

1: The French National Institute for Agricultural Research

2: The French National Agency for Water and Aquatic  
Environments

# Assessing the water quality of large lakes: should lake monitoring account for spatio- temporal heterogeneities?

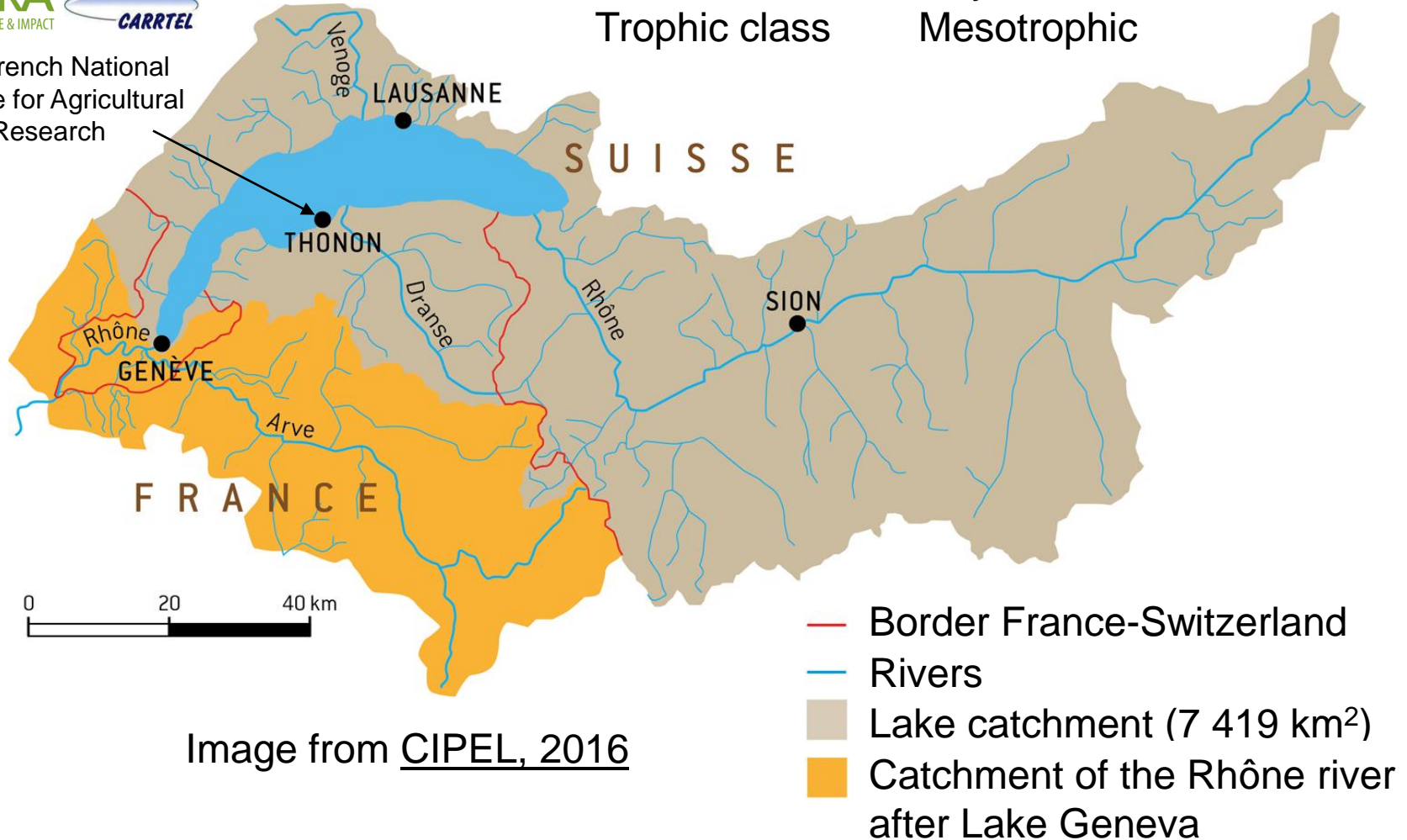
Frédéric Souignac<sup>1</sup>, P.-A. Danis<sup>2,10</sup>, D. Bouffard<sup>3</sup>,  
V. Chanudet<sup>4</sup>, E. Dambrine<sup>5</sup>, Y. Guenand<sup>6</sup>, T. Harmel<sup>7,10,2</sup>,  
B. Ibelings<sup>8</sup>, D. Trevisan<sup>1</sup>, R. Uittenbogaard<sup>9</sup> and O.  
Anneville<sup>1</sup>

# Lake Geneva

Surface area	580 km <sup>2</sup>
Max. depth	309 m
Volume	89 km <sup>3</sup>
Residence time	11 years
Trophic class	Mesotrophic



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Research



# Evaluation of lake ecological status

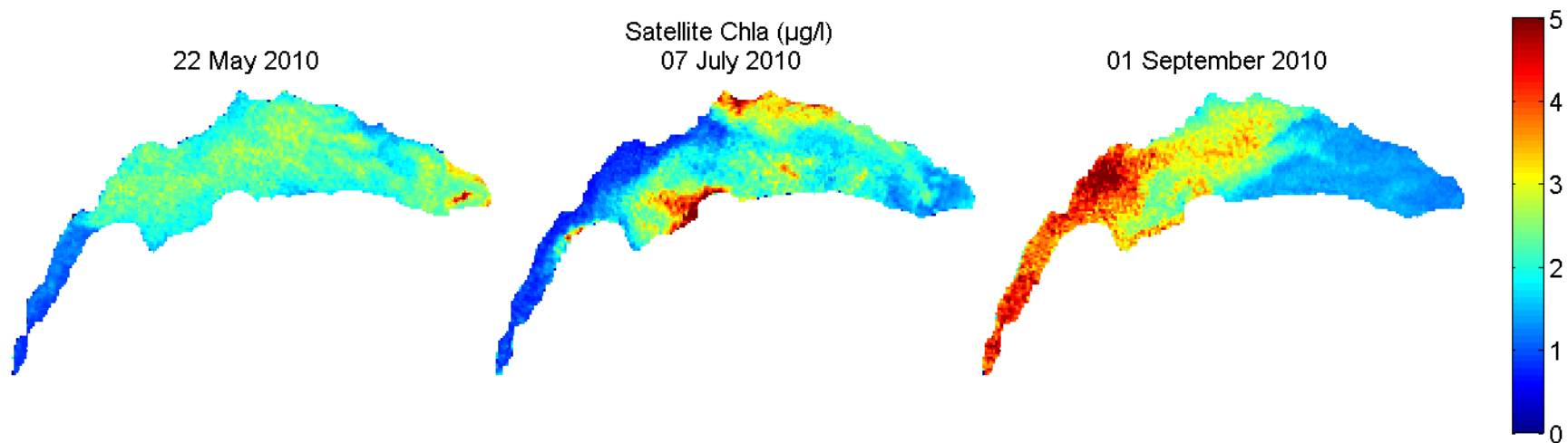
- European water framework directive (WFD) (EU, 2000)
- In France (French technical guide for evaluating ecological status of lakes and reservoirs, 2016 ; De Bortoli and Argillier, 2008)
  - 3 types of indicators: **biological**, **physico-chemical** and **hydromorphological**
  - Annual evaluation based on **4 samples** taken over the year and at **1 sampling station**
  - Parameters
    - Chlorophyll a concentration (**Chla**)
    - Ammonium concentration (**NH4**)
    - Nitrate concentration (**NO3**)
    - Total Phosphorus concentration (**TP**)
    - Secchi Disk Depth (**SDD**)
    - etc.
- Lake Geneva sampling stations:
  - **SHL2**: used for this evaluation
  - **GE3**: used for another monitoring



