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# Predicting diffuse microbial pollution risk across catchments: The performance of SCIMAP and recommendations for future development

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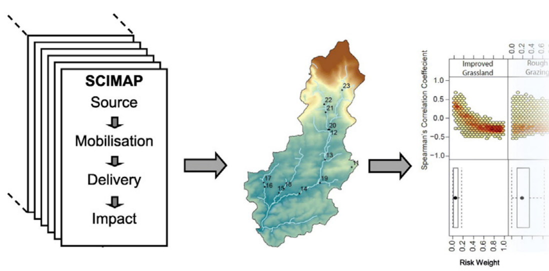
## HIGHLIGHTS

- A catchment risk modelling framework is applied to FIO pollution for the 1st time.
- Performance was variable with assignment of risk to land cover types uncertain.
- Information on livestock densities and management regimes may improve performance.
- Modelled results reinforce the importance of seasonal variation in FIO pollution.
- Varying land-use mosaic is important for the success of the SCIMAP fitted approach.

## GRAPHICAL ABSTRACT




SCIMAP risk modelling framework repeated many times with different model parameters

Compare each of the model realisations against spatially distributed observed FIO concentrations

Compare the performance of the different models

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## ABSTRACT

Microbial pollution of surface waters in agricultural catchments can be a consequence of poor farm management practices, such as excessive stocking of livestock on vulnerable land or inappropriate handling of manures and slurries. Catchment interventions such as fencing of watercourses, streamside buffer strips and constructed wetlands have the potential to reduce faecal pollution of watercourses. However these interventions are expensive and occupy valuable productive land. There is, therefore, a requirement for tools to assist in the spatial targeting of such interventions to areas where they will have the biggest impact on water quality improvements whist occupying the minimal amount of productive land. SCIMAP is a risk-based model that has been developed for this purpose but with a focus on diffuse sediment and nutrient pollution. In this study we investigated the performance of SCIMAP in predicting microbial pollution of watercourses and assessed modelled outputs of *E. coli*, a common faecal indicator organism (FIO), against observed water quality information. SCIMAP was applied to two river catchments in the UK. SCIMAP uses land cover risk weightings, which are routed through the landscape based on hydrological connectivity to generate catchment scale maps of relative in-stream pollution risk. Assessment of the model's performance and derivation of optimum land cover risk weightings was achieved using a Monte-Carlo sampling approach. Performance of the SCIMAP framework for informing on FIO risk was variable with better performance in the Yealm catchment ($r_s = 0.88$; $p < 0.01$) than the Wyre ($r_s = -0.36$; $p > 0.05$). Across both catchments much uncertainty was associated with the application of optimum risk weightings

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attributed to different land use classes. Overall, SCIMAP showed potential as a useful tool in the spatial targeting of FIO diffuse pollution management strategies; however, improvements are required to transition the existing SCIMAP framework to a robust FIO risk-mapping tool.

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## 1. Introduction

Faecal pollution has the potential to negatively impact upon ecosystem services associated with clean and safe recreational bathing and shellfish harvesting water (Clements et al., 2015; Wu and Jackson, 2016). Microbial contamination of such aquatic environments can expose humans to harmful pathogens that may cause gastro intestinal illness (Wade et al., 2006). Direct measurement of pathogens in environmental water samples is uncommon due to challenges associated with their enumeration in the laboratory, e.g. cost, detection limits etc., and so faecal indicator organisms (FIOs) such as *Escherichia coli* and intestinal enterococci provide an internationally accepted framework for the assessment of faecal pollution of water bodies. In the European Union, the health risks of faecal pollution of aquatic environments are recognised via the Bathing Water (EU, 2006a) and Shellfish Water (EU, 2006b) Directives. Regulators must compare measured FIOs against stringent standards of microbial water quality in order to comply with these directives. Risk assessment tools that can identify 'hotspots' of FIO pollution in catchment systems are therefore welcomed by regulatory agencies as a mechanism to help understand origins of pollution and to spatially target catchment management and interventions for improvements in microbiological water quality (Dymond et al., 2016).

Diffuse sources of FIO pollution, such as organic fertilisers applied to land and excretion of faeces by grazing livestock to pasture, provide challenges to water quality managers. This is because the loading of diffuse sources, and their propensity to connect to watercourses, varies spatially and temporally (Heathwaite et al., 2005). The impact of diffuse sources of microbial pollution on watercourses can be reduced through the use of mitigation measures such as streamside fencing (Kay et al., 2007a), vegetated buffer strips (Tate et al., 2006), wetlands (Morató et al., 2014) and retention ponds (Jenkins et al., 2015). These measures can be expensive and occupy valuable productive land. Therefore, methods to spatially identify and target locations in catchments where interventions will provide the best improvement in water quality are warranted. Past research has used regression approaches to attribute sources of FIOs to different land cover types and/or discrete point sources (Kay et al., 2010; Tetzlaff et al., 2012; McGrane et al., 2014). However, these approaches do not account for the spatial heterogeneity of landscape to watercourse connectivity (Tetzlaff et al., 2012).

