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Research article

A novel application of remote sensing for modelling impacts of tree shading on water quality

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ABSTRACT

Uncertainty in capturing the effects of riparian tree shade for assessment of algal growth rates and water temperature hinders the predictive capability of models applied for river basin management. Using photogrammetry-derived tree canopy data, we quantified hourly shade along the River Thames (UK) and used it to estimate the reduction in the amount of direct radiation reaching the water surface. In addition we tested the suitability of freely-available LIDAR data to map ground elevation. Following removal of buildings and objects other than trees from the LIDAR dataset, results revealed considerable differences between photogrammetry- and LIDAR-derived methods in variables including mean canopy height (10.5 m and 4.0 m respectively), percentage occupancy of riparian zones by trees (45% and 16% respectively) and mid-summer fractional penetration of direct radiation (65% and 76% respectively). The generated data on daily direct radiation for 2010 were used as input to a river network water quality model (QUESTOR). Impacts of tree shading were assessed in terms of upper quartile levels, revealing substantial differences in indicators such as biochemical oxygen demand (BOD) (1.58–2.19 mg L^{-1} respectively) and water temperature (20.1 and 21.2 °C respectively) between 'shaded' and 'non-shaded' radiation inputs. Whilst the differences in canopy height and extent derived by the two methods are appreciable they only make small differences to water quality in the Thames. However such differences may prove more critical in smaller rivers. We highlight the importance of accurate estimation of shading in water quality modelling and recommend use of high resolution remotely sensed spatial data to characterise riparian canopies. Our paper illustrates how it is now possible to make better reach scale estimates of shade and make aggregations of these for use at river basin scale. This will allow provision of more effective guidance for riparian management programmes than currently possible. This is important to support adaptation to future warming and maintenance of water quality standards.

1. Introduction

The influence that riparian vegetation exerts on river water temperatures and light availability by intercepting incoming solar radiation has long been studied (Davies-Colley and Rutherford, 2005; Greenberg et al., 2012; Moore et al., 2005; Webb et al., 2008). Shading is a key parameter due to the control it exerts over the amount of direct radiation reaching the river surface making it an important consideration in water quality modelling and management. Solar radiation has direct effects on rates of primary production of both macrophytes and algae (Bowes et al., 2016, 2012b; Wood et al., 2012) which is important for river metabolic regime and is known to be influenced by riparian shade (Bernhardt et al., 2017). Water temperature also directly influences river fauna and dissolved oxygen concentrations. Therefore considerations of shading are of growing importance given the increasing stress on the water environment likely to arise under future climate. Effective and realistic riparian planting schemes to mitigate against these unwanted effects will become increasingly valuable and enhance water ecosystem services (Martin-Ortega et al., 2015). They will provide alternatives to traditional end-of-pipe solutions arising primarily from the EU Urban Wastewater Treatment Directive, which have been assessed through modelling (e.g. at large basin scale across Europe: Grizzetti et al., 2011).

1.1. Methods for estimating shade

Shade is spatially and temporally heterogeneous. Spatial variations are related to canopy characteristics (e.g. canopy cover extent, structure

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and tree height) and landscape characteristics (e.g. orientation, hill shade and channel width) (Li et al., 2012). Temporal effects are related to seasonal variation of canopy structure and sun position both during the day and over the year. Traditional methods for estimating reach-average shade have relied on location and time-specific field measurements (e.g. hemispherical photography or clinometer) taken at a small number of points along a river stretch which may not be representative, requiring onerous manual surveying and computation to extrapolate the results to wider areas (Davies-Colley and Rutherford, 2005; Ghermandi et al., 2009). As a result, these methods fail to capture the spatio-temporal heterogeneity of shade and introduce high uncertainty and bias in the estimates of shade. Without access to extensive remotely captured data, Chen et al. (1998b) identified that spatio-temporal variation of riparian shade could not be represented adequately for the purposes of simulating stream temperature for two main reasons: (i) lack of access to basin-wide riparian information (i.e. data that captured the vegetation characteristics in the basin); and (ii) limited ability to compute dynamic shading (i.e. algorithms to account for the geometric relationships between the diurnal arc of the sun, stream latitude, location and orientation, and the height and extent of all vegetation objects). Therefore, there is a need for simple but quantitative methods for measuring riparian vegetation shading along stream reaches comprising the two above-mentioned main features (Bode et al., 2014; Chen et al., 1998b, 1998a; Greenberg et al., 2012; Li et al., 2012).

As an alternative to measuring riparian shade, estimating radiation with GIS-based solar models to develop daily time series of incoming solar radiation could be undertaken. However, this is not a practical solution due to the inability of the GIS models to account for highly-chaotic and poorly-understood atmospheric conditions and processes, requiring the use of observed data to either parametrize the model or correct the output (Ruiz-Arias et al., 2009). Instead, for purposes of providing inputs for water quality models it is more effective to pursue efforts to model shade as a means of correcting observed radiation (Loicq et al., 2018; Wawrzyniak et al., 2017). Recent technological developments in data acquisition, greater capacity to handle large amounts of data and the development and widespread use of GIS systems, have created the opportunity to simulate the spatio-temporal variation of this important environmental parameter.