Image from CIPEL, 2016

# Satellite observations

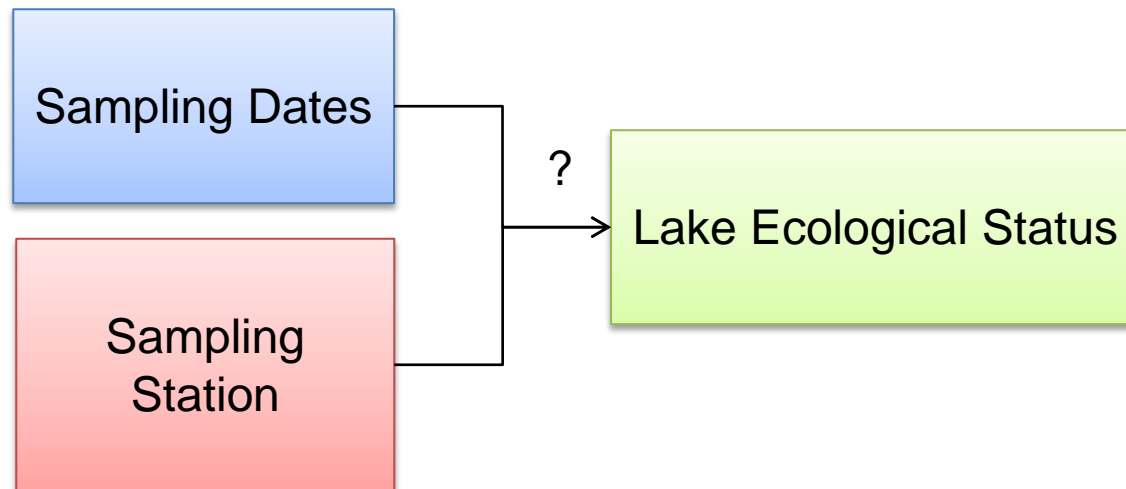
- **Chla** heterogeneities in Lake Geneva (Kiefer et al, 2015)



- **Do spatio-temporal heterogeneities induce spatial variability in the evaluation of lake ecological status ?**
- **Does it exist a more suitable sampling station to evaluate lake ecological status ?**

# Objectives

- To simulate in the 3 dimensions 5 parameters **Chla**, **NH4**, **NO3**, **TP** and **SDD** used for the assessment of lake ecological status
- To evaluate the sensitivity of the lake ecological status estimation to the 4 sampling dates and the sampling station



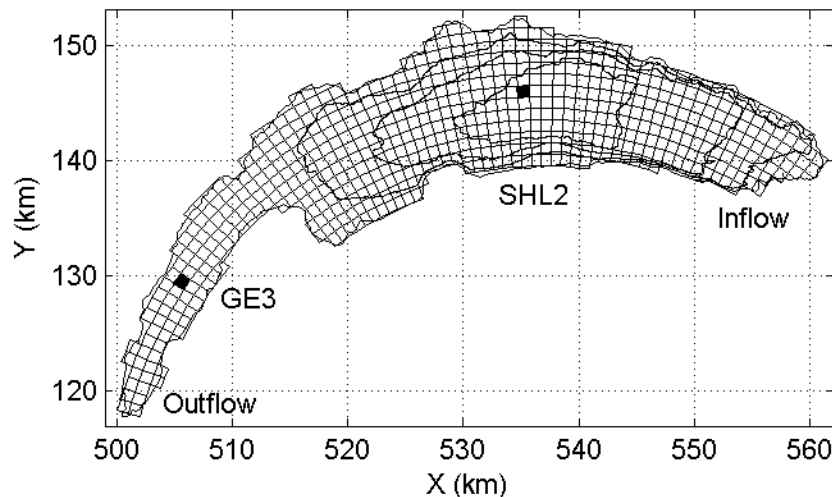
- To evaluate the representativeness of a sampling station and to locate the most representative sampling station



