Journal of Environmental Management 180 (2016) 147–163

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Modelling the impacts of agricultural management practices on river water quality in Eastern England

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form
29 April 2016
Accepted 2 May 2016

Keywords:
Catchment management
Catchment modelling
Diffuse water pollution
Mitigation scenarios
SWAT
Water quality

ABSTRACT

Agricultural diffuse water pollution remains a notable global pressure on water quality, posing risks to aquatic ecosystems, human health and water resources and as a result legislation has been introduced in many parts of the world to protect water bodies. Due to their efficiency and cost-effectiveness, water quality models have been increasingly applied to catchments as Decision Support Tools (DSTs) to identify mitigation options that can be introduced to reduce agricultural diffuse water pollution and improve water quality. In this study, the Soil and Water Assessment Tool (SWAT) was applied to the River Wensum catchment in eastern England with the aim of quantifying the long-term impacts of potential changes to agricultural management practices on river water quality. Calibration and validation were successfully performed at a daily time-step against observations of discharge, nitrate and total phosphorus obtained from high-frequency water quality monitoring within the Blackwater sub-catchment, covering an area of 19.6 km^2. A variety of mitigation options were identified and modelled, both singly and in combination, and their long-term effects on nitrate and total phosphorus losses were quantified together with the 95% uncertainty range of model predictions. Results showed that introducing a red clover cover crop to the crop rotation scheme applied within the catchment reduced nitrate losses by 19.6%. Buffer strips of 2 m and 6 m width represented the most effective options to reduce total phosphorus losses, achieving reductions of 12.2% and 16.9%, respectively. This is one of the first studies to quantify the impacts of agricultural mitigation options on long-term water quality for nitrate and total phosphorus at a daily resolution, in addition to providing an estimate of the uncertainties of those impacts. The results highlighted the need to consider multiple pollutants, the degree of uncertainty associated with model predictions and the risk of unintended pollutant impacts when evaluating the effectiveness of mitigation options, and showed that high-frequency water quality datasets can be applied to robustly calibrate water quality models, creating DSTs that are more effective and reliable.

1. Introduction

Agricultural diffuse water pollution remains a notable global pressure on surface water and groundwater quality (Carpenter et al., 1998; Vörösmarty et al., 2010; European Environment Agency, 2012), and trends suggest that agricultural expansion will continue to exacerbate those pressures well into the 21st Century (Tilman et al., 2001). Legislation has been introduced in many parts of the world to protect water bodies from agricultural diffuse water pollution and to improve water quality, including the Nitrates Directive and Water Framework Directive (WFD) in Europe (Council of the European Union, 1991, 2000), and the Clean Water Act in the United States (United States Environmental Protection Agency, 2002). The WFD seeks to improve or maintain water quality through the establishment of River Basin Management Plans (RBMPs) and the development of Programmes of Measures (PoMs), which can be implemented to ensure that each water body within a river basin district achieves good ecological and chemical status (Council of the European Union, 2000). Member states committed to achieving this status by 2015 but many water bodies were not expected to meet the necessary water quality standards before this deadline (European Environment Agency, 2012). According to Solheim et al. (2012), 56% of rivers, 44% of lakes, 67% of transitional waters and 49% of coastal waters that have been classified in

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http://dx.doi.org/10.1016/j.jenvman.2016.05.002
0301-4797/

Europe do not achieve a good ecological status or potential and 6% of rivers, 2% of lakes, 10% of transitional waters, 4% of coastal waters and 25% of groundwater bodies by surface area are of a poor chemical status. Agricultural diffuse water pollution is cited as a significant pressure in 40% of rivers and coastal water bodies and one-third of lakes and transitional water bodies. Such poor water quality has consequences for the health of aquatic ecosystems, biodiversity, human health, the use of water in industry and agriculture and as a resource for public water supply and recreation (Carr and Neary, 2008).

In Europe, agricultural diffuse water pollution contributes 50–80% of the total nitrogen load and approximately 50% of the total phosphorus load in surface water bodies (European Environment Agency, 2005; Kronvang et al., 2009). In the United Kingdom (UK) specifically, agricultural diffuse water pollution is estimated to be responsible for 61% of the total nitrogen load and 28% of the total phosphorus load experienced within surface water bodies (Hunt et al., 2004; White and Hammond, 2007). Nutrient enrichment within surface waters due to the oversupply of phosphorus and nitrogen in agriculture increases the risk of eutrophication (Richardson and Jørgensen, 1996; Withers and Lord, 2002; Carr and Neary, 2008). While phosphorus pollution has implications for ecosystem health, nitrate pollution also has implications for the supply of water and human health (Withers and Lord, 2002). To protect human health, water is considered to be unfit for human consumption under the Drinking Water Directive applied within Europe if it contains a nitrate concentration above 50 mg L^{-1} (equivalent to 11.3 mg NO_3-N L^{-1}) (Council of the European Union, 1998), but many surface water and groundwater bodies within the UK contain concentrations of nitrate that approach or exceed this limit (European Environment Agency, 2012).

