Modelling fixed plant and algal dynamics in rivers: an application to the River Frome

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Modelling fixed plant and algal dynamics in rivers: an application to the River Frome

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Abstract
The development of eutrophication in river systems is poorly understood given the complex relationship between fixed plants, algae, hydrodynamics, water chemistry and solar radiation. However there is a pressing need to understand the relationship between the ecological status of rivers and the controlling environmental factors to help the reasoned implementation of the Water Framework Directive and Catchment Sensitive Farming in the UK. This research aims to create a dynamic, process-based, mathematical in-stream model to simulate the growth and competition of different vegetation types (macrophytes, phytoplankton and benthic algae) in rivers. The model, applied to the River Frome (Dorset, UK), captured well the seasonality of simulated vegetation types (suspended algae, macrophytes, epiphytes, sediment biofilm). Macrophyte results showed that local knowledge is important for explaining unusual changes in biomass. Fixed algae simulations indicated the need for the more detailed representation of various herbivorous grazer groups, however this would increase the model complexity, the number of model parameters and the required observation data to better define the model. The model results also highlighted that simulating only phytoplankton is insufficient in river systems, because the majority of the suspended algae have benthic origin in short retention time rivers. Therefore, there is a need for modelling tools that link the benthic and free-floating habitats.

Introduction

The development of eutrophication in river systems is poorly understood given the complex relationship between fixed plants, algae, hydrodynamics, water chemistry and solar radiation (Hilton *et al.* 2006). Recent studies calculated the costs of eutrophication in the UK in terms of (i) the improvement in sewage treatment technologies (£950 million in the past 15 years; Kinniburgh and Barnett (2010), and (ii) the remediation costs (£75-114 million per year in England and Wales; Pretty *et al.,* 2002). In addition, the Water Framework Directive (Council of the European Union 2000) has placed a legal pressure on the European Member States to manage their aquatic environments to improve chemical and ecological status. Therefore, there is a pressing need to understand the relationship between ecological status of rivers and the environmental factors controlling to inform the reasoned implementation of the Water Framework Directive and Catchment Sensitive Farming in the UK.

The chemical and ecological status of river systems can be identified with surveys and monitoring of targeted parameters. Aquatic ecosystem models are useful because they provide a methodology to integrate process understanding derived from such monitoring and other experiments and they can be used as 'learning tools' with which to explore how the system responds to changes in the flow, water chemistry, solar radiation and water temperature.

Dynamic mathematical models can also be used as supporting tools to explore management options by carrying out scenario runs. Clearly there is a vast amount of information and available supporting tools to prepare the river basin management plans. However, these tools mainly target one or a few components of the riverine ecology, disregarding the spatial (longitudinal) heterogeneity of vegetation composition and the dynamic ecological interactions within the system. Only complex food-web models include all vegetation and animal types in the simulation; therefore, providing a very detailed 'map' of the cause-effect relationships. However, as a consequence of this, these models require numerous parameters and many observations, such as species data for all ecological components to set up the model and validate the results. Finally, the use of such a full food-web model requires significant time to set-up and run (Sourisseau *et al.,* 2008). Therefore, there is a need for a medium complexity model which includes the main vegetation types and environmental factors, but which is less data, parameter and resource intensive.

This research aims to create a dynamic, process-based, mathematical in-stream model to simulate the growth and competition of different vegetation types (macrophytes, phytoplankton and benthic algae) in rivers. Specifically the objectives are to (i) improve the scientific knowledge on how eutrophication develops in lowland river systems, (ii) determine whether process-based models could be used to simulate complex ecological interactions (stability, suitability), and (iii) to run climate and water resources based scenarios to predict the likely ecological status of the study sites if the present conditions change. The model was applied to the River Frome in southern England, a data-rich study area being part of the Natural Environment Research Council - Lowland Catchment Research Programme (NERC-LOCAR) and other contemporary studies.