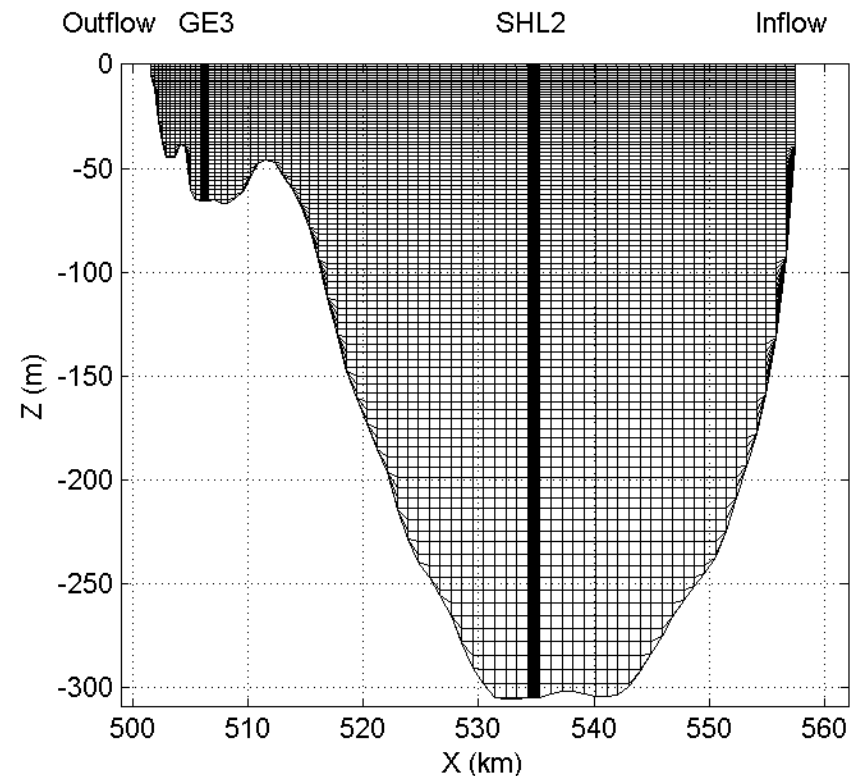
# Numerical domain

Open Source Software Delft3D

**Surface: Curvilinear grid (589 cells of resolution 1 km<sup>2</sup>)**



**Vertical direction: 100 Z-layers (resolution from 1 to 7 m)**





# Model configuration

Open Source Software Delft3D

## 1. Hydrodynamic simulations

- Initial conditions (observations):  
Vertical profiles of water temperature
- Forcing: meteorology (hourly 2D data) and hydrology (weekly observations of the 5 main rivers)
- > Outputs: hourly 3D maps of current velocity, water temperature and vertical dispersion

## 2. Ecological simulations

- Initial conditions (observations):  
Vertical profiles of chemical and biological state variables
- Forcing: hydrodynamics (hydrodynamic simulation outputs), meteorology (daily observations), rivers (weekly observations) and grazing (monthly/bimonthly observation)
- > Outputs: daily 3D maps of **Chla**, **NH4**, **NO3**, **TP** and **SDD**

Start: 01-Jan

Stop: 01-Jan (next year)

## • Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

## • Horizontal equations of motion

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + v \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + f_v$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + v \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) - f_u$$

## • Hydrostatic pressure equation

$$\frac{\partial p}{\partial z} = -\rho g z$$

## • Transport equation of heat

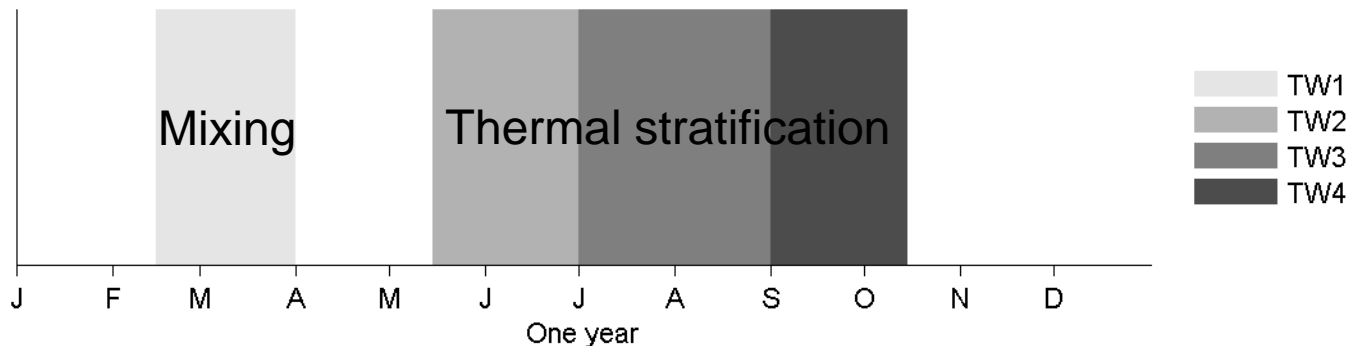
$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \frac{\lambda}{\rho C_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \frac{1}{C_p} \frac{\partial Q}{\partial z}$$

## • Advection-diffusion-reaction equation

$$M_i^{t+\Delta t} = M_i^t + \Delta t \times \left( \frac{\Delta M}{\Delta t} \right)_{Tr} + \Delta t \times \left( \frac{\Delta M}{\Delta t} \right)_p + \Delta t \times \left( \frac{\Delta M}{\Delta t} \right)_s$$

# Calculation of lake ecological status

- Sampling protocol for biological and physico-chemical parameters (French technical guide for evaluating ecological status of lakes and reservoirs, 2016 ; De Bortoli and Argillier, 2008)
  - 4 integrated samples in the euphotic zone
  - At 1 monitoring station, the deepest point of the lake
  - One observation per temporal window (TW1-4)

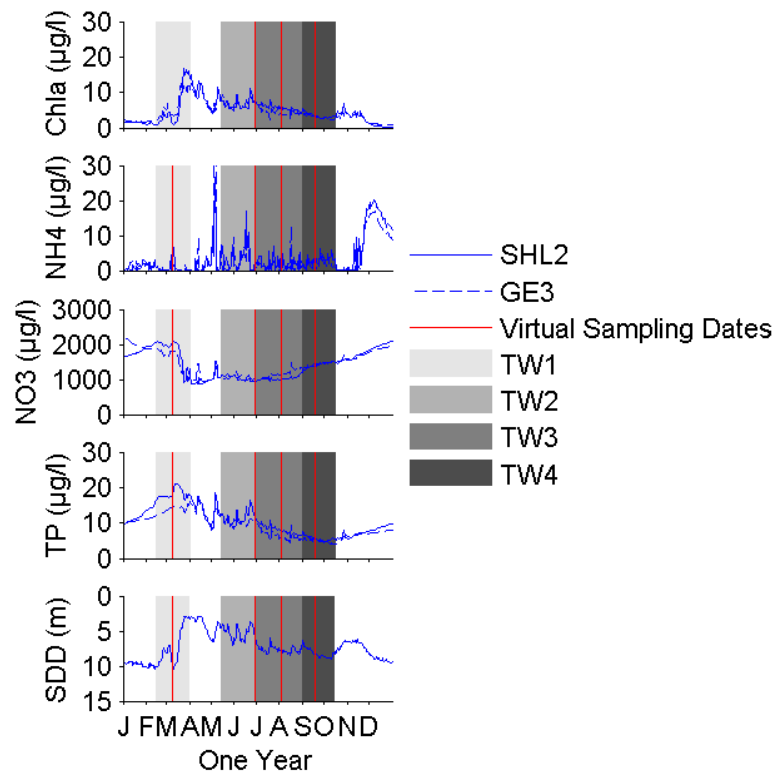


- Annual metrics
  - **Chla**: mean value of TW2-4
  - **NH4** and **NO3**: maximal value of TW1-4
  - **TP** and **SDD**: median value of TW1-4

