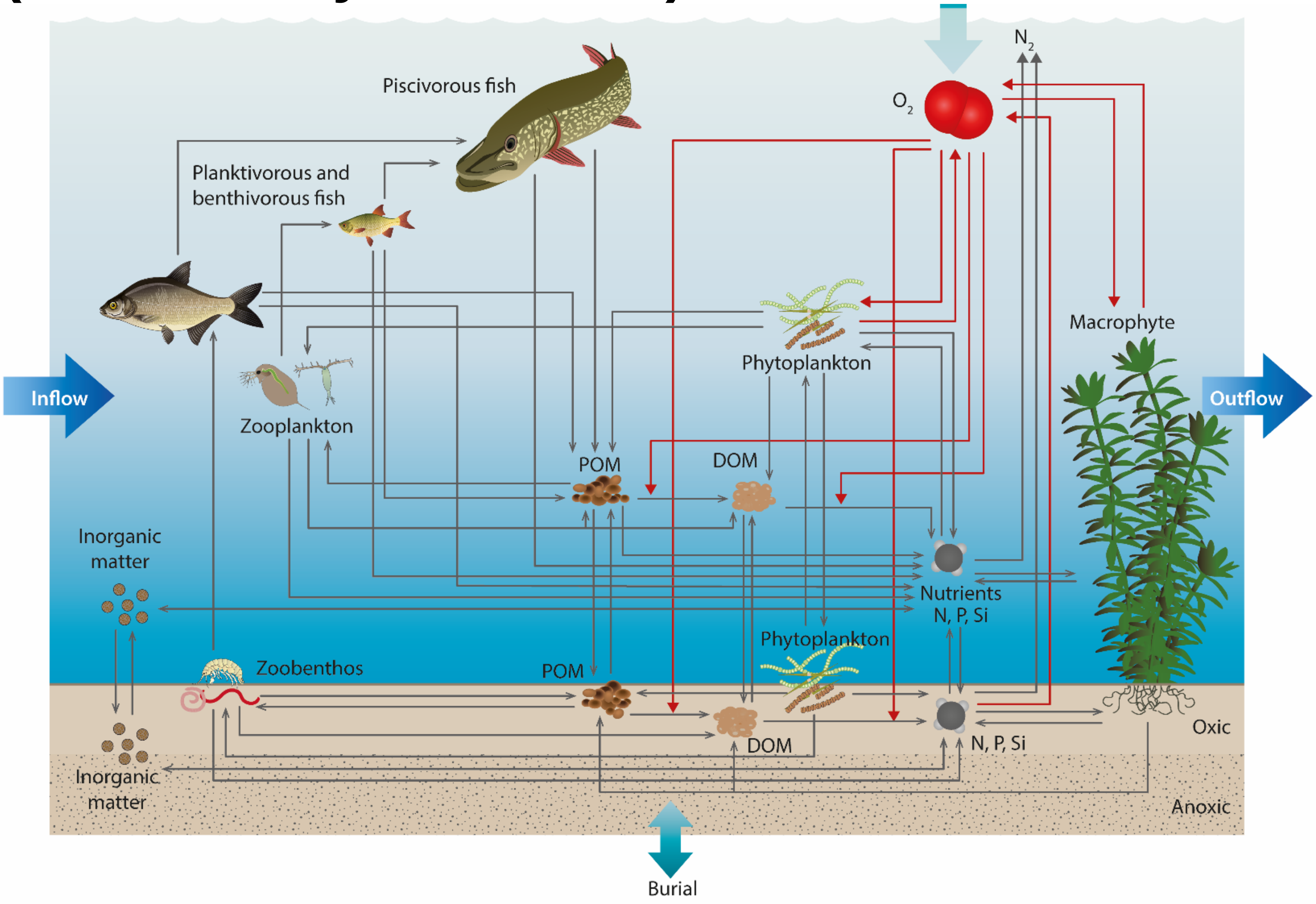
Tobias K Andersen, Xiangzhen Kong

Theory on lake ecosystem modelling with a focus on WET

This presentation is based on some material developed by Dennis Trolle and Anders Nielsen, Aarhus University

WET (Water Ecosystems Tool)



Aim of presentation

Learning outcomes:

Part I: Basic introduction to

- Model types
- Process-based aquatic models
- The modelling process

Part II: Basic introduction to **Water Ecosystems Tool (WET)**

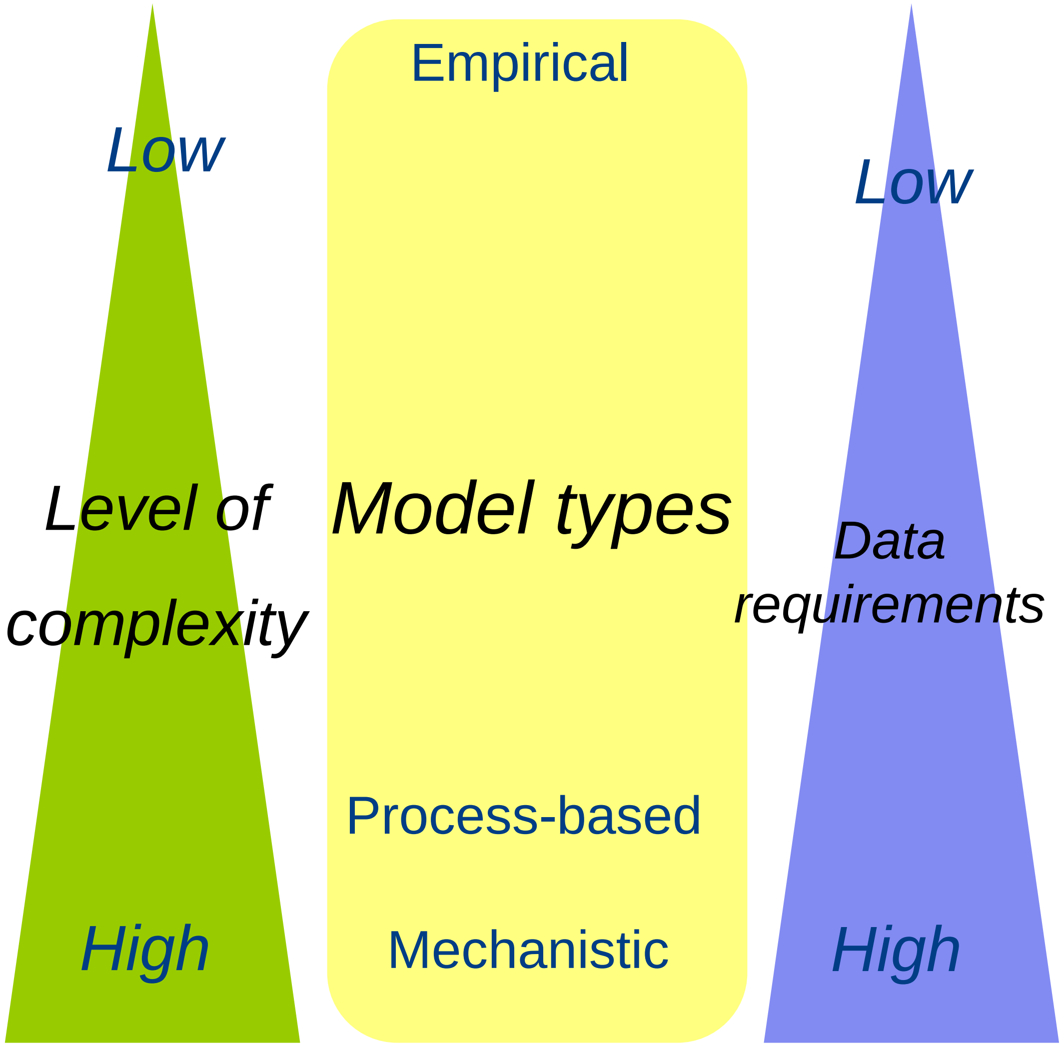
- GOTM: 1-dimensional water column model
- FABM: Coupling hydrodynamic and ecology
- Food web configuration
- Important process formulations in WET

Part I

What is a process-based aquatic ecosystem model?
And why is model and application is tightly linked?

Model classifications

Models differ widely in complexity (and data requirements) and may be classified in a number of ways



Examples:

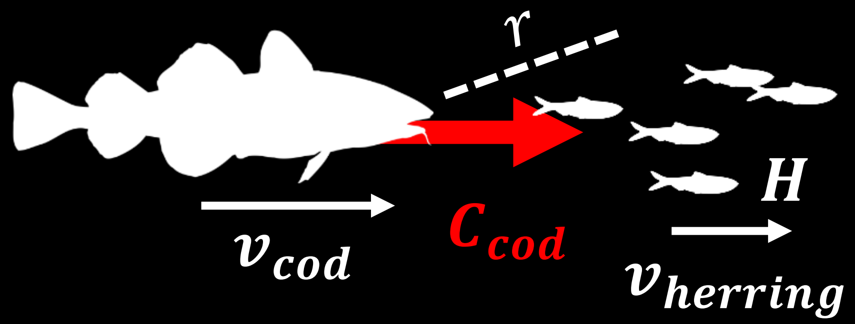
Runoff coefficients models
Empirical lake model

Lumped models
(e.g., NAM)

Semi-distributed models, based on curve number and linear reservoir (e.g., SWAT)

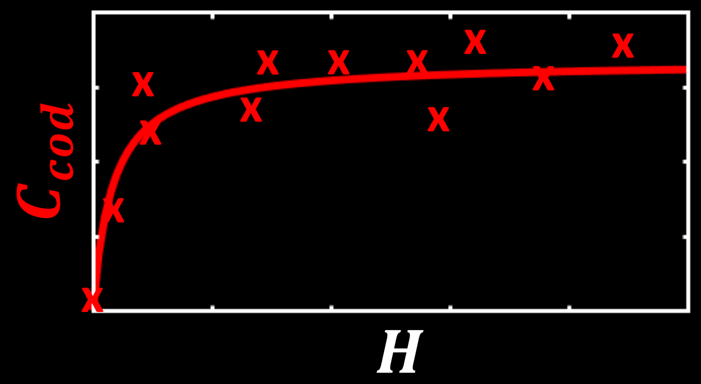
Fully distributed 3D models
(e.g., MikeShe, SWAT-MODFLOW)
Coupled hydrodynamic-ecosystem models

What is a mathematical model?



What determines how many herring a cod can eat in one hour?

$$C_{cod} = \frac{H(v_{cod} - v_{herring})r^2}{hH(v_{cod} - v_{herring})r^2 + 1}$$



What is a mathematical model?

- Models are simplified representations of real world systems, and are always based on some fundamental assumptions:

  ”Ecology will never be understood from quantum physics.”
  Geritz and Kisdi (2012)

- Mathematic models are formulated in equations and/or computer code

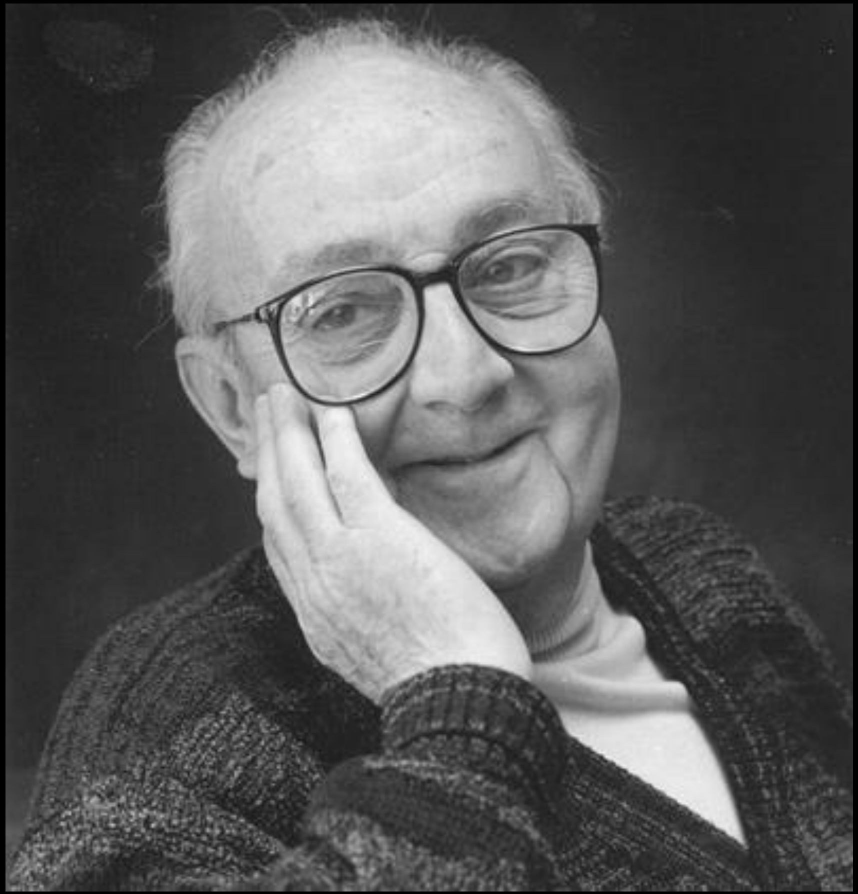
- Models are intended to mimic essential features of a system **while leaving out inessentials**

  ”simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system.”
  US EPA (2012)

- **Models can be viewed as virtual laboratories**
  In many cases, it is simply not practical or economical to conduct real-world experiments in full temporal and spatial scale (for example heating up an entire lake)

“All models are wrong”

“All models are approximations. Assumptions, whether implied or clearly stated, are never exactly true. **All models are wrong, but some models are useful**. So the questions you need to ask is not “Is the model true?” (it never is) but “Is the model good enough for this particular application?”



George Box

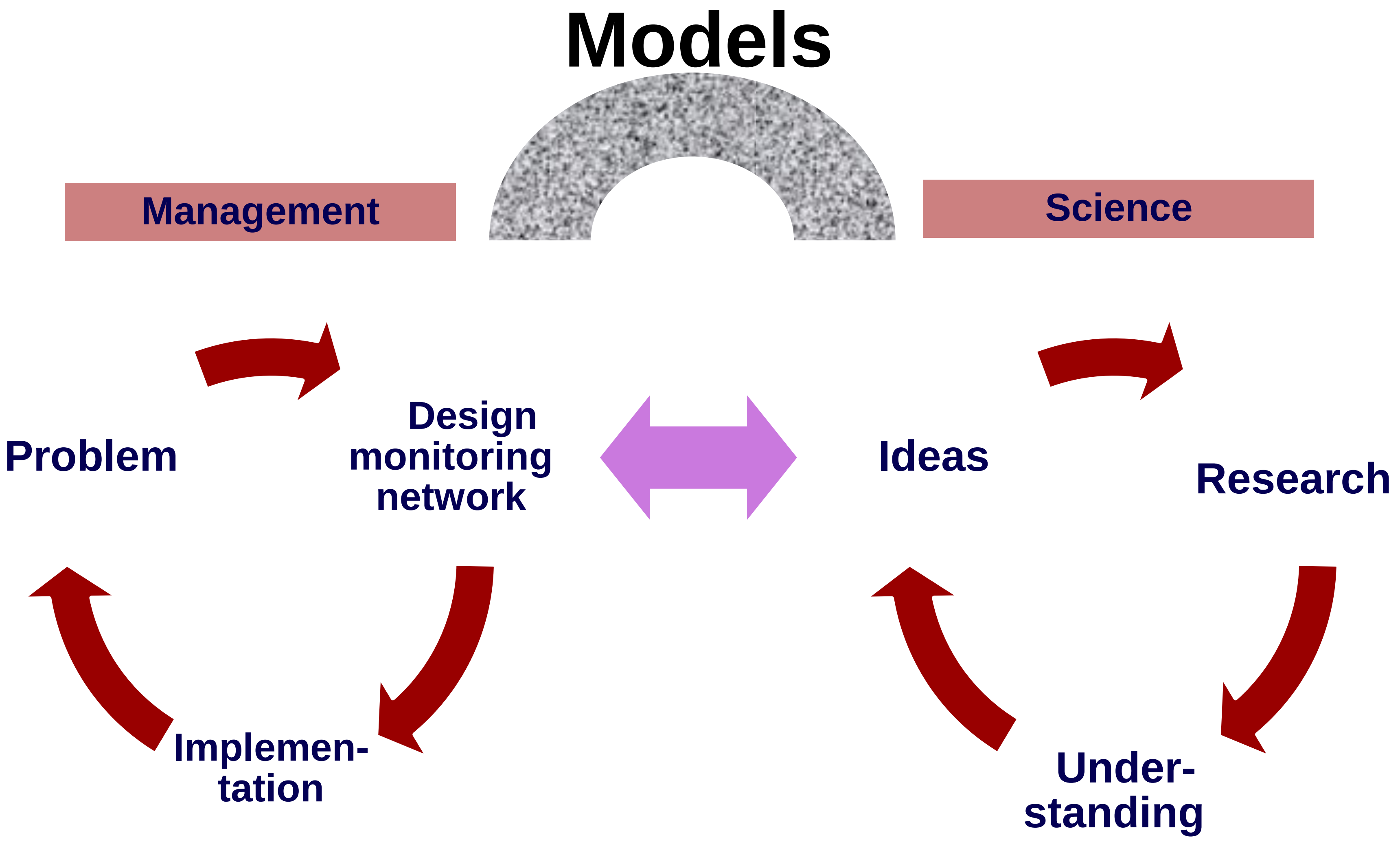
Why use models?

- Models may be used in **environmental management**
- For example, to calculate maximum allowable pollutant load to a given aquatic ecosystem
- To fill in data gaps
- For answering ”what if” questions

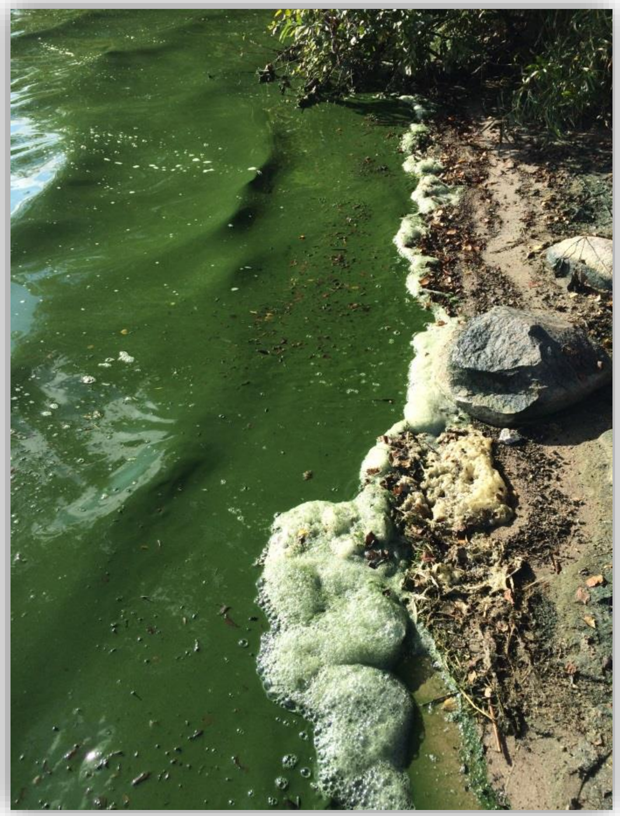
- Models may be used for **research and teaching**
- To help understand interactions and quantify processes in a system
- To test and develop scientific hypotheses
- To understand and predict effects of future climate etc.

- Models can be viewed as **virtual laboratories**
- In many cases, it is simply not practical or economical to conduct real-world experiments in full temporal and spatial scale (for example heating up an entire lake)

Models provide a way for science to support decision making in management



Typical issues to address using models



Example of **blue-green algae** (potentially toxin producing) bloom in Lake Stilling, Denmark (2016)

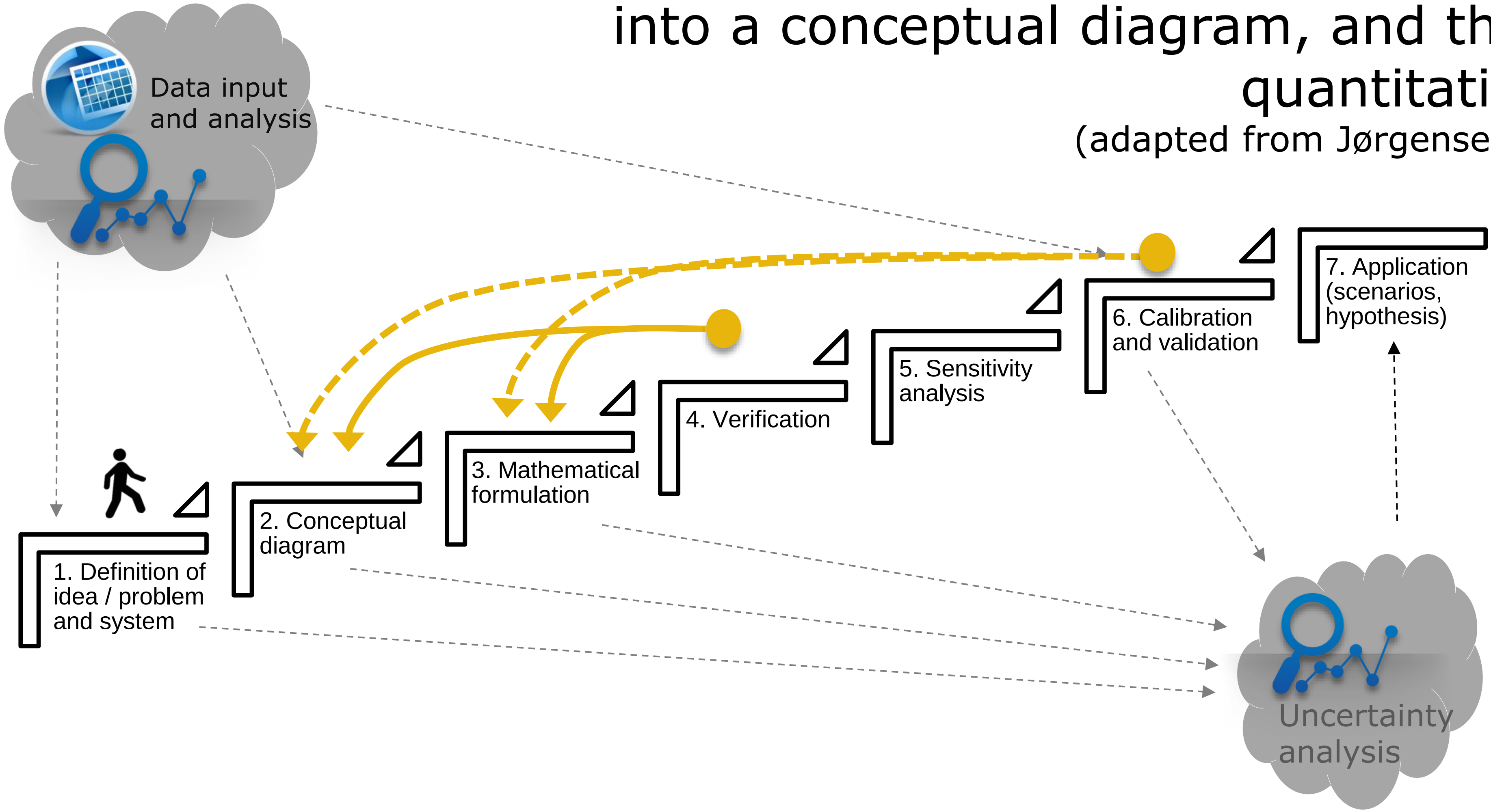
Lake Benmore, New Zealand’s largest man-made lake used for recreation and hydropower.

Ensuring a safe and stable water storage, e.g. for drinking water supply, storage for crop irrigation, flood storage/protection in association with river corridors, hydropower creation, nature conservation and recreation.

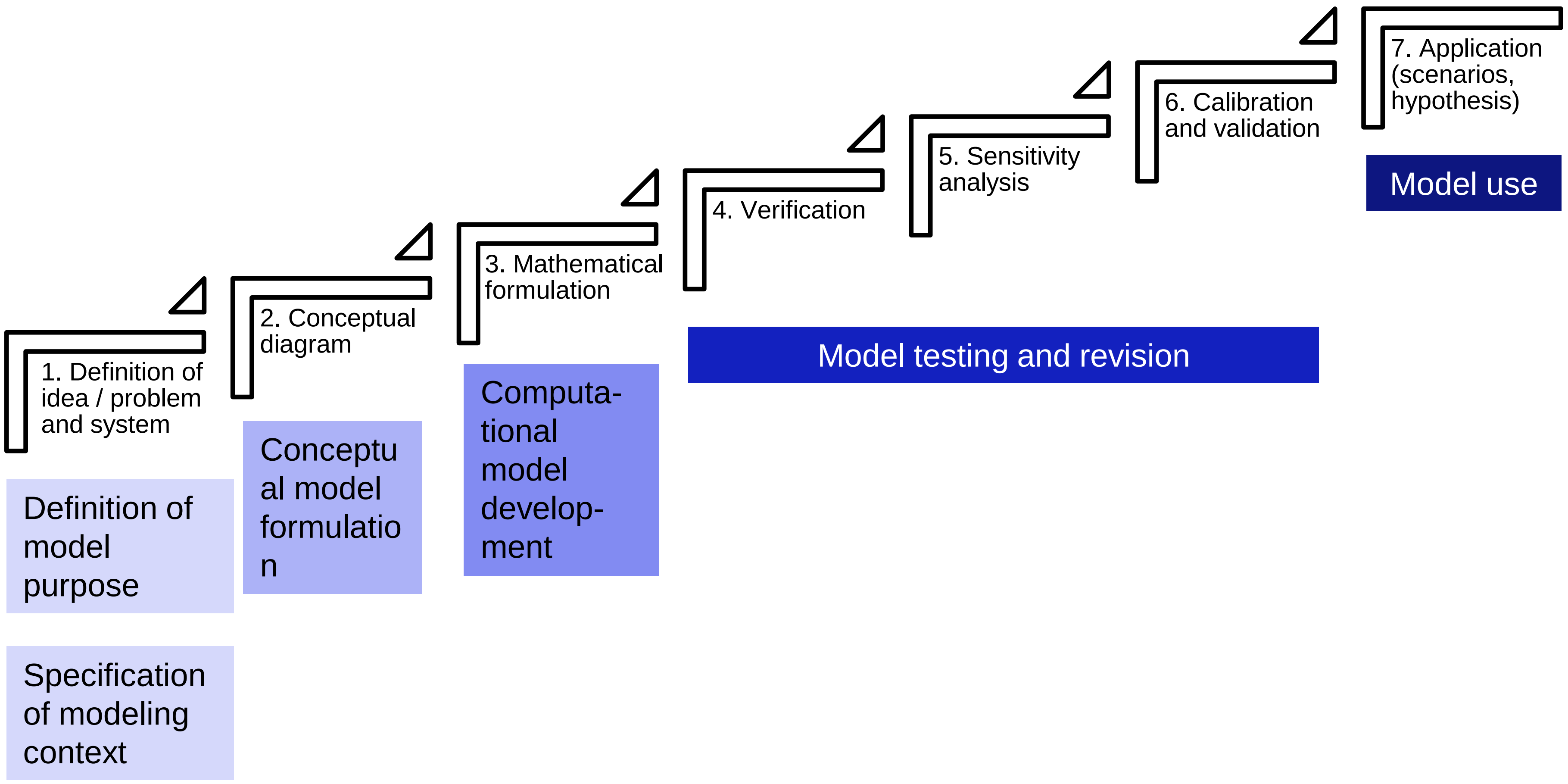
Example of **fish kill** due to hypoxia followed by water column turnover in Lake Erie (September, 2012), picture by Ontario Ministry of the Environment

The modelling process

A series of steps are taken to implement an idea first into a conceptual diagram, and then into a quantitative model
(adapted from Jørgensen et al. 1995)



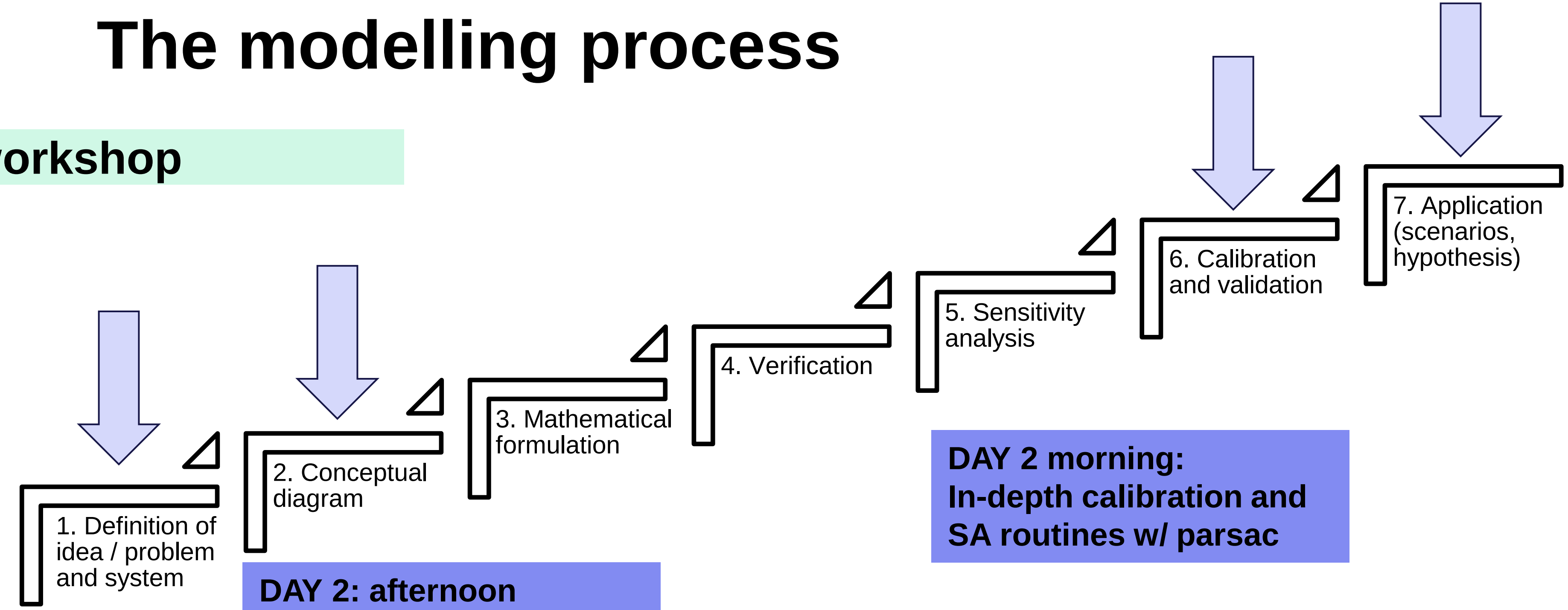
The modelling process



USE EPA: Basic Steps in the Process of Modeling for Environmental Decision Making

