calculated phytoplankton biomass (BA, [g/m^3]) - Petrozavodsk Bay, year 2001
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000

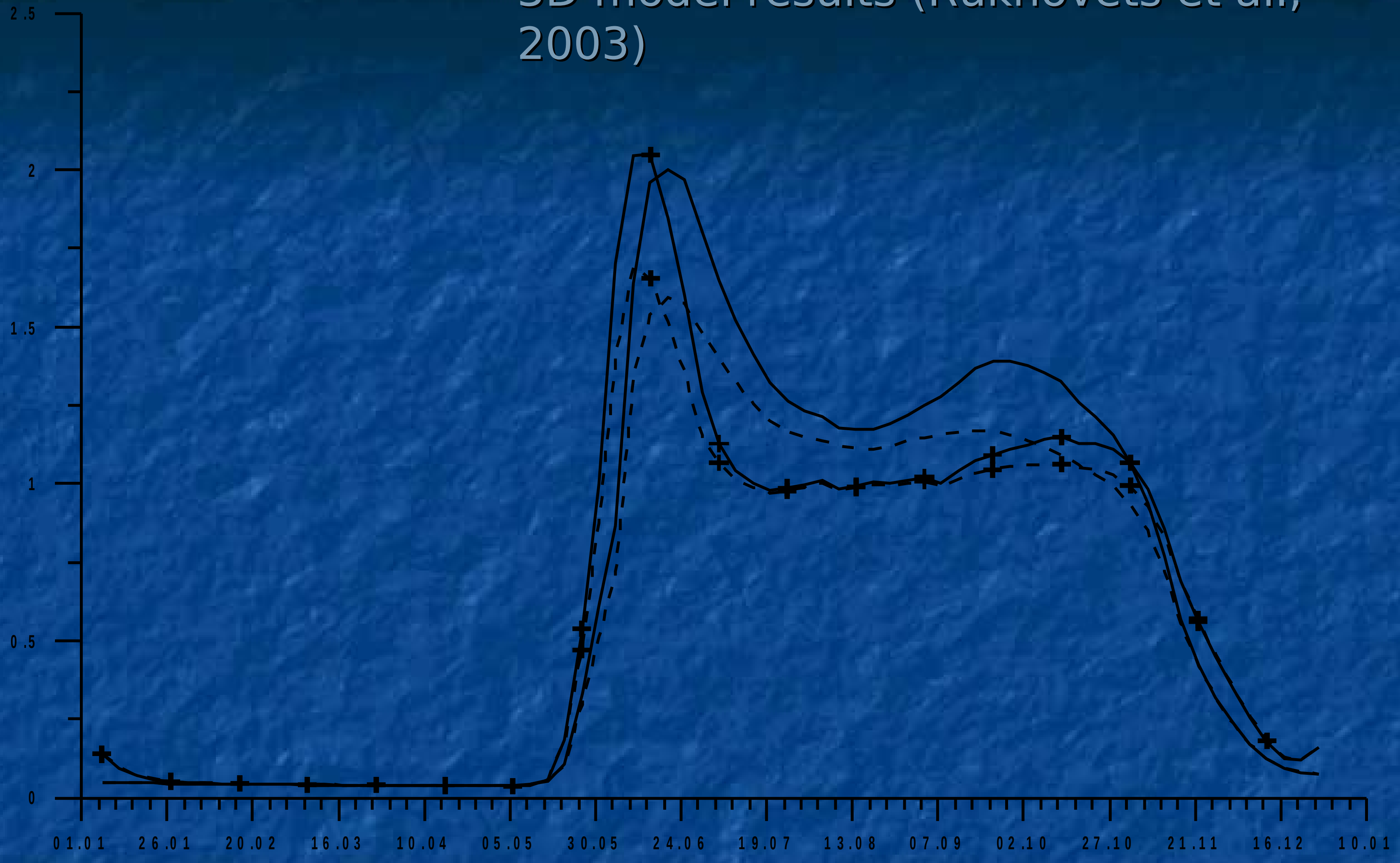

Calculated zooplankton biomass (BZ [g/m^3]) - Petrozavodsk Bay, year 2001
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000