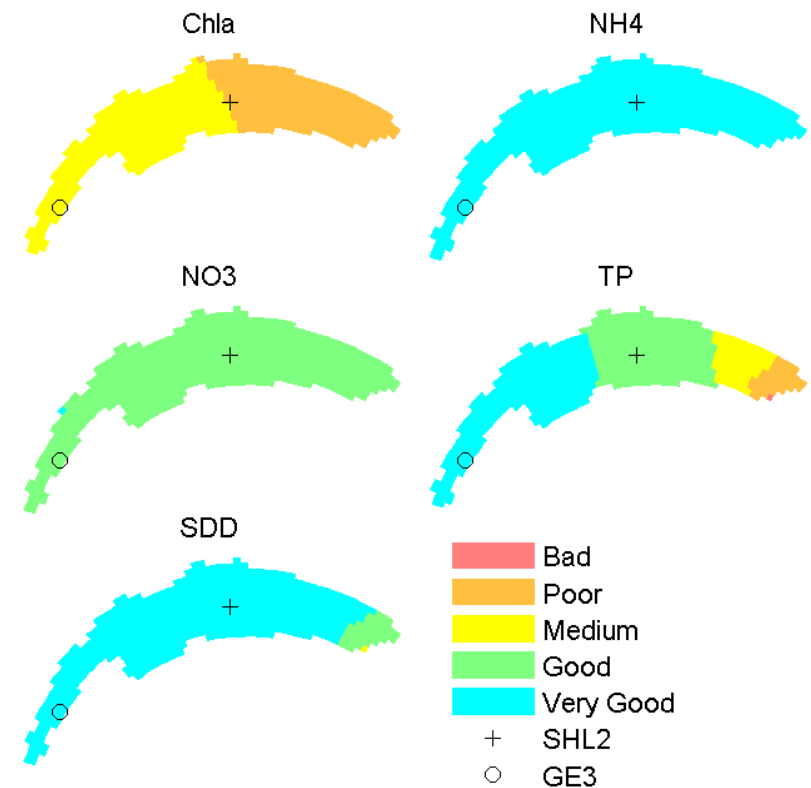
# Calculation of lake ecological status

From Delft3D Simulations

## Parameters



## Lake Ecological status

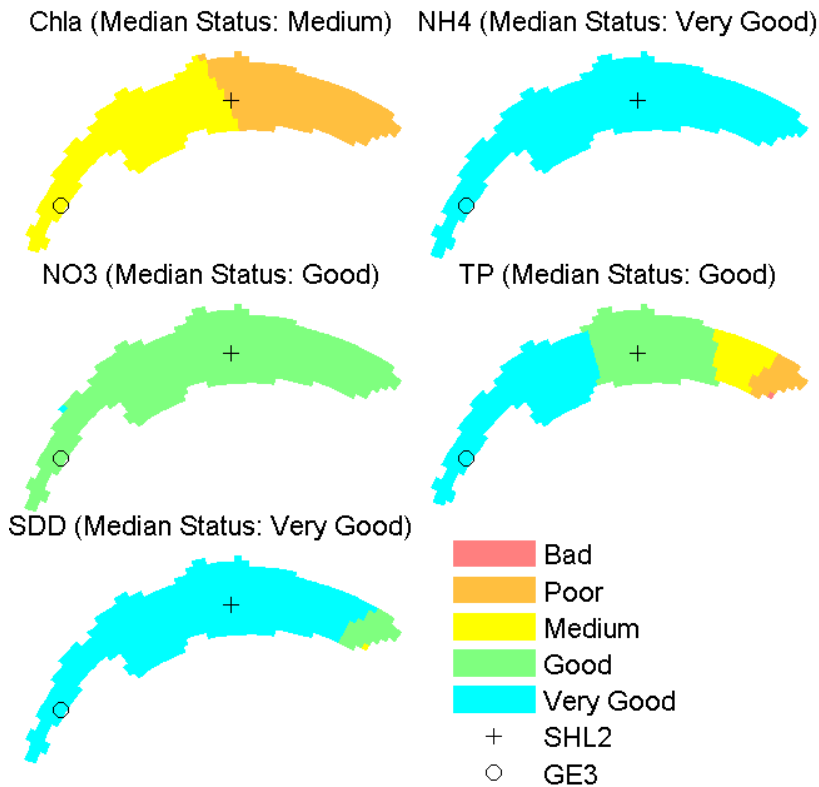


**This operation is repeated 1000 times**

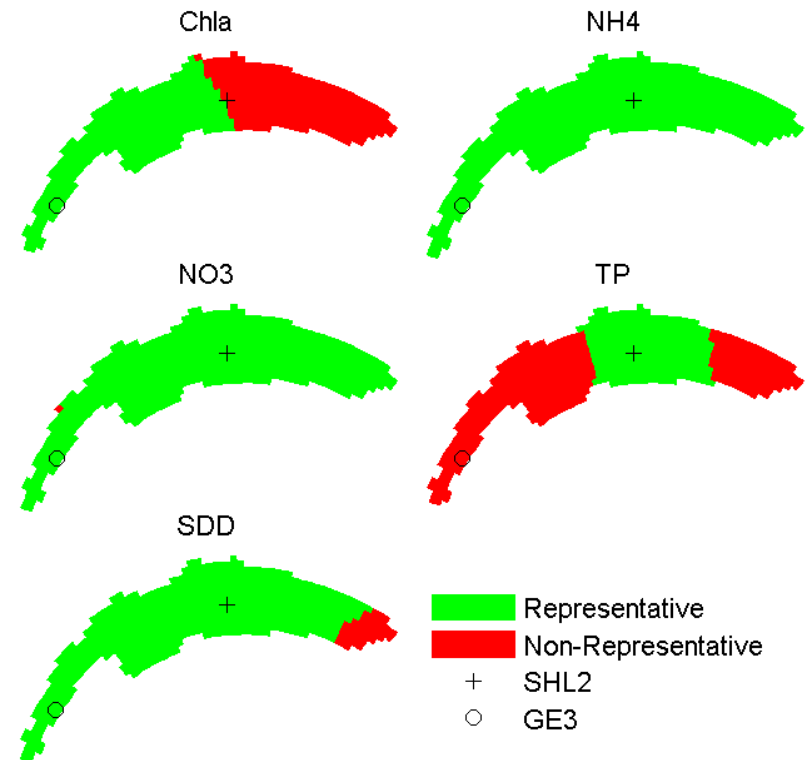
# Calculation of grid cell representativeness