The River Frome system

The River Frome (414 km^2) is a Site for Special Scientific

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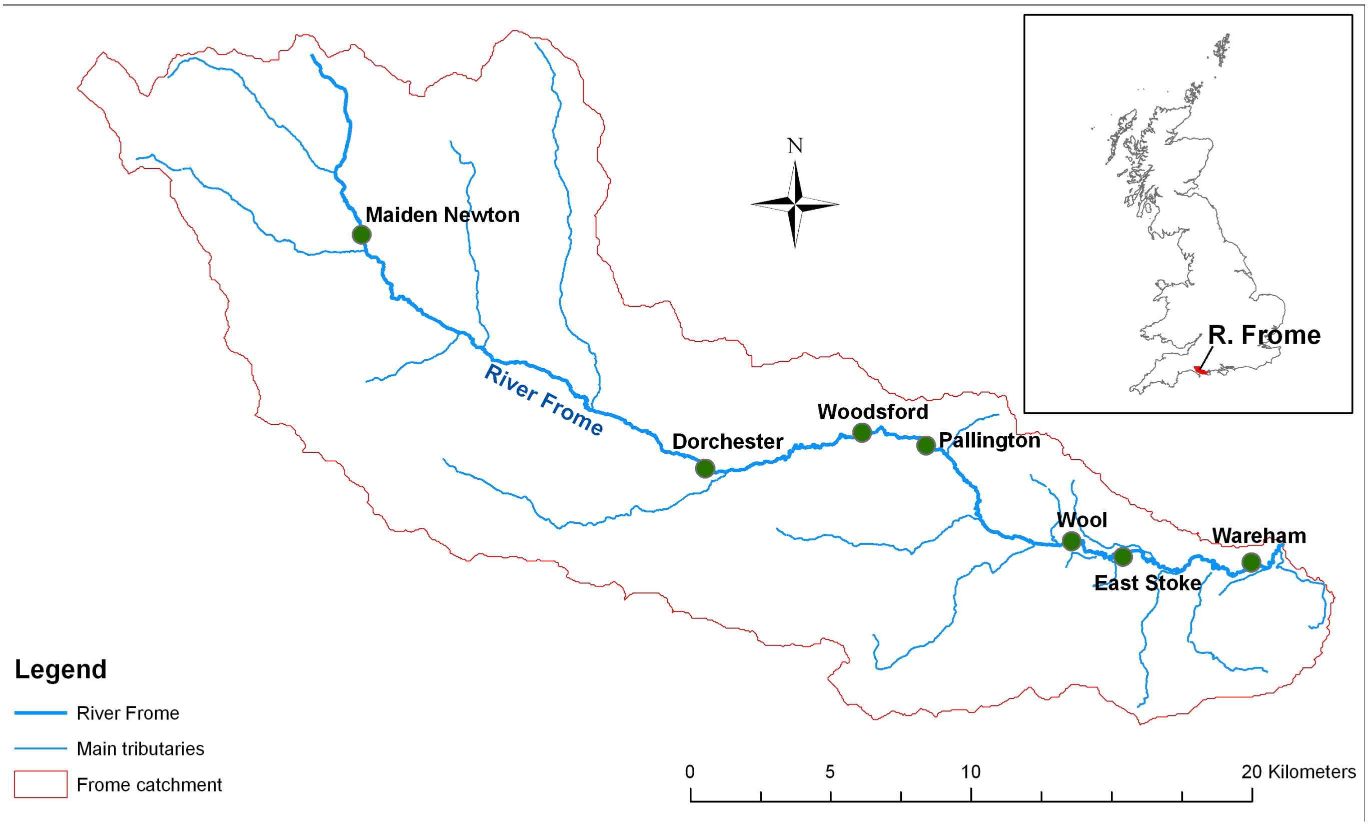

Figure 1 *The River Frome catchment*

Interest (SSSI) and a classic example of a chalk river, dominated by the macrophyte *Ranunculus penicillatus* subsp. *pseudofluitans* (water crowfoot) which provides cover for the fish community (Figure 1). The mean annual discharge at East Stoke is 6.38 $m^3 s^{-1}$, which increases up to 24 $m^3 s^{-1}$ during flood events. The Base Flow Index is 0.84 which indicates groundwater dominance. The mean annual precipitation is 1020 mm $year^{-1}$. At Dorchester, the mean flow is 3.09 $m^3 s^{-1}$, the BFI is 0.83, and the mean annual precipitation is 1072 mm.

The geology of the catchment is mainly Chalk, but Jurassic limestones, Upper Greensand, Tertiary sand deposits, and sand/gravel/clay are also present (Wharton *et al.,* 2006). The main land uses are agricultural (arable) and grassland (above East Stoke these are 47% and 37% of the catchment area, respectively). Dorchester is the biggest town in the catchment, and there are ten sewage treatment works that discharge directly into the Frome. The main STWs are Dorchester (Population Equivalent, PE, 27 600) and Wool (PE 8000). In the River Frome, *Ranunculus penicillatus* dominates the aquatic vegetation. In the case of the study sites used in this research (Maiden Newton and Lower Kingscombe), the open areas had very limited marginal vegetation. However, in other parts of the Frome, marginal vegetation can be more important.

The overall status of the River Frome is 'Poor' (Table 1) according to the EU Water Framework Directive status assessment (EA, 2009). This 'poor' status is caused by the ecological elements and the risk associated with the Drinking Water Protected Areas in the catchment. Fish populations in the entire river and phytobenthos populations (bottom-dwelling multi-cellular and unicellular aquatic plants such as some species of diatom) in the lower part of the Frome are less than satisfactory. Nitrate and hazardous substances concentrations in groundwater, and other flow-related pressures such as abstractions from groundwater also cause concerns.

