Dynamic modelling of five different phytoplankton groups in the River Thames (UK)

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1 - Introduction

A **process-based phytoplankton model**, developed to simulate the movement and growth of five phytoplankton groups in river systems, is presented.

The model was implemented in five reaches of the River Thames (UK) with a **daily time-step** over a period of three years based on a novel weekly **flow cytometry** dataset which includes concentration of 5 phytoplankton groups.

Aims of the study:
- Model **development**
- Model **implementation**
- Model testing and **multi-objective general sensitivity analysis**

2 - Model

The model is based a mass balance (Whitehead and Hornberger 1984):

$$\frac{dx}{dt} = \frac{x_{IN} - x}{T_c} - k_{death}x + k_{growth}x \cdot CF_T \cdot .CF_P \cdot CF_{RAD} \cdot CF_{SS} \cdot CF_{Si}$$

x = phytoplankton concentration

CF_T: temperature (T) control factor $CF_T = (\theta^{T-20})$

CF_P: phosphorus (P) control factor $CF_P = \left(\frac{P}{k_P + P}\right)$

CF_{RAD}: radiation (R) control factor $CF_{RAD} = \frac{R}{R_{max}}$

CF_{SS}: self-shading control factor $CF_{SS} = \left(\frac{k_{ss}}{k_{ss} + x}\right)$

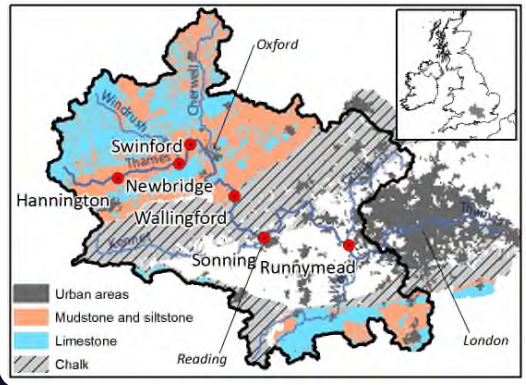
CF_{Si}: silicon (Si) control factor $CF_{Si} = \left(\frac{P}{k_{Si} + P}\right)$

Parameter name	Parameter symbol	Units	Range
Death rate	k_{death}	days^{-1}	0-2
Growth rate	k_{growth}	days^{-1}	0-4
P half-saturation	k_P	mg l^{-1}	0-0.1
Self-shading	k_{SS}	cell ml^{-1}	0-1,000,000
Si half-saturation	K_{Si}	mg l^{-1}	0-5

3 - Case study

River Thames catchment:
- Water supply for 14 million people
- Wastewater discharge from almost 3 million population equivalent)
- Agriculture and sewage treatment works supply phosphorus to the river, increasing the risk of eutrophication

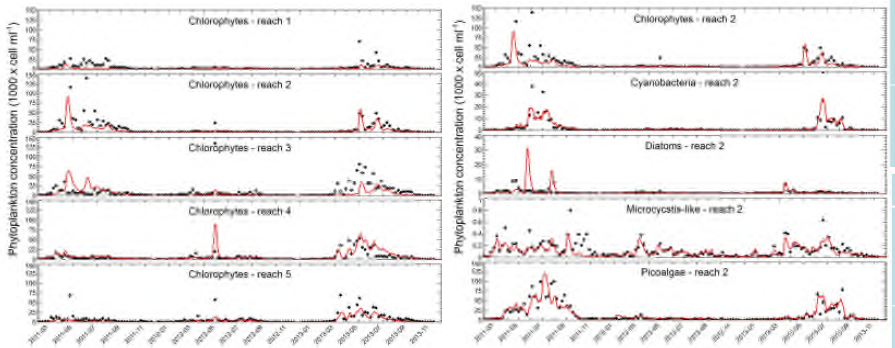
Reach	Upstream section	Downstream section	Length of reach (m)	Drainage area (km²)
1	Hannington	Newbridge	28,000	1558
2	Newbridge	Swinford	10,800	1625
3	Swinford	Wallingford	39,300	4178
4	Wallingford	Sonning	25,300	4600
5	Sonning	Runnymead	55,000	8156



Flow cytometry data (Read et al., 2014):
- Weekly dataset from 2011 to 2014
- Five phytoplankton groups:
  - Chlorophytes
  - Cyanobacteria
  - Diatoms
  - Microcystis-like cyanobacteria
  - Picoalgae
- More detailed than Chlorophyll-*a*
- Used to implement the model and assess its performances

4 - Results

Calibration and validation



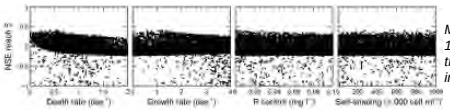
black dots: observed phytoplankton concentration, red line: simulated concentration – for the chlorophyte groups, all reaches (left) and for reach 2, all groups (right)