From Delft3D Simulations

## Lake Ecological Status

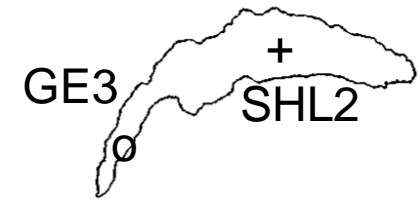


## Grid Cell Representativeness

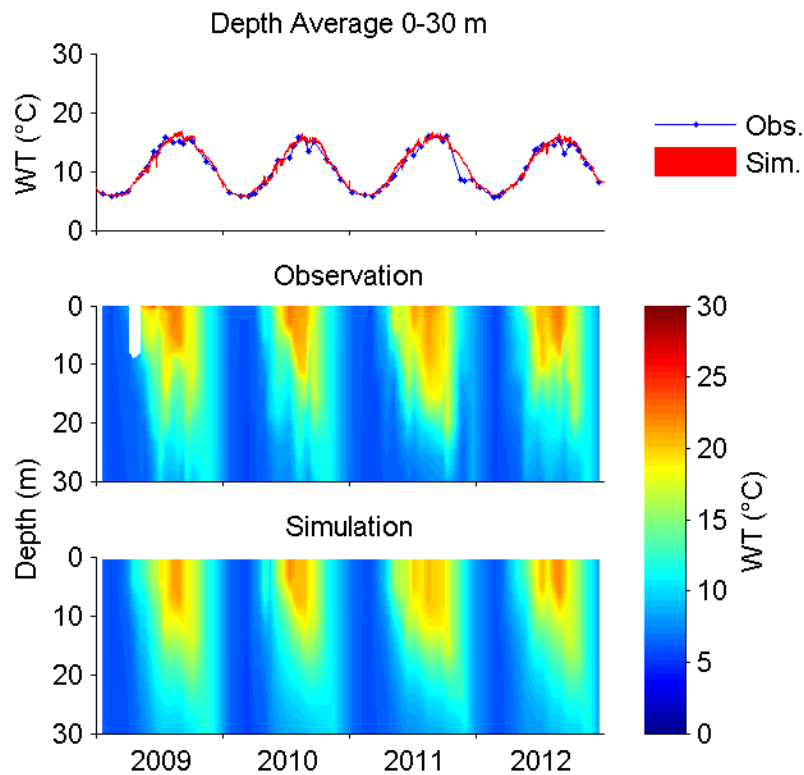


# Hydrodynamic model validation

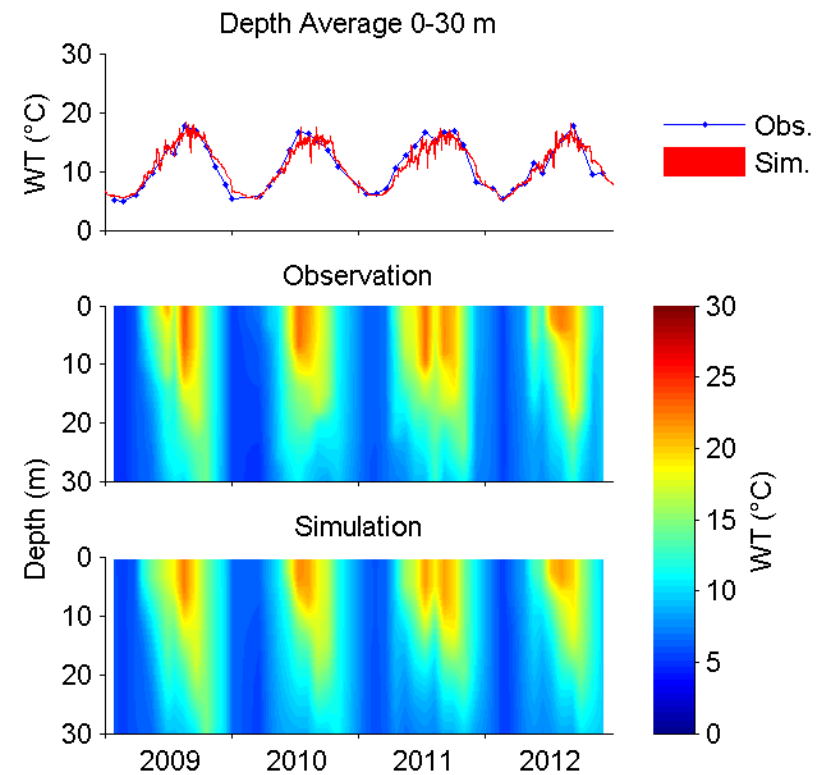
Water Temperature (WT)