Table 1 *WFD status of the River Frome (based on EA 2009, Annex B)*

River sections	*Length*[1]	*Overall Status*	*Element with less then Good Status*
Headwater (GB108044009620)	5 km	Poor	Fish (Poor) Invertebrate (Moderate)
Upper (HMWB[2]) (GB108044009780)	3.5 km	Good (potential)	Fish (Moderate)
Middle-Lower (GB108044009690)	40 km	Poor	Fish (Moderate) Macrophytes (Moderate) Phytobenthos (Poor)
Upper Dorset Stour Chalk (groundwater) (GB40801G803100)	-	Poor	Drinking Water Protected Area (Poor) Nitrate and phosphate levels and nitrate trends
Lower (groundwater) (GB40802G805600)	-	Poor	Drinking Water Protected Area (Poor) Nitrate levels and trends

Note: [1] – approximate length based on the on-line EA map (River Basin Management Plans – Rivers: http://maps.environment-agency.gov.uk/wiyby/wiybyController?ep=maptopicsandlang=_e;)
[2] - HMWB: Heavily Modified Water Body

To improve the overall status of the water bodies, a number of mitigation actions are planned (EA, 2009, Annex C):

- implementing a SSSI management agreement and an agri-environment scheme;
- implementing river restoration projects;
- investigation into the source of aluminium (lower Frome);
- pollution action plan, and amending discharge consents (nutrients);
- implementing invasive fish species control programme.

The Vegetation Composition Model

A new Vegetation Composition Model (VCM) was developed to aid the understanding of the behaviour of aquatic vegetation and the process of river eutrophication. The VCM is a dynamic, process-based mathematical model which simulates the system on a daily timestep. The model represents a medium complexity model structure simulating average river reach conditions.

The **physical model** (Figure 2) uses different daily average time series (inflow discharge, solar radiation, water temperature, nutrient and suspended sediment concentration) to (i) calculate the residence time and outflow discharge for each reach, and (ii) to estimate the light attenuation in the water column caused by the abiotic water, inorganic suspended matter and vegetation biomasses (macrophytes, fixed- and suspended algae). The **ecological model** (Figure 3) simulates the growth of both free-floating algae (phytoplankton and metaphyton) and fixed vegetation (bottom algae and macrophytes). Not only the flow (damage and losses caused by turbulence), water chemistry, radiation and temperature affect the calculated biomasses, but also the available light and the interaction of different ecological pools influence the growth and losses.

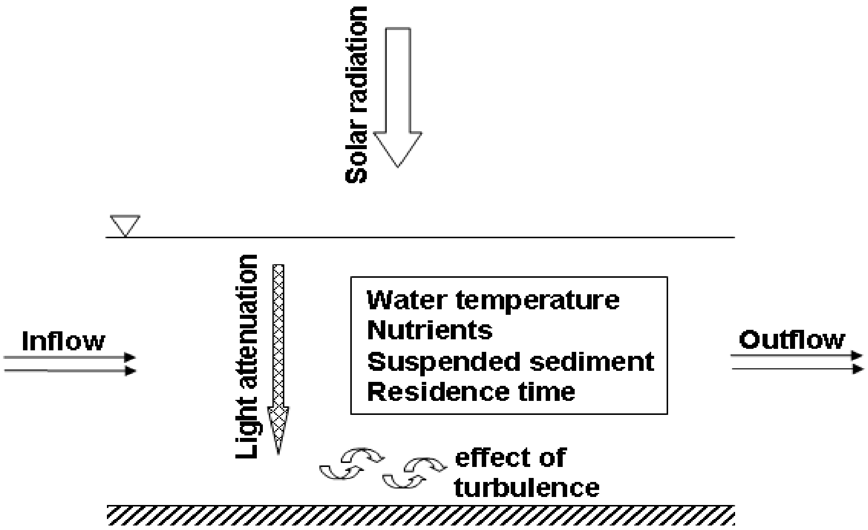

Figure 2 *Physical conceptual model. The daily mean inflow, solar radiation, water temperature, nutrient and suspended sediment concentration time series drive the model equations. The residence time and the outflow discharge are calculated for each day based on reach characteristics. The effect of turbulence on the vegetation types is also considered in the simulations.*

