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Transient evolution of suspended and benthic algae in a riverine ecosystem: A numerical study

Sumit Sinha

School of Architecture, Geography and Environmental Science, University of Reading, Whiteknights, Reading RG6 6AB, UK

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ABSTRACT

It is a well-established fact that there is no direct resource competition between pelagic and benthic primary producers when their habitats are located in physically separate areas. However, the benthic habitat located at the bottom of the water column is affected by the light rays that gets attenuated as it passes through the pelagic zone and is obstructed by the algal cells and suspended material present in the water column. Therefore, benthic primary production is very much influenced by the conditions and concentrations in the pelagic zone. Another level of complexity is added to the system while considering the impact of flowing water in a riverine environment. In the research presented here a numerical model is developed to examine the impact of flow and nutrients on pelagic and benthic primary producers. The aforementioned numerical model solves advection diffusion and reaction (ADR) equation through TVD (total variation diminishing) – MacCormack scheme. The diffusion term is solved through central difference scheme. The model results are first validated by comparing the results with analytical solutions for the simplified case. The validated model is then applied to a 30 kms stretch of the Bode River and simulations are conducted for multiple flow conditions. Impact of transient flow and nutrient boundary conditions on the evolution of algal trait is examined. Our simulation exercise highlights the importance of residence time in the temporal evolution of algae in pelagic and benthic zone and further identifies the most sensitive parameter influencing the evolution of the algal community modelled. Our research also reveals that largest uncertainty in the modelling stems from the wide range of entrainment rate that could be used for modelling resuspension of benthic algae in pelagic zone. The use of higher entrainment rate increased the algal concentration in the water column by 48% for identical flow conditions.

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1. Introduction

Eutrophication leading to algal bloom is one of the most severe ecological and environmental problems for both inland and coastal water bodies (Chun et al., 2007; David et al., 2010; Heisler et al., 2008; Simon et al., 2010). Increased frequency of algal blooms is detrimental to economic and recreational pursuits, human and aquatic ecosystems in general (Muttil and Lee, 2005). One of the major issues associated with algal bloom is depletion of dissolved oxygen and creation of hypoxic zone (Cox, 2003). The hypoxic zone thus created has a destabilizing impact on the fish habitat in the surface waters. Beyond a certain threshold value algae can also lead to occasional human poisoning through intake of contaminated food sources (Huppert et al., 2005; Allen et al., 2008). It has been established that algal blooms are primarily caused by some combination of climatic conditions, nutrient concentrations in surface waters and critical hydrodynamic conditions. The problem of understanding the physics behind the algal bloom is further exacerbated by algal traits, benthic and suspended/pelagic algae, which are located in physically separate areas. Bottom attached benthic algae observed in the range of 100–150 mg chlorophyll-a have been deemed unacceptable for river recreation (Welch et al., 1988; Suplee et al., 2009). Elevated level of benthic algae also is also detrimental for tourism and business (Pretty et al., 2002; Dodds et al., 2009). Increased agricultural activity in the wake of green revolution at the starting of twentieth century, combined with excessive use of fertilizers and manure has led to increase nutrient concentration in streams flowing through agricultural and urban areas (Smil, 1999; Spaulding and Exner, 1993). Multiple researchers have examined the dynamics of algal bloom from hydrodynamic and eutrophication point of view (Dodds et al., 2002; Yamamoto et al., 2002; Mitrovic et al., 2003; Gao et al., 2007). However, most of these studies are either experimental or statistical in nature based on the observed data. Although, of inherently sound scientific value, the observed data for bottom attached algae is usually

E-mail address: sumit.sinha@reading.ac.uk

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studied for low flow conditions and shallow streams that fails to disentangle the impact of changing flow conditions on the dynamics of benthic algae. The spatiotemporal evolution of suspended and benthic algae under transient flow and nutrient boundary conditions in aquatic environment is a tightly coupled and a highly non-linear phenomenon. The problem of tracking the evolution of different algal trait is compounded further by the asymmetric competition for light and nutrients across habitat boundary in shallow aquatic ecosystems by benthic and pelagic primary producers (Jager et al., 2014). In a shallow aquatic ecosystems light that is supplied from above first passes through suspended algae where it gets attenuated by the presence of dissolved substance and suspended particles, consequently the benthic primary producers are distinctly influenced by attenuation of the light coming from the top (Kirk, 1994; Vadeboncoeur et al., 2001). In contrast nutrients are usually released and supplied from the river bed. It is a well-known fact that particulate nutrients accumulate in sediments which are eventually released back in the water column (Rizzo et al., 1992; Caraco and Likens, 1992). The transfer of nutrients from the bottom of the river can be hampered by the production of benthic algae. This cyclical connection and asymmetric competition for resources makes a unique and interesting setting for examining the evolution of benthic and suspended algae under varying flow, nutrients and light conditions. Furthermore, algal cells are of higher specific density than water, consequently they sink out of the pelagic zone and part of their nutrient content is mineralized in the sediment layer (Jager et al., 2010). It is the hydrodynamic entrainment rate near the bed, varying with the flow condition, combined with turbulent mixing in the vertical direction is then responsible to get the nutrient back into the water column. Although the importance of the impact of fluvial processes (shear velocity, water depth, surface width and flow velocity) on spatial and temporal dynamics of algal biomass is well recognized in the lake research community (Riley et al., 1949; Sverdrup, 1953; Anita, 2005; Peterson et al., 2005), an equivalent study in a riverine environment is somewhat missing. To quote, Nijboer and Verdonschot (2004), "models are needed for forecasting the effect of eutrophication on stream and river ecosystems". In recent years with concomitant advances in computing power and numerical methodology there has been a renewed interest in understanding and disentangling the various effects of physical processes on biological variables.