## SHL2



## GE3

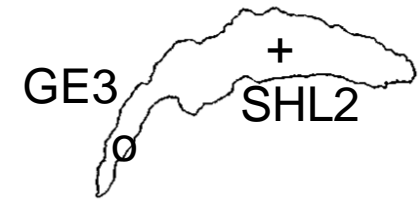


**The hydrodynamic model reproduces well the lake thermal structure**

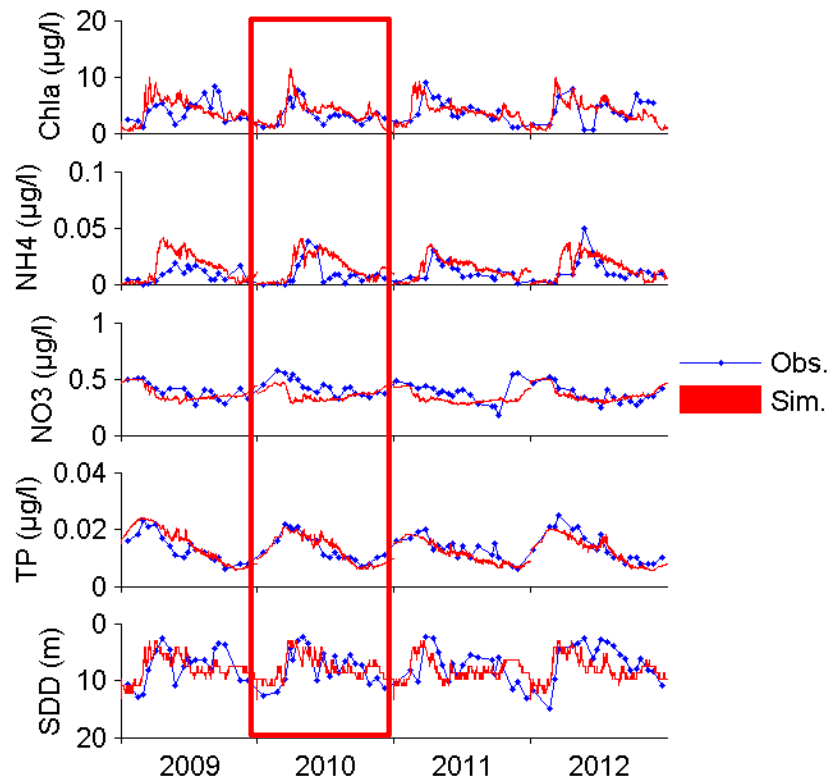
# Ecological model validation

Depth Average 0-30 m\*

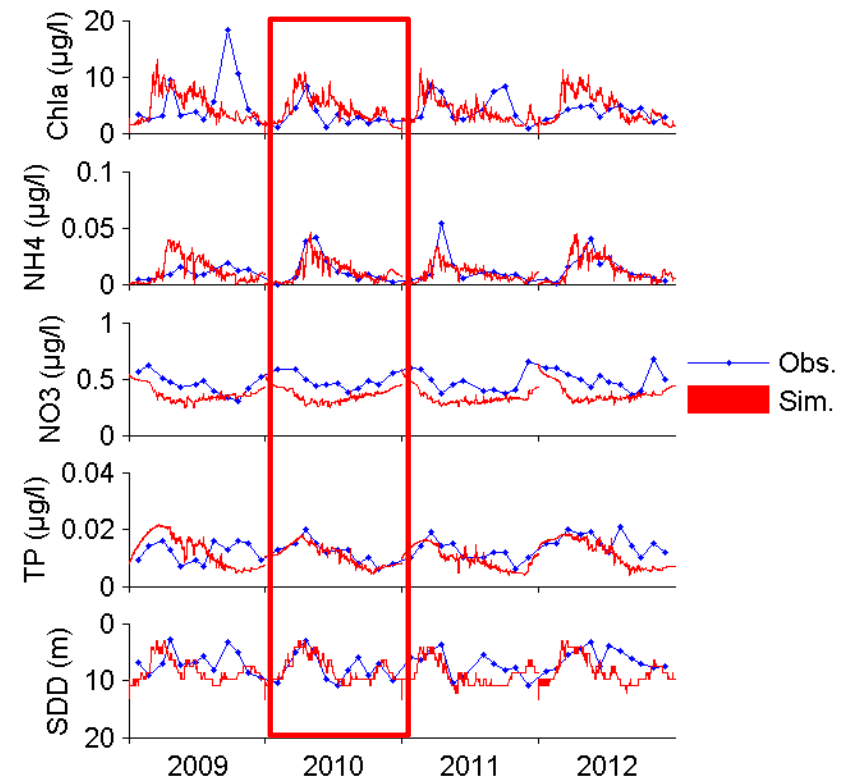
\* Except for Chla at GE3: Depth Average 0-20 m



## SHL2



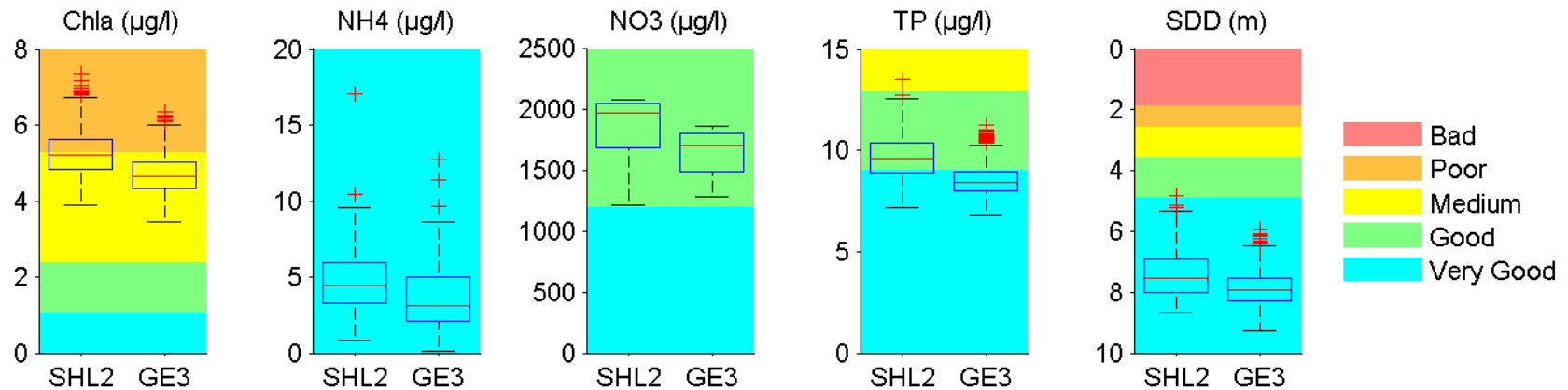
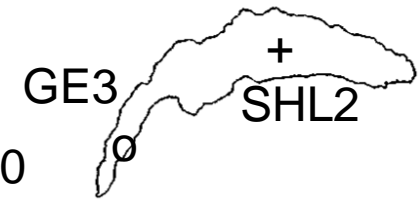
## GE3