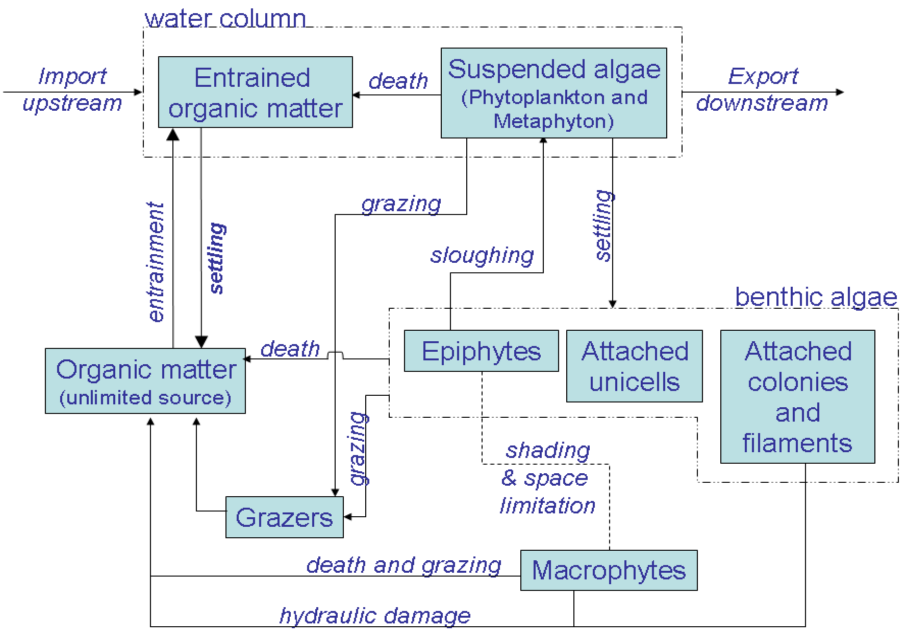

Figure 3 *Ecological conceptual model. The model has four main parts: (i) water column containing live and dead suspended algae, (ii) macrophytes, (iii) benthic algae of different habitats and (iv) grazers of algae. The settled dead organic matter of the bed sediment is considered as an unlimited source. The interactions between these pools are shown with arrows.*

Table 2 Model applications

Name	Suspended Algae	Macrophytes	Epiphytes	Sediment biofilm	Filament / Colonies	Calibration period	Test period
River Thames (UK)	X					1997-2000	2001-2003
River Thame (UK)	X					2000-2002	2006-2007
River Kennet (UK)	X					2003-2005	2006-2007
River Kennet (UK)	X	X	X			1997-1999	2000-2005
River Frome (UK)	X	X	X	X		2003-2005	-
Silver Springs (USA)		X	X	X	X	2002-2005	-

Total biomasses are calculated and species of vegetation are not differentiated. In case of fixed algae, habitat-based accounting is implemented: algae living on macrophytes (epiphytes), unicellular organisms living on the substratum within the sediment biofilm layer and multicellular algae attached on the substratum. The bulk biomass of algal grazers is also separately simulated to make the simulation more realistic (EPA, 1985). The grazing of macrophytes, on the other hand, is represented with a simple first order loss term. Settled dead organic matter is not accounted for; rather it is considered as an unlimited source. Shading by riparian vegetation (e.g. trees) is also not considered in the model because it could significantly influence the model results (significant reduction in light), and such assumptions (i.e. the effect of shading on a river reach caused by riparian trees) are difficult to validate. The model calculation uses the 'gram carbon per day' unit for the suspended algae and entrained dead organic matter, and the 'gram carbon per metre squared per day' unit for all other ecological components. The model requires 7–9 calibration parameters for each simulated vegetation type.

The VCM was applied to five river systems, where ecological time series were available (Table 2). The water column part of the model was separately tested on three study sites in the Thames River Basin (River Thames, River Thame and River Kennet; Lázár *et al.* submitted). Unfortunately, no study site was found, where all vegetation types were measured together for a prolonged period. Therefore, different parts of the full model were tested partly in the UK (River Kennet and River Frome) and partly in Florida (Silver Springs, USA). This paper presents the results of the River Frome application.

Model setup for the River Frome

The River Frome was divided into 11 reaches based on the location of gauging stations, water quality and ecology monitoring points. Reach lengths and sub-catchment areas were calculated by using a 50 m resolution Digital Elevation Model accessed through EDINA, derived from Ordnance Survey (OS) data, and river network shape files (Centre for Ecology and Hydrology, CEH). The average reach widths were estimated by using Carto Maps sourced from EDINA (1:10 000 OS mapping).

This new algae model has no terrestrial hydrological component and the diffuse discharge entering the reaches was assumed to be proportional to the area of the sub-catchments draining to each reach. This diffuse flow was calculated from the time series of the nearest gauging stations (Environment Agency, EA). The Frome application utilised the National Water Archive's discharge ($m^3 s^{-1}$) time series for Dorchester and East Stoke. The hourly observations of the LOCAR meteorological stations (CEH Winfrith; Telegraph Hill) were used to provide the daily total solar radiation ($W m^{-2}$ converted to $kJ m^{-2}$) and daily mean air temperature (^oC) measurements. The input daily mean water temperature time series of the model was estimated from the daily mean air temperature measured at the LOCAR meteorological stations. The discontinuously measured water temperature of the EA was used to validate the estimated water temperature time series. This method is described in more detail elsewhere (Lázár *et al.* submitted).