The modelling process

This workshop



**DAY 2 morning:
In-depth calibration and SA routines w/ parsac**

**DAY 2: afternoon
WET modules and new developments to come**

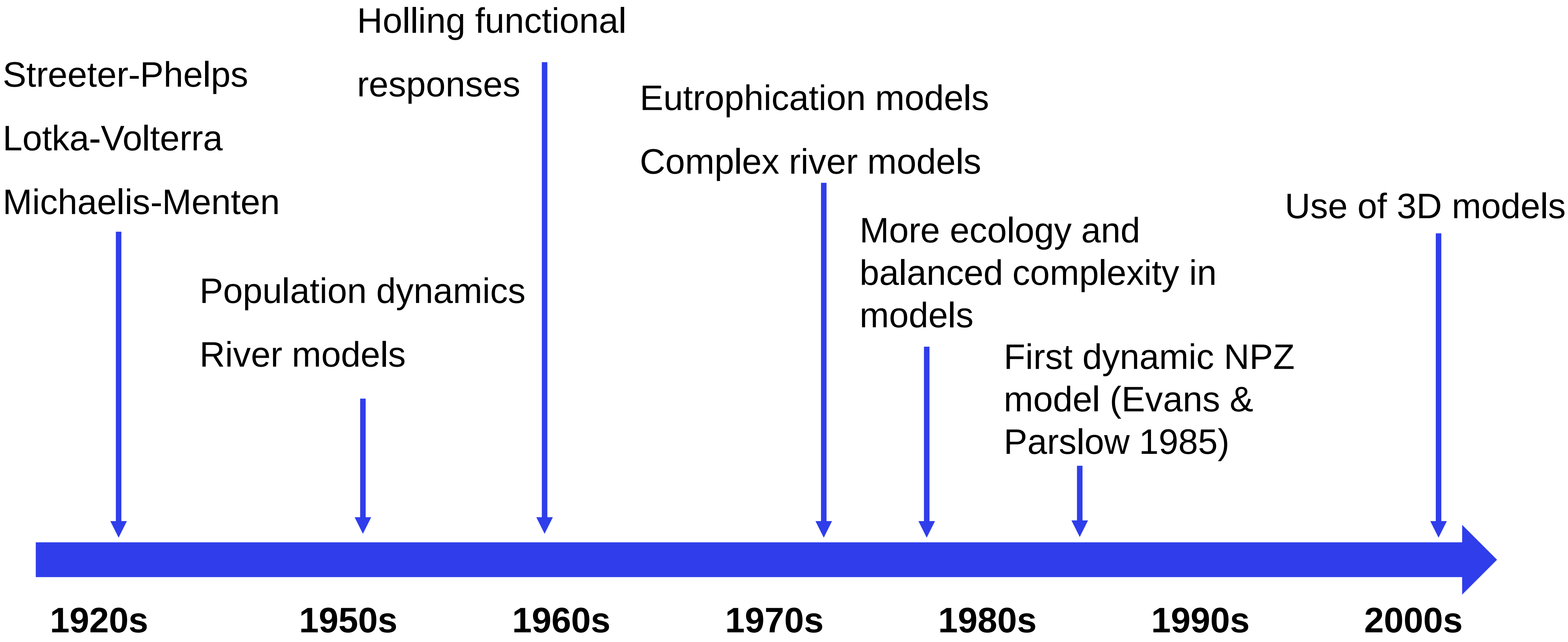
**DAY 3 morning:
Code compilation and documentation**

DAY 1: QWET exercise – from scratch to model set-up, simulation and scenarios

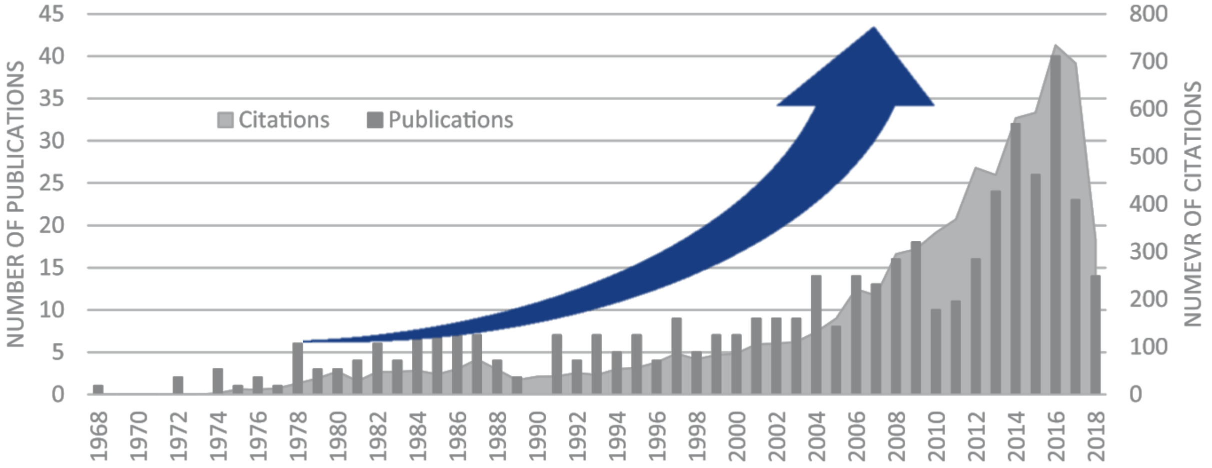
The modelling process

1. Definition of idea / problem and system
2. Conceptual diagram
3. Mathemati-cal formulation
4. Verification
5. Sensitivity analysis
6. Calibration and validation
7. Application (scenarios, hypothesis)

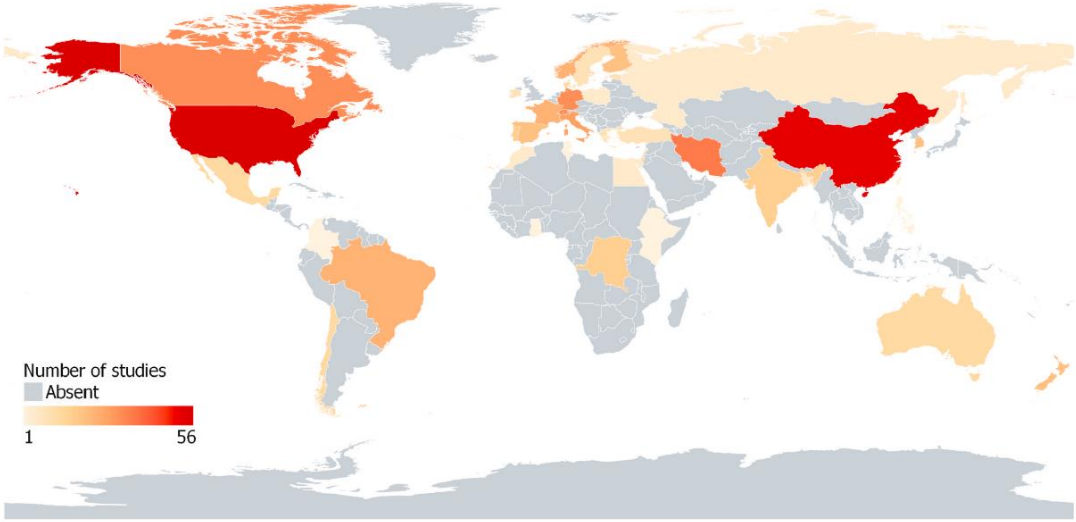
Some highlights in the history of lake modelling



History of lake modelling /2



From Vincon-Leite and Casenave, 2019: Modelling eutrophication in lake ecosystems: A review



Global distribution of study sites in lake ecosystem modelling from 2015 to 2020. From Soares and Calijuri, 2021, Environmental Modelling and Software.

Overview of lake models

AED2

Aquatic Ecodynamics Modelling Library

WET

Water Ecosystems Tool

MyLake

Multi-year simulation model for Lake thermo- and phytoplankton dynamics

SALMO

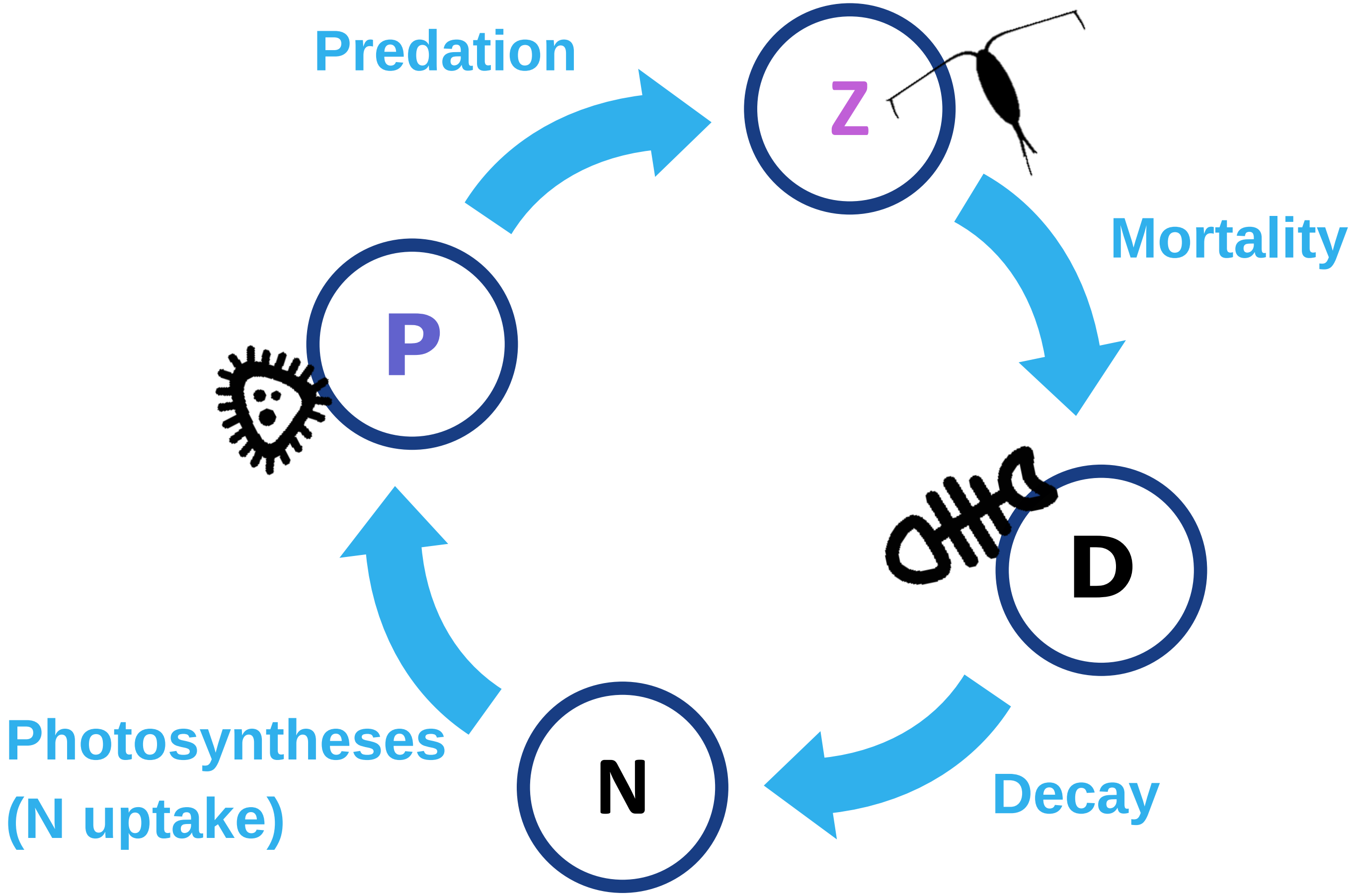
Simulation of an Analytical Lake MOdel

PCLake+

For more information, have a look at Aquatic Ecosystem Model Library:
https://github.com/aemon-j/aquatic-ecosystem-model-library/wiki

Basic concepts of ecosystem modelling

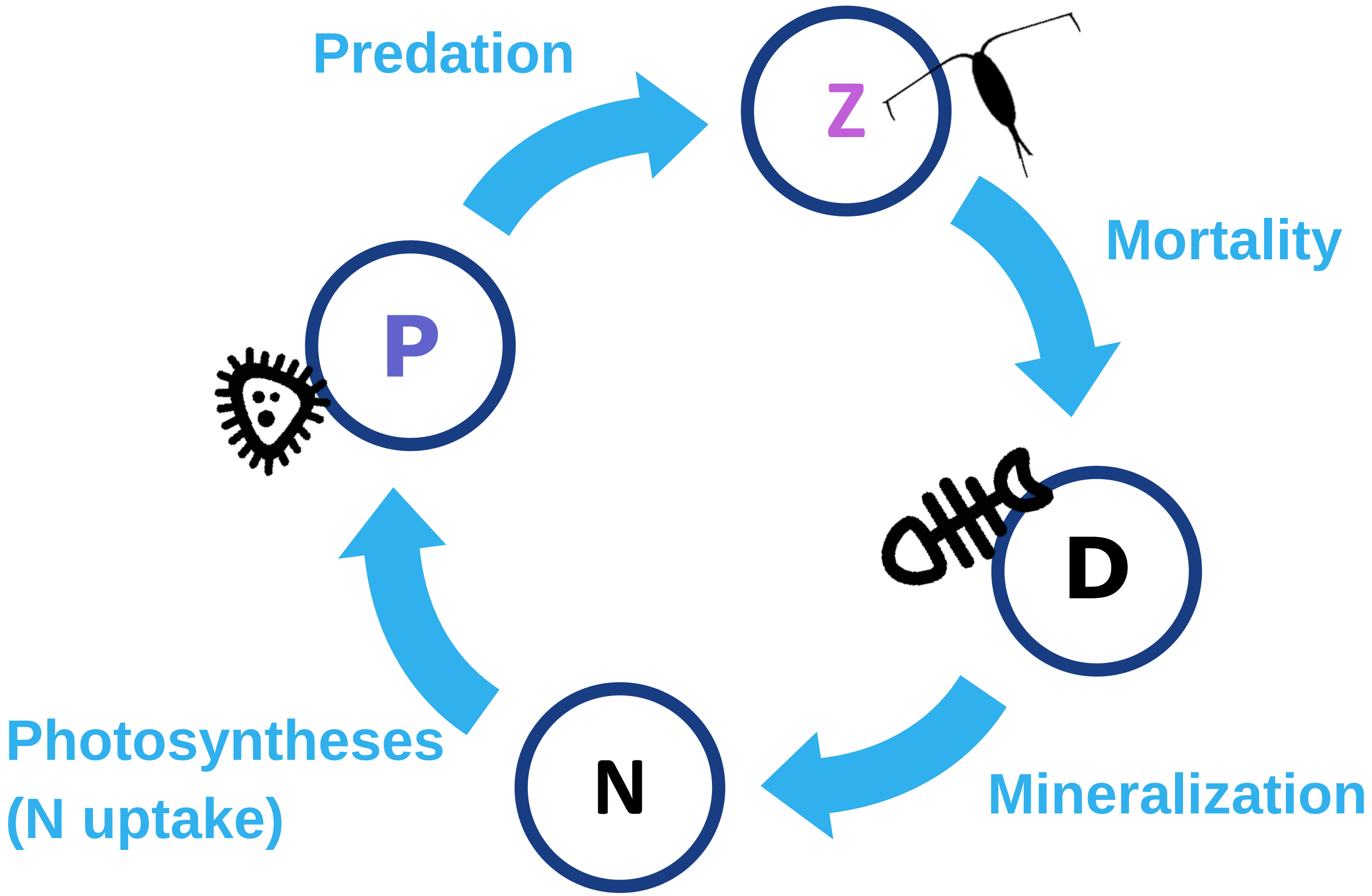
- POOLS and PROCESSES with a common currency
- POPULATIONS AND
- FOOD WEBS
- Trophic levels: 0,1,2,3..



Basic concepts of ecosystem modelling

Dynamics prescribed by differential equations:

$$\frac{dy}{dt} = sources - sinks$$



Basic concepts of ecosystem modelling

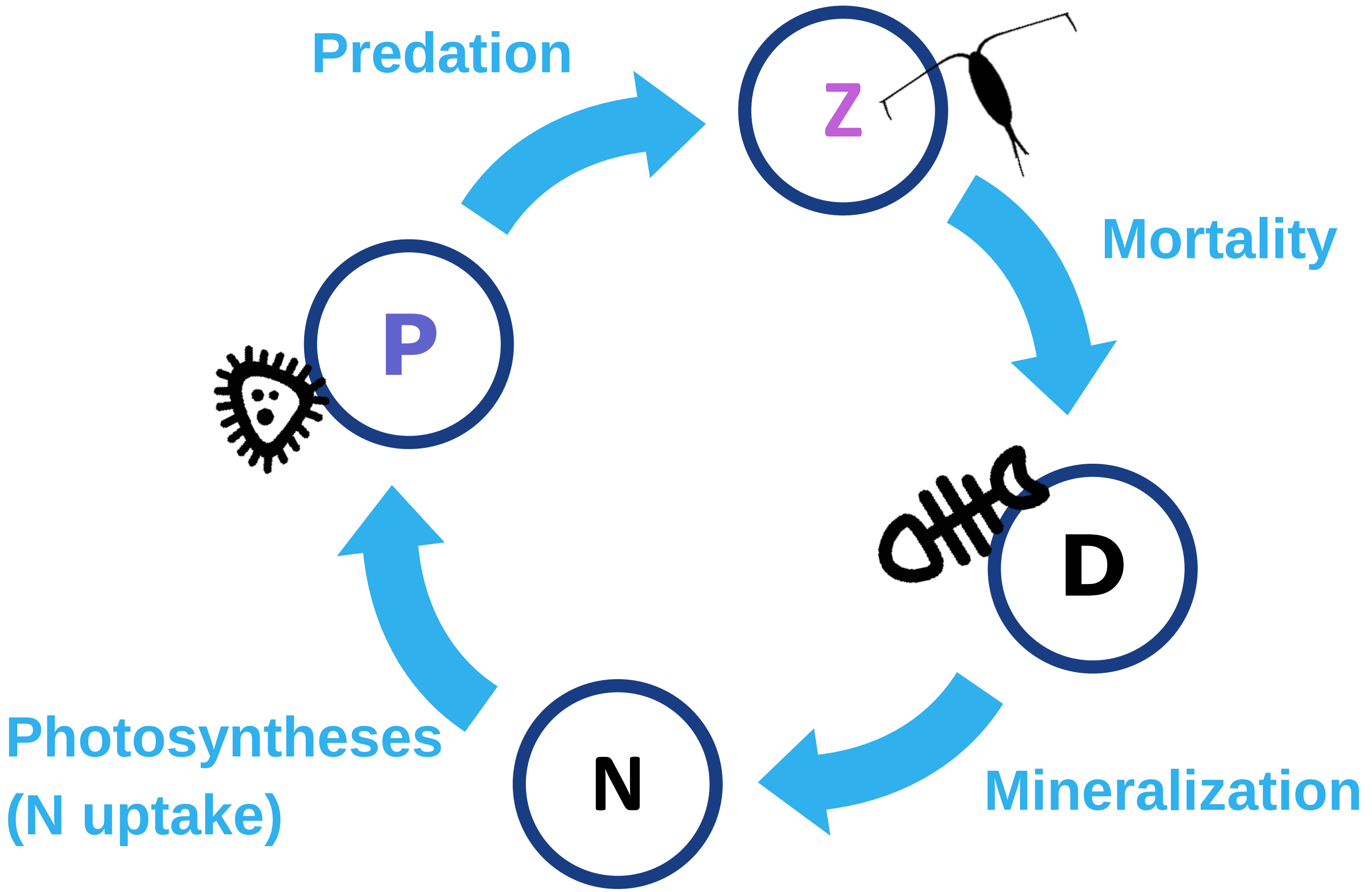
Dynamics prescribed by differential equations:

$$\frac{dN}{dt} = remineralization - N\ uptake$$

$$\frac{dP}{dt} = N\ uptake\ -\ predation$$

$$\frac{dZ}{dt} = predation\ - mortality$$

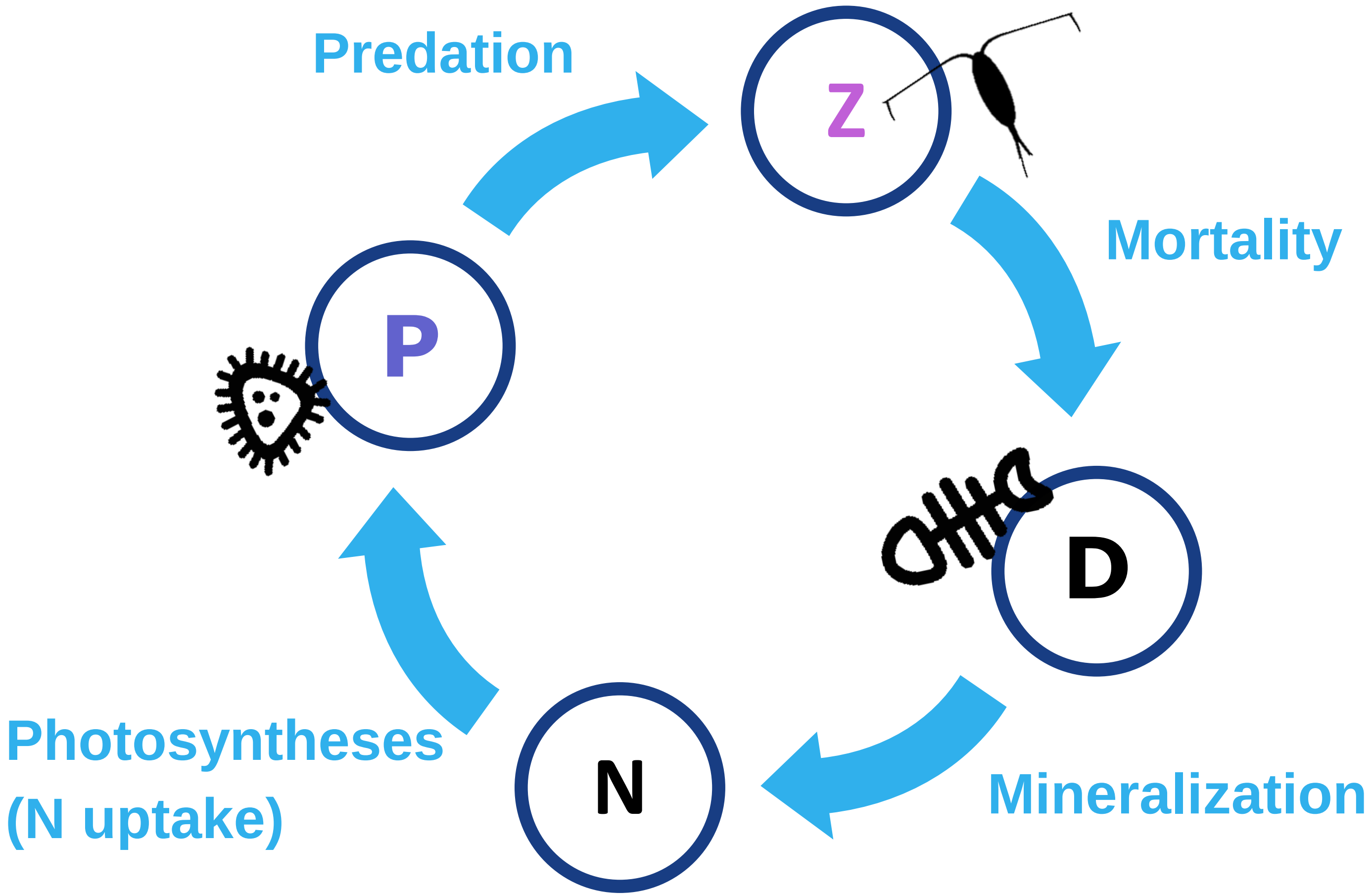
$$\frac{dD}{dt} = mortality - mineralization$$



Basic concepts of ecosystem modelling

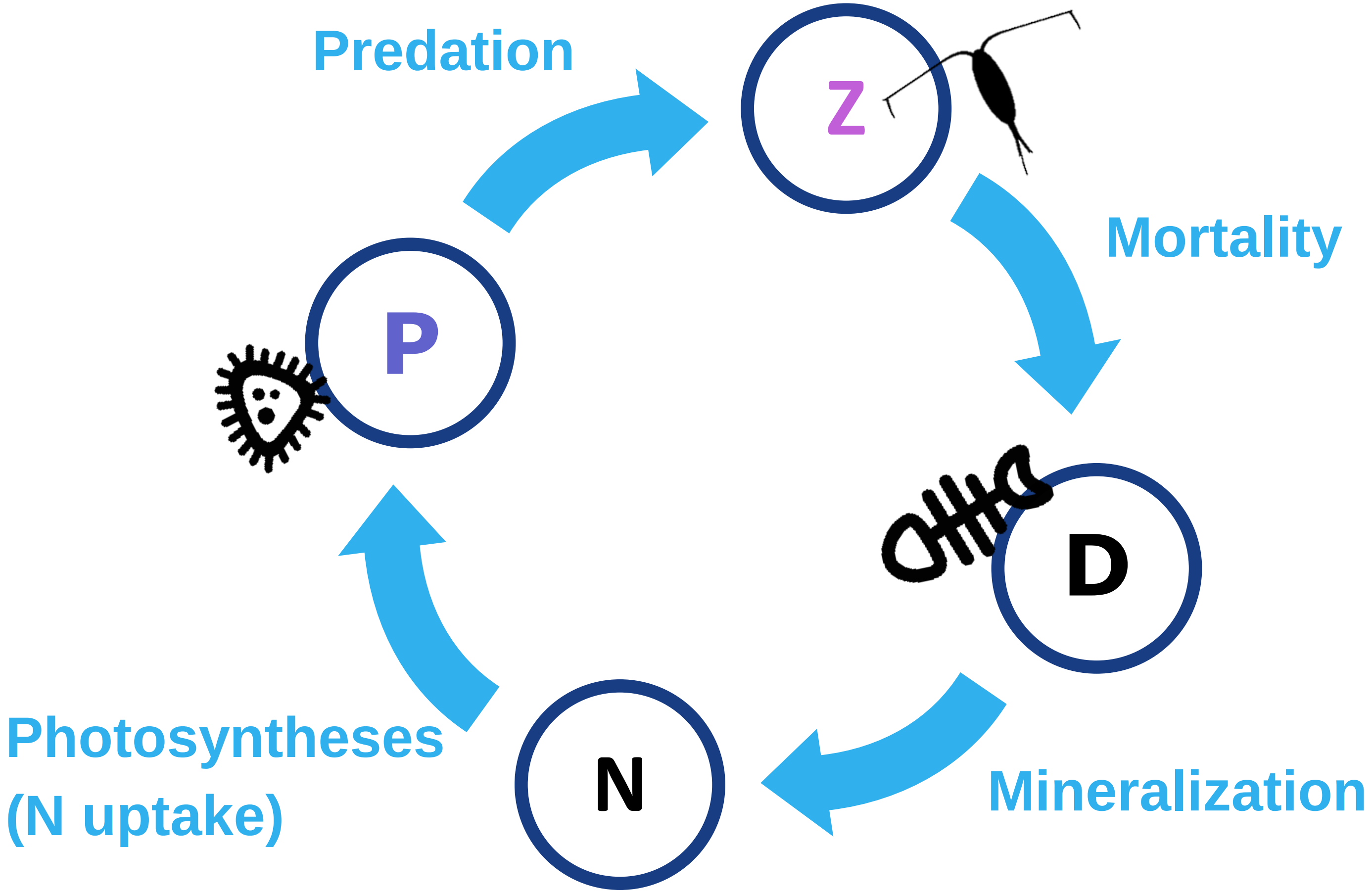
Mass balance:

$$\frac{dN}{dt} + \frac{dP}{dt} + \frac{dZ}{dt} + \frac{dD}{dt} = 0$$



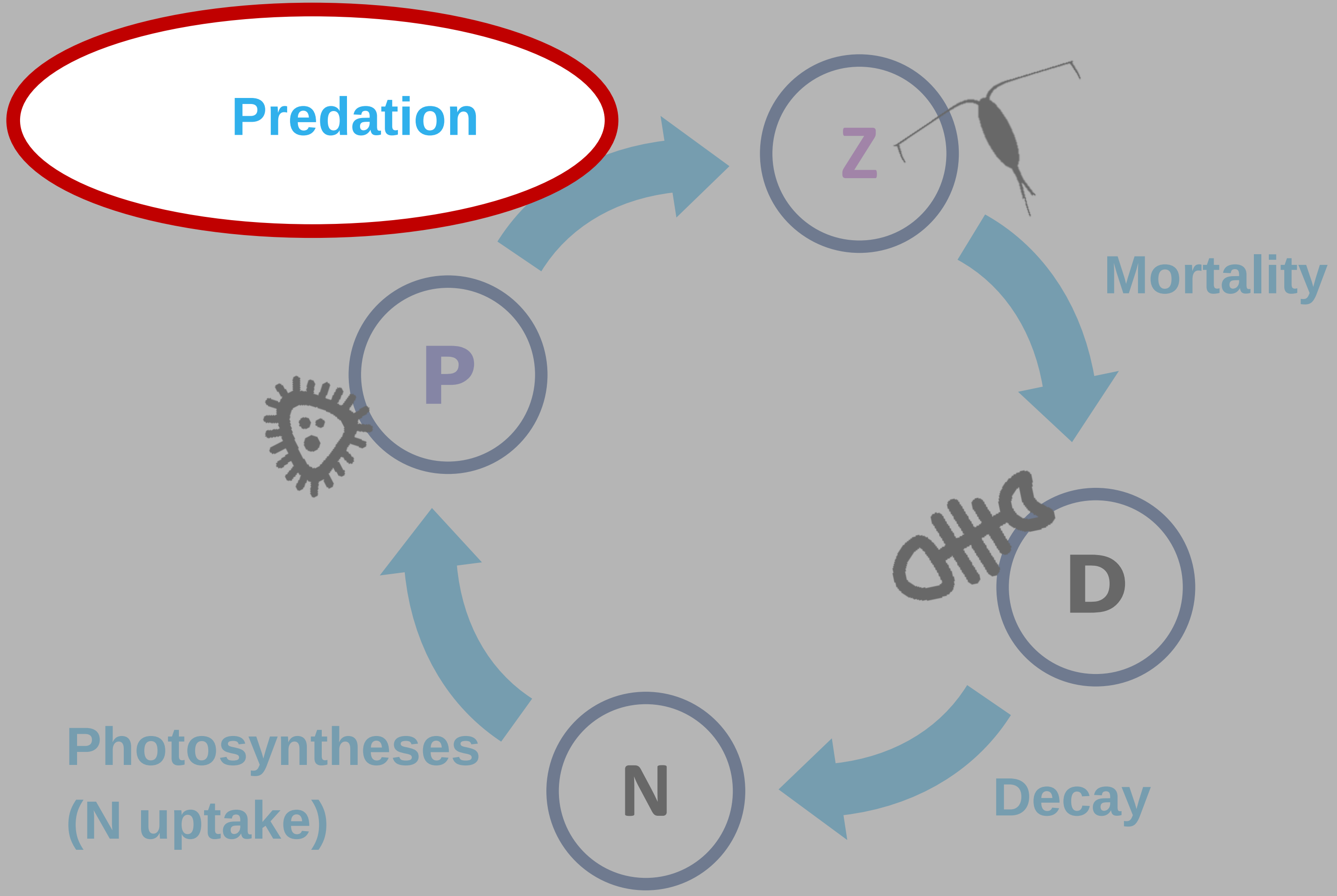
Basic concepts of ecosystem modelling

Functional response,
Parameters and Forcing



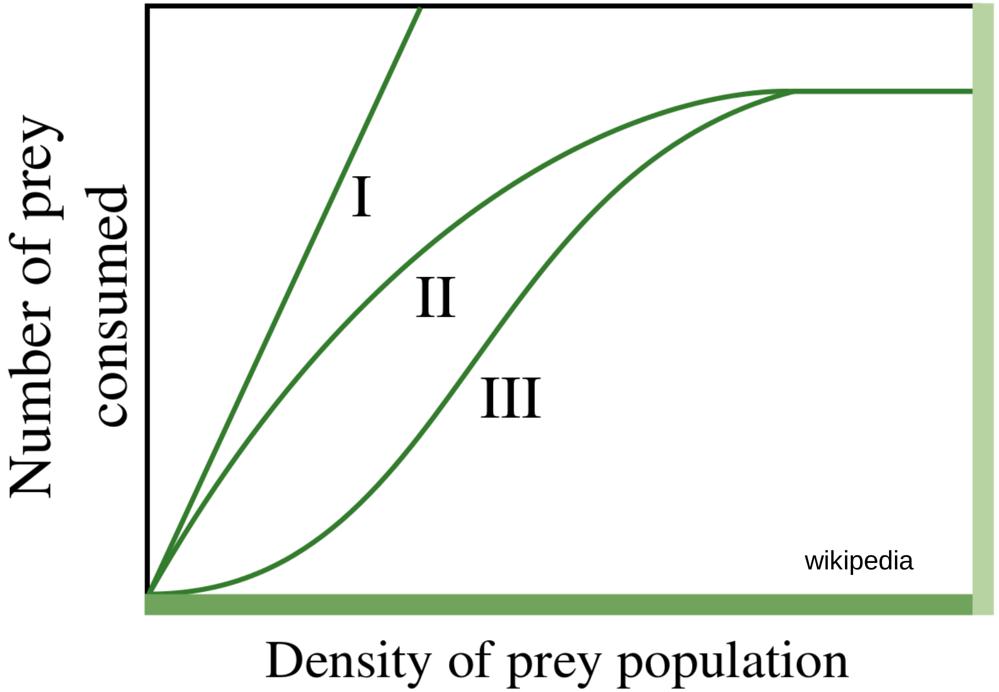
Basic concepts of ecosystem modelling

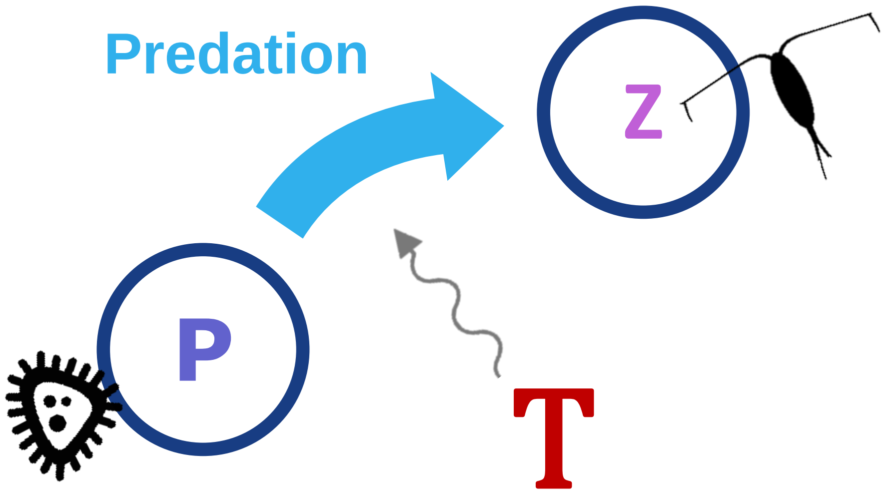
Functional response, Parameters and Forcing