To develop PoMs that can be implemented under the WFD, authorities responsible for establishing RBMPs must be able to assess the effectiveness of potential mitigation options. Given the limited resources available to monitor and quantify the impacts of mitigation options in-field, and the need to provide timely evidence to inform policy, water quality models which can quantify the impacts of mitigation options on nutrient losses have been increasingly applied as Decision Support Tools (DSTs) within Decision Support Systems (Collins and McGonigle, 2008; Volk et al., 2008). This approach can be used to develop targeted mitigation plans, identify critical source areas and times, assess the cost-effectiveness of mitigation options, identify pollution swapping and involve stakeholders in the development of suitable management plans (Bouraoui and Grizzetti, 2014). Effective dialogue and engagement between stakeholders and scientific experts is essential to ensure that the PoMs are appropriate, cost-effective and sustainable and to maximise the effectiveness of the mitigation practices that are introduced (Van Ast, 2000; Gerrits and Edelenbos, 2004).

The Benchmark Models for the Water Framework Directive project established a set of criteria to assess which models have the potential to assist in the implementation of the WFD (Saloranta et al., 2003). As part of this project, the suitability of the Soil and Water Assessment Tool (SWAT) water quality model for assessing the impacts of mitigation options proposed to meet WFD targets on water quality was examined by Bärlund et al. (2007). Rode et al. (2008) and Volk et al. (2009) also applied SWAT to examine the potential for changes in catchment management to ensure that water bodies achieve WFD targets. SWAT has been widely and successfully applied to assess the impacts of agricultural mitigation options on water quality and can therefore be considered to be an appropriate DST for assisting authorities in managing catchments to achieve statutory water quality targets (e.g. Santhi et al., 2006; Hu et al., 2007; Ullrich and Volk, 2009; Lam et al., 2011; Moriasi et al., 2011; Glavan et al., 2012; Aouissi et al., 2014; Boithias et al., 2014; Santhi et al., 2014). Examples of mitigation options that have been modelled include buffer strips, nutrient management plans, alternative tillage techniques, alternative crop rotations and changes in land use.

In this study, based in the River Wensum catchment in Eastern England (Fig. 1), the availability of a high-quality, high-frequency dataset of water quality enabled the performance of SWAT in simulating multiple pollutants at a daily time-step to be assessed. SWAT was also used to investigate the impacts of agricultural mitigation options on long-term water quality at a daily resolution and to assess the uncertainties of the predicted impacts of mitigation options on water quality. The unique water quality dataset applied within this study is derived from continuous monitoring at a 30-min temporal resolution. Such a monitoring strategy reduces the uncertainty associated with estimates of in-stream nutrient loads relative to datasets derived from fewer samples collected at longer time intervals and ensures that the model applied within this investigation has been robustly calibrated. This lower uncertainty allows the model to be applied with a higher degree of confidence, creating a more effective and reliable DST.

There is no standard or universally accepted metric applied to assess model performance but Moriasi et al. (2007) suggested that models should achieve a Nash-Sutcliffe Efficiency (NSE) coefficient of greater than 0.5 for flow, nitrogen and total phosphorus at a monthly time-step for performance to be considered satisfactory. If we consider this performance criterion to apply at all time-steps, over half of the 115 SWAT hydrological assessments and 37 SWAT pollutant loss studies summarised by Gassman et al. (2007), achieved this level of model performance, but some studies reported poor results for all variables particularly at a daily time-step and it is in this context that we consider the performance of SWAT within the River Wensum catchment.

Since 2010, the River Wensum catchment has been the focus of the Wensum Demonstration Test Catchment (DTC) Project which aims to provide evidence to test the hypothesis that it is economically feasible to reduce agricultural diffuse water pollution through the introduction of agricultural mitigation practices whilst maintaining agricultural productivity (Wensum Alliance, 2014). The Blackwater sub-catchment has been selected as a pilot area where the effects of changes in management will be investigated and is considered to be representative of the rest of the River Wensum catchment. To identify the mitigation options that are most relevant for the River Wensum catchment, there has been close cooperation and engagement between local land owners, farm managers, environmental organisations, government agencies and scientific experts. With knowledge gained from these stakeholders, the aim of this investigation is to apply SWAT to the Blackwater sub-catchment to quantify the long-term impacts of potential changes to agricultural practices on water quality, to assess the uncertainties of those predictions and to identify mitigation options that have the potential to be applied within similar arable catchments to improve water quality. This is one of the first studies to quantify the impacts of agricultural mitigation options, both singly and in combination, on long-term water quality for nitrate and total phosphorus at a daily time-step, in addition to providing an estimate of the uncertainties of those impacts.

In the remaining parts of this paper, a brief review of the study area, the datasets used and the methodology adopted in applying SWAT to the Blackwater sub-catchment is provided. A detailed summary of the mitigation options that were selected and modelled is also supplied. The results of model calibration and validation and the impacts of each agricultural measure on water quality, both singly and in combination, are also presented and discussed. Finally, conclusions and a summary of findings are