Calibration	Phytoplankton type	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Nash and Sutcliffe efficiency (-)	Chlorophytes	0.04	0.48	-0.35	-3.29	0.17
	Cyanobacteria	-0.12	0.75	0.45	-3.52	-1.59
	Diatoms	0.04	0.48	-0.10	0.60	0.52
	Microcystis-like	-0.14	0.34	-0.22	-0.07	-0.04
	Picoalgae	0.59	0.73	0.41	-1.63	0.52
Peak error (%)	Chlorophytes	-92	-57	-52	352	-79
	Cyanobacteria	-89	-49	-31	68	25
	Diatoms	-95	-57	-84	-47	-54
	Microcystis-like	-68	-50	-89	-45	-86
	Picoalgae	-63	-38	-65	7	-44

Validation	Phytoplankton type	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Nash and Sutcliffe efficiency (-)	Chlorophytes	0.18	0.80	-0.05	0.51	0.57
	Cyanobacteria	-0.12	0.69	0.14	0.42	0.89
	Diatoms	0.74	0.80	-0.22	0.68	0.75
	Microcystis-like	0.35	0.58	-0.30	-1.94	0.15
	Picoalgae	-0.06	0.60	-0.07	0.37	0.56
Peak error (%)	Chlorophytes	-84	21	-59	18	-47
	Cyanobacteria	-94	-44	-75	70	-17
	Diatoms	5	21	-88	-38	-13
	Microcystis-like	4	-44	-88	125	-83
	Picoalgae	43	-18	-66	19	-47

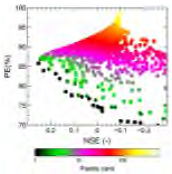
Multi-objective general sensitivity analysis (Hornberger and Spear, 1980, Bastidas et al., 1999)

Step 1: 10,000 model runs with different random parameter sets for each reach and each phytoplankton group



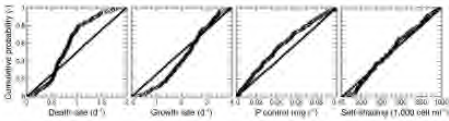
Model results of the 10,000 model runs for the chlorophyte group in reach No. 5

Step 2: a Pareto Rank is assigned to all model runs (and corresponding parameter sets) depending on their results in terms of Nas and Sutcliffe Efficiency (NSE) and Peak Error (PE)



Example of Pareto Ranking based on two criteria (Nash and Sutcliffe Efficiency and Peak Error)

Step 3: all parameter sets are divided into behavioural and non-behavioural, and the distribution functions of both sub-sets of parameters are built

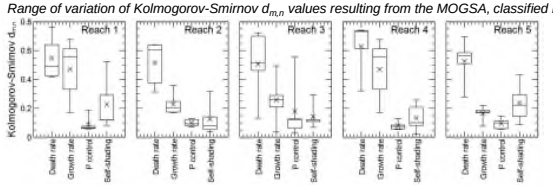


Behavioural (circles) and non-behavioural (line) distribution functions for four model parameters for the chlorophyte group in reach No. 5

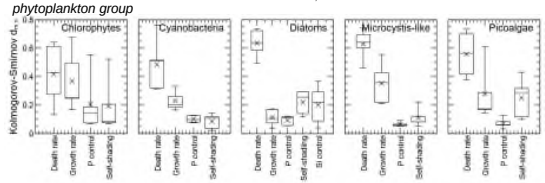
Step 4: the Kolmogorov-Smironv ($d_{n,m}$, distance between two distribution fucntion, S_m and S_n) was calculated for all the parameters (for each reach and for each phytoplankton group): $d_{m,n} = sup_x|S_n(x) - S_m(x)|$

It indicates the sensitivity of model results to one of its parameters.

Range of variation of Kolmogorov-Smirnov $d_{m,n}$ values resulting from the MOGSA, classified by reach



Range of variation of Kolmogorov-Smirnov $d_{m,n}$ values resulting from the MOGSA, classified by phytoplankton group



Death rates: highly influential. **Growth rates**: influential. **Self-shading parameter**: influential for diatoms and picoalgae. **Phosphorus half-saturation**: not influential

5 - Conclusions

The model results were satisfactory in terms of fitting the observed data, with validation NSEs greater than 0.5 for 12 cases out of 25, and greater than 0 for 18 out of 25 cases.

The growth and death rate obtained in this study were found to be in agreement with previous river modelling studies.

The death rate parameter is highly influential for all phytoplankton groups and all reaches. The phosphorus half-saturation parameter proved to exert almost no influence, given that phosphorus is not a limiting nutrient in the River Thames.

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