Basic concepts of ecosystem modelling

Functional response, Parameters and Forcing





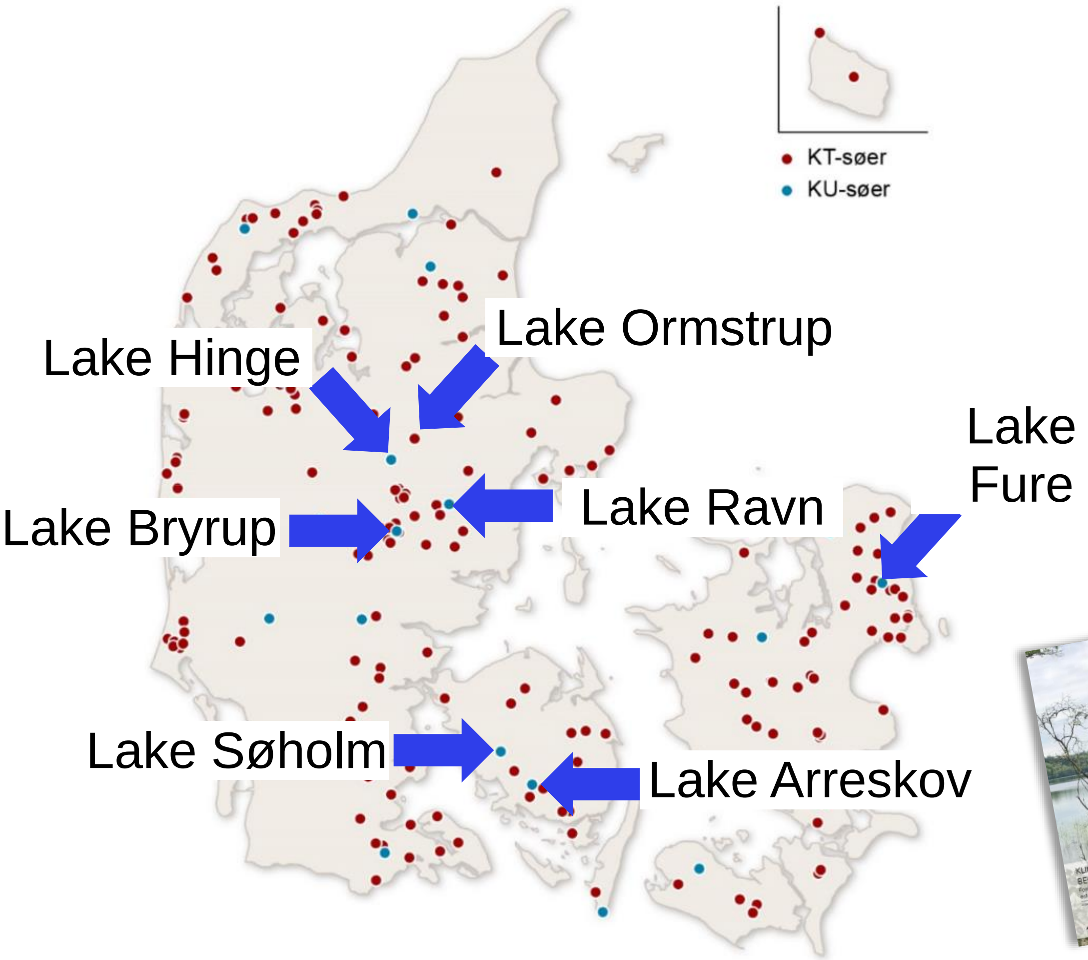
Holling type II: $F_z(T,P,Z) = Z\,\frac{c_Z P}{h c_Z P + 1}$,

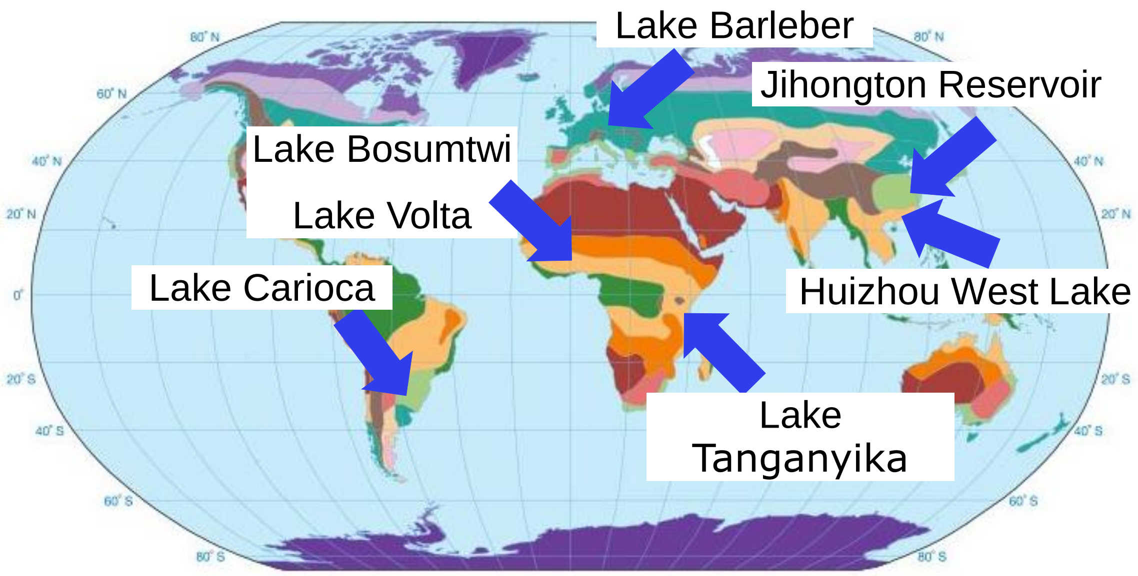
where $c_Z, h = f(T)$

Part II

Water Ecosystems Tool (WET)

Lakes and their lake models





The model core

The core of **QWET** is based on the coupled one-dimensional hydrodynamic-ecosystem model

GOTM-(FABM)-WET

- **GOTM (General Ocean Turbulence Model)** is a one-dimensional, vertically resolved (water column) hydrodynamic model, originally initiated by Hans Burchard and Karsten Bolding in 1998, and since further developed by a community of scientists.

- **FABM (Framework for Aquatic Biogeochemical Models)** is a model coupling framework by Bolding and Bruggeman ApS (Bruggeman, J. and Bolding, K. 2014). FABM allows coupling of several hydrodynamic models, including GOTM (1D) and GETM (3D), with a range of freshwater and marine biogeochemical models, including, for example, FABM-PCLake, ERSEM and ERGOM.

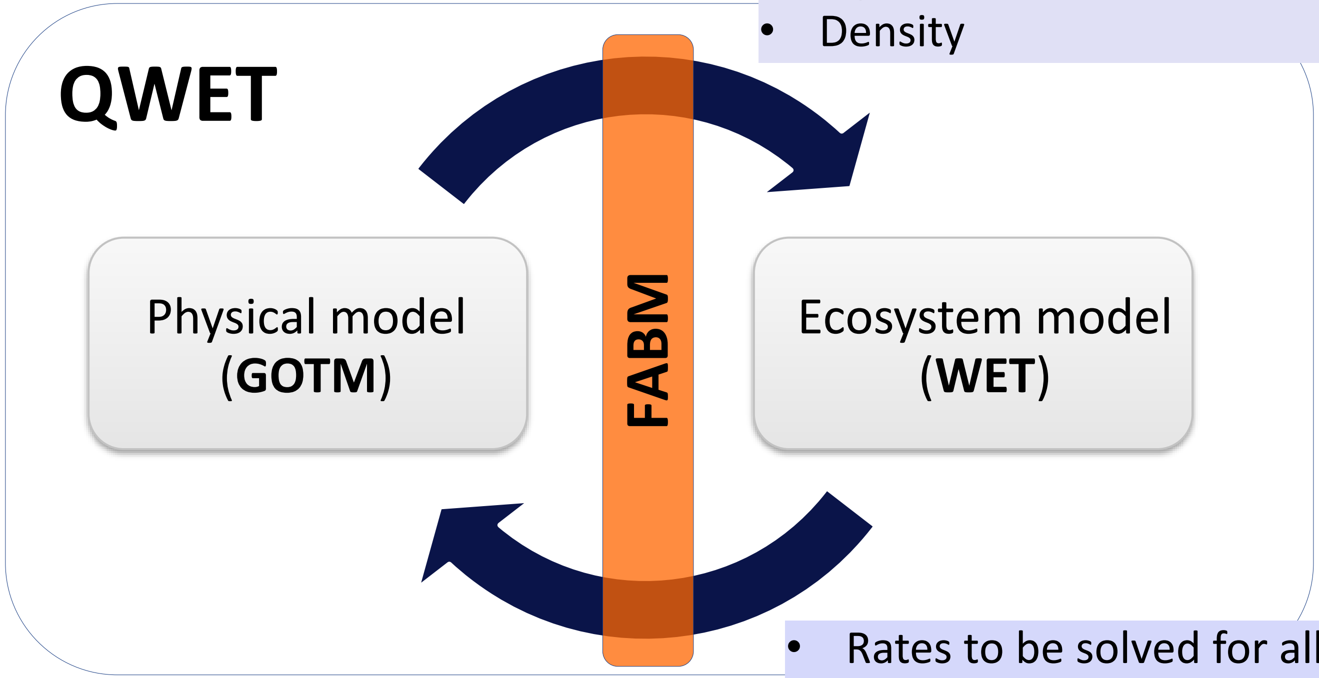
- **WET (Water Ecosystems Tool)** is an ecosystem model by Aarhus University, Denmark and Technical University of Denmark (Schnedler-Meyer et al. 2016), and a further development FABM-PCLake (Hu et al. 2016) of the original PCLake aquatic ecosystem model by Janse and van Liere (1995).

- **QWET** is a QGIS based graphical interface by Aarhus University (Nielsen et al. 2017) that enable a full workflow for the application of the coupled **GOTM-WET** model.

- All of the above are **open source**

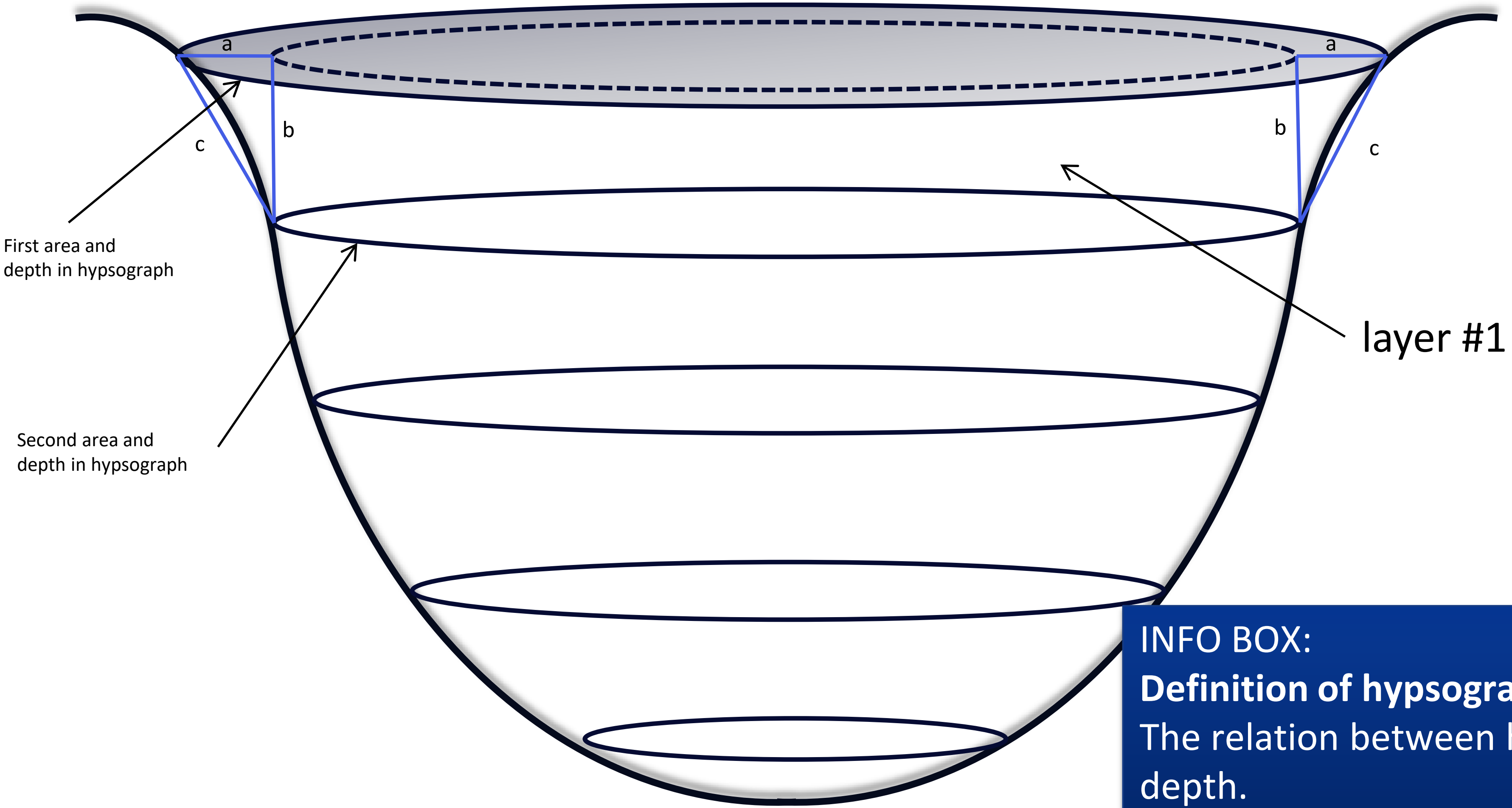
The model core

- Updated state variables
  - Solving ODEs
  - Advection, molecular and turbulent mixing (redistribution of state variables)
- Shear stress (e.g. used at bottom for resuspension)
- Water temperature
- Light
- Density



- Rates to be solved for all state variables (ODEs)
- Light attenuation (contribution)

The 1D domain



INFO BOX:
Definition of hypsograph:
The relation between horizontal area and depth.

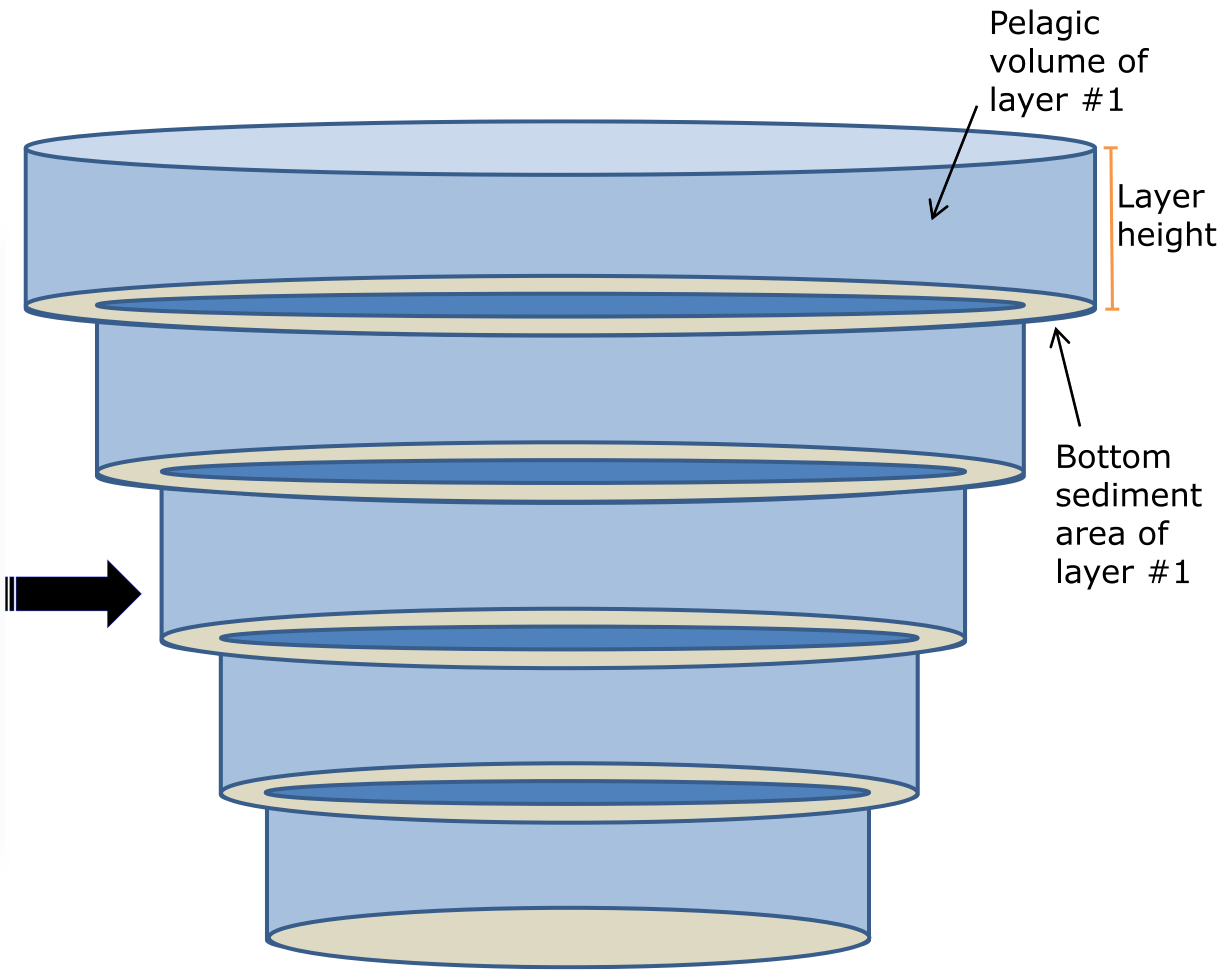
Number of vertical layers is defined by user. The depth and horizontal area of each individual layer is derived from interpolation of the hypsograph provided by the user.

Bottom-sediment areas can be interpreted as horizontal discs (i.e. with width = a).

Deriving the 1D domain

hypsograph.dat

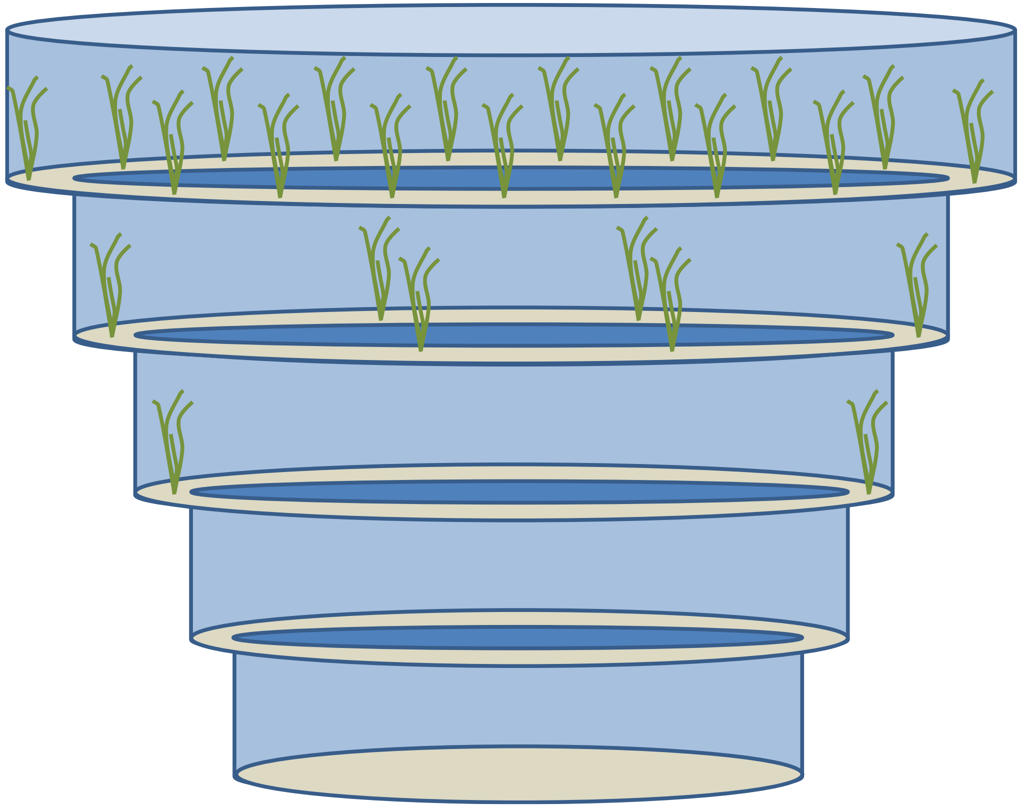
```
! first line specifies 36 data points,
! and reading format according to case(3)
! column one is height/depth (m) and column two is area (m2)
!   case(1)  ! surface ref, read from bottom
!   case(2)  ! surface ref, read from surface
!   case(3)  ! bottom ref, read from bottom
!   case(4)  ! bottom ref, read from surface
36      3
0.0   0
0.7   1541
1.5   16921
2.5   45021
3.5   88521
4.5   136421.002
5.5   180321.004
6.5   241721.006
7.5   318621.008
8.5   469321.008
9.5   555021.005
10.5  646421.007
```



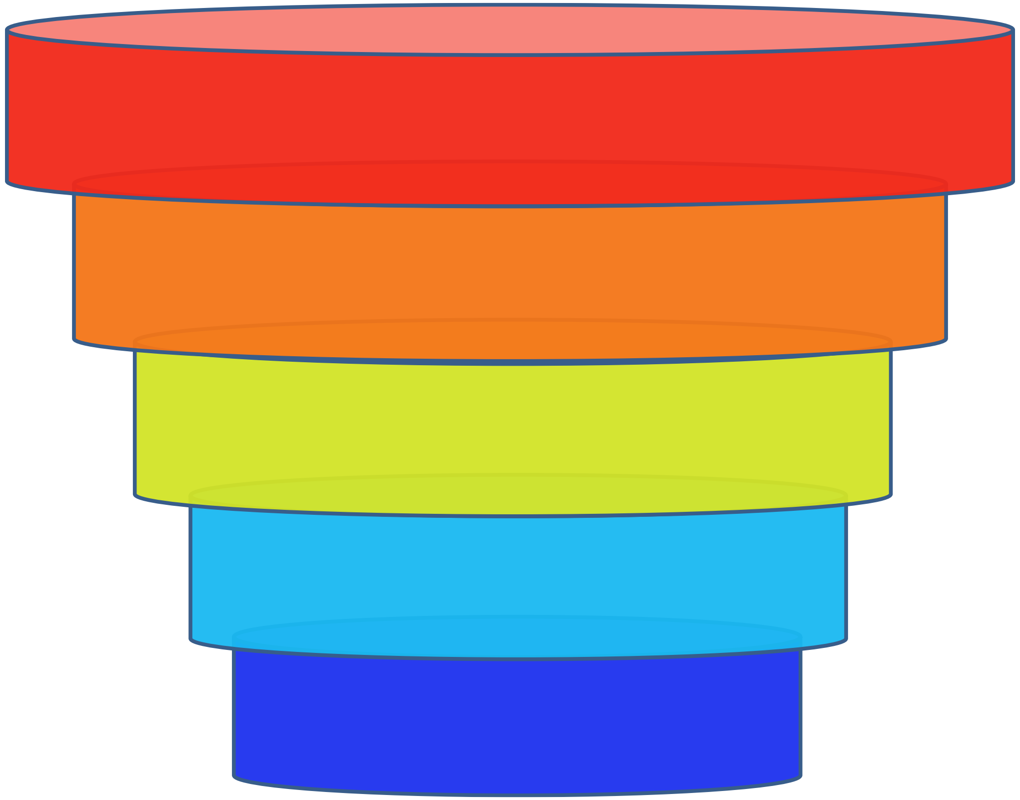
Example of simple physical domain where number of layers have been set to 5 by user (*nlev* = *5*) without the use of the optional gridzooming.

Illustration of the principle for state variable output representation in the 1D domain

Benthic domain
g/m²



Pelagic domain
g/m³



GOTM (the 1D physical model)

GOTM includes several options for calculating mixing based on models for the turbulent kinetic energy (TKE) and a turbulent length scale. By default, the k-epsilon model is used for calculating TKE and the turbulent dissipation (used as a proxy for the turbulent length scale). The main output of the turbulence sub-model is diffusivity and viscosity – used for calculating mixing of scalars (e.g. temperature, nutrients, etc.) and velocities respectively.