**The ecological model reproduces well the seasonal variability in 2010**

# Lake Geneva ecological status

Variability linked to the choice of the 4 sampling dates in 2010

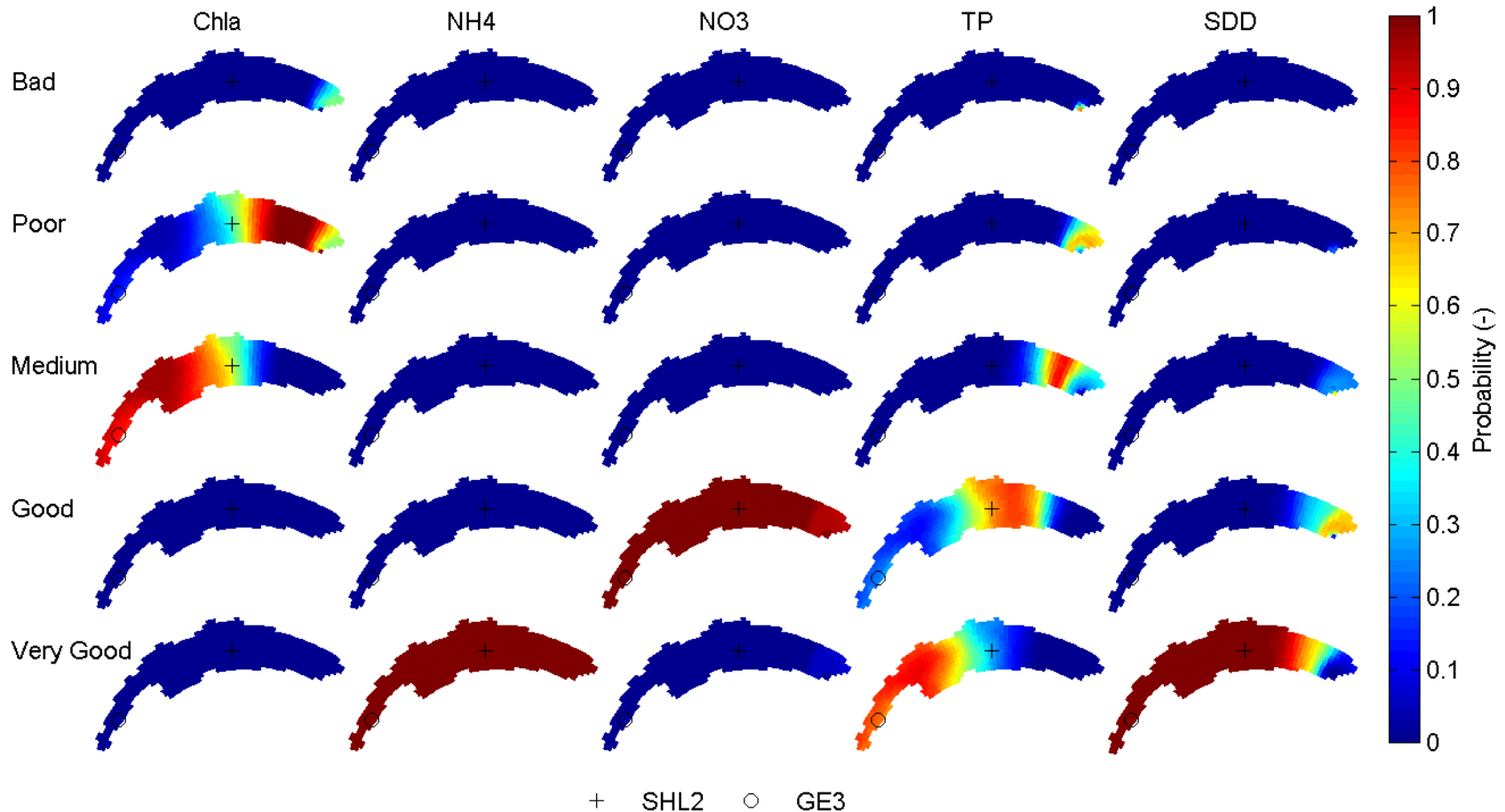


SHL2	GE3	SHL2	GE3	SHL2	GE3	SHL2	GE3	SHL2	GE3
46%	14%								
54%	86%								
				100%	100%	72%	23%		
		100%	100%	28%	77%	100%	100%		

**The choice of the sampling dates induce a variability of Lake Geneva ecological status for Chla and TP at SHL2 and GE3**