The EA's water quality data was used for 15 stations (Sandhills, Notton, Bradford Peverell, Whitfield Lodge, Greys Bridge, upstream Dorchester STW, Pallington, upstream Golden Springs Fish Farm, downstream Golden Springs Fish Farm, Moreton Footbridge, Winfrith Heath, Wool Bridge, East Stoke, Holme Bridge, Wareham). The in stream vegetation data were provided by the Queen Mary University of London for Maiden Newton and Pallington: macrophyte/epiphyte by Dr. Ian Sanders; sediment biofilm by Dr. Sion Roberts (Trimmer *et al.,* 2009; Wharton *et al.,* 2006). Chlorophyll-a concentrations in the river water was only measured at Wareham by the EA.

Results

Four types of ecological data were available for the River Frome: suspended chlorophyll-a concentration, macrophyte biomass, epiphyte biomass and sediment biofilm biomass. Unfortunately, these data were measured at different time periods; therefore, all data had to be used for the calibration, and model testing was not possible. The model results are summarised in Table 3 and Figure 4.
The simulation resulted in high Pearson goodness of fit coefficients (R^2), but the Nash-Sutcliff (N-S) coefficients did not support the high R^2 values. The visual inspection of the model results shows that the seasonal variation of the vegetation types was captured well by the model. Based on the model results, the growth and interaction of each vegetation type in the River Frome are briefly discussed below.

The simulated **suspended algae** (chlorophyll-a concentrations of phytoplankton and metaphyton, Figure 4b) values represent the observations well. Re-suspension of dead organic matter from the river bed was simulated as a function of the discharge (an approximation of the flow turbidity), and was significant during the winter months. The spring/summer growth of algae was severely limited by the short residence time of the flow. This inhibited the efficient algal doublings in the reaches and therefore, high spring/summer phytoplankton biomasses could not develop in the River Frome. The effect of the benthic vegetation on the

Table 3 *Goodness of fit coefficients of the River Frome application*

	Maiden Newton R2 / N-S	Pallington R2 / N-S	Wareham R2 / N-S
Suspended chl-a			0.27 / -0
Macrophytes	0.29 / -0	0.98 / -0	
Epiphytes	0.65 / -0	0.33 / -0	
Sediment biofilm	0.47 / -0		