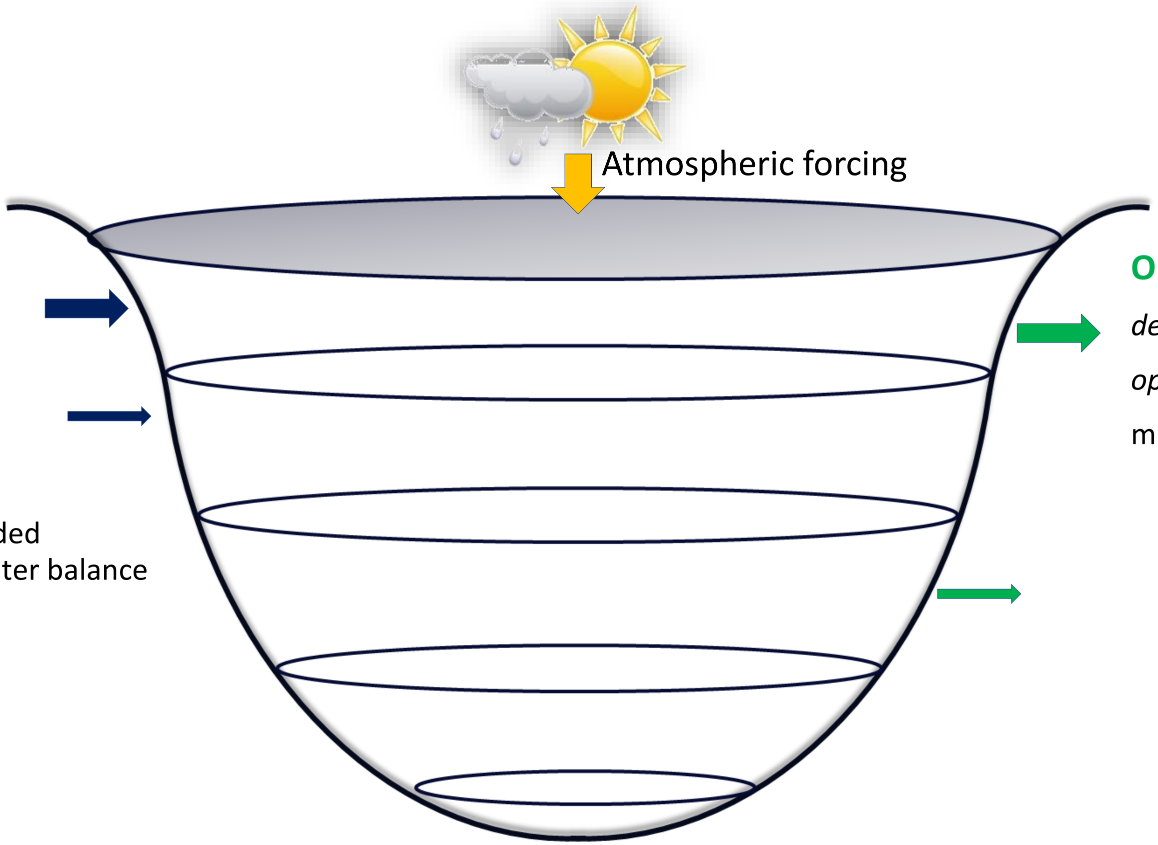
Inflows

default: **interleaving**

option: **depth range**

multiple inflows possible

residual streams can be added automatically to correct water balance



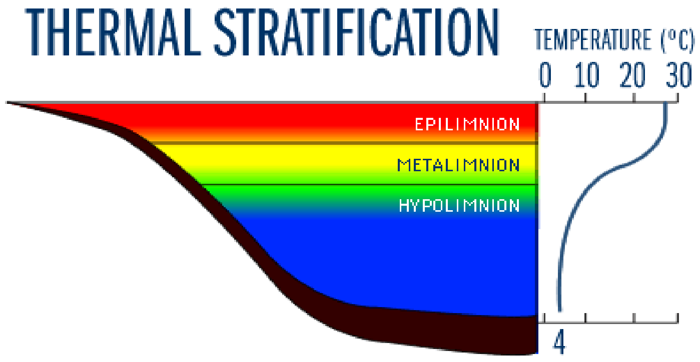
Outflows

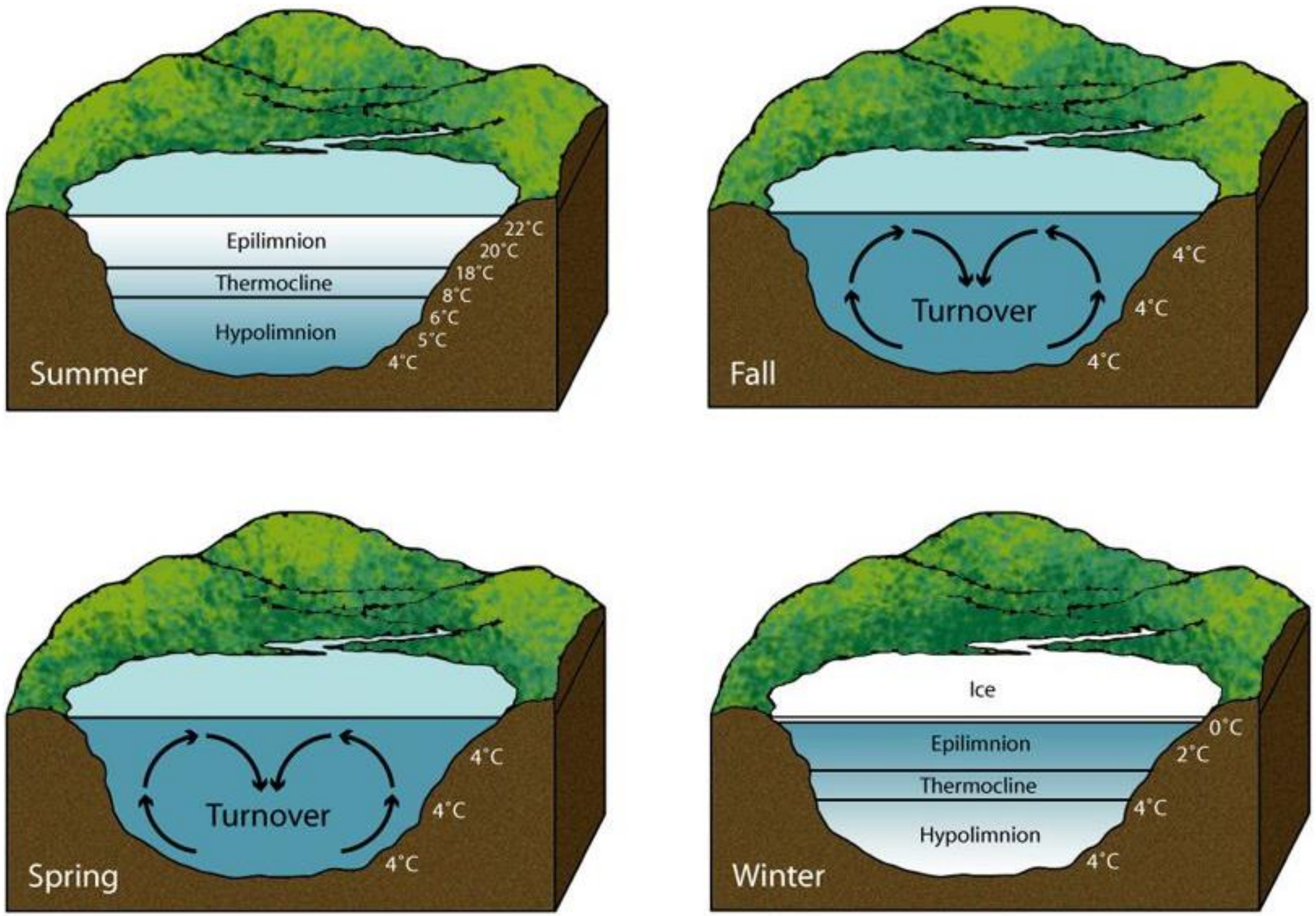
default: surface outflow

option: depth range

multiple outflows possible

GOTM can simulate the seasonality of thermal stratification





INFO BOX:
Density of freshwater:

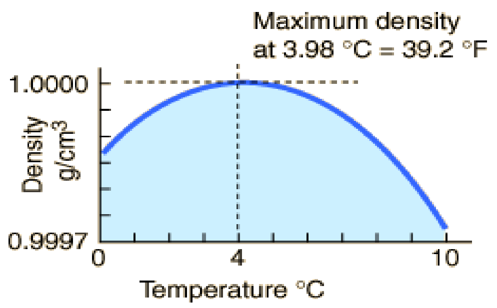
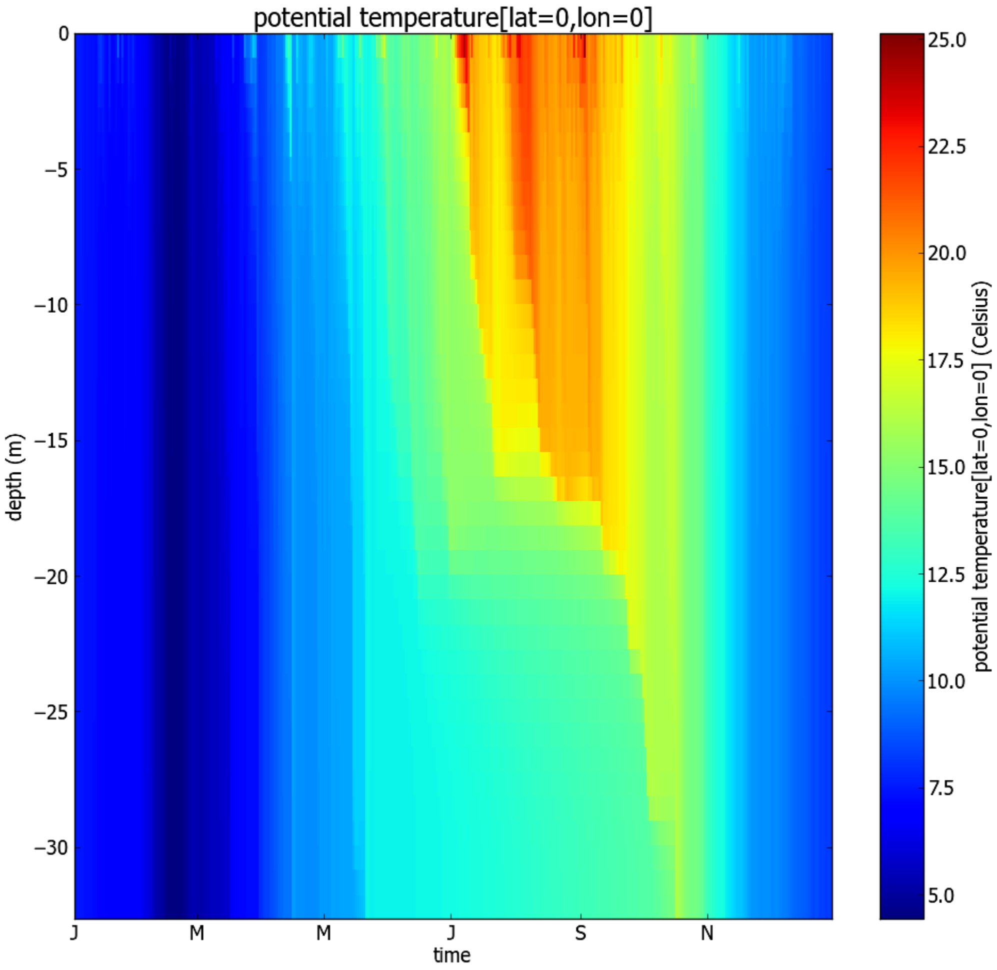
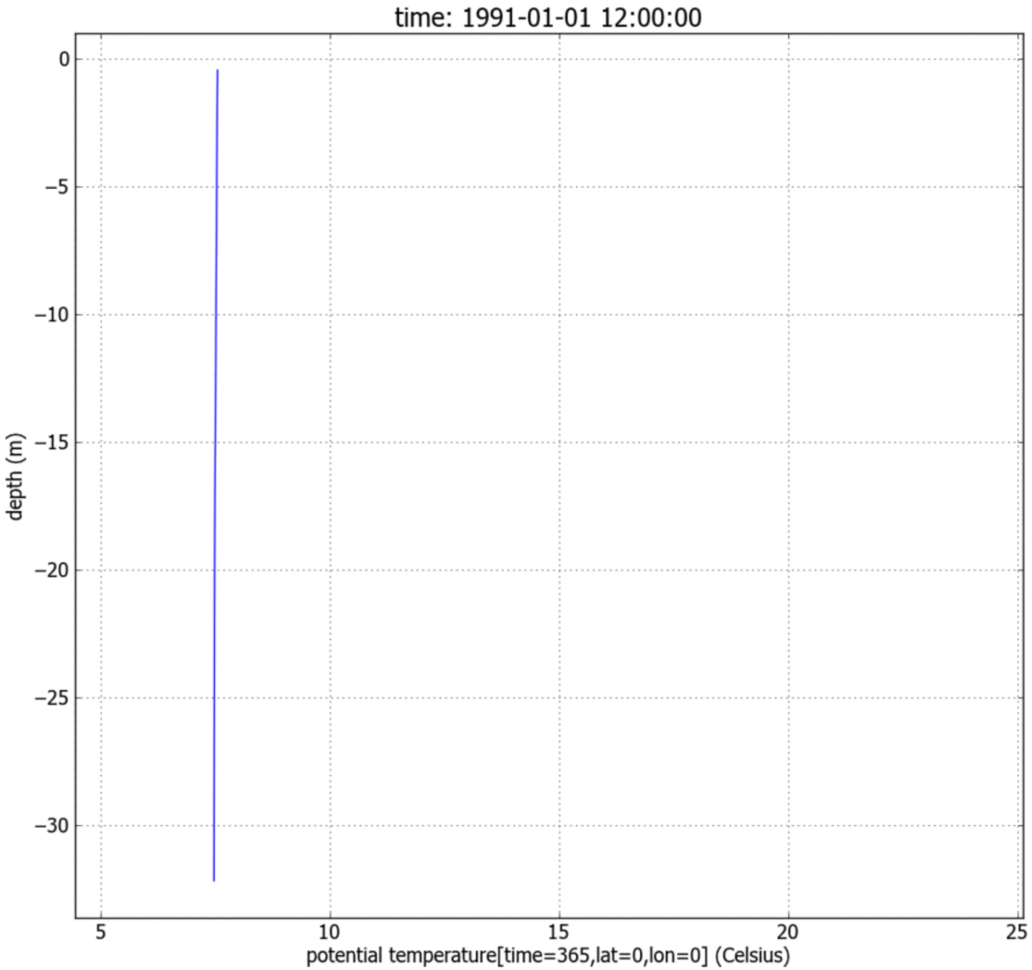


Illustration by Tim Gunther
on https://www.**nationalgeographic**.org/media/lake-turnover

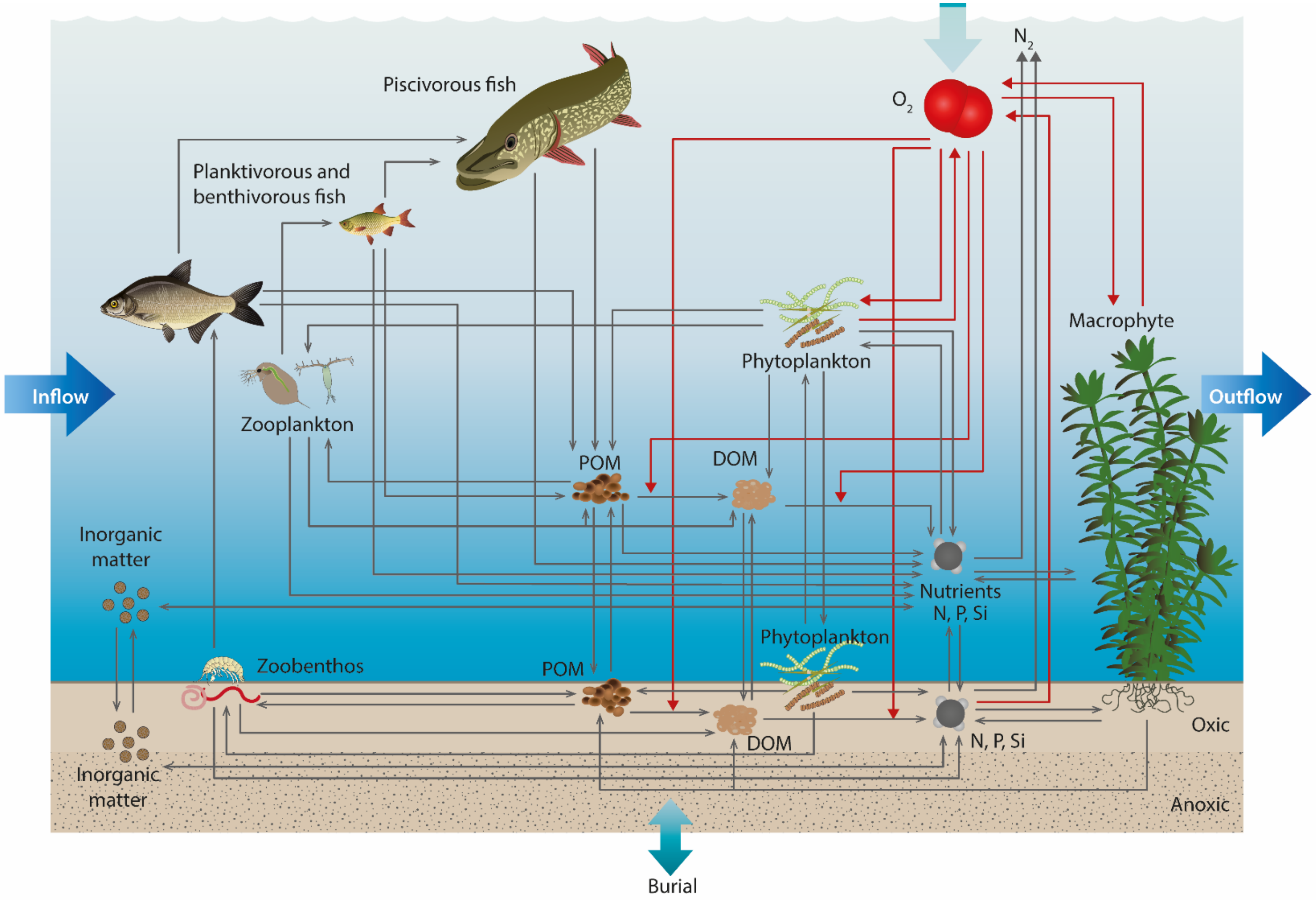
GOTM can simulate the seasonality of thermal stratification





WET (Water Ecosystems Tool)

The configuration of the conceptual ecosystem model is flexible, but by default it describes interactions between multiple trophic levels, including piscivorous, zooplanktivorous and benthivorous fish, zooplankton, zoobenthos, phytoplankton and rooted macrophytes. The ecosystem model also accounts for oxygen dynamics and a fully closed nutrient cycle for nitrogen and phosphorus.



WET conceptual model from Schnelder-Meyer et al. in prep.
Model developed by AU.

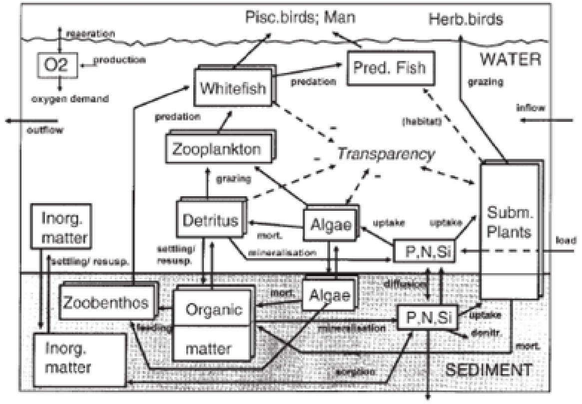
Development of WET

Biogeochemical

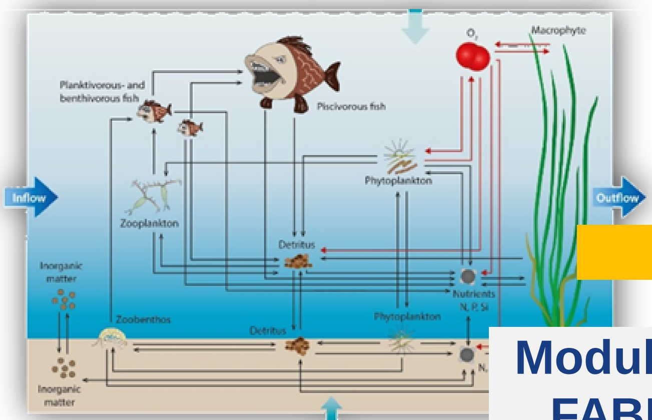
PCLake

FABM-PCLake

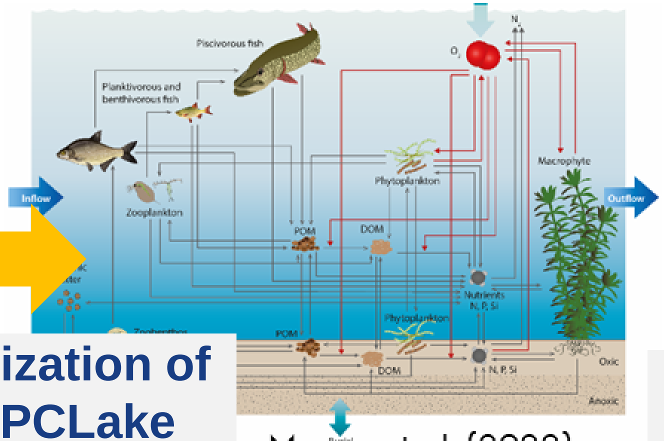
WET



Janse (2005)



Fenjuan et al. (2016)



er-Meyer et al. (2022)

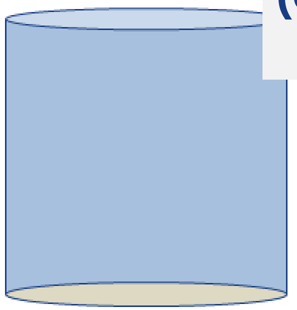
WET v2.0
and beyond

Modularization of FABM-PCLake (among others)

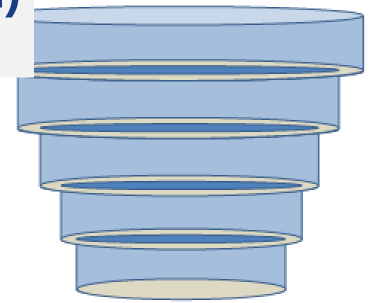
New modules and improvements

Physical

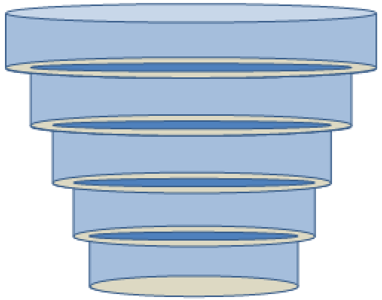
Coupling PCLake (ecological model) to GOTM



Internal box (0D) model

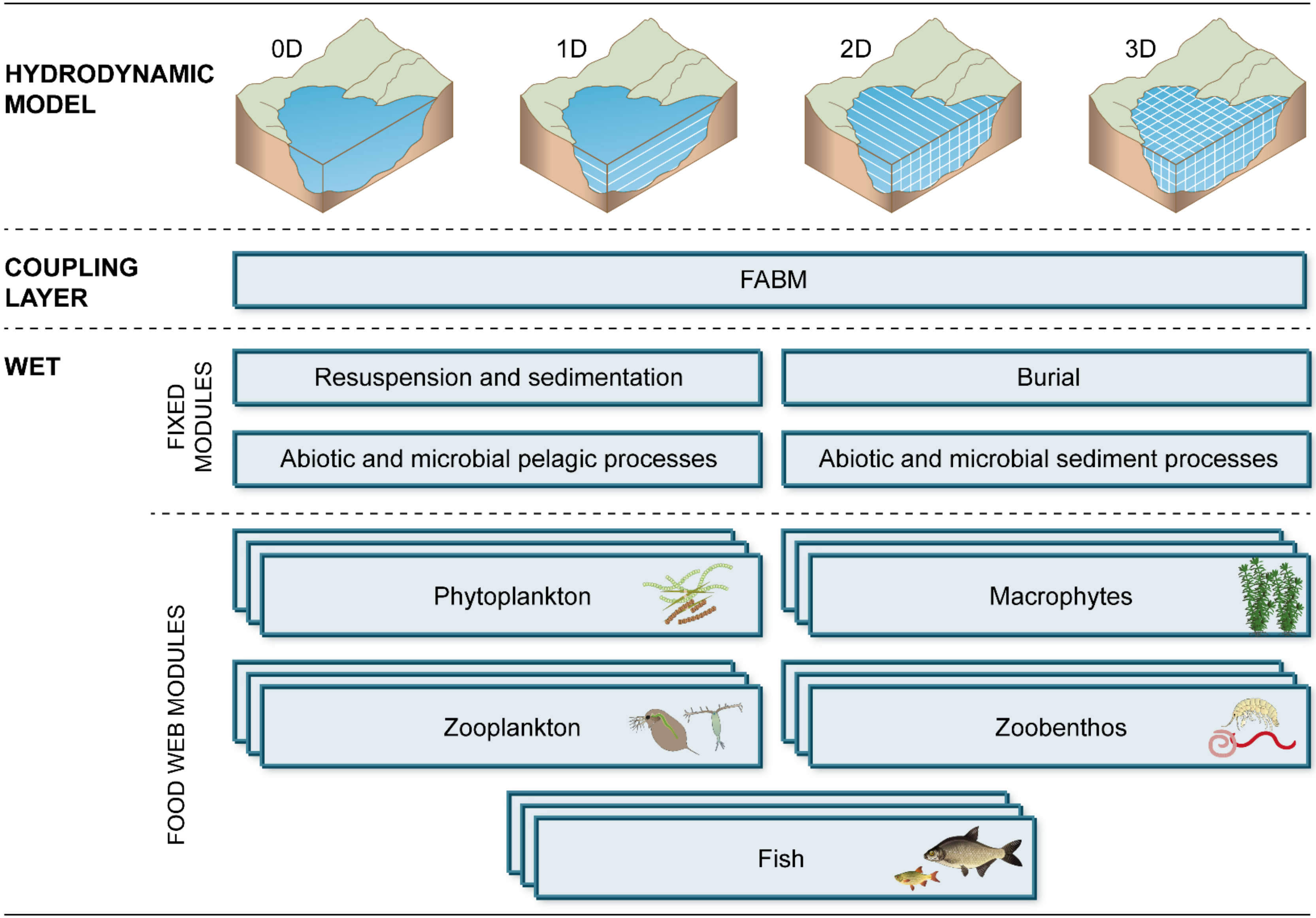


Connect to 1D GOTM (AU)

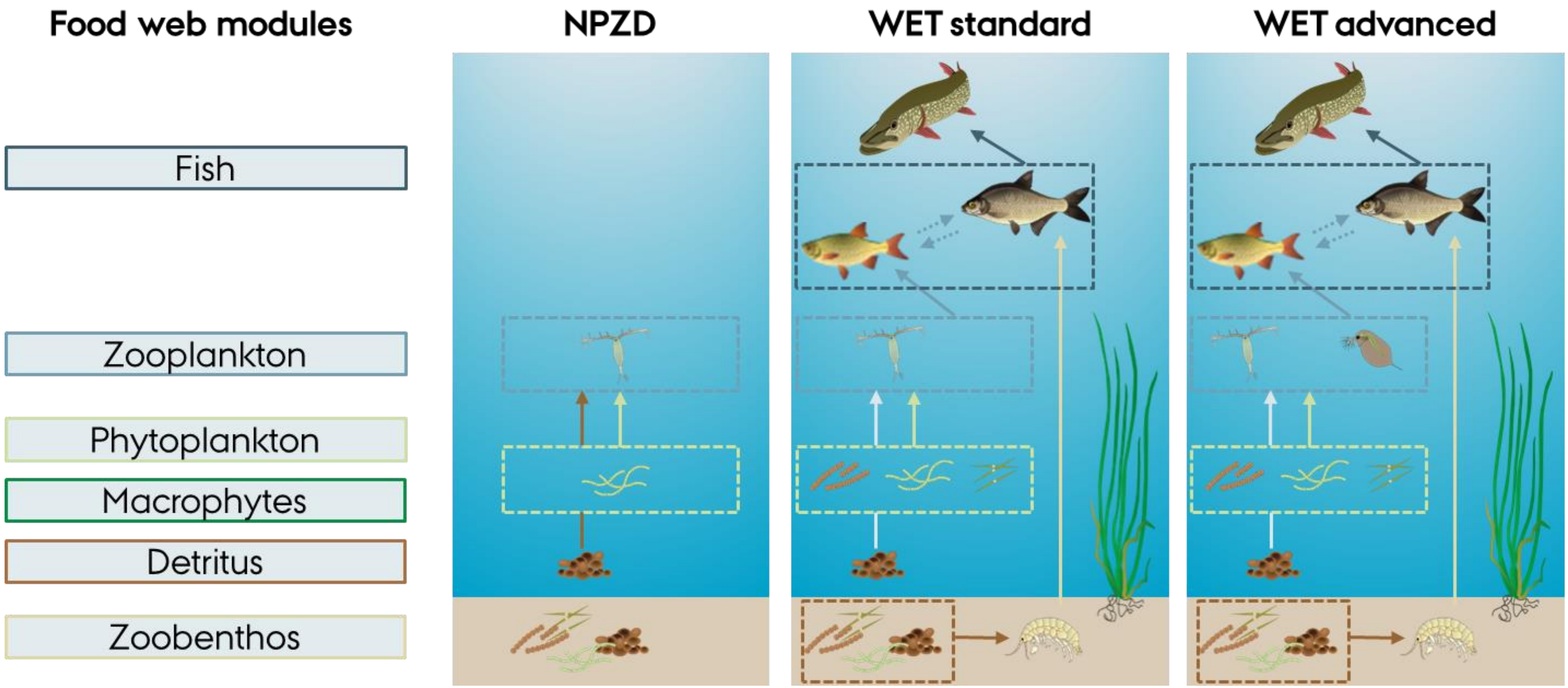


Connect to 1D GOTM (AU)

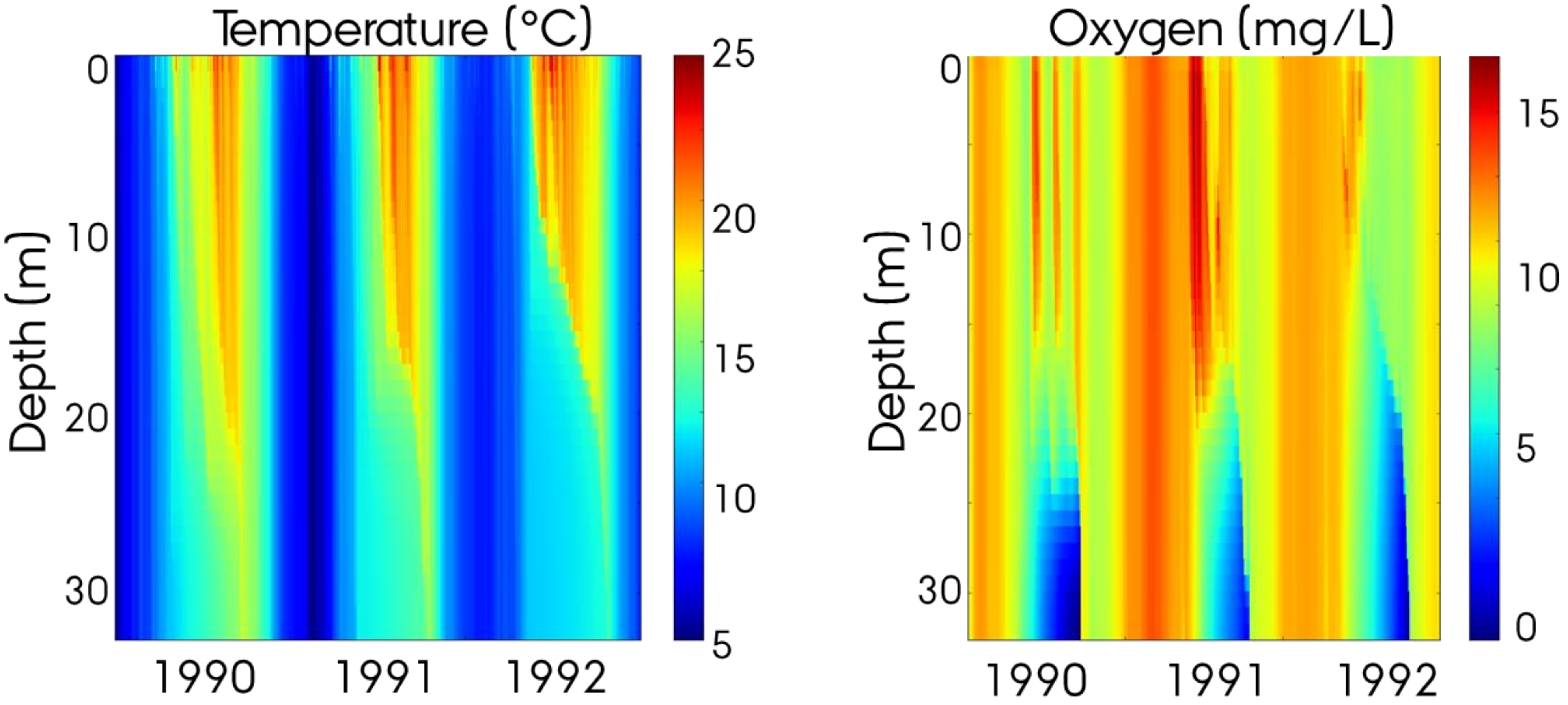
WET allows for flexible model configuration