The main objective of the research presented in this paper is to examine the spatiotemporal evolution of suspended and benthic algae in river reach under transient flow and nutrient boundary concentrations. Furthermore, we also examine the impact of changing light conditions as well as loss/death rate of both suspended and benthic algae on the temporal evolution of both suspended and benthic algae. In order to accomplish the aforementioned objective we developed a computationally efficient numerical model to solve Advcection Dispersion Reaction (ADR) equation in a channel with linear as well as non-linear decay term. Simulation results were validated against the analytical solution where present. The validated model was than enhanced to include various terms that represent the impact of light and nutrients on the pertinent state variables. The fully developed model is then applied to a 30 kms stretch of the Bode River located in central Germany. Numerical simulations were conducted for a period of 48 h to examine the impact of changing light penetration and death rate of suspended and benthic algae on the spatiotemporal evolution of algal traits under different flow conditions.

This remainder of the paper is organized as follows. In Section 2 the conceptual framework along with numerical scheme behind the developed model is presented. The model is validated, where possible, with the help of analytical solution at the end of Section 2. Section 3 provides the details about the field site and the river reach where the developed hydro-ecological model is applied. The relationship between the major fluvial variables for the reach under consideration is obtained via setup and application of HEC-RAS model, the details of which are provided in Section 3. Spatiotemporal evolution of suspended and benthic algae as obtained by the application of the developed hydro-ecological model is presented in the Section 4. The model is developed in FORTRAN-90 and is highly modular in nature for future developments.

2. Method

2.1. Hydro-ecological model

The hydro-ecological model developed and presented in this study numerically resolves suspended and benthic algae along with nutrients in a given river reach. Water column is divided into separate suspended/pelagic and benthic zones and spatiotemporal evolution of algae along with nutrients in surface waters and benthic zone is modelled by a mix of partial and ordinary differential equations (ODE) as shown in Eqs. (1)–(4).

The model is one-dimensional in nature and is extended from Jager and Diehl (2014), developed for lake ecosystems, to account for advection and longitudinal dispersion of suspended algae and nutrients in a river reach. The flow velocity in the domain is denoted by v (ms^{-1}) and longitudinal dispersion D_x(m^2s^{-1}). The biomass of suspended and benthic algae is denoted by A (mg of Carbon m^{-3}) and B (mgC m^{-3}) respectively. Reaction kinetics affecting the spatiotemporal evolution of suspended algae (A) can be classified broadly either as a source or a sink term for suspended algae. Growth rate, second term on the right hand side (rhs) of Eq. (1), and entrainment of benthic algae from benthic zone to the suspended zone, modelled by the third term on the rhs of Eq. (1), are the two source terms. The loss of suspended algae due to death rate, potentially attributed to grazing, and sedimentation or settling of the suspended algae are the two sink terms and are modelled by third and fourth term on the rhs of Eq. (1) respectively.

$$\frac{\partial A}{\partial t}+v\frac{\partial A}{\partial x}=D_x\frac{\partial^2 A}{\partial x^2}+\frac{A}{Z_{max}}\int_0^{Z_{max}}P_A\left(I(z),R_{surf}\right)dz+\frac{E}{Z_{max}}u_*B-l_A\cdot A-Sed_{rt}A \quad (1)$$

$$\frac{dB}{dt}=BP_B\left(I\left(z_{\max}\right),R_{bl},K_B\right)+\Gamma.Sed_{rt}Z_{\max}A-l_B\cdot B-Eu_*.B \quad (2)$$

$$\frac{\partial R_{surf}}{\partial t}+v\frac{\partial R_{surf}}{\partial x}= D_x\frac{\partial^2 R_{surf}}{\partial x^2}+\frac{a_{bl}}{Z_{\max}}\left(R_{bl}-R_{surf}\right)+c_Al_AA-\frac{c_A}{Z_{\max}}A\int_0^{Z_{\max}}P_A\left(I(z),R_{surf}\right)dz \quad (3)$$

$$\frac{dR_{bl}}{dt}=-\frac{a_{bl}}{z_{bl}}\left(R_{bl}-R_{surf}\right)-\frac{c_BB}{z_{bl}}P_B\left(I_{z\max},R_{bl},K_B\right) \quad (4)$$

$$P_A\left(I(z),R_{surf}\right)=p_A\frac{I(z)}{I(z)+h_A}\frac{R_{surf}}{R_{surf}+m_A} \quad (5)$$

$$P_B\left(I_{z\max},R_{bl},K_B\right)=p_B\left(1-\frac{B}{K_B}\right)\frac{I_{z\max}}{I_{z\max}+h_B}\frac{R_{bl}}{R_{bl}+m_B} \quad (6)$$

$$I(z)=I_oe^{-(k_AA+k_{bg})z} \quad (7)$$

The growth rate of the suspended algae is affected by the light intensity, which varies along the water column, and is also dependent on nutrient concentration in the surface water as shown in Eq. (5). The zero-order maximum photosynthesis rate for suspended algae is denoted by p_A (day^{-1}). The impact of nutrient concentration and light intensity on the growth rate of suspended algae is modelled via Monod expression (Michaelis and Menten, 1913; Michaelis et al., 2011; Monod, 1949) which varies between 0 and

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