Alternative approaches include the development of fully process-based models that attempt to account for the mechanisms that govern FIO fate and transfer in more detail. For example, the modified Soil and Water Assessment Tool (Cho et al., 2016a) and INCA-pathogens (Rankinen et al., 2016). There are, however, limitations in our understanding of FIO fate and transfer that can amplify uncertainties in fully quantitative, process-based risk assessment approaches. For example, there are knowledge gaps regarding the complex behaviour of FIO persistence in different matrices such as faecal deposits (Soupir et al., 2008; Martinez et al., 2013; Oliver and Page, 2016), soil (Muirhead and Littlejohn, 2009; Park et al., 2016) and stream bed sediment (Pachepsky and Shelton, 2011; Shelton et al., 2014; Pandey and Soupir, 2013; Pandey et al., 2016). Such limits in understanding make it difficult for all processes to be considered in complex process-based models (Beven, 2006, Cho et al., 2016b). These complex models also require a significant amount of data for model parameterisation and validation. This is especially problematic in the field of catchment microbial dynamics due to the relative scarcity of data on FIO concentrations and loads compared to nutrient and sediment flux (Muirhead, 2015; Oliver et al., 2016). Semi-quantitative risk assessment frameworks, which provide a basis for decision support, are therefore useful tools to inform on relative risk of FIO transfers in space and time. This is because, despite gaps or limitations in the current evidence-base concerning FIO behaviour in complex catchment systems, they are able to provide a '1st approximation' of risk (Goss and Richards, 2008; Oliver et al., 2010).

The Sensitive Catchment Integrated Mapping Analysis Platform (SCIMAP) has demonstrated significant potential as a framework to inform on catchment-scale risks for diffuse nutrient and sediment pollution (Reaney et al., 2011). The approach provides an estimate of in-stream risk relative to the catchment being considered, and provides information at multiple spatial scales but within a time integrated framework. SCIMAP is underpinned by the source-mobilisation-delivery-impact (SMDI) continuum (Haygarth et al., 2005) and critical source area (CSA) concepts, which describe how a source of pollution can only convert to a pollution risk if there are no interruptions to the SMDI continuum (Heathwaite et al., 2005). At present, the SCIMAP approach is optimised for diffuse fine sediment (Reaney et al., 2011) and nutrient pollution (Milledge et al., 2012) but offers scope for addressing a number of additional diffuse pollutants, including FIOs. Given the growing interest and uptake in the use of SCIMAP among different stakeholder communities in the UK, its continued development to account for a wider array of pollutants is justified. Furthermore there are, at present, few risk-based modelling approaches for informing on FIO impairment of surface waters at the catchment scale.

The aim of this study was to assess the effectiveness of the current SCIMAP framework for informing on risk of FIO pollution in contrasting catchment systems by comparing FIO pollution risk predicted by SCIMAP with observed FIO risk, e.g. FIO concentrations. To deliver on this aim the objectives were to: (i) quantify variation in model performance as a result of risk weightings being assigned to a particular land cover type; and (ii) determine whether there was an association between SCIMAP predicted FIO risk and observed FIO risk in our study catchments. The intention was to develop initial risk weightings for land cover types and benchmark model performance on the assumption that FIOs behave similarly to sediment, albeit in a 'living' form.

## 2. Methods

Most modelling frameworks predict in-stream pollution by defining a function, e.g. a relationship derived from regression analysis, and these can be described as forward models. Our study adopted an inverse approach (Reaney et al., 2011; Milledge et al., 2012), because it defined a function (in the case of SCIMAP, land cover risk weightings) based on observed FIO concentrations, i.e. the approach queries how a model needs to be parameterised in order to simulate observed pollution, and is therefore 'fitted' to observed data. This 'fitted' approach is described in detail in Milledge et al. (2012). Briefly, the fitted approach involves pseudo randomly generating simulations from forward models whose output is compared to observed data. In this case the forward model used is SCIMAP and the user definable parameters are risk weightings for different land cover types. Model outputs were compared against a spatial FIO water quality dataset provided by the Environment Agency. This dataset spans 6 years (2007–2012) and was collected as part of the Catchment Sensitive Farming (CSF) initiative (Environment Agency, 2016). The FIO dataset reported here concerns *E. coli* concentrations, measured using the standard method of membrane filtration, reported across two catchments in England: The River Wyre, Lancashire and The River Yealm, Devon (Fig. 1).

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