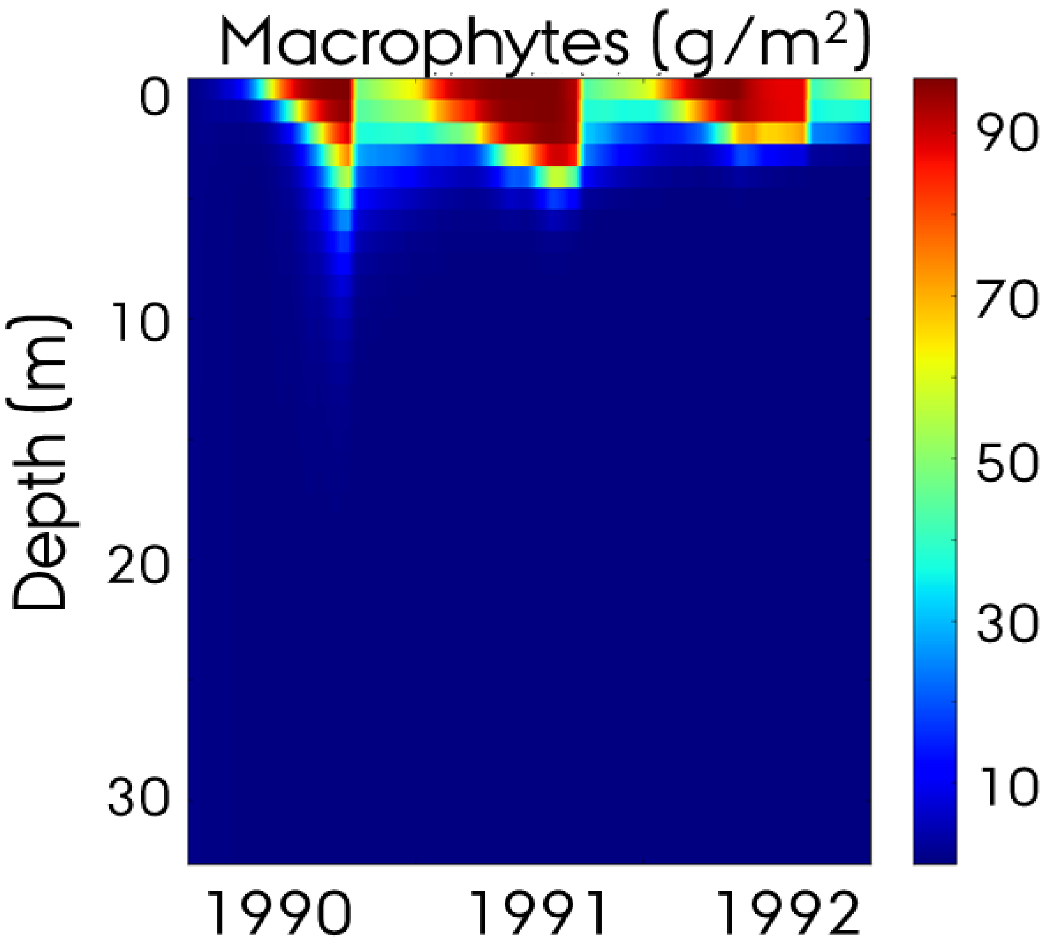
WET food web configurations

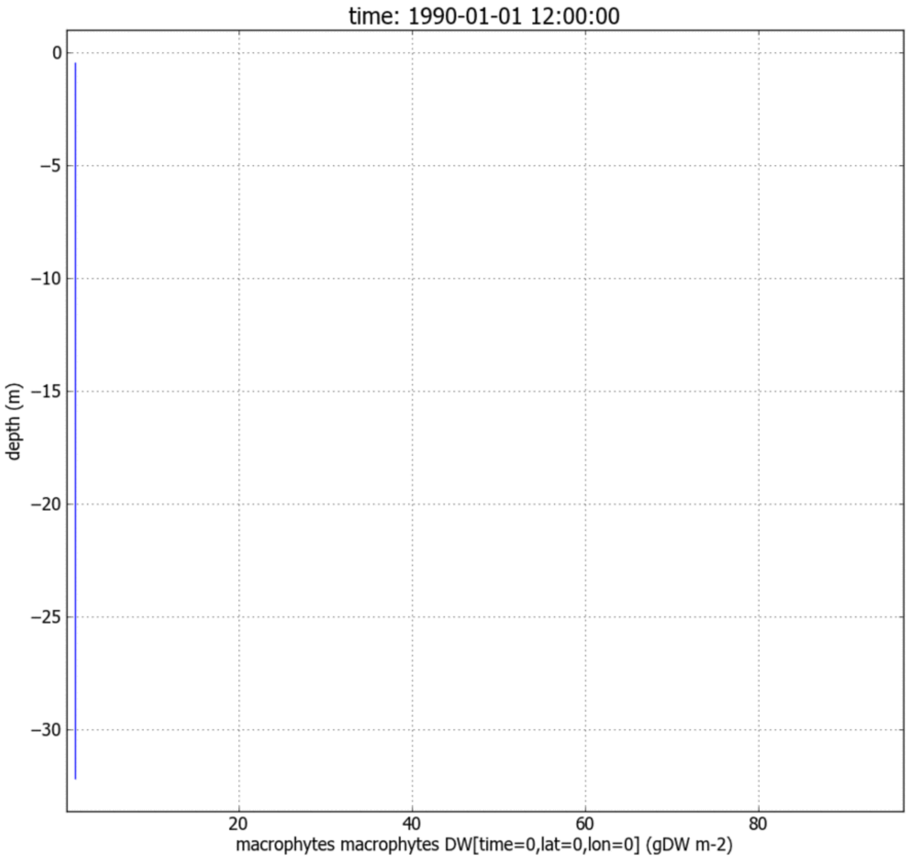


GOTM-WET can simulate foodweb dynamics and a wide range of biogeochemical processess – and how these interact with physics



GOTM-WET can simulate foodweb dynamics and a wide range of biogeochemical processess





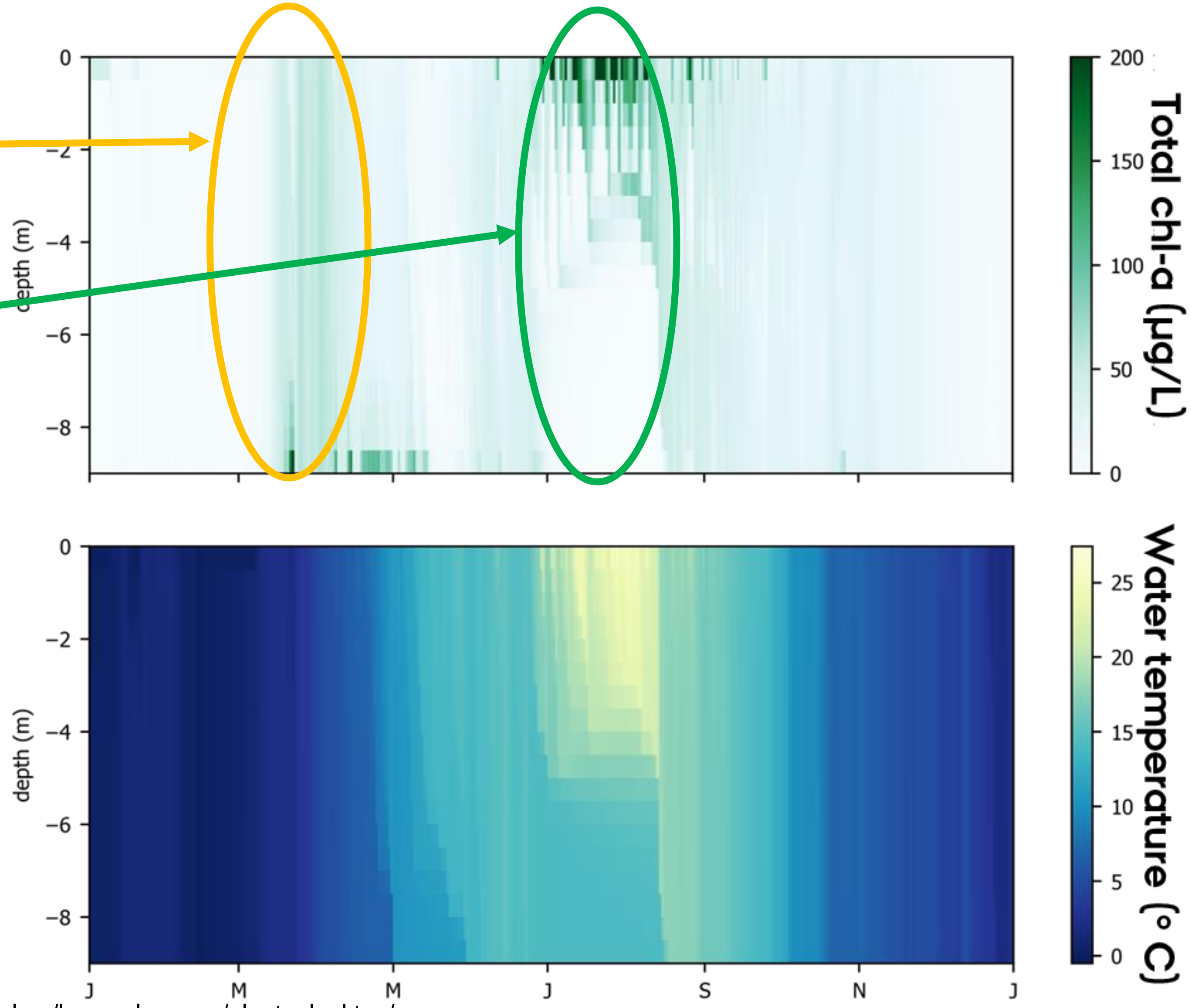
WET can simulate cyanobacteria surface blooms

Diatom bloom

Passive settling

Cyanobacteria surface bloom

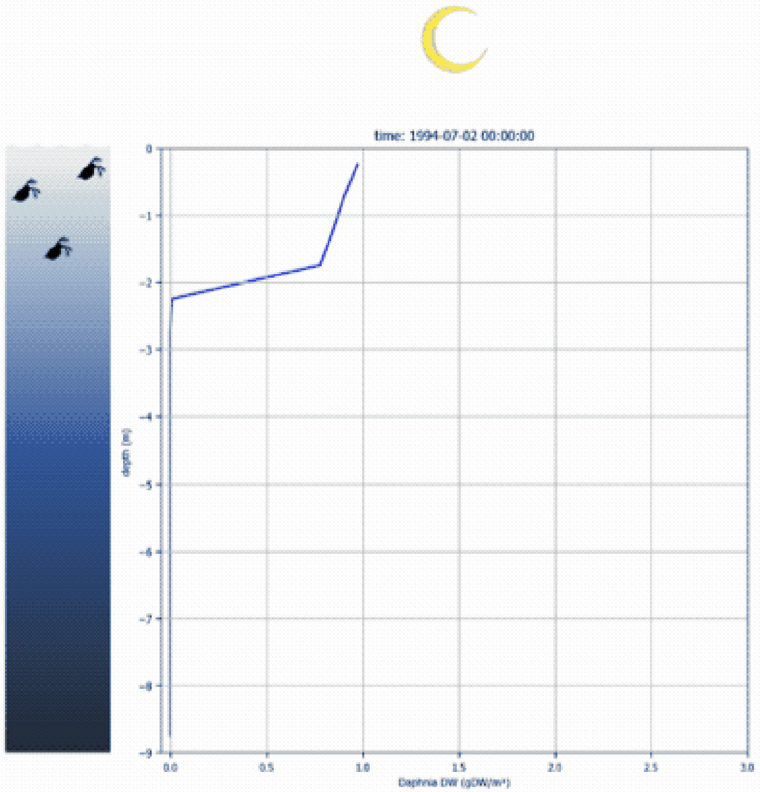
Active upward swim

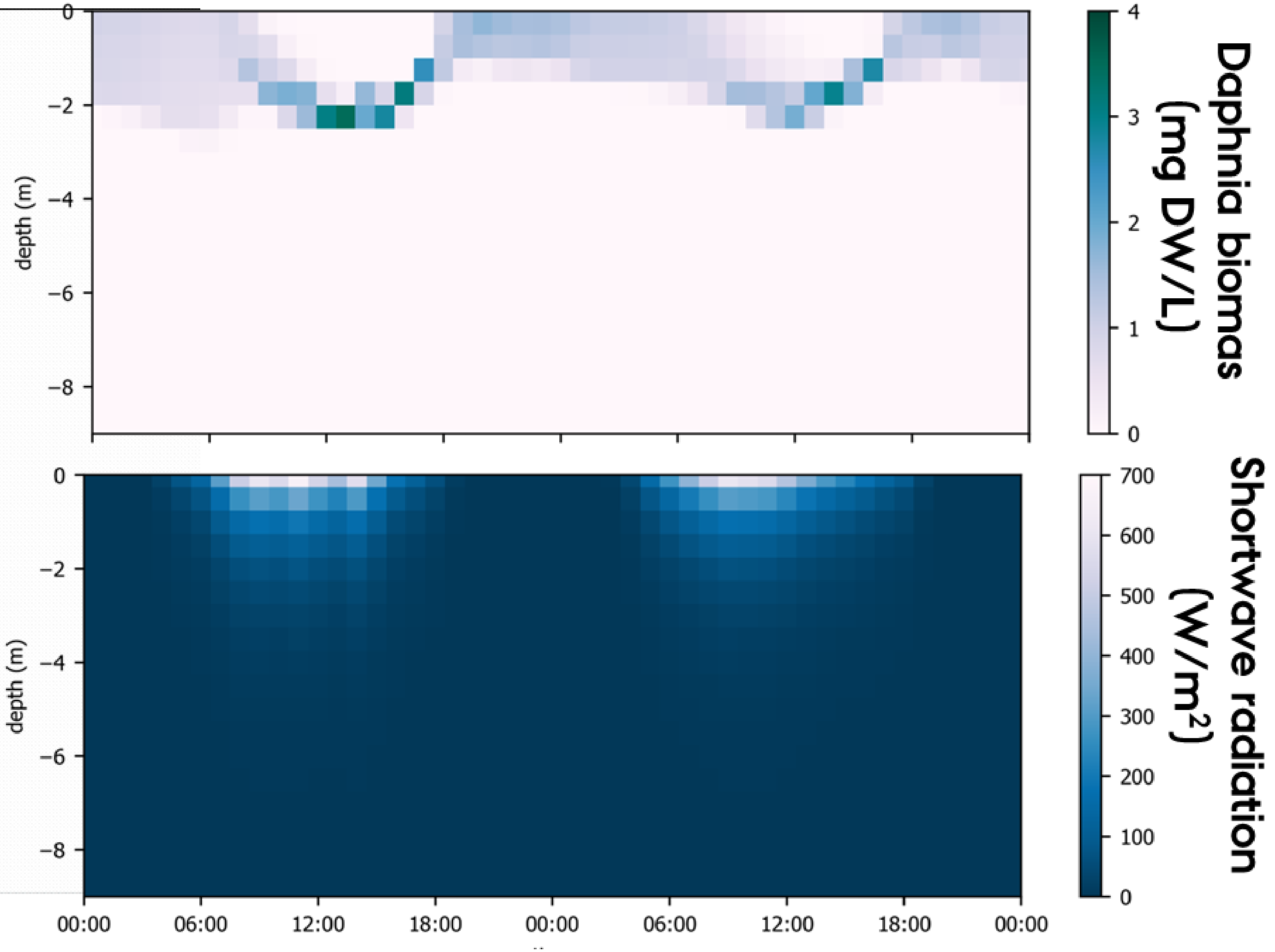


Cyanobacteria surface blooms occur frequently in Danish Lake Bryrup.

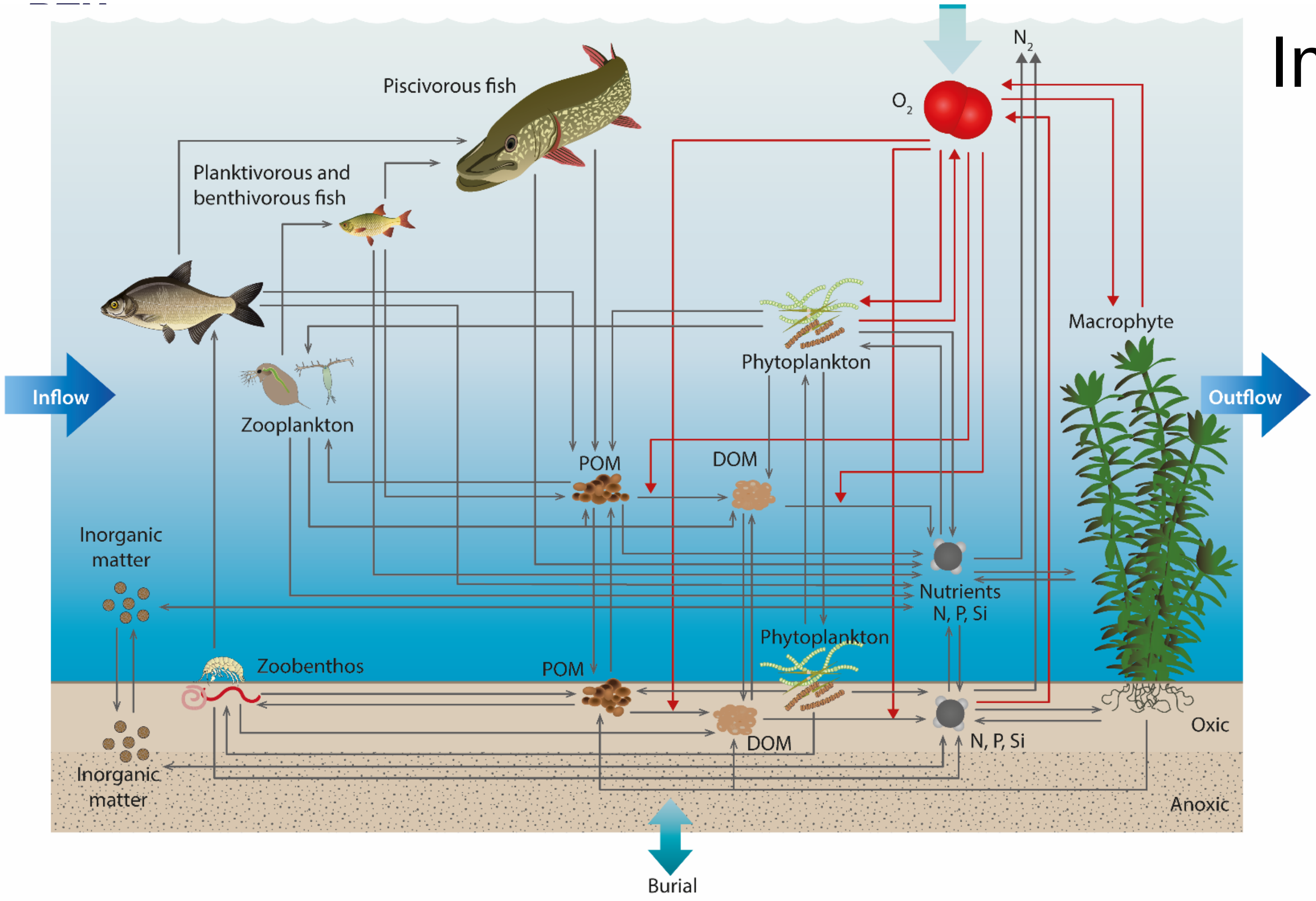
Photo by the Danish EPA.
https://mst.dk/natur-vand/overvaagning-af-vand-og-natur/lokalitetsbeskrivelser/bryrup-langsoe/planteplankton/

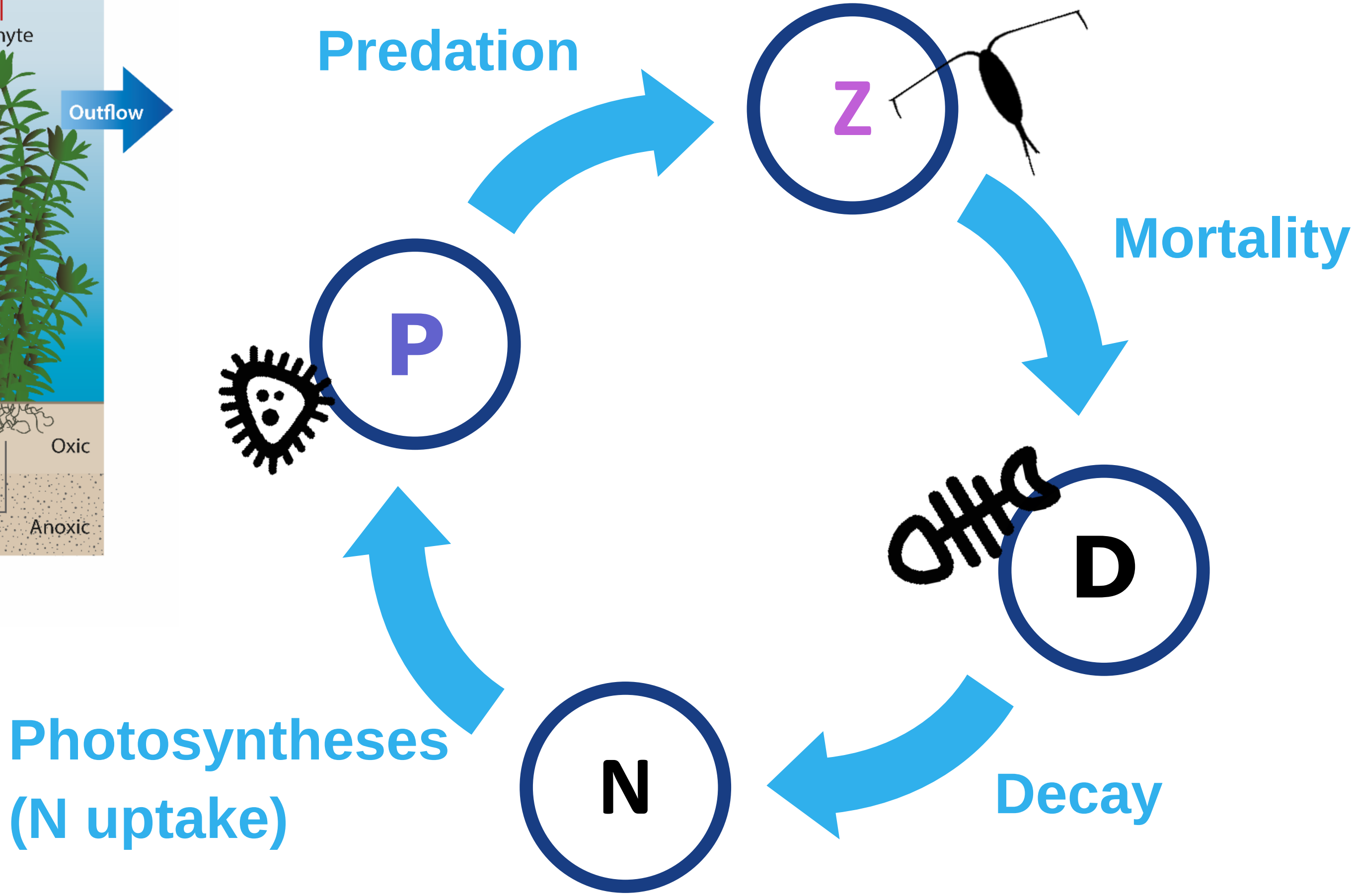
WET can simulate vertical migration – by phytoplankton, zooplankton as well as fish

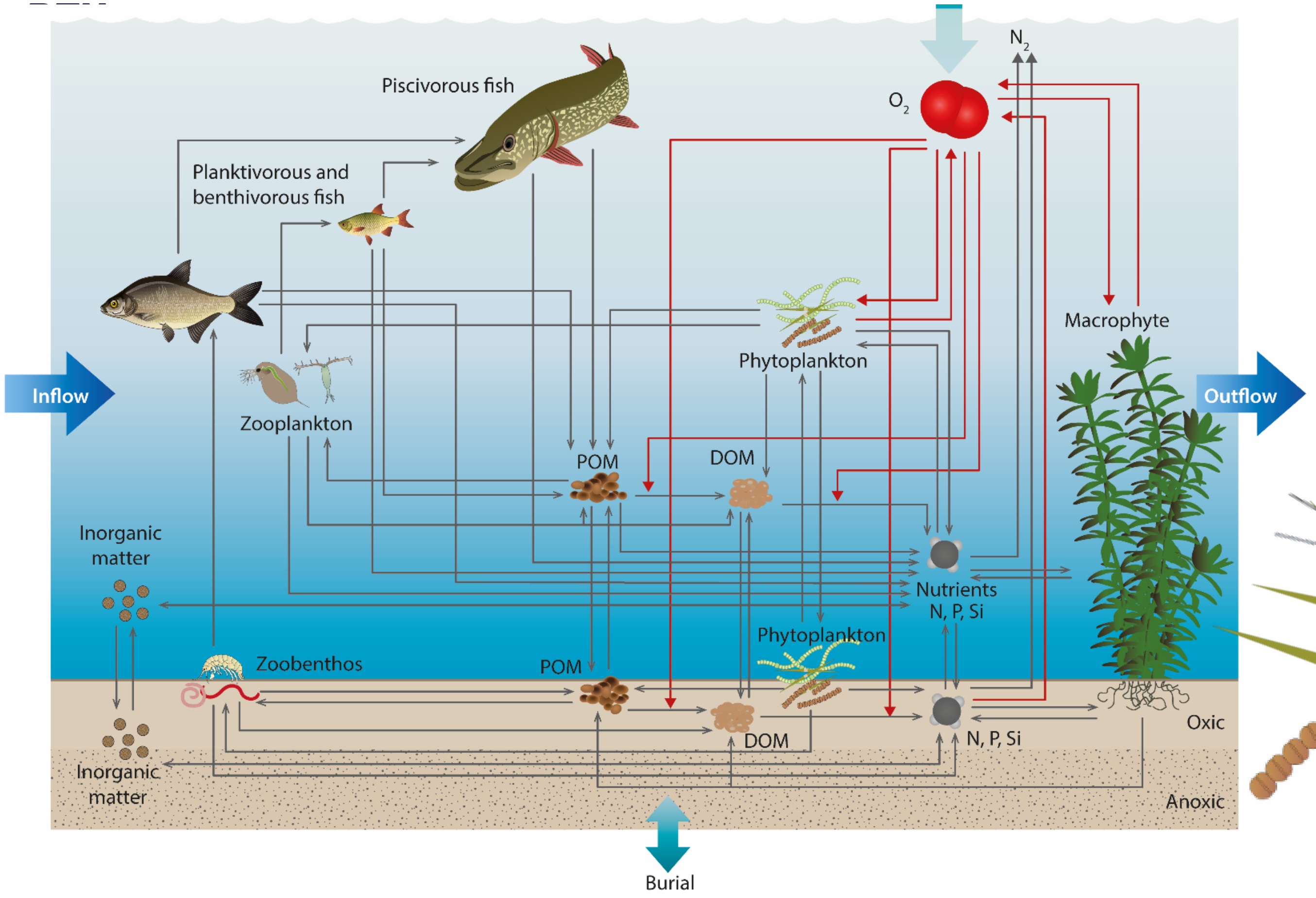




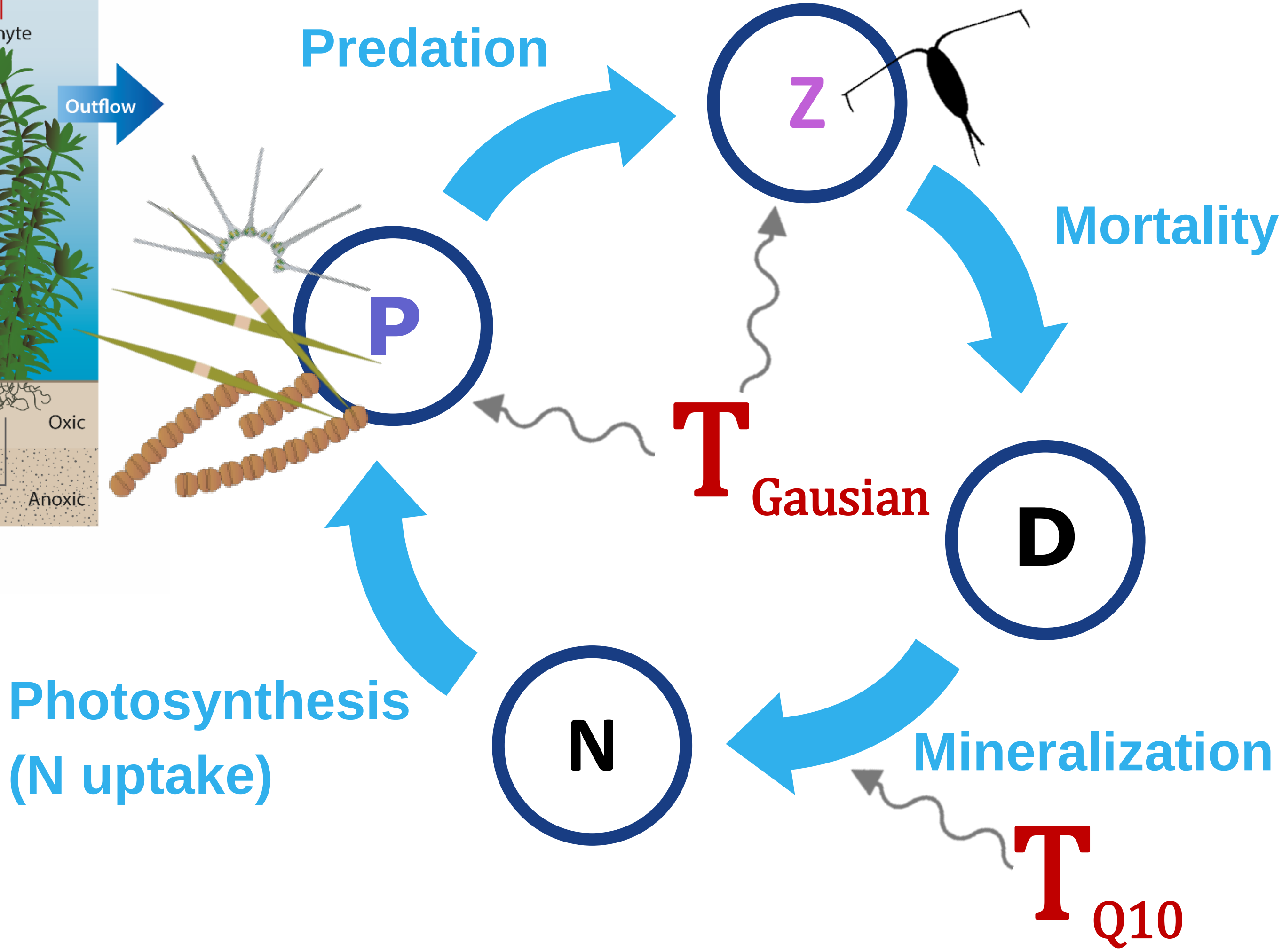
Important functions to know in WET







Piscivorous fish
Planktivorous and benthivorous fish
O2
N2
Macrophyte
Phytoplankton
Zooplankton
Inflow
Outflow
POM
DOM
Inorganic matter
Nutrients N, P, Si
Phytoplankton
Zoobenthos
POM
DOM
N, P, Si
Oxic
Anoxic
Inorganic matter
Burial