# Lake Geneva ecological status

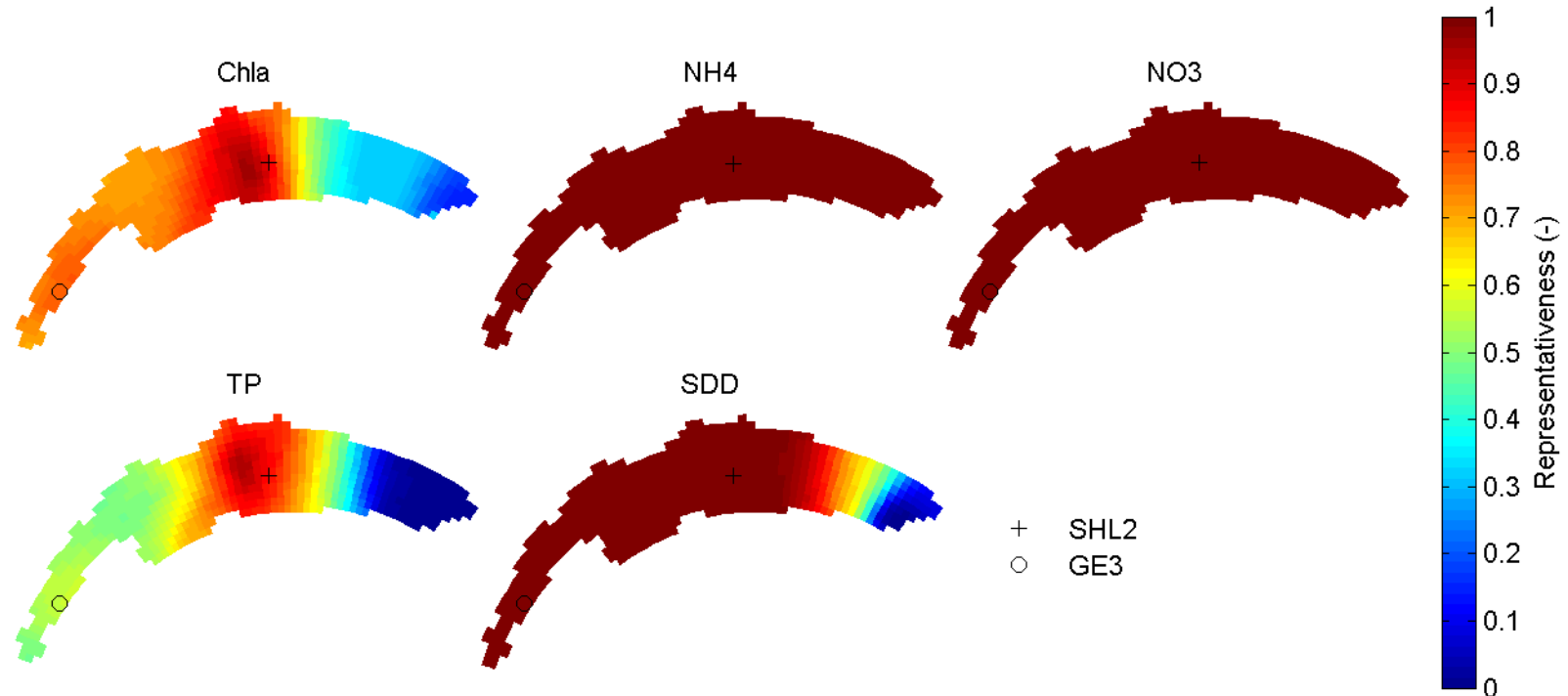
Spatial variability in 2010



**Spatio-temporal heterogeneities induce a spatial variability of the lake ecological status based on Chla, TP and SDD**

# Grid cell representativeness

Spatial variability in 2010

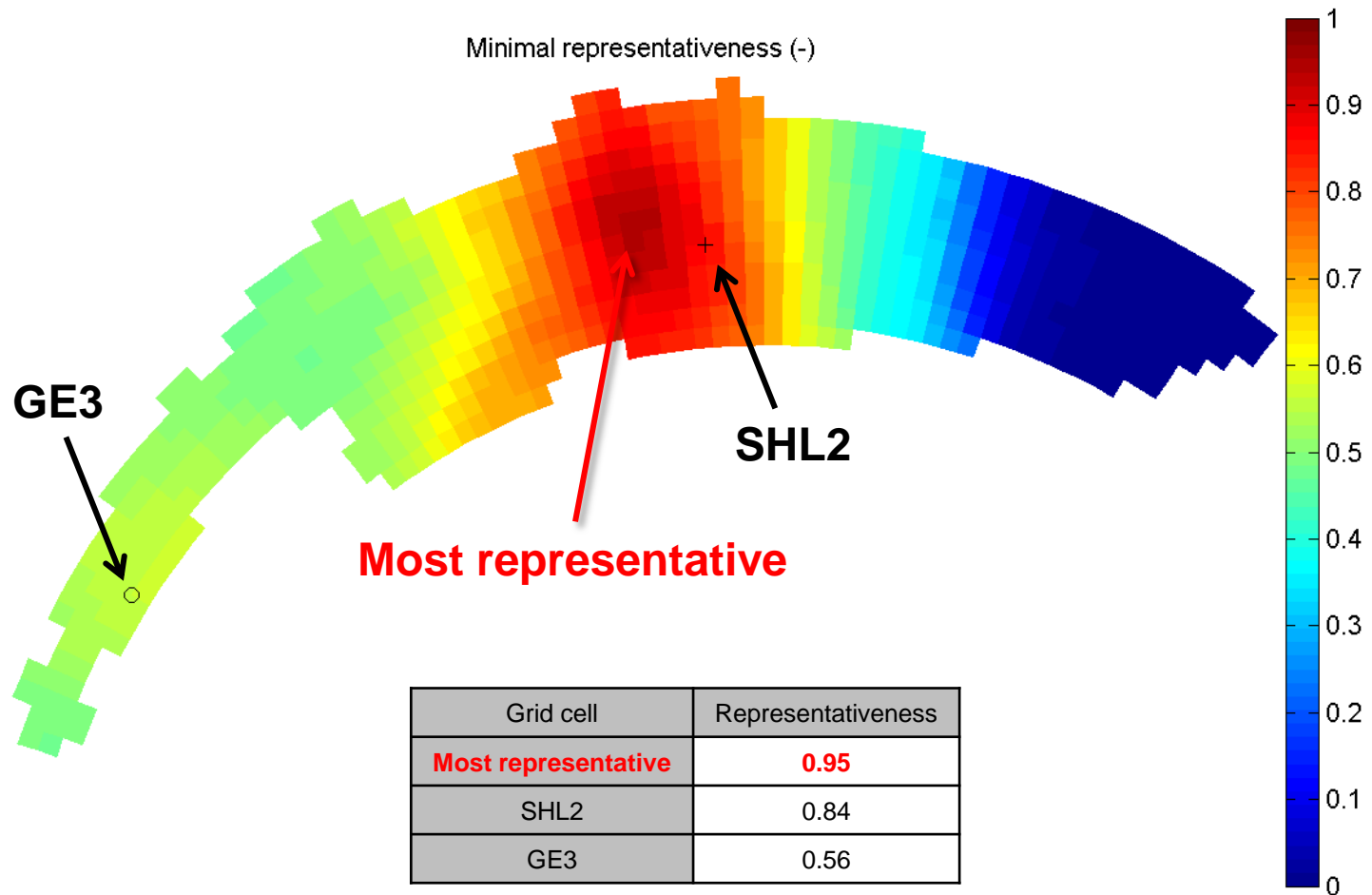


	Chla	NH4	NO3	TP	SDD
SHL2	0.84	1	1	0.85	1
GE3	0.77	1	1	0.56	1

**SHL2 is more representative than GE3 for Chla and TP**

# Most representative grid cell

Year 2010



# Conclusions

- A method is proposed to quantify the variability of lake ecological status and locate the most representative sampling station by using Delft3D in agreement with the European WFD
- The lake thermal structure is well reproduced by the hydrodynamic model
- The seasonal variability and vertical distribution of the 5 studied ecological parameters (**Chla**, **NH4**, **NO4**, **TP** and **SDD**) is well reproduced by the model
- Spatio-temporal heterogeneities
  - induce a spatial variability of Lake Geneva ecological status based on **Chla**, **TP** and **SDD**
  - don't induce any variability of Lake Geneva ecological status based on **NH4** and **NO3**
- Spatio-temporal heterogeneities can bias our evaluation of lake ecological status but only for some parameters. For the other parameters, the proposed metrics to evaluate an ecological status are robust and the trophic status estimated is not influenced by spatio-temporal heterogeneities



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# Thank you for your attention 😊

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4



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