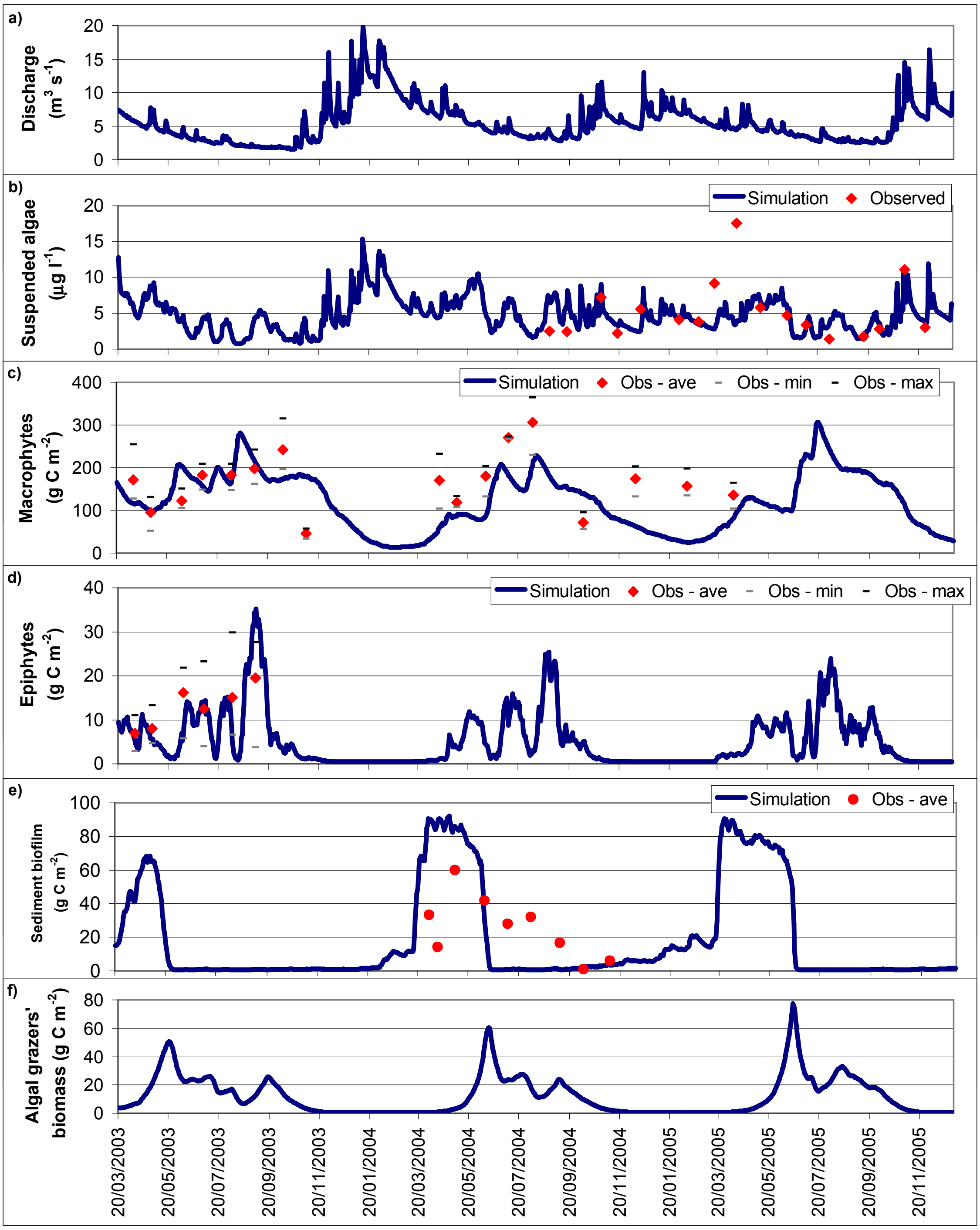

Figure 4 *Selected simulation results (Fig 4 a-b: Wareham; Fig 4 c-f: Maiden Newton)*

free-floating algal community was observed to be important in short retention time rivers (Jarvie *et al.*, 2003), and this finding was supported by the modelled results, simulating the recruitment of suspended algae from epiphytes (sloughing) was moderate to high during the summer months, varying between 1 and 20 µg Chla l^{-1} day^{-1} (not shown on Figure 4). This sloughed algal biomass was frequently higher than the simulated free- floating biomass in the water column (Figure 4b). The difference between the sloughed biomass and the water column concentration was explained by the VCM model to be partially transported downstream by the flow and partially lost from the water column as a result of herbivorous grazing of filter feeder groups.

Macrophytes were simulated with moderate success (Figure 4c). The simulated biomass was between, or close to, the minimum-maximum ranges observed for 2003, but were slight underestimates of the biomass observed in 2004. Macrophytes were severely affected by the epiphyte population. It is evident from Figure 4c that the decrease in macrophyte biomass occurred when the epiphyte biomass increased (Figure 4d) during spring/summer. High winter flows damaged the macrophyte stands in the simulation. The winter macrophyte biomasses were not simulated well by the model. The 2003 winter macrophyte biomass was overestimated, whereas the 2004 winter biomass was underestimated. The Environment Agency does not cut weed on the Frome except in close proximity to discharge gauges (Brian Scott, *personal communication on 9 November 2009*). It is unclear whether sediment instability or some other activity (e.g. cattle grazing) caused the significant drop in macrophyte biomass in October 2003 and in October 2004. However, it might also be possible that the model representation of the macrophyte die-back process is not optimal in the model. This will require further model tests.

The current model calibration was therefore a compromise between the winter observations and the hydrological damage calculation. Finally, the observed biomass increase between November 2004 and January 2005 were not simulated with the model because the winter macrophyte growth was severely restricted by the light limitation formula using a linear relationship between the solar radiation and growth rate and also by the losses caused by the high winter flows. Overall, macrophyte growth during the study period was mainly controlled by the available light (epiphytic algae growth and seasonal solar radiation variation) and by the hydraulic damage.

Epiphyte growth was simulated relatively well by the model. The simulated values were between the measured minimum and maximum biomasses. The growth of epiphytes during the spring/summer months was constrained by three factors: space limitation (available macrophyte biomass to grow on), herbivorous grazing and, to a lesser extent, sloughing caused by the turbulent flow. The effect of grazing is evident when Figure 4d and 4f are compared. The grazing effect on epiphytes might be overestimated by the model which was indicated by the occasional drop in epiphyte biomass close to zero. Preferential grazing of vegetation is not included in the model; a limitation of this medium complexity model. Although sloughing was indicated as a significant process for suspended algae, the sloughed epiphyte biomass was relatively insignificant ($<0.4\,g\,C\,m^{-2}$) when it was compared with the daily epiphyte biomass. Therefore, as a result of the sheltering effect of macrophytes, sloughing did not control epiphytic growth in the River Frome; rather, water temperature, available light and herbivorous grazing regulated its biomass.