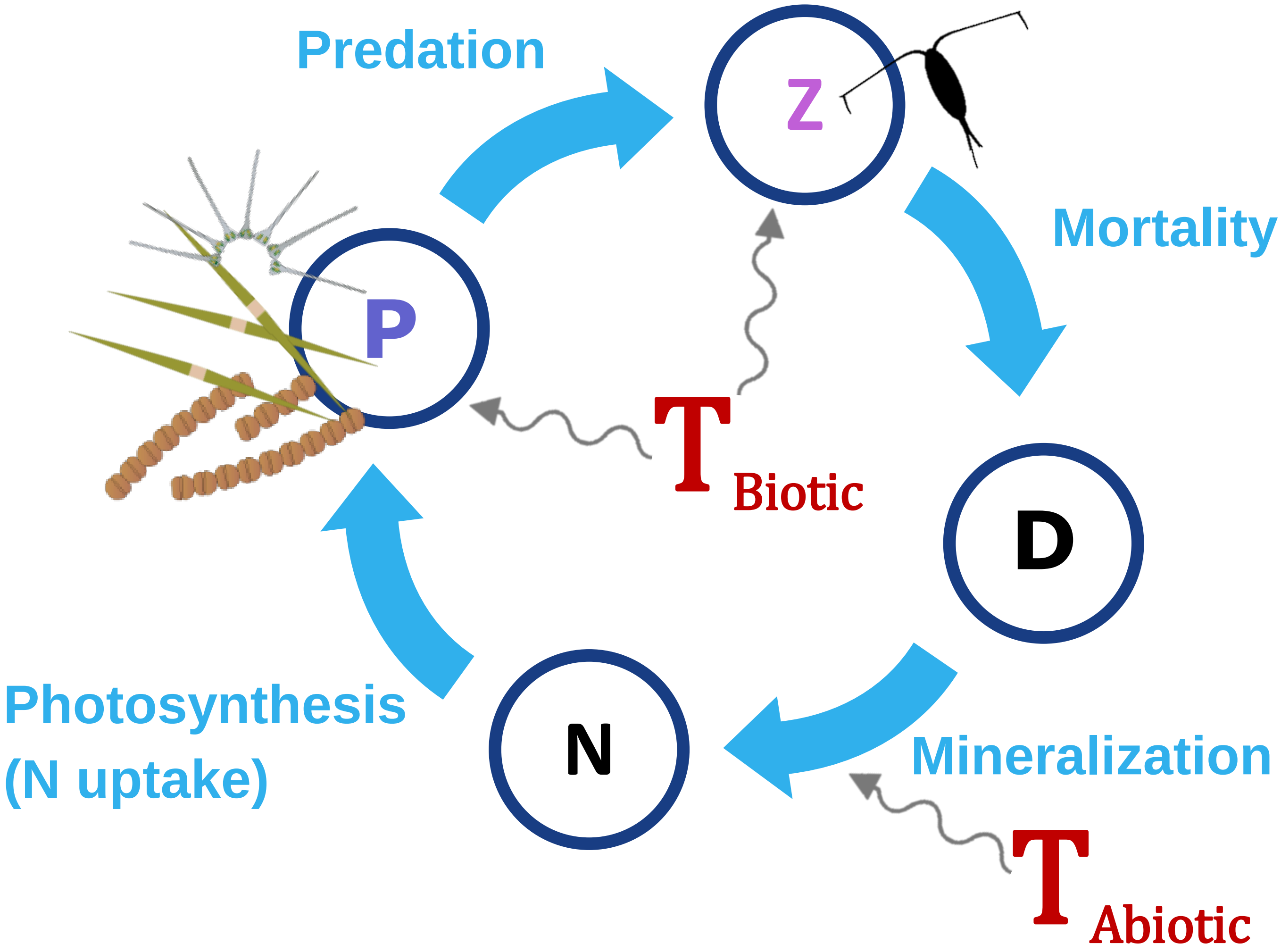
Predation
Z
Mortality
P
T Gausian
D
Photosynthesis (N uptake)
N
Mineralization
T Q10

Temperature functions in WET

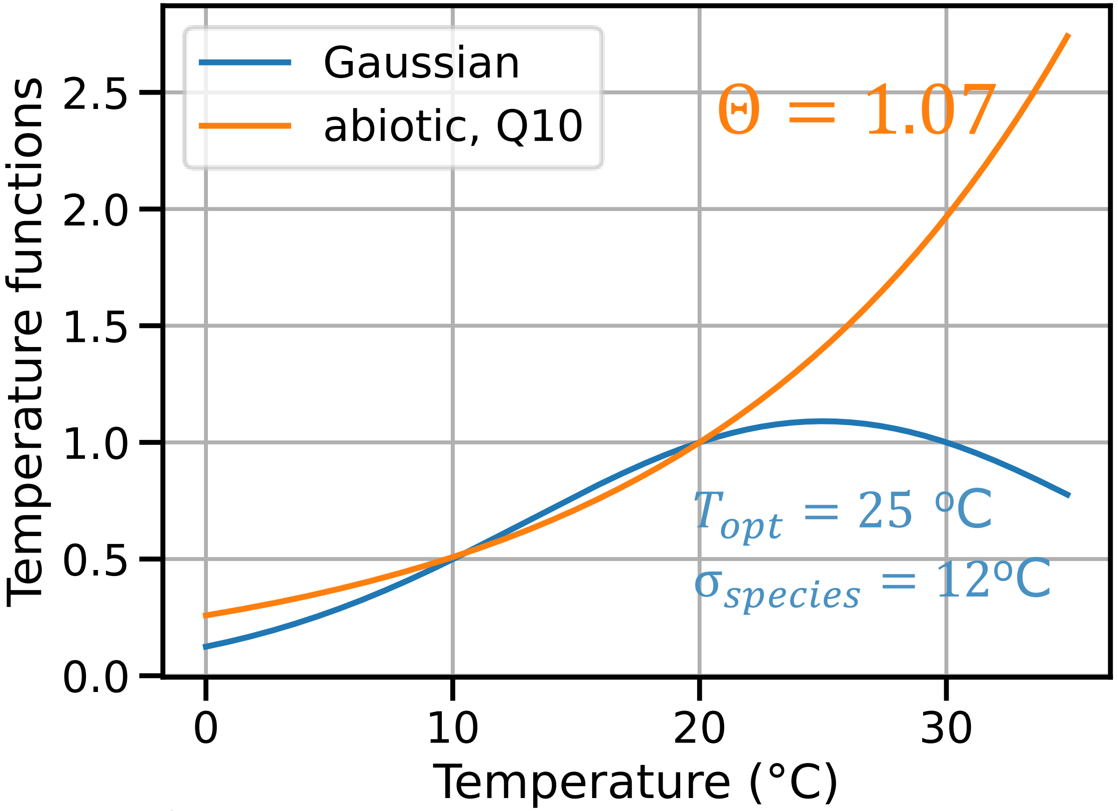
$$FunTm_{Abiotic} = \Theta^{(T-T_{ref})}$$

$$FunTm_{Biotic} = e^{\frac{-0.5}{\sigma_{species}{}^2} \times (T-T_{opt})^2 \times (T_{ref}-T_{opt})^2}$$

where T is temperature (celsius), T_{ref} is 20 celsius, Θ is a measure of the narrowness in the Gaussian curve and T_{opt} is the optimum temperature.



Temperature functions in WET



$$FunTm_{Abiotic} = \Theta^{(T-T_{ref})}$$

$$FunTm_{Biotic} = e^{\frac{-0.5}{\sigma_{species}{}^2} \times (T-T_{opt})^2 \times (T_{ref}-T_{opt})^2}$$

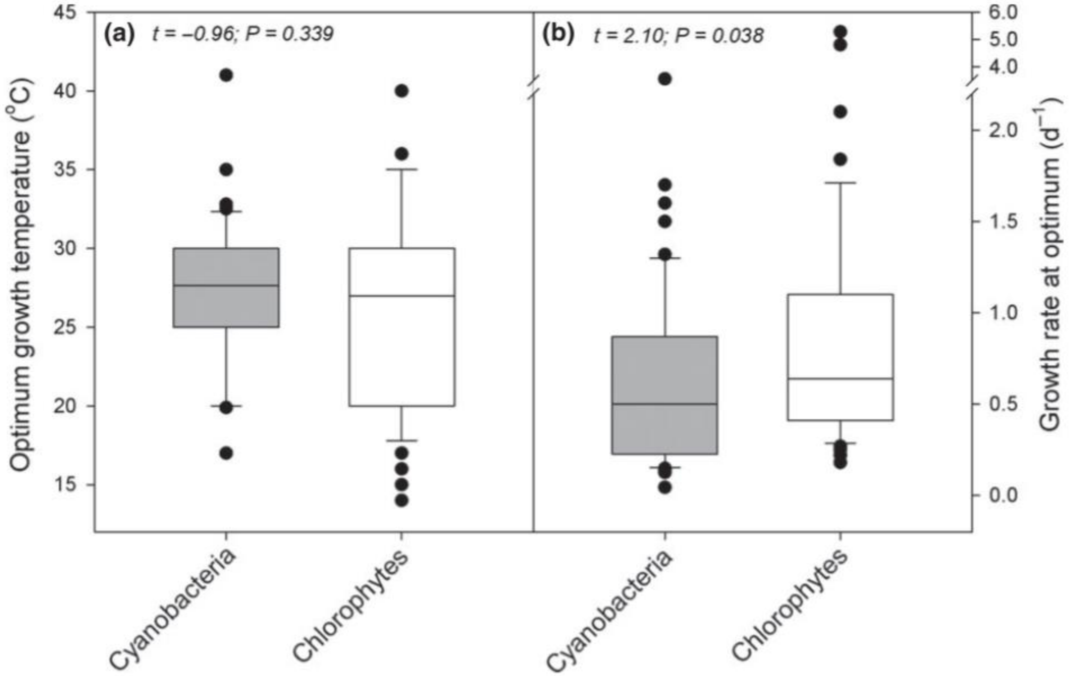
where T is temperature (celsius), T_{ref} is 20 celsius, $\sigma_{species}$ is a measure of the narrowness in the Gaussian curve and T_{opt} is the optimum temperature.

Functions regulating phytoplankton growth: Temperature

$$FunTm_{Biotic} = e^{\frac{-0.5}{\sigma_{species}{}^{2}} \times (T - T_{opt})^{2} \times (T_{ref} - T_{opt})^{2}}$$

where T is temperature (celsius), T_{ref} is 20 celsius, Θ is a measure of the narro Gaussian curve and T_{opt} is the optimum temperature.

	Green algae	Diatoms	Cyanobacteria
SigTm	15	14	10
TmOpt	26	20	27

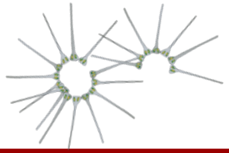


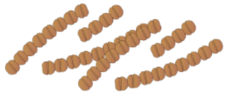
Lürling et al. (2013). Comparison of cyanobacterial and green algal growth rates at different temperatures. *Freshwater Biology*, *58*(3), 552–559.

Functions regulating phytoplankton growth: Temperature

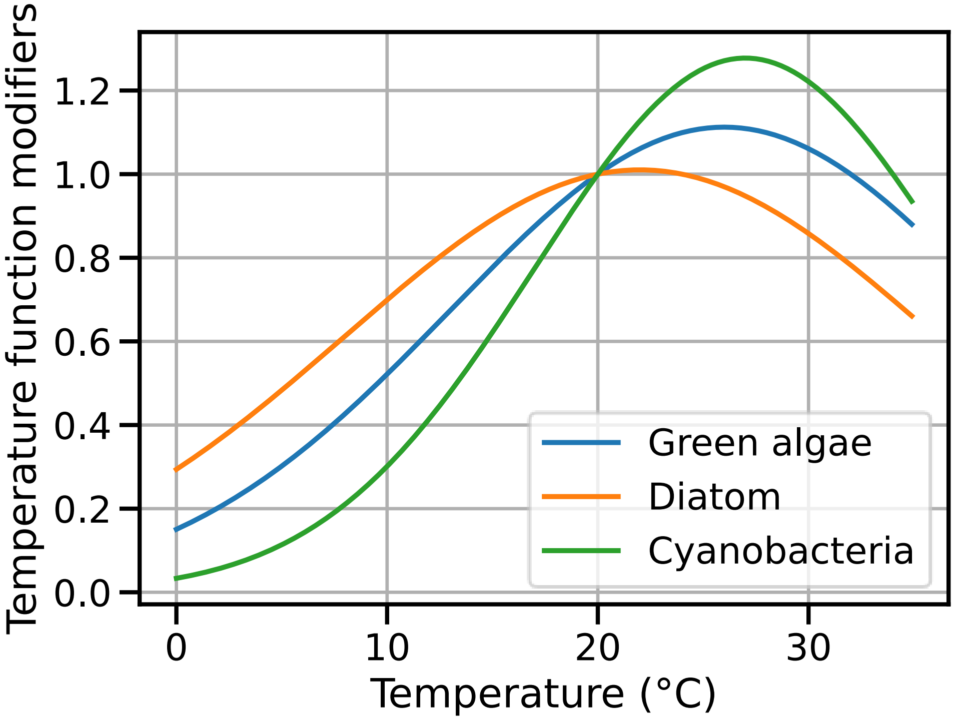
$$FunTm_{Biotic} = e^{\frac{-0.5}{\sigma_{species}{}^2}\times(T-T_{opt})^2\times(T_{ref}-T_{opt})^2}$$

where T is temperature (celsius), T_{ref} is 20 celsius, Θ is a measure of the narrownes
Gaussian curve and T_{opt} is the optimum temperature.



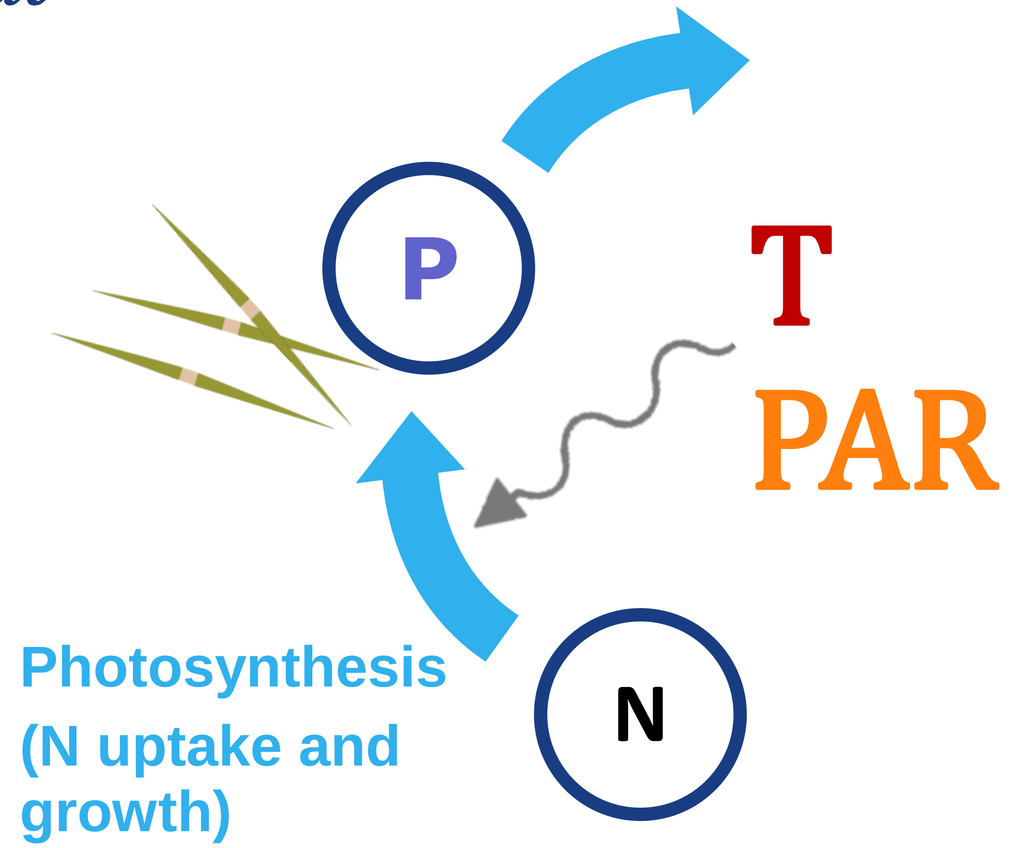


	Green algae	Diatoms	Cyanobacteria
SigTm (σ)	13	14	10
TmOpt	26	22	27



Functions regulating phytoplankton growth

$$\frac{dP}{dt} = growth(N, T, PAR) - predation$$



Functions regulating phytoplankton growth

$$\frac{dP}{dt} = growth(N, T, PAR) - predation$$

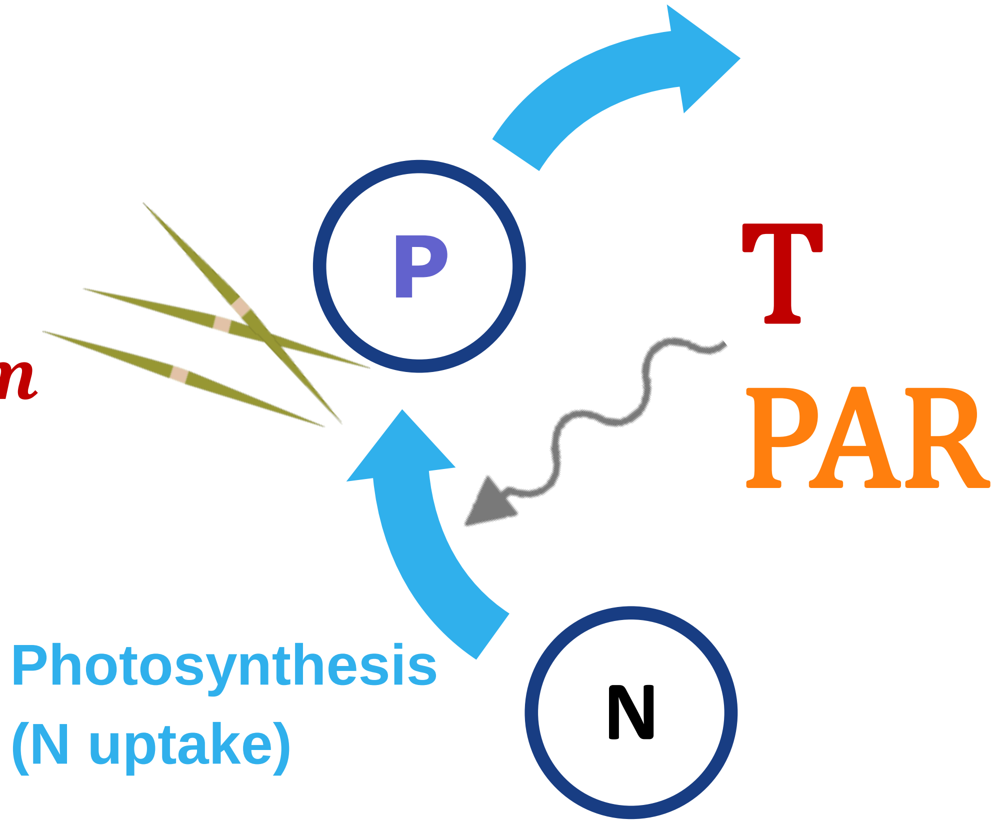
Growth rate parameter

Light limitation

$$cMuMax \times aNutLim \times aLLim \times uFunTm$$

Nutrient limitation

Temperature function



Functions regulating phytoplankton growth: Nutrient

Droop cell quota model (1968, 1983)

Q_0 is the minimum quota for growth

$$\mu(q) = \mu_m \left(1 - \frac{Q_0}{q}\right)$$

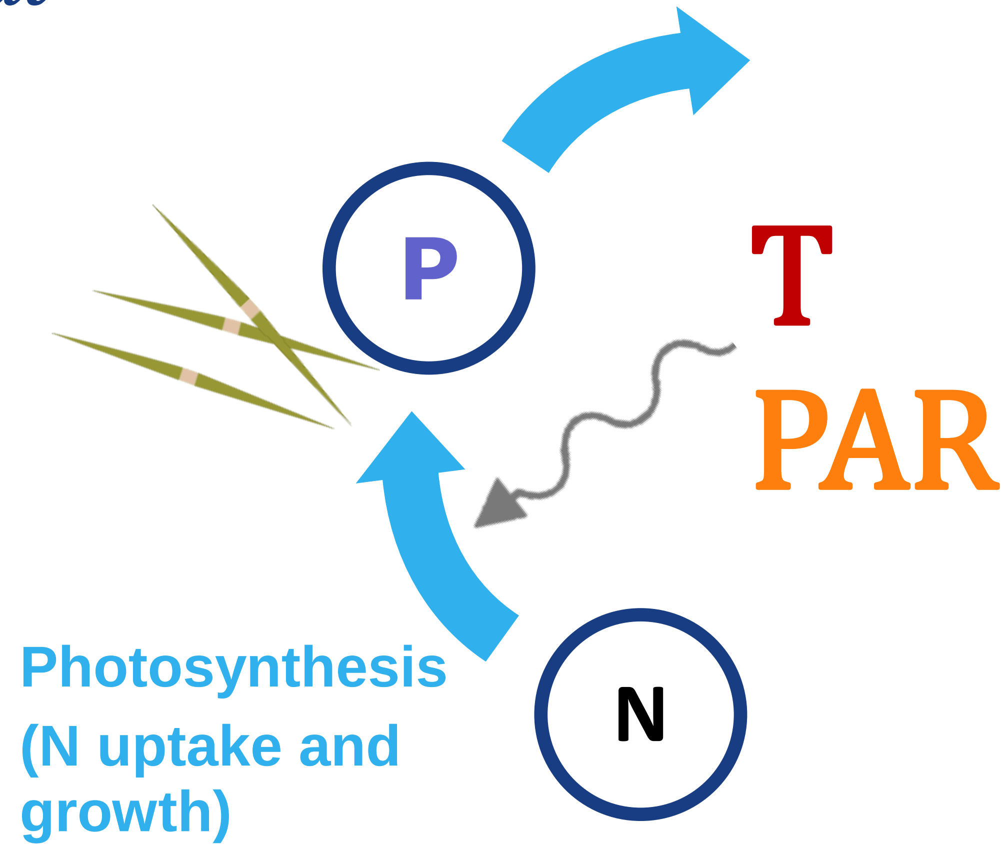
intracellular quota of the limiting nutrient q

Implementation in WET (PCLake)

$$NutLim_{Droop} = \left(1 - \frac{cNDW_{min}}{rNDW}\right) \frac{cNDW_{max}}{cNDW_{max} - cNDW_{min}}$$

where
$rNDW$ is N to DW ratio of phytoplankton [mgN/mgDW]
$cNDW_{min}$ is minimum N to DW ratio of phytopl. [mgN/mgDW]
$cNDW_{max}$ is max. N to DW ratio of phytopl. [mgN/mgDW]

$$\frac{dP}{dt} = growth(N, T, PAR) - predation$$



Functions regulating phytoplankton growth: Nutrient

Droop cell quota model (1968, 1983)

Q_0 is the minimum quota for growth

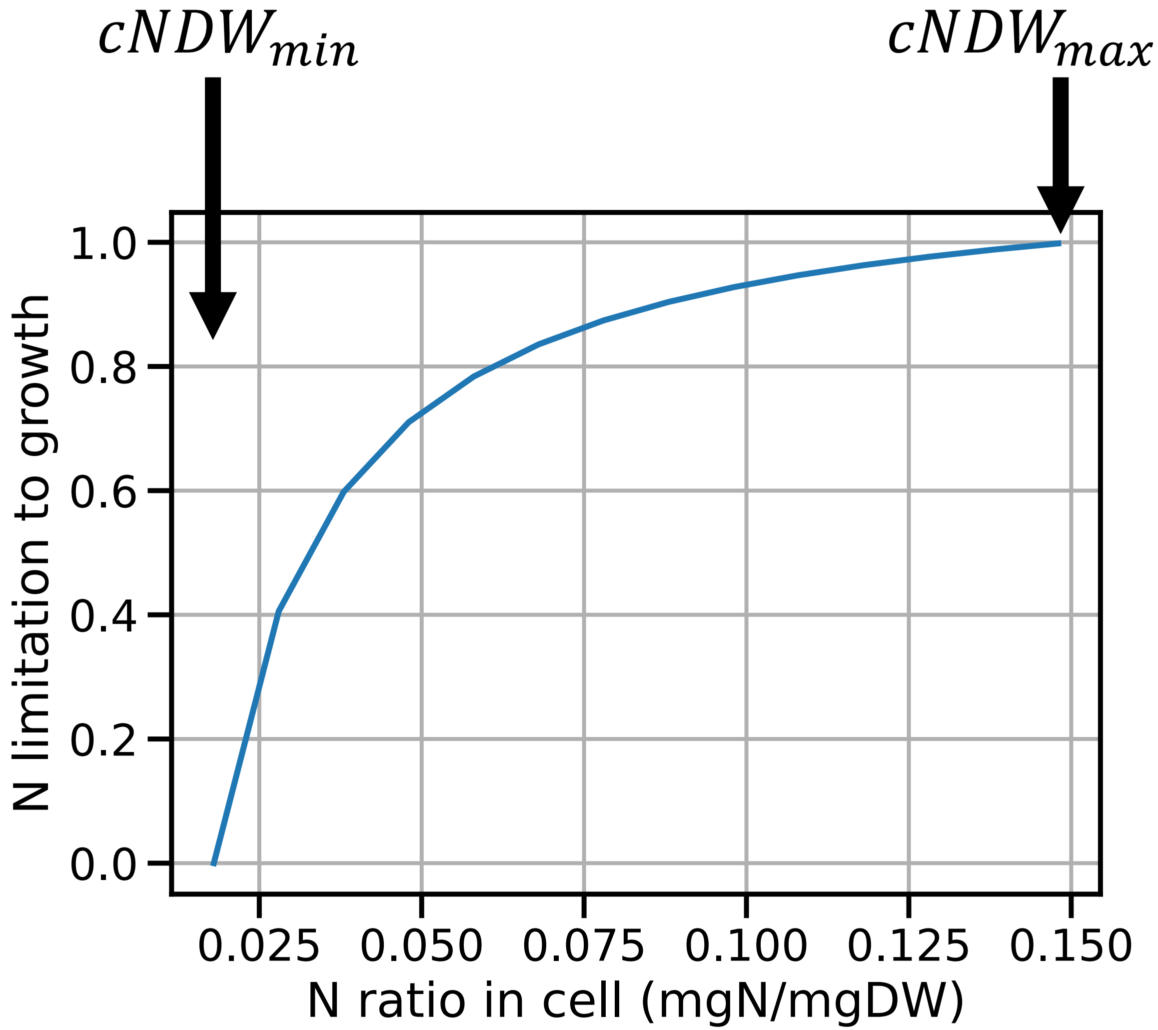
$$\mu(q) = \mu_m \left(1 - \frac{Q_0}{q}\right)$$

intracellular quota of the limiting nutrient q

Implementation in WET (PCLake)

$$NutLim_{Droop} = \left(1 - \frac{cNDW_{min}}{rNDW}\right) \frac{cNDW_{max}}{cNDW_{max} - cNDW_{min}}$$

where
$rNDW$ is N to DW ratio of phytoplankton [mgN/mgDW]
$cNDW_{min}$ is minimum N to DW ratio of phytopl. [mgN/mgDW]
$cNDW_{max}$ is max. N to DW ratio of phytopl. [mgN/mgDW]



Functions regulating phytoplankton growth: Light

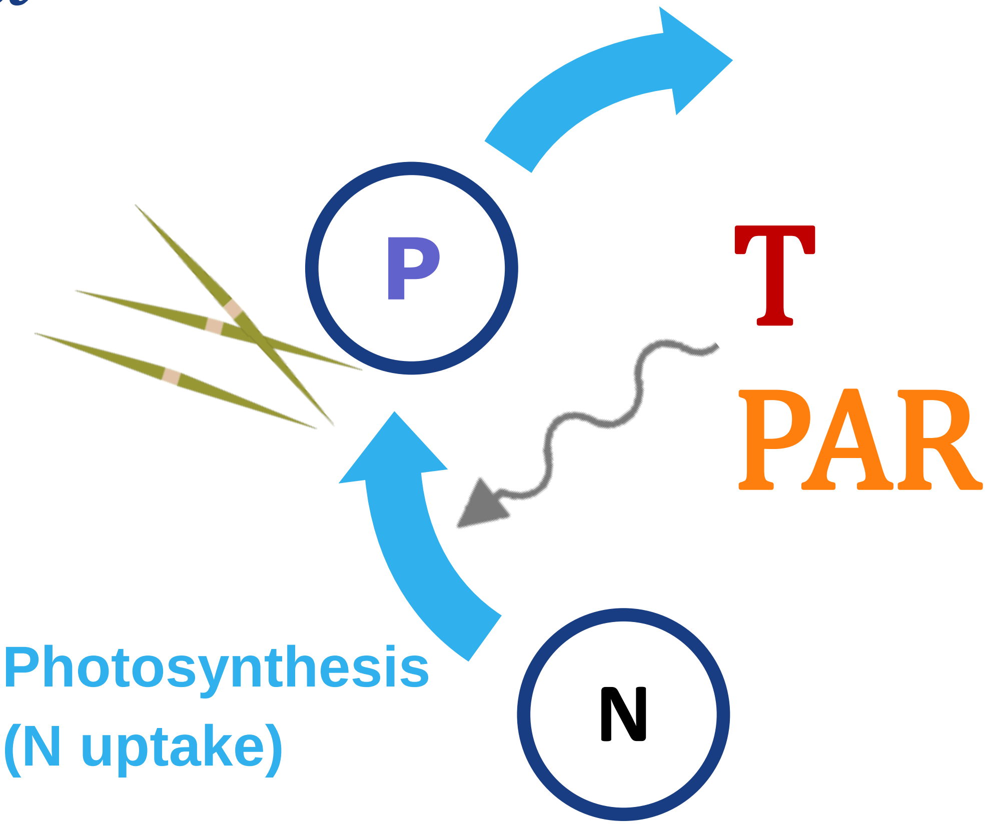
$$\frac{dP}{dt} = uptake(N, T, PAR) - predation$$

$$light\ limitation_{Monod} = \frac{PAR}{PAR + K}$$

$$light\ limitation_{Schmidt} = \frac{PAR}{\sqrt{PAR^2 + K^2}}$$

$$light\ limitation_{Steele} = \frac{PAR}{PAR_{opt}} \times e^{1-\frac{PAR}{PAR_{opt}}}$$

where *PAR* is the photosynthically active radiation, *K* is half-saturation coefficient, and PAR_{opt} is the optimal PAR where no light limitation occurs. All with the unit (W/m^2).



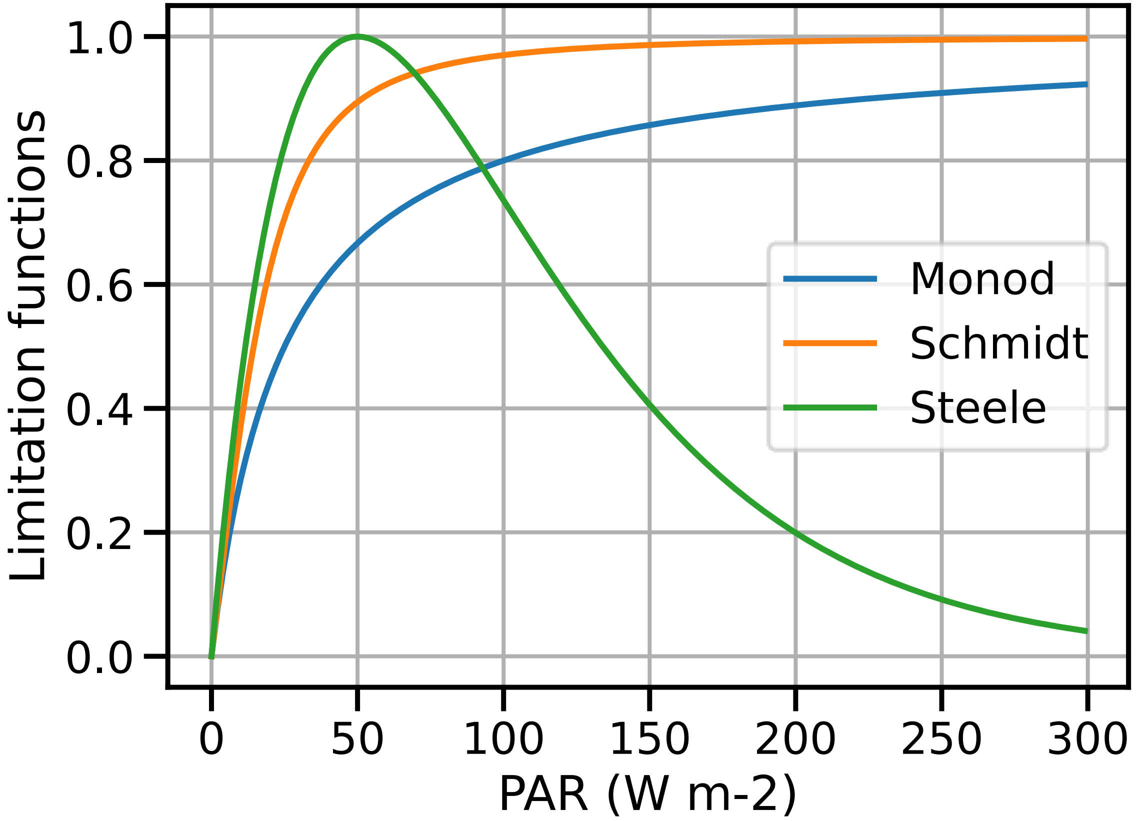
Functions regulating phytoplankton growth: Light

$$light\ limitation_{Monod} = \frac{PAR}{PAR + K}$$

$$light\ limitation_{Schmidt} = \frac{PAR}{\sqrt{PAR^2 + K^2}}$$

$$light\ limitation_{Steele} = \frac{PAR}{PAR_{opt}} \times e^{1-\frac{PAR}{PAR_{opt}}}$$

where *PAR* is the photosynthically active radiation, *K* is half-saturation coefficient, and PAR_{opt} is the optimal PAR where no light limitation occurs. All with the unit (W/m²).