# 3D coupled hydrodynamic and ecosystem model of Lake Onega (Rukhovets et al., 2003)

**Main features of the thermal structure**

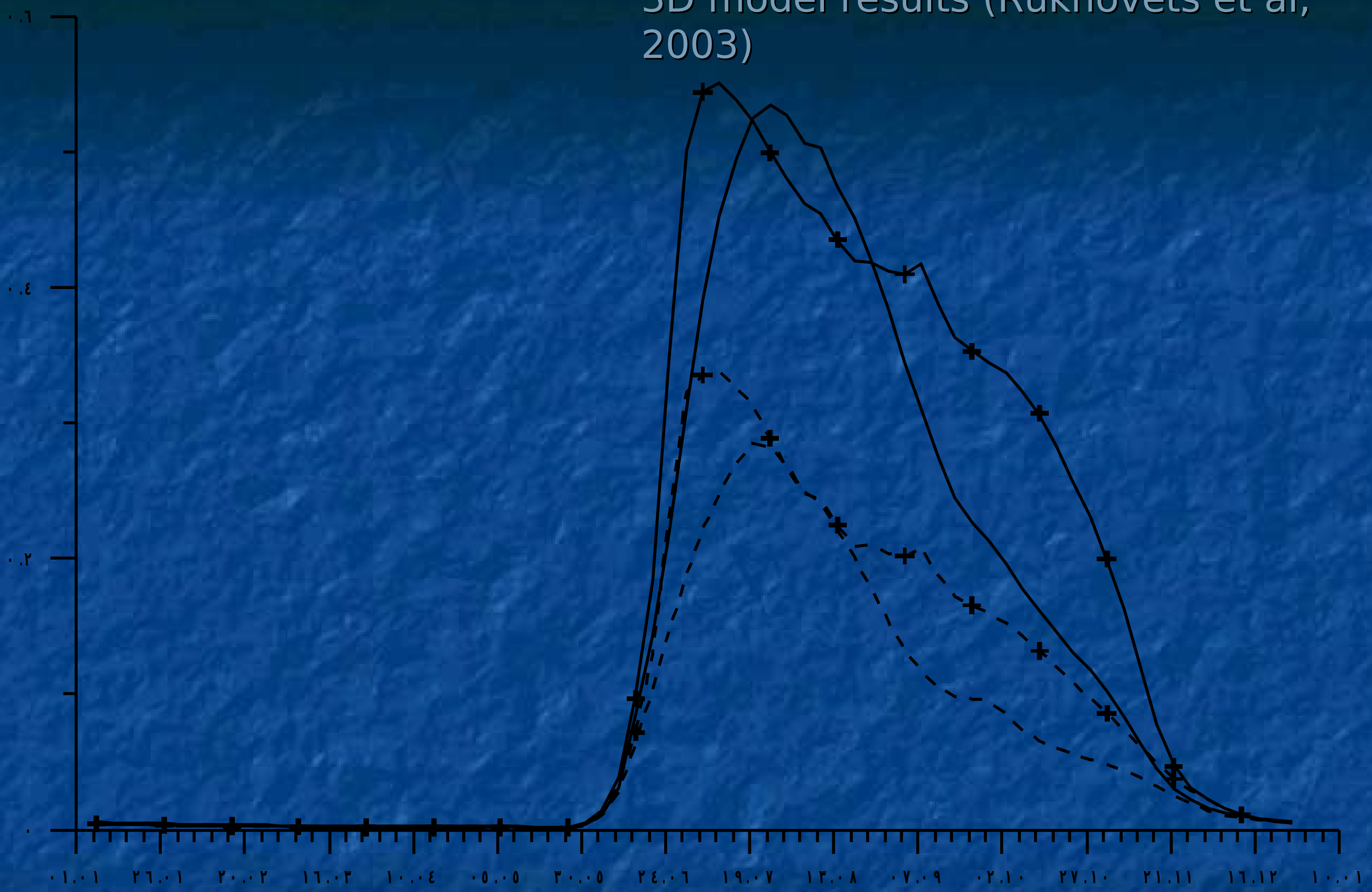
| Feature | Observed | Simulated |
|---|---|---|
| **Ice cover disappearance** | **18 May** | **20 May** |
| **Appearance of 4°C isotherm** | **10-25 May** | **21 May** |
| **End of spring heating** | **20-25 June** | **13 June** |
| **Thickness of epilimnion in late summer** | **20-25 m** | **25-50 m** |
| **Appearance of 4°C isotherm** | **Late Oct. – Early Nov.** | **Mid-Nov.** |
| **Disappearance of 4°C isotherm** | **Mid-Dec.** | **Mid-Dec.** |
| **Full ice cover** | **Mid-Jan.** | **6 Feb.** |

# 3D model results (Rukhovets et al., 2003)




Phytoplankton in Lake Onego epilimnion (mg/l) under climatic circulation and corresponding load (solid line – 1003 t P/year, 17739 t N/year; dotted line - 786 t P/year, 15051 t N/year; the same lines with crosses – the ‘warm’ circulation case).

# 3D model results (Rukhovets et al, 2003)




Zooplankton in Lake Onego epilimnion (mg/l) under climatic circulation and corresponding load (solid line – 1003 t P/year, 17739 t N/year; dotted line - 786 t P/year, 15051 t N/year; the same lines with crosses – the ‘warm’ circulation case).

# Summary

- The ecological model satisfactorily describes seasonal variations of phyto- and zooplankton biomasses
- It is sensitive to a number of parameters such as optimal water temperatures and the rates  of phyto- and zooplankton growth
- Calculated phyto- and zooplankton biomass maximum values are shifted in time towards the latest dates compared to 3D model results and observations
- To get more reliable set of the model parameters additional simulations for longer time periods and different

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- EMI (St.-Petersburg): Leonid Rukhovets
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# Thank you !