The chlorophyll-a content of the **sediment biofilm** (fixed unicellular organisms on the substratum) rapidly increased when conditions were favourable (sufficient light and water temperature). However, as a result of the shading of macrophytes and the overlying water column, biomass growth of sediment biofilm was always initiated by the available light in early spring (around March). Available space limited these sharp biomass increases. Grazing was an important controlling factor in the sediment biofilm simulation, forcing the biomass rapidly back to zero. Sediment biofilm population rarely recovered after these severe grazing events as a result of the shading by the elevated macrophyte biomass during spring and summer. This was a further limitation of the lumped grazer biomass simulation, which could only be resolved if different grazer groups were simulated separately considering food preferences.

Relevance to the Water Framework Directive implementation

The UK Technical Advisory Group on the Water Framework Directive defined the river classification system for use in the UK to define ecological status (UKTAG, 2004). According to this classification, the lower section of the River Frome belongs to River Type 2. This means that there is an increased emphasis on macrophyte species typical of more base- and nutrient-rich environments and species richness should be around 35 species per 1 km reach. Apart from these, there is a list of species which should (including *Ranunculus penicillatus*) or should not be present in this river type. In terms of phytobenthos, epilithic diatom biofilms should be dominated by different pollution-sensitive taxa, and *Cladophora* should be either absent or present in a small quantities. Thus the UK WFD river classification considers the species richness and the individual species present. Unfortunately, the River Basin Management Plan (EA, 2009) provides only an overview of the status and does not explain why the macrophytes are in the moderate and phytobenthos in the poor status category.

This new vegetation composition model currently does not simulate individual species, but only bulk habitat types. Therefore, the change in total biomass and the presence or absence of habitat types (epilithic biofilms, epiphytes, filamentous substratum algae such as *Cladophora* and macrophytes) can be assessed with it. The present study only considered the epilithic biofilms, epiphytes and macrophytes, and did not consider the filamentous benthic algae due to data scarcity. Although species richness and the individual species cannot be estimated with the model, the longitudinal and seasonal changes of vegetation biomasses can be assessed. Figure 5 shows the variation of vegetation biomasses during the simulation period for three study reaches. Reach 2 (Maiden Newton) and Reach 7 (Woodsford) appear to have similar vegetation composition patterns and Reach 11 (Wareham) shows a slightly different vegetation behaviour. Macrophytes dominate the vegetation in all reaches except in early spring, when sediment biofilm is very productive (Figure 5).

The dominance of the sediment biofilm in primary production increases downstream and the abundant presence of the biofilm are prolonged in the lower reaches. This is probably a result of the change in the growth pattern of macrophytes, namely, that the growth of macrophyte biomass is delayed in the lower reaches as a consequence of the higher discharges (causing hydraulic damage) and deeper water column (leading to light attenuation at depth). This is consistent with the observation of Dawson (1976), namely that there was a 2-month time-lag in flowering time, and thus in the start of growth of *Ranunculus* between the source and the mouth of the Chalk River Piddle that is adjacent to the River Frome.

However, despite the initial delay, the peak macrophyte biomasses are slightly higher than in the upper reaches (not shown in Figure 5). As a consequence of this higher biomass, more epiphytes can grow (more available space and more protection against sloughing) which potentially increases the proportion of epiphytes in the reach (Figure 5) and causes the decline in the macrophyte community. Suspended algae have an insignificant presence in the River Frome (in terms of primary production) compared to fixed vegetation. This is not surprising, because the residence time is short and a significant free-floating algae population cannot develop.

Although the number of macrophyte species cannot be estimated with this vegetation composition model, the model results shows that the excessive growth of epiphytes in the lower reaches potentially endangers the macrophyte population and can result in a less than good ecological status. In terms of phytobenthos, the simulation did not include filamentous substratum algae (*Cladophora*) and therefore, the assessment of its presence or absence would require a new model application and field observations to test the modelled representation. The sediment biofilm population was predicted by the model as productive during the early spring period until grazers appeared in higher numbers. The species composition of these algae cannot be predicted with the model, although it would be useful for the EU WFD implementation. Since the primary concern in terms of nutrient concentration is the nitrate in the River Frome (EA, 2009), one could speculate that the phosphate is then the limiting nutrient of the algal growth (nitrate levels are high). However, the growth of sediment biofilm population was not limited by phosphorus in the model simulations. Thus it can be assumed that nutrients are not limiting the algal growth, and sensitive phytobenthos taxa are not present in