Functions regulating phytoplankton growth

$$\frac{dP}{dt} = growth(N, T, PAR) - predation$$

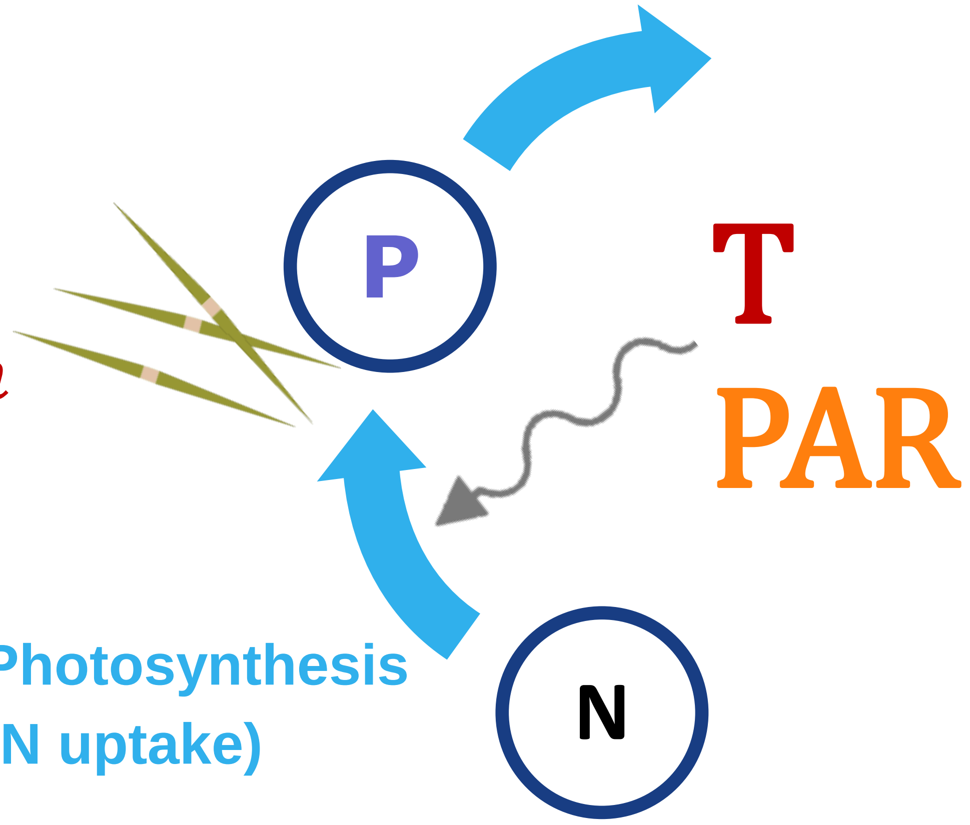
Growth rate parameter

Light limitation

$$cMuMax \times aNutLim \times aLLim \times uFunTm$$

Nutrient limitation

Temperature function



Part III

Water Ecosystems Tool (WET) – technical notes

Required user input

Physical model (GOTM)

Physical domain:

- Hypsograph

Weather forcing:

- U10 wind component (subdaily)
- V10 wind componant (subdaily)
- Air temperature (subdaily)
- Air pressure (subdaily, e.g. constant)
- Dew-point temperature or relative humidity (subdaily)
- Cloud cover fraction (subdaily, e.g. constant)

Boundary conditions:

- Inflows (e.g., daily, optional)
- Outflows (optional)

Initial conditions:

- Initial temperature (e.g., constant or a profile)

Ecosystem model (WET)

Nutrient loads:

- Nitrogen and phosphorus conc. in inflows
- NO_3, NH_4, Org. N, PO_4, Org. P

Initial conditions:

- Estimates of initial concentration for all WET state variables (e.g., nutrient concentrations, phytoplankton etc.)

Model config and parameter files

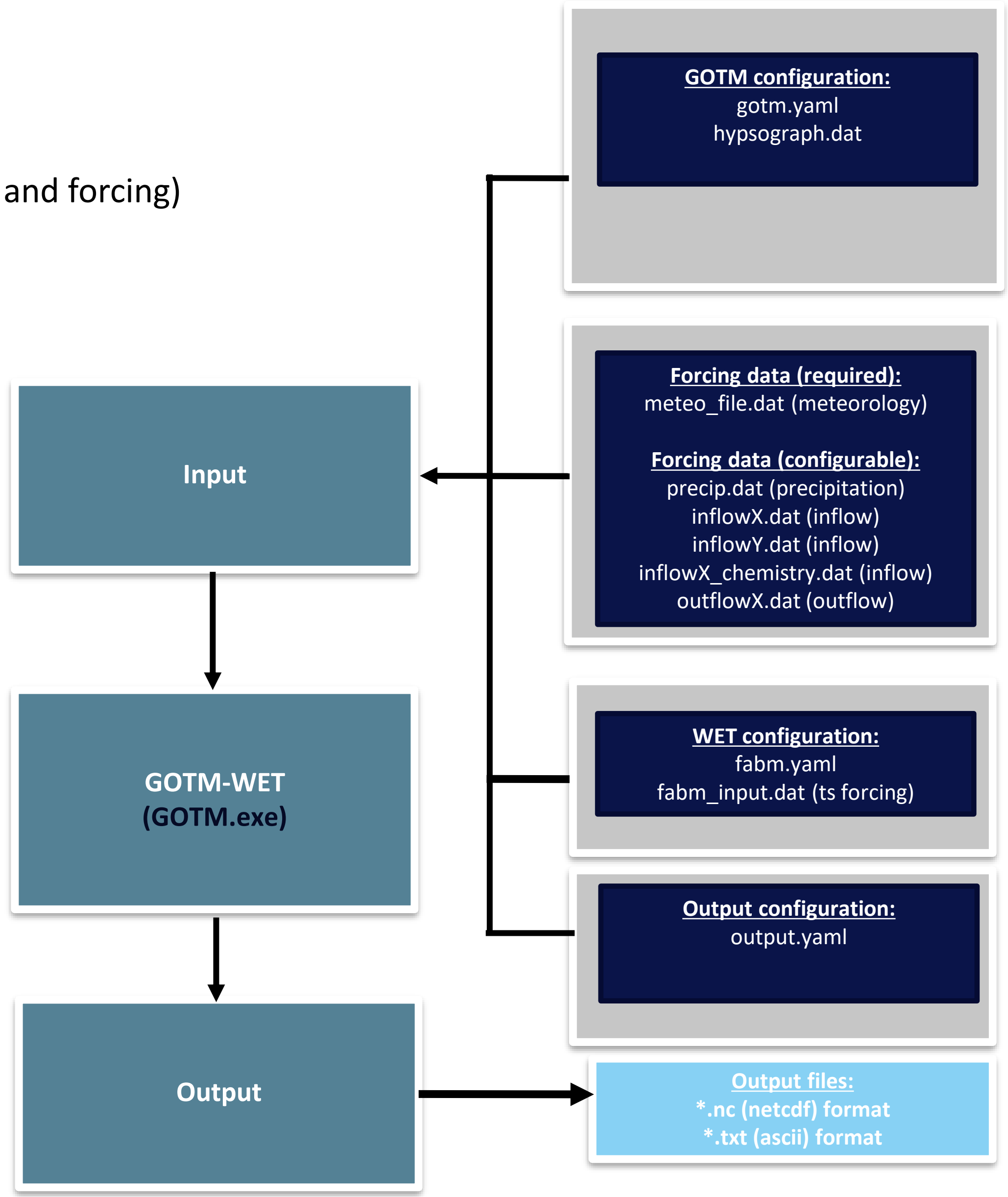
yaml files:

- fabm.yaml, gotm.yaml, output.yaml

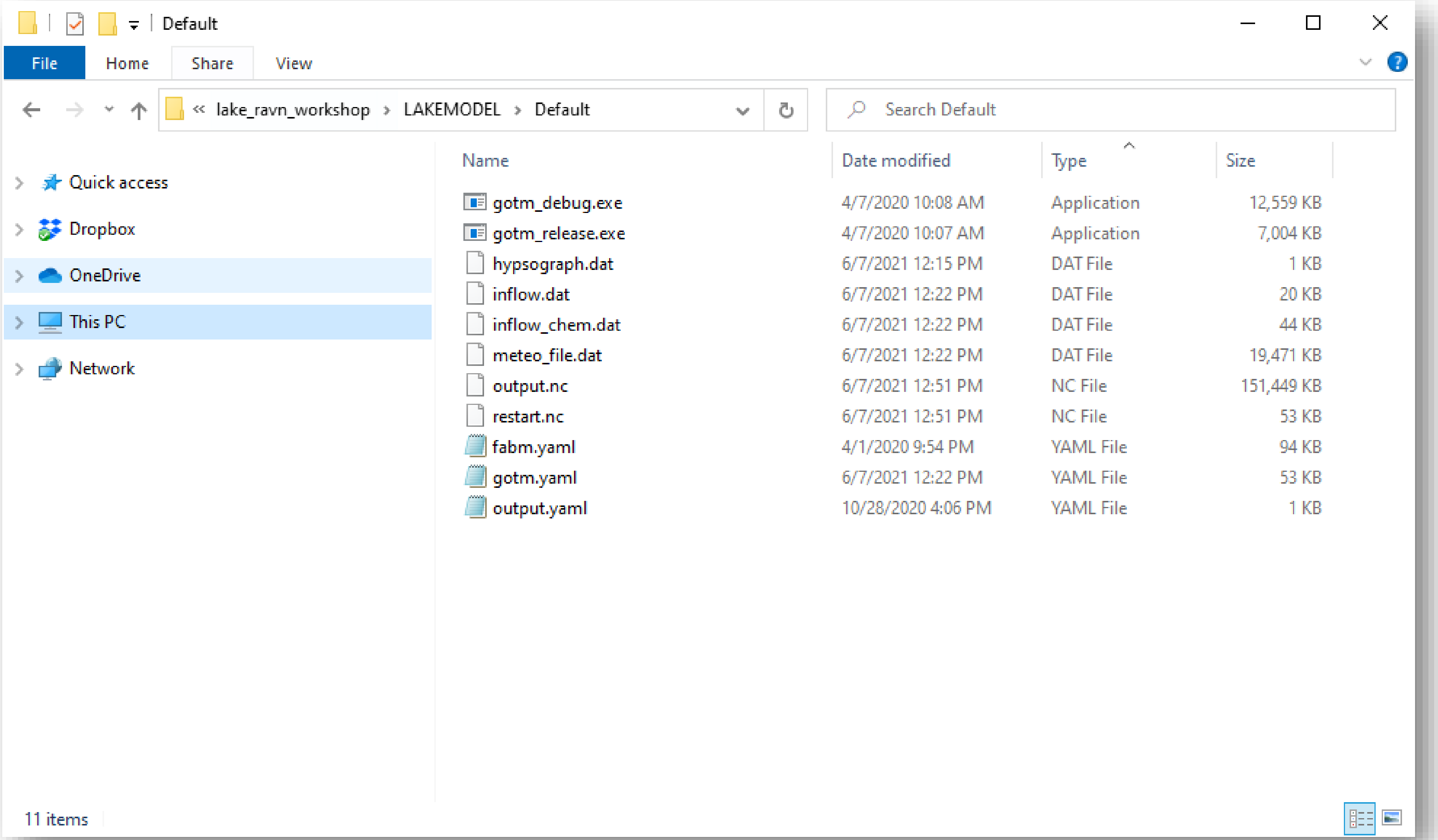
GOTM-WET input files

Generally:

- YAML (*.yaml) files are used for model configuration
- ascii (e.g., .dat or .txt) are used for model input (model initialization and forcing)
- Output is flexible and can be provided in netcdf and ascii format
- Yaml files (*.yaml) can be opened in any text editor.

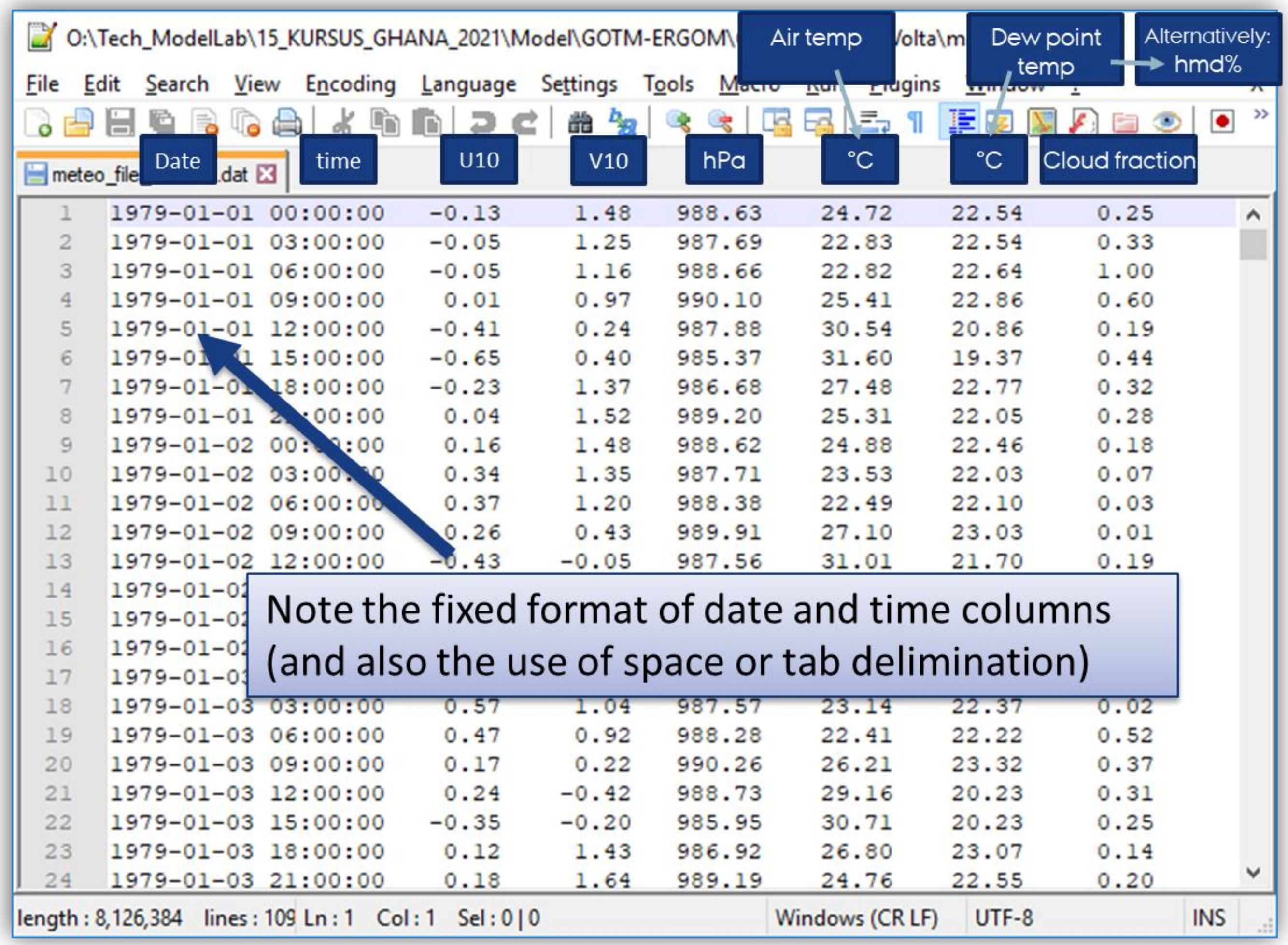


Example of a complete working directory



Example 1 of an input file

meteo_file.dat: meteorological forcing data.



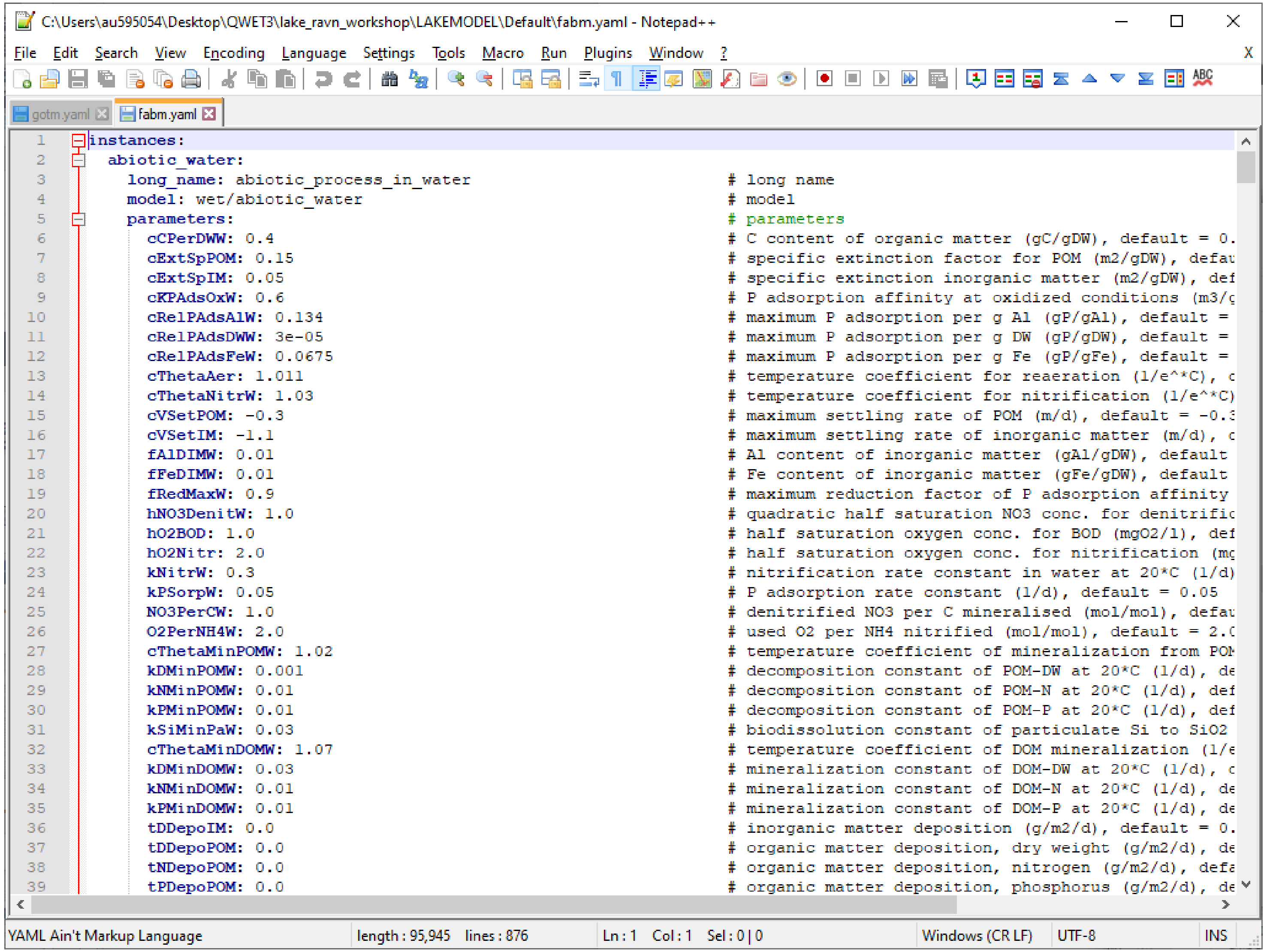
Line	Date	time	U10	V10	hPa	°C	°C	Cloud fraction
1	1979-01-01	00:00:00	-0.13	1.48	988.63	24.72	22.54	0.25
2	1979-01-01	03:00:00	-0.05	1.25	987.69	22.83	22.54	0.33
3	1979-01-01	06:00:00	-0.05	1.16	988.66	22.82	22.64	1.00
4	1979-01-01	09:00:00	0.01	0.97	990.10	25.41	22.86	0.60
5	1979-01-01	12:00:00	-0.41	0.24	987.88	30.54	20.86	0.19
6	1979-01-01	15:00:00	-0.65	0.40	985.37	31.60	19.37	0.44
7	1979-01-01	18:00:00	-0.23	1.37	986.68	27.48	22.77	0.32
8	1979-01-01	21:00:00	0.04	1.52	989.20	25.31	22.05	0.28
9	1979-01-02	00:00:00	0.16	1.48	988.62	24.88	22.46	0.18
10	1979-01-02	03:00:00	0.34	1.35	987.71	23.53	22.03	0.07
11	1979-01-02	06:00:00	0.37	1.20	988.38	22.49	22.10	0.03
12	1979-01-02	09:00:00	0.26	0.43	989.91	27.10	23.03	0.01
13	1979-01-02	12:00:00	-0.43	-0.05	987.56	31.01	21.70	0.19
14	1979-01-0							
15	1979-01-0							
16	1979-01-0							
17	1979-01-0							
18	1979-01-03	03:00:00	0.57	1.04	987.57	23.14	22.37	0.02
19	1979-01-03	06:00:00	0.47	0.92	988.28	22.41	22.22	0.52
20	1979-01-03	09:00:00	0.17	0.22	990.26	26.21	23.32	0.37
21	1979-01-03	12:00:00	0.24	-0.42	988.73	29.16	20.23	0.31
22	1979-01-03	15:00:00	-0.35	-0.20	985.95	30.71	20.23	0.25
23	1979-01-03	18:00:00	0.12	1.43	986.92	26.80	23.07	0.14
24	1979-01-03	21:00:00	0.18	1.64	989.19	24.76	22.55	0.20

<u>Forcing data from left to right:</u>
date/time, U10, V10 (10 m wind component in m/s), air pressure (hPa), T2 (two meter air temperature in ° C or K), dew point temperature (° C) - or humidity (in %), cloud cover (fraction)

Note: if only wind speed is available and not direction/components, then either U10 or V10 may be set to 0.

Example 2 of an input file

fabm.yaml:
defines the model(s) i.e. (instances) to activate.



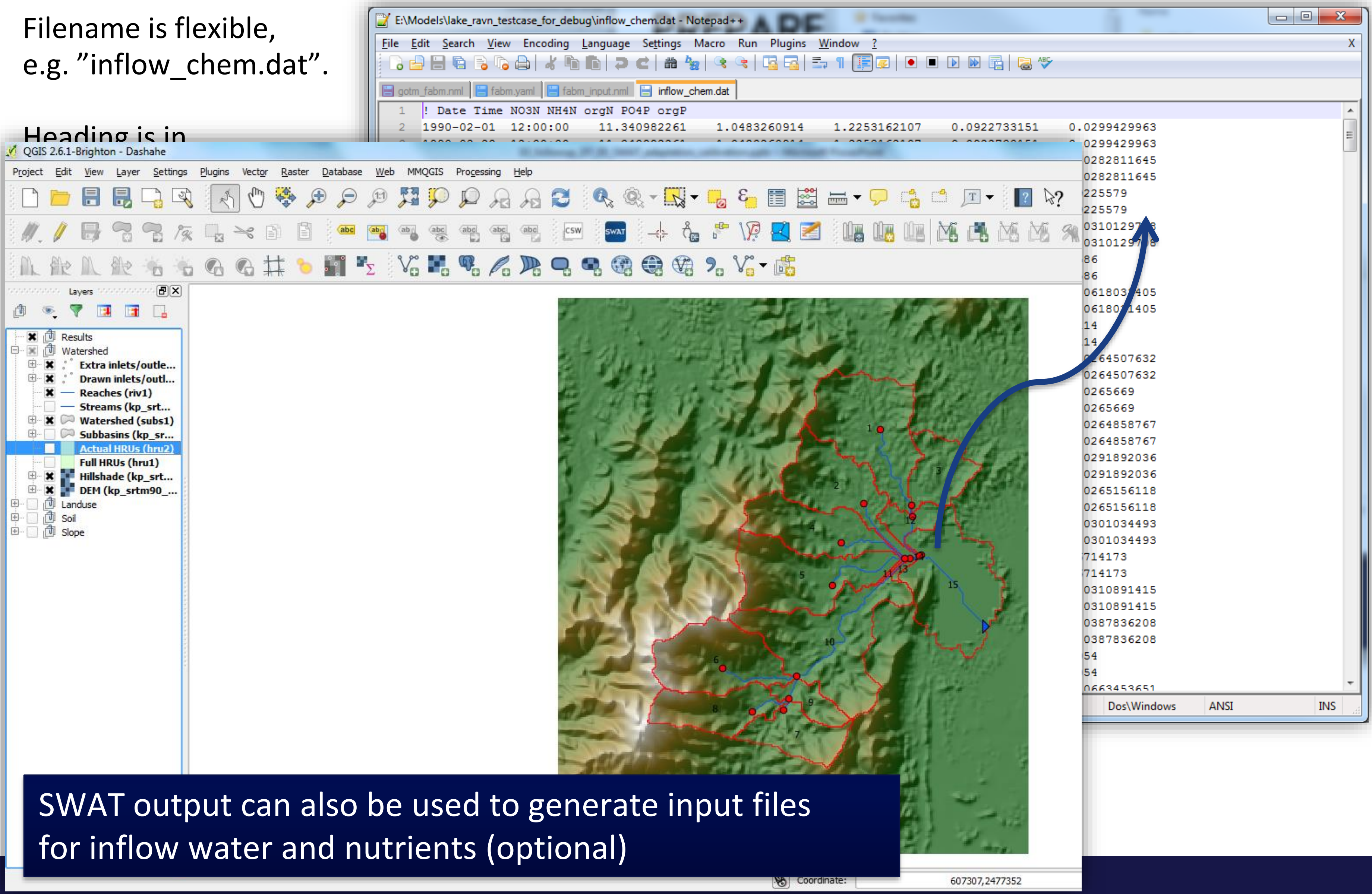

```yaml
instances:
  abiotic_water:
    long_name: abiotic_process_in_water                      # long name
    model: wet/abiotic_water                                 # model
    parameters:                                              # parameters
      cCPerDWW: 0.4                                          # C content of organic matter (gC/gDW), default = 0.
      cExtSpPOM: 0.15                                        # specific extinction factor for POM (m2/gDW), defau
      cExtSpIM: 0.05                                         # specific extinction inorganic matter (m2/gDW), def
      cKPAdsOxW: 0.6                                         # P adsorption affinity at oxidized conditions (m3/g
      cRelPAdsAlW: 0.134                                     # maximum P adsorption per g Al (gP/gAl), default =
      cRelPAdsDWW: 3e-05                                     # maximum P adsorption per g DW (gP/gDW), default =
      cRelPAdsFeW: 0.0675                                    # maximum P adsorption per g Fe (gP/gFe), default =
      cThetaAer: 1.011                                       # temperature coefficient for reaeration (1/e^*C), c
      cThetaNitrW: 1.03                                      # temperature coefficient for nitrification (1/e^*C)
      cVSetPOM: -0.3                                         # maximum settling rate of POM (m/d), default = -0.3
      cVSetIM: -1.1                                          # maximum settling rate of inorganic matter (m/d), c
      fAlDIMW: 0.01                                          # Al content of inorganic matter (gAl/gDW), default
      fFeDIMW: 0.01                                          # Fe content of inorganic matter (gFe/gDW), default
      fRedMaxW: 0.9                                          # maximum reduction factor of P adsorption affinity
      hNO3DenitW: 1.0                                        # quadratic half saturation NO3 conc. for denitrific
      hO2BOD: 1.0                                            # half saturation oxygen conc. for BOD (mgO2/l), def
      hO2Nitr: 2.0                                           # half saturation oxygen conc. for nitrification (mg
      kNitrW: 0.3                                            # nitrification rate constant in water at 20*C (1/d)
      kPSorpW: 0.05                                          # P adsorption rate constant (1/d), default = 0.05
      NO3PerCW: 1.0                                          # denitrified NO3 per C mineralised (mol/mol), defau
      O2PerNH4W: 2.0                                         # used O2 per NH4 nitrified (mol/mol), default = 2.
      cThetaMinPOMW: 1.02                                    # temperature coefficient of mineralization from PO
      kDMinPOMW: 0.001                                       # decomposition constant of POM-DW at 20*C (1/d), de
      kNMinPOMW: 0.01                                        # decomposition constant of POM-N at 20*C (1/d), def
      kPMinPOMW: 0.01                                        # decomposition constant of POM-P at 20*C (1/d), def
      kSiMinPaW: 0.03                                        # biodissolution constant of particulate Si to SiO2
      cThetaMinDOMW: 1.07                                    # temperature coefficient of DOM mineralization (1/e
      kDMinDOMW: 0.03                                        # mineralization constant of DOM-DW at 20*C (1/d), c
      kNMinDOMW: 0.01                                        # mineralization constant of DOM-N at 20*C (1/d), de
      kPMinDOMW: 0.01                                        # mineralization constant of DOM-P at 20*C (1/d), de
      tDDepoIM: 0.0                                          # inorganic matter deposition (g/m2/d), default = 0.
      tDDepoPOM: 0.0                                         # organic matter deposition, dry weight (g/m2/d), de
      tNDepoPOM: 0.0                                         # organic matter deposition, nitrogen (g/m2/d), defa
      tPDepoPOM: 0.0                                         # organic matter deposition, phosphorus (g/m2/d), de
```

Example 3 of an input file

Nutrient inflow concentrations.

Filename is flexible,
e.g. ”inflow_chem.dat”.