The challenge of obtaining information about spatio-temporal heterogeneity of shading was initially overcome using infrared aerial photographs and GIS technology to develop a model to simulate stream temperature at a catchment scale (Chen et al., 1998b, 1998a). Their model calculated the shadow cast on the water surface by riparian vegetation and topography every hour based on latitude, stream orientation and tree height. Nevertheless the resolution of the aerial photographs that were used was relatively coarse (1:40,000 infrared aerial photography) compared to the resolution of remotely captured data available nowadays (e.g. LIDAR) and their method of data capture relied on manual digitisation and transfer (Chen et al., 1998a). More recently, LIDAR data have been used, in conjunction with GIS-based solar models to estimate the effect of vegetation-cast shade in incoming solar radiation in the US (Bode et al., 2014; Greenberg et al., 2012), in the UK (Johnson and Wilby, 2015) and in France (Wawrzyniak et al., 2017; Loicq et al., 2018). In this way, variation across large areas of landscape and on river water surface is captured at a high spatial and temporal resolution. These studies demonstrate the utility of the growing pool of LIDAR data to characterise vegetation cover (Anderson et al., 2006; Seavy et al., 2009; Slatton et al., 2007; Greenberg et al., 2012; Bode et al., 2014; Loicq et al., 2018) for a variety of ecological and forestry studies. When coupled with GIS tools, the capability of LIDAR data to capture the canopy structure offers great potential to provide the radiation inputs required of water quality models.

The last few decades have seen an increase in LIDAR surveys being commissioned for the production of terrain models, and thus are carried out during winter to minimise the interference of vegetation on the ground signal; this data is referred to as leaf-off LIDAR. This has led many authors to assess the fitness of leaf-off LIDAR data to capture vegetation structure for ecology and forestry studies (Brubaker et al., 2014; Gopalakrishnan et al., 2015; Parent and Volin, 2014; Tompalski et al., 2017; Wasser et al., 2013). Outcomes have been generally favourable but complications exist. Leaf-off LIDAR may misrepresent the canopy characteristics, and in addition the data tend to include any other objects on the ground at the time of capture. Consequently strong biases may be introduced, yielding an incorrect representation of the actual canopy structure.

1.2. Use of shade estimates in river eutrophication studies

Recent eutrophication research has identified light limitation, as induced by riparian shade, to be a very important moderator on the development of river algal blooms (Bowes et al., 2016, 2012a; Hardenbicker et al., 2014; Waylett et al., 2013). Establishing riparian vegetation has been suggested as a more cost-effective means of preventing undesirable eutrophication impacts than reducing nutrient loads (Bowes et al., 2012a; Hutchins et al., 2010). However, for the purposes of managing eutrophication, establishment of riparian shade has traditionally been considered very much of secondary importance to the mitigation of nutrient inputs, and so modelling approaches to account for shade have tended to be rudimentary at best. For example, estimates of tree height and river width taken from phenology studies and aerial photography respectively (Halliday et al., 2016; Waylett et al., 2013) have been used to estimate height to width ratios used for calculating fractional penetration of radiation (Davies-Colley and Rutherford, 2005; DeWalle, 2010, 2008). The ratio, typically applied as a static value of the amount shade has been used in conjunction with estimates of occupancy based on satellite imagery or other land cover mapping products (Waylett et al., 2013). This pragmatic approach to estimating shade does not involve any additional computation, but is achieved at the expense of accuracy, since not taking into account the spatial and temporal heterogeneities introduces high uncertainty making its potential to provide management solutions limited.

1.3. Aims and objectives

The aim of this paper is to present and test a pragmatic method for reducing uncertainty in shade estimates to improve the utility of water quality modelling to inform management decisions. Developing such an approach is potentially very powerful as it circumvents the need for detailed field surveying of shade. The method quantifies average stream shading from nearby vegetation using high-resolution remotely-acquired data. The approach extends analysis to water quality beyond temperature simulation alone. The method was also tested on the River Thames as it has high levels of gross primary productivity due to long residence times and its water quality is known to be sensitive to shading (Bowes et al., 2016, 2012b).

The specific objectives of our study are to:

1) assess how well two high resolution elevation data products characterise riparian vegetation;
2) produce daily shade maps using those two datasets (section 3.2);
3) evaluate the consequences of using these two products for water quality modelling using the QUESTOR model on the river Thames (Hutchins et al., 2016; Waylett et al., 2013) and comparing these outcomes to those previously generated using the method of Waylett et al. (2013) and an application which disregarded shading influence (section 3.3).

The study is novel in making these comparisons between elevation data products and assessing their impacts in water quality modelling scenarios.