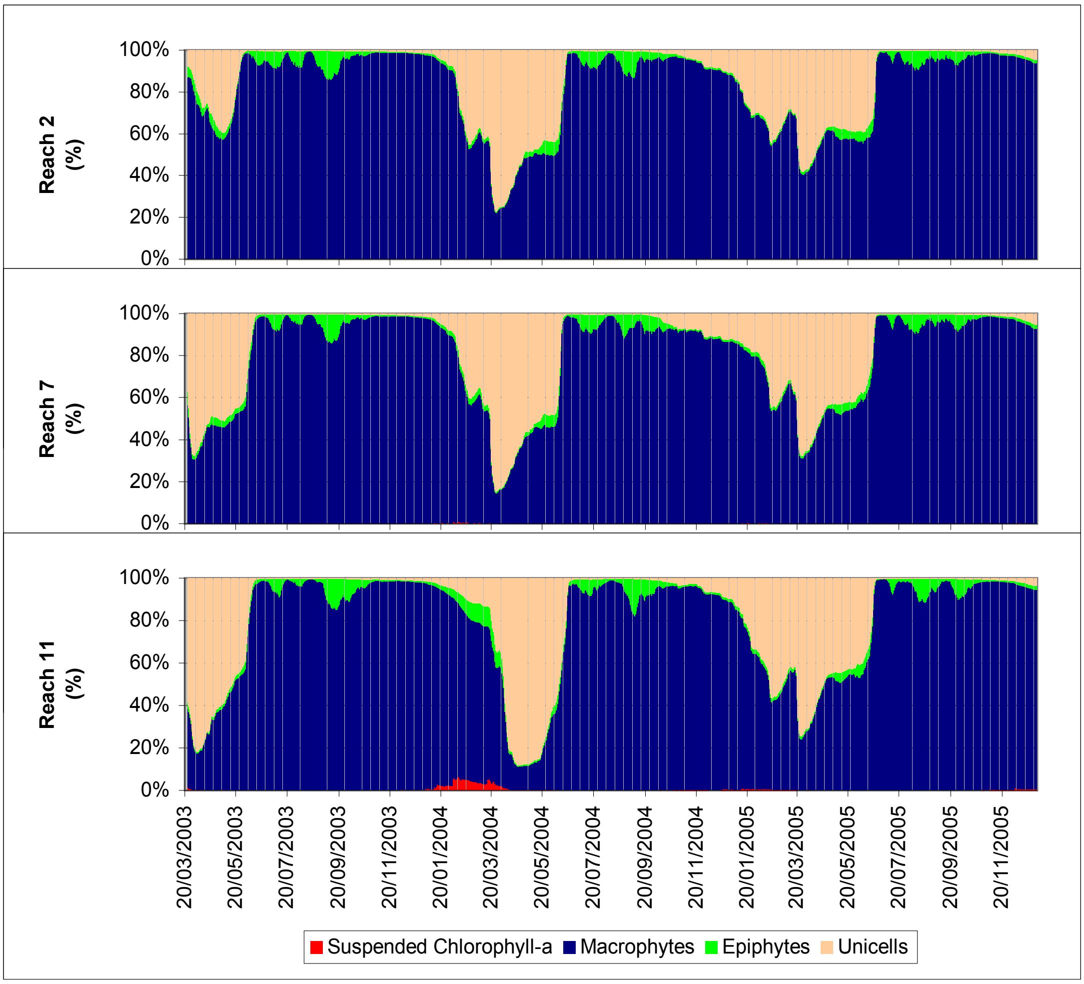

Figure 5 *Vegetation composition along the River Frome. The figure compares the calculated g C m^{-2} biomasses of the simulated vegetation types for an upstream (Reach 2: Maiden Newton), a middle (Reach 7: Woodsford) and a lower reach (Reach 11: Wareham) along the River Frome.*

the river. Although in an indirect way, this also agrees with the EU WFD classification, namely that the status of the phytobenthos is less than desirable.

Conclusions

A new vegetation composition model was presented which offered a medium complexity approach to simulate the behaviour (growth and competition) of riverine vegetation. The model included the important processes of river systems and included all major vegetation habitats. This allowed the simulation of both short and medium retention time rivers. This paper presents the simulation results of the River Frome (Dorset, UK) application. The model captured the seasonality of the simulated vegetation types well (suspended algae, macrophytes, epiphytes, sediment biofilm). Simulation of macrophytes showed that local knowledge is important to explain unusual changes in biomass such as the sudden autumn drop and winter increment of macrophyte biomass.

Fixed algae simulations indicated the need for a more detailed representation of the various herbivorous grazer groups; however, this would increase the model structural complexity, the number of model parameters and the required observation data to define the model. The model simulation also highlighted that modelling phytoplankton only is insufficient in river systems; rather, there is a need for simulation tools that link the benthic and free-floating habitats if longer river systems are to be simulated.

Acknowledgements

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