Heading is in



SWAT output can also be used to generate input files for inflow water and nutrients (optional)

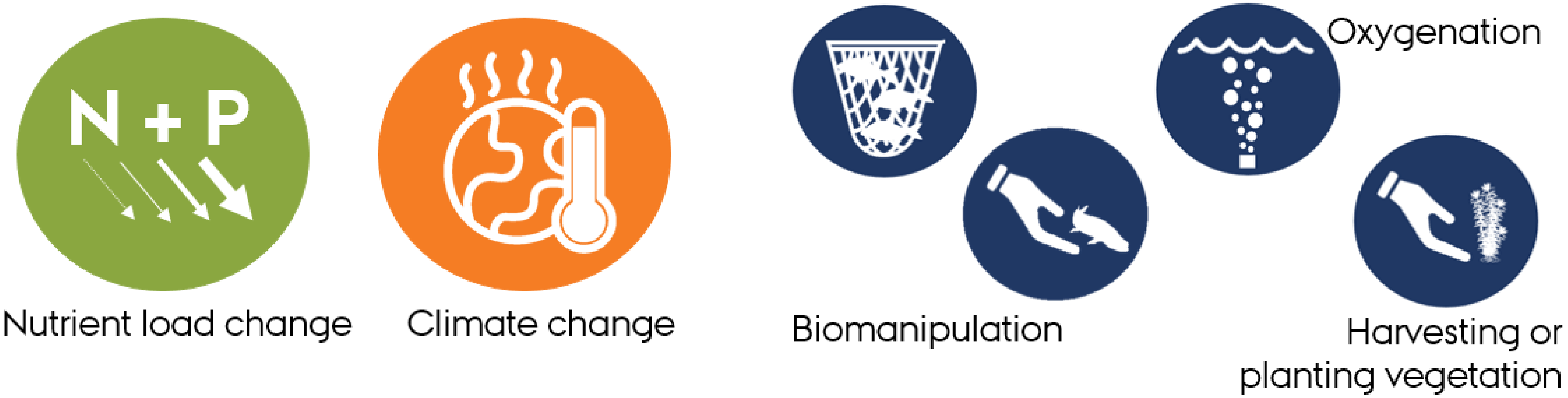
Potential use of the model

- **Quantification of ecosystem interactions and processes (e.g., internal loading)**
- **Assessment of system response to external changes**
  - Climate change
  - Nutrient load change
- **Assessment of system response to internal changes (within lake process)**
  - Biomanipulation
  - Sediment dredging
  - Oxygenation
  - Harvesting or planting vegetation
  - Chemical flocculants
- **Short-term and longer term water and ecosystem forecasts**
  (and assimilation of observation-data into model simulation)

Potential applications

Assessment of system response to

external changes | internal changes

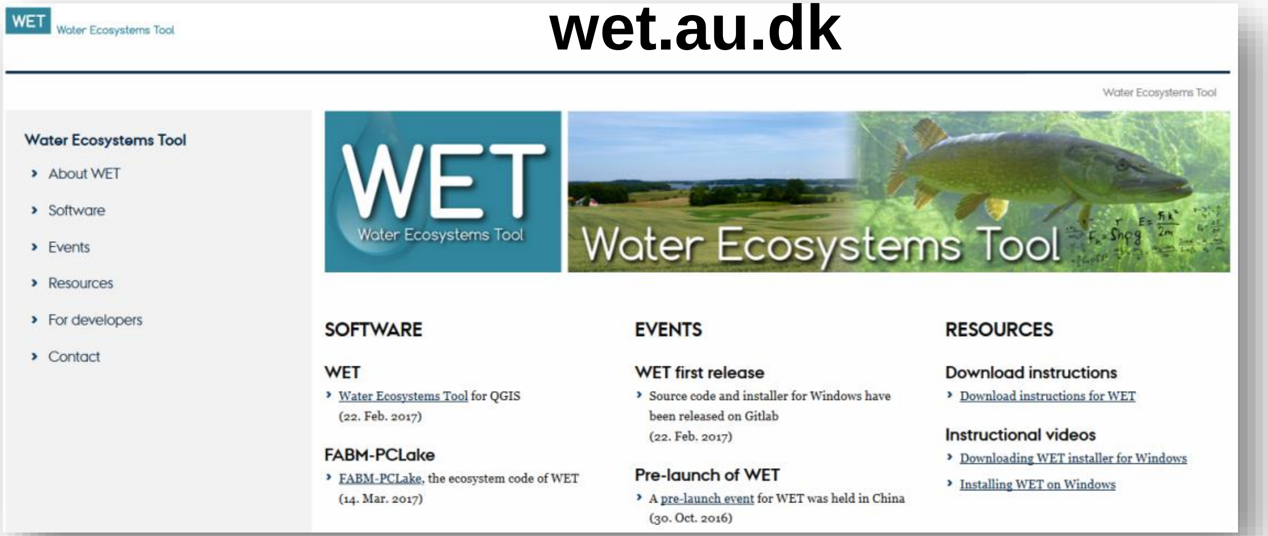


Quantification of ecosystem interactions and processes
(e.g., internal loading)

Short-term and longer-term water and ecosystem forecasts

QWET: QGIS plugin for GOTM-WET setup

wet.au.dk



Environmental Modelling and Software 135 (2021) 104886

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: http://www.elsevier.com/locate/envsoft

Introducing QWET – A QGIS-plugin for application, evaluation and experimentation with the WET model
Environmental Modelling and Software

Anders Nielsen[a,*], Fenjuan Rose Schmidt Hu[a], Nicolas Azaña Schnedler-Meyer[a], Karsten Bolding[a,b], Tobias Kuhlmann Andersen[a,b,c], Dennis Trolle[a,b]

[a] Aarhus University, Department of Bioscience, Vejlsøvej 25, 8600 Silkeborg, Denmark
[b] Sino-Danish Centre for Education and Research, University of Chinese Academy of Sciences, Beijing, China
[c] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

ARTICLE INFO

Keywords:
Lake and reservoir modelling
QGIS plugin
Python
WET
GOTM
SWAT

ABSTRACT

We wish to introduce QWET, a new version of the free and open-source QGIS plugin for the aquatic ecosystem model WET. QWET is as a graphical user interface for the application, evaluation and experimentation of WET. Several new features have been incorporated since its predecessor and, here, we demonstrate elements of the new plugin by applying it to Danish Lake Ravn. Among others, we compare model simulations against observations and describe how the scenario platform now supports scheduling of state-variable manipulation, which allows users to explore lake or reservoir restoration interventions such as biomanipulation and oxygenation. With QWET, we seek to aid practitioners who do not possess the sufficient technical expertise to operate a state-of-the art complex model system, such as WET, and thereby hope to facilitate a wider use and adaptation of aquatic ecosystem models.

Software availability

Name of software: QWET
Developers: Anders Nielsen, Fenjuan Rose Schmidt Hu, Nicolas Azaña Schnedler-Meyer, Karsten Bolding, Tobias Kuhlmann Andersen & Dennis Trolle.
Contact address: Department of Bioscience, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark.
Email: wet.info@wet.au.dk.
Availability: www.wet.au.dk.
License: freely available under GNU General Public License (GPL) version 2.

1. Introduction

Eutrophication of lakes and reservoirs is a global challenge (Wurtsbaugh et al., 2019) with severe implications for their ecosystem services (Schallenberg et al., 2013). Whether a lake or reservoir provides recreational facilities or acts as a fundamental drinking water resource for local communities, scientists, policy makes, managers and consultants aim to understand the reasons behind or examine ways to restore and improve deteriorated water quality. To support decision making or scientific examination, mathematical models provide a fundamental platform by acting as a virtual laboratory for hypothesis testing or scenario simulation prior to actual implementation of mitigation measures (Hipsey et al., 2015). However, application of mathematical models to lakes and reservoirs requires a substantial level of expertise, which may hamper their broader adaptation and utilization.

To provide users with a standardised and easy-to-use workflow for model application and evaluation of aquatic ecosystems, the Water Ecosystems Tool (WET) was introduced in 2017 as a plugin for QGIS 2. x. (Nielsen et al., 2017). The plugin operated on top of the coupled one-dimensional hydrodynamic-ecosystem model GOTM-FABM-PClake (Bruggeman and Bolding, 2014; Hu et al., 2016; Umlauf et al., 2005). However, recent efforts by Schnedler-Meyer et al. (2020) have made significant advances to the designated aquatic ecosystem model FABM-PClake, producing an update representing a new generation, still FABM-compatible (enabling coupling to multiple physical models), completely modularised aquatic ecosystem model that allows flexibility

* Corresponding author.
E-mail address: an@bios.au.dk (A. Nielsen).

https://doi.org/10.1016/j.envsoft.2020.104886
Accepted 29 September 2020
Available online 6 October 2020

QWET: a QGIS based user interface for GOTM-WET

The key principle:

GOTM-WET is the engine (model core)

QWET is the steering wheel (interface)

Background

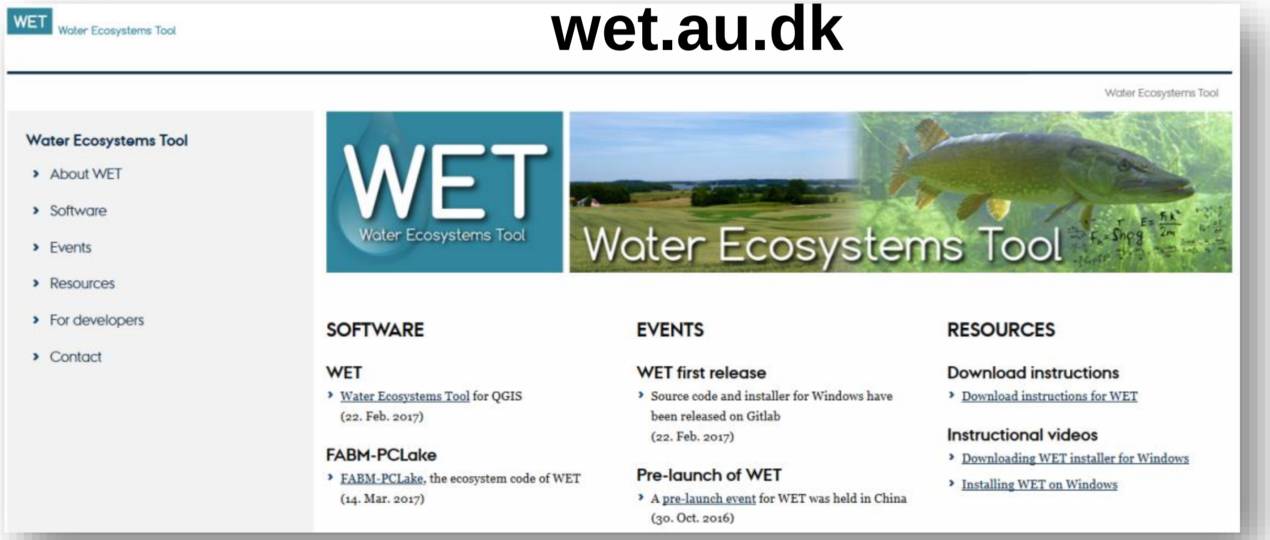
QWET (QGIS plugin for Water Ecosystems Tool) is an open source QGIS plugin aiming to provide an easy-to-use tool (graphical user interface) for user adaptation and application of a state-of-the-art aquatic ecosystem model, **GOTM-WET**.

Why do we use QWET to apply GOTM-WET?

- QWET can greatly **reduce the time (and cost)** needed for complex model applications
- The standardized workflow in QWET will help **reduce model configuration and input errors by users**
- QWET enable **a direct link between an aquatic ecosystem and its watershed** through a link to SWAT
- QWET can **allow more users** to make use of models
- QWET enable easy application of otherwise **complex model scenarios** (e.g., biomanipulation, climate change etc.)
- QWET can provide a bridge between state-of-the-art **science and decision making processes**

QWET is also open source and free to download

wet.au.dk



Environmental Modelling and Software 135 (2021) 104886

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: http://www.elsevier.com/locate/envsoft

ELSEVIER

Introducing QWET – A QGIS-plugin for application, evaluation and experimentation with the WET model
Environmental Modelling and Software

Anders Nielsen [a,*], Fenjuan Rose Schmidt Hu [a], Nicolas Azaña Schneider-Meyer [a], Karsten Bolding [a,b], Tobias Kuhlmann Andersen [a,b,c], Dennis Trolle [a,b]

[a] Aarhus University, Department of Bioscience, Vejlsøvej 25, 8600 Silkeborg, Denmark
[b] Sino-Danish Centre for Education and Research, University of Chinese Academy of Sciences, Beijing, China
[c] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

ARTICLE INFO

Keywords:
Lake and reservoir modelling
QGIS plugin
Python
WET
GOTM
SWAT

ABSTRACT

We wish to introduce QWET, a new version of the free and open-source QGIS plugin for the aquatic ecosystem model WET. QWET is as a graphical user interface for the application, evaluation and experimentation of WET. Several new features have been incorporated since its predecessor and, here, we demonstrate elements of the new plugin by applying it to Danish Lake Ravn. Among others, we compare model simulations against observations and describe how the scenario platform now supports scheduling of state-variable manipulation, which allows users to explore lake or reservoir restoration interventions such as biomanipulation and oxygenation. With QWET, we seek to aid practitioners who do not possess the sufficient technical expertise to operate a state-of-the art complex model system, such as WET, and thereby hope to facilitate a wider use and adaptation of aquatic ecosystem models.

Software availability

Name of software: QWET
Developers: Anders Nielsen, Fenjuan Rose Schmidt Hu, Nicolas Azaña Schneider-Meyer, Karsten Bolding, Tobias Kuhlmann Andersen & Dennis Trolle.
Contact address: Department of Bioscience, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark.
Email: wet.info@wet.au.dk.
Availability: www.wet.au.dk.
License: freely available under GNU General Public License (GPL) version 2.

1. Introduction

Eutrophication of lakes and reservoirs is a global challenge (Wurtsbaugh et al., 2019) with severe implications for their ecosystem services (Schallenberg et al., 2013). Whether a lake or reservoir provides recreational facilities or acts as a fundamental drinking water resource for local communities, scientists, policy makes, managers and consultants aim to understand the reasons behind or examine ways to restore and improve deteriorated water quality. To support decision making or scientific examination, mathematical models provide a fundamental platform by acting as a virtual laboratory for hypothesis testing or scenario simulation prior to actual implementation of mitigation measures (Hipsey et al., 2015). However, application of mathematical models to lakes and reservoirs requires a substantial level of expertise, which may hamper their broader adaptation and utilization.

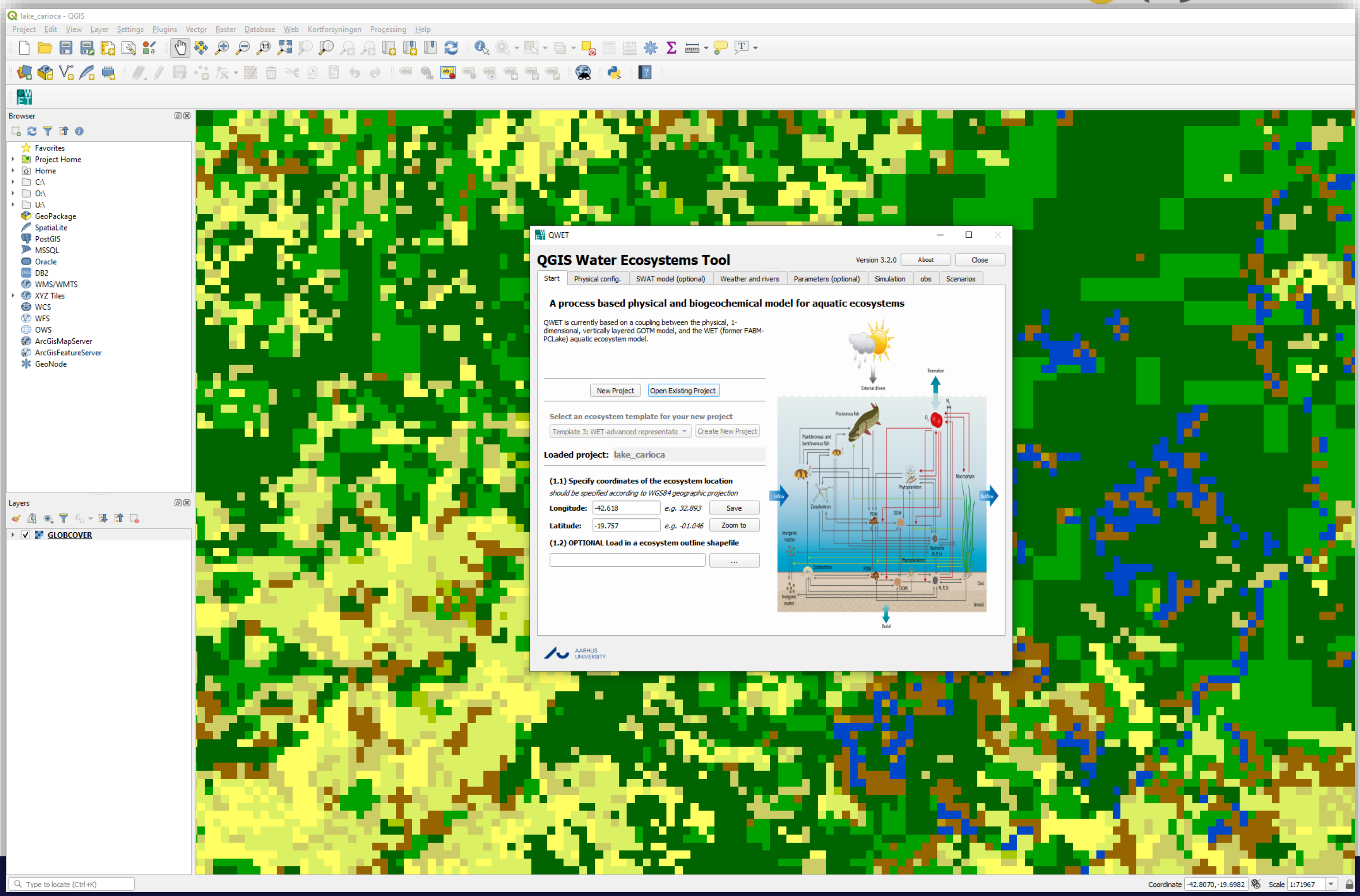
To provide users with a standardised and easy-to-use workflow for model application and evaluation of aquatic ecosystems, the Water Ecosystems Tool (WET) was introduced in 2017 as a plugin for QGIS 2. x. (Nielsen et al., 2017). The plugin operated on top of the coupled one-dimensional hydrodynamic-ecosystem model GOTM-FABM-PCLake (Bruggeman and Bolding, 2014; Hu et al., 2016; Umlauf et al., 2005). However, recent efforts by Schneider-Meyer et al. (2020) have made significant advances to the designated aquatic ecosystem model FABM-PCLake, producing an update representing a new generation, still FABM-compatible (enabling coupling to multiple physical models), completely modularised aquatic ecosystem model that allows flexibility

* Corresponding author.
E-mail address: an@bios.au.dk (A. Nielsen).

https://doi.org/10.1016/j.envsoft.2020.104886
Accepted 29 September 2020
Available online 6 October 2020

Key features of QWET

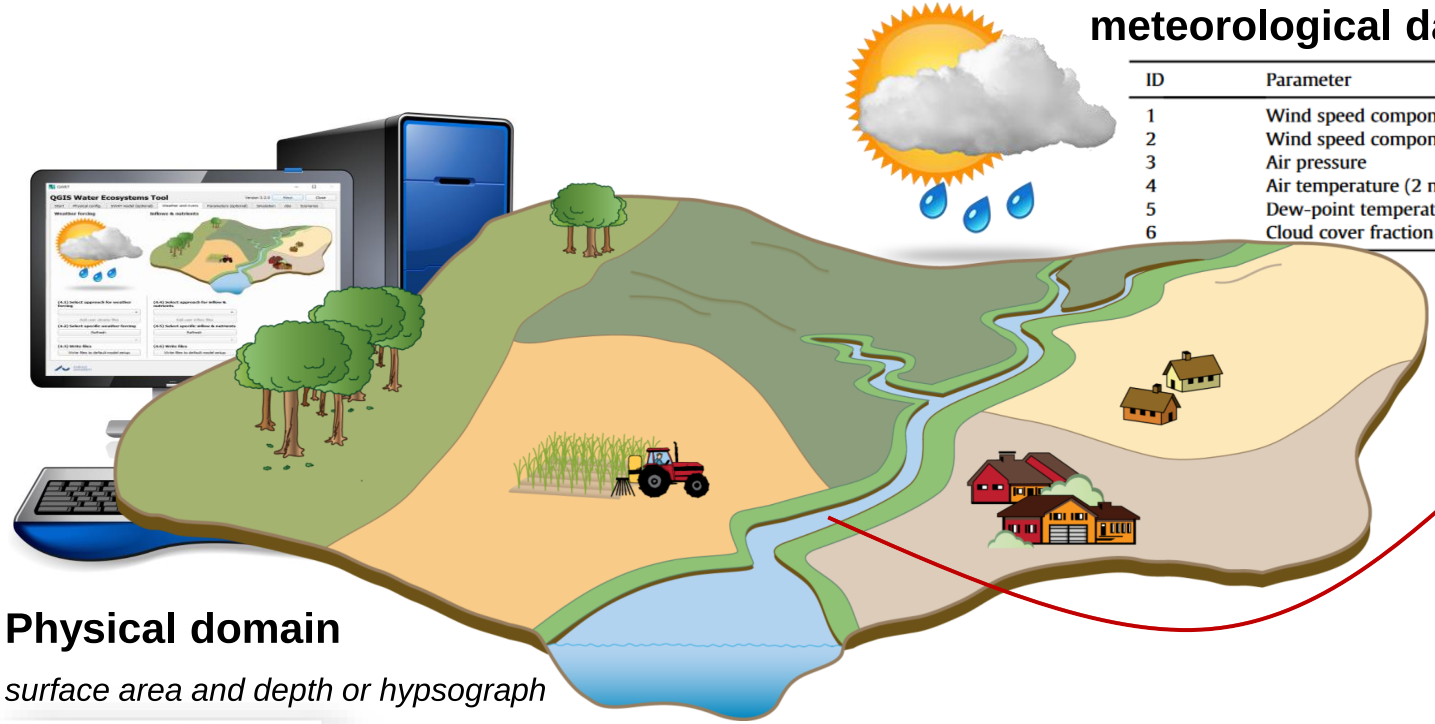
- QWET is a python based QGIS plugin
- QWET runs within the QGIS environment



Workflow in QWET

1. Model configuration and setup
2. Parameter adjustments
3. Model simulation
4. Model output visualization
   - including comparison with observations
5. Scenario design
6. Scenario simulation
7. Scenario output visualization and evaluation

Data needed to run QWET



meteorological data

ID	Parameter	Unit
1	Wind speed component in x-direction (U10)	[m s^{-1}]
2	Wind speed component in y-direction (V10)	[m s^{-1}]
3	Air pressure	[hPa]
4	Air temperature (2 meters height)	[°C]
5	Dew-point temperature	[°C]
6	Cloud cover fraction (varying from 0-1)	[-]

External loads

nutrients and water

SWAT
Soil & Water Assessment Tool

Physical domain

surface area and depth or hypsograph

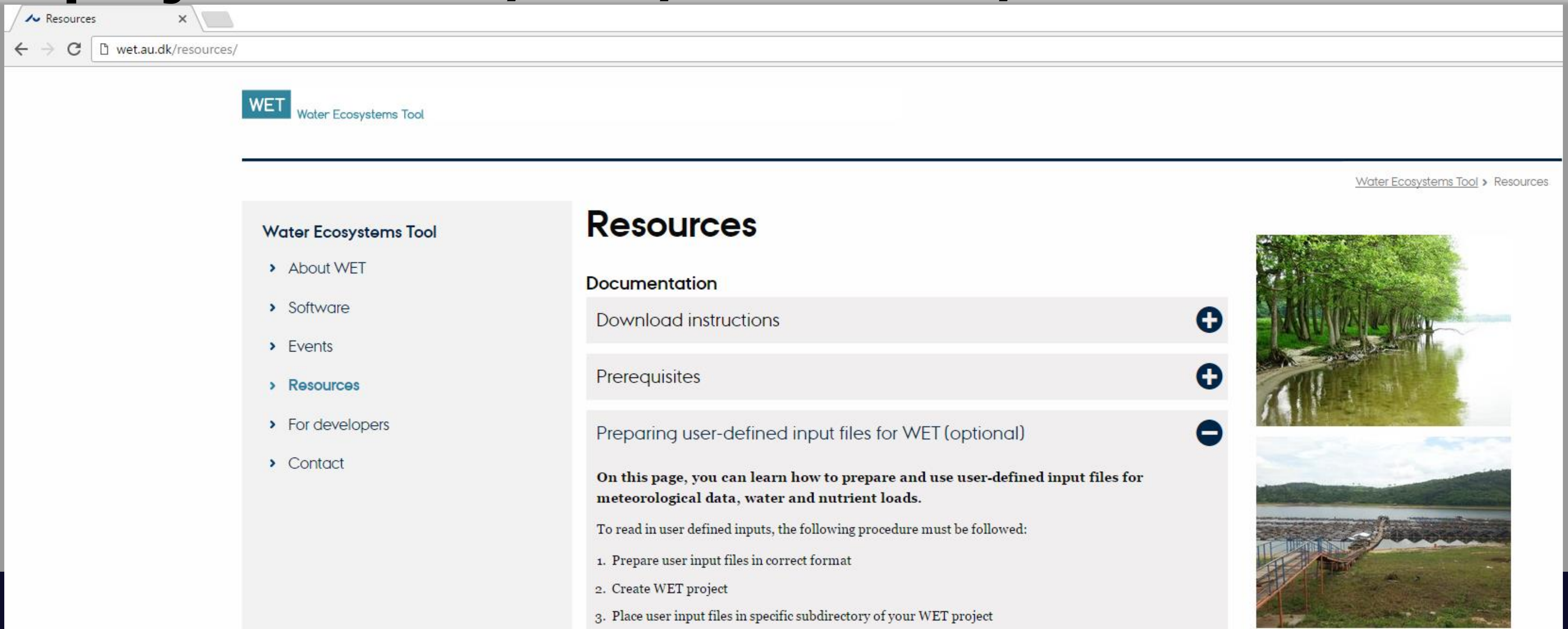
ID	Inputs	Minimum	Refinements
1	Physical domain	Box approach: Specify surface area (m^2) and max depth (m) of the system.	Hypsographic approach: Specify the relationship between depth (m) and horizontal area (m^2) for n cross sections throughout the water column.
2	External water load	Constant approach: Specify the inflow of water (m^3 s^{-1}) as an average constant value for the system.	Time series approach: Import pre-formatted measured time series of water inflow (m^3 s^{-1}). Or import a SWAT model-simulation to serve as time series of water inflow.
3	External nutrient load	Constant approach: Specify the nutrient inlet concentrations (mg l^{-1}) as average constant values for the system.	Time series approach: Import pre-formatted measured time series of inlet nutrient concentrations (mg l^{-1}). Or import a SWAT model-simulation to serve as time series of inlet nutrient concentrations.
4	Meteorological conditions	Pre-defined time series approach: Select between WET included time series of meteorology.	User-defined time series approach: Import pre-formatted time series of, for instance, locally observed data or climate model data.

Adapting a QWET application to your own case study

Currently, you can import four key inputs through QWET:

1. Weather forcing (meteo_file.dat)
2. Water input from inflowing rivers (inflow.dat)
3. Nutrient concentrations in the inflowing rivers (inflow_chem.dat)
4. Observation data (*.obs)

Instructions on how to format and import files are available on **projects.au.dk/wet/resources/wet-tutorial-videos**



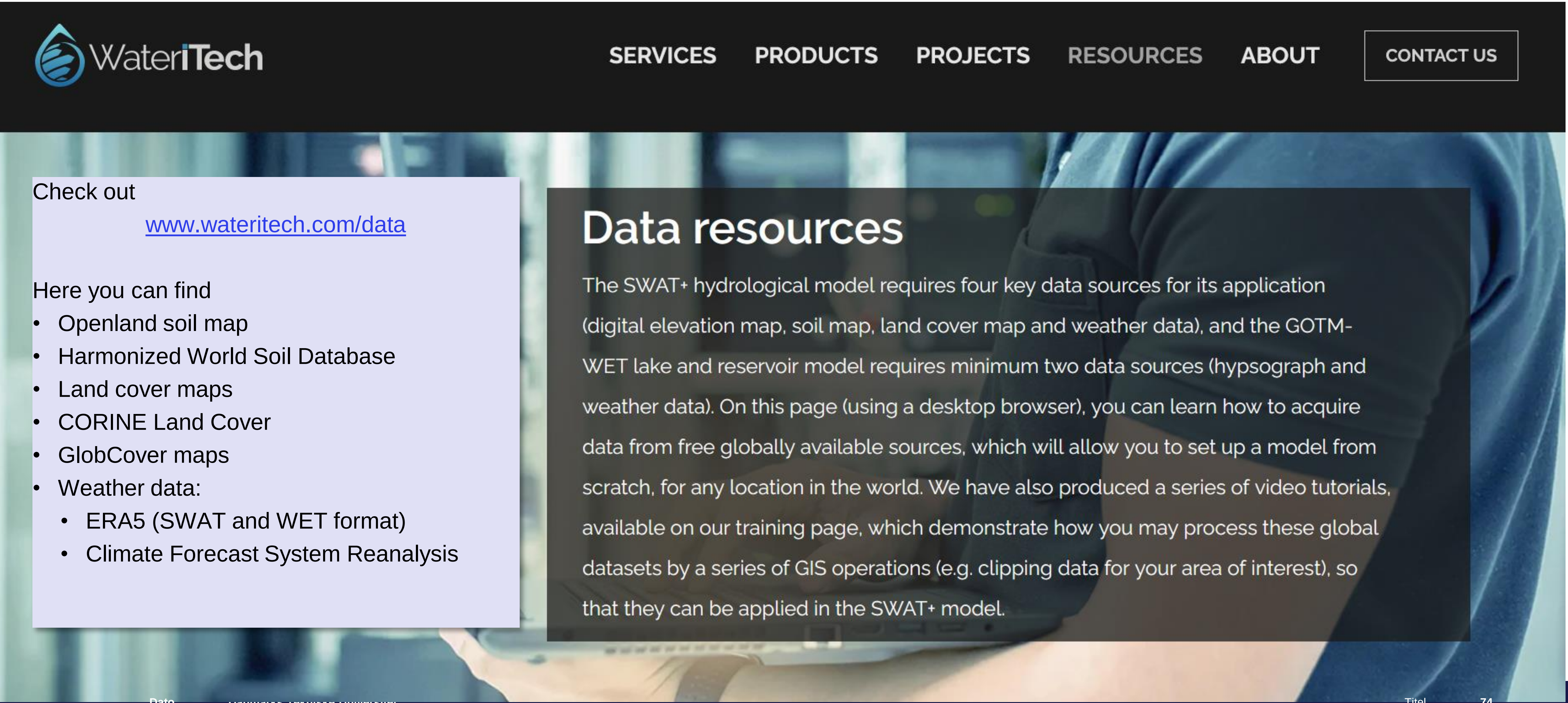
Access to open source data?

Check out

www.wateritech.com/data

Here you can find

- Openland soil map
- Harmonized World Soil Database
- Land cover maps
- CORINE Land Cover
- GlobCover maps
- Weather data:
    - ERA5 (SWAT and WET format)
    - Climate Forecast System Reanalysis



QWET perspectives

- QWET enables application of the GOTM-WET model
- QWET enables both quick and simple (e.g., constant nutrient load) and more detailed (user-defined time series input) model applications
- QWET can currently run climate change and nutrient load change scenarios
- Future potential expansions:
  - Enhanced GIS functionality to help defining the system of interest.
  - Supporting imports and visualization of in-system observations.
  - Implementation of sensitivity analysis and auto-calibration routines.
  - Easier local weather data download from e.g. ECMWF.
  - Expansion of the scenario inventory.
- Download and compilation info available on **wet.au.dk**

NOW TRY IT!
EXERCISE #1