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Design of a decision support tool for visualising *E. coli* risk on agricultural land using a stakeholder-driven approach

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ABSTRACT

Enabling knowledge exchange between scientists and decision-makers is becoming increasingly necessary to promote the development of effective decision-support tools (DSTs) for environmental management. Participation of stakeholders in the design process beyond a basic level of consultation is essential for promoting trust in modelled outputs and accelerating eventual uptake of resulting tools and models by end-user communities. This study outlines the development of a DST to visualise and communicate the spatial and temporal patterns of *E. coli* (a faecal indicator organism) on agricultural land, as a first step in managing microbial pollution risks to the wider environment. A participatory approach was used to engage regulators, catchment managers, environmental scientists, farmers and farm advisors, researchers in geospatial technologies and water industry staff in the co-design of a novel, user-friendly and accessible DST for guiding on-farm microbial risk assessment. Recommendations for maximising the benefits of a participatory process to DST design are discussed with reference to a series of opportunities and limitations identified by our stakeholder cohort during the development of the Visualising Pathogen & Environmental Risk (ViPER) DST. The resulting toolkit provides environmental managers and farm advisors with one of the first freely-available DSTs for visualising patterns of *E. coli* inputs to pasture in space and time, and begins to address the lack of advisory tools currently available for informing decision-making with respect to managing microbial risks in agricultural systems.

1. Introduction

The visualisation of environmental risk provides a powerful tool to communicate the outcome of complex environmental risk assessment to decision makers (Lahr and Kooistra, 2010). Despite this power, many approaches for communicating risk are poorly received by end-users, which is often attributed to a lack of engagement with end-user communities in the design of such tools (Whitman et al., 2015). Thus, any attempt to bridge the gap between complex scientific tools and user-friendly systems for risk communication requires a 'human-centric' approach. This requirement is especially true in the field of catchment management where important advances in soil and water science often remain inaccessible to those who manage landscape risk on a day-to-day basis (Oliver et al., 2016).

The establishment of mechanisms that enable an exchange of knowledge between scientists and decision-makers is therefore becoming increasingly necessary to promote the development of effective tools and guidance for helping to tackle complex environmental challenges (Karpouzoglou et al., 2016). Indeed, participatory approaches recognise the benefits of capitalising on a wealth of stakeholder expertise to enable the co-design of, for example, decision support tools (DSTs) (Evans et al., 2016; Maskrey et al., 2016; Dupas et al., 2015; Wilkinson et al., 2015). This marks a significant departure from tool development conducted in isolation by technical experts, which can subsequently result in poor uptake by end-users because of complex and inaccessible design, to one of joint ownership in the design of engaging and user-friendly tools and models. Not surprisingly, the involvement of stakeholders in the process of designing and developing a DST is likely to result in greater trust in the model outputs, which in turn helps to promote the acceptance and uptake of the resulting DST (Hewett et al., 2016; Oliver et al., 2012a).

Significant developments in the field of agricultural decision support have focused on nutrient management planning tools (e.g. Heathwaite et al., 2003a, 2003b; Brown et al., 2005; Bechmann et al., 2007), with some approaches offering interactive and user-friendly engagement with the resulting DST. Examples include, the

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Phosphorus Export Risk Matrix (PERM) (Hewett et al., 2004, 2010), the Floods and Agriculture Risk Matrix (FARM) (Wilkinson et al., 2013) and the Nitrate Export Risk Matrix (NO3RM) (Hewett et al., 2016), among others. Conceptual frameworks to inform decision-making with respect to multiple pollutants of concern to the water industry, including nutrients, pesticides, dissolved organic carbon and sediments, are also emerging (Bloodworth et al., 2015). By contrast, relatively little attention has been given to the development of tools and models for visualising risks concerning microbial pollution from agriculture, most often determined via quantification of faecal indicator organisms (FIOs) in environmental samples. The most commonly used FIO is *E. coli*, and its presence in soil and water suggests a connection between the point of sampling and a faecal source. Efforts to visualise on-farm microbial pollution risks thus far extend to a number of simple index concepts and approaches that have been developed to consider how *E. coli* and potential pathogens accrue in agricultural systems (e.g. Muirhead, 2015; Oliver et al., 2010a; Oliver et al., 2009; Goss and Richards, 2008). Others have started to explore the mapping of *E. coli* sources connected to waterways under current land use in order to highlight the relative importance of different processes involved and hence identify relative priorities for mitigation (Dymond et al., 2016). However, while these tools may be structurally simple, their operation and functionality are not currently accessible to those who would benefit most from their use. In many cases the development of a user-friendly graphic user interface (GUI), coupled with web-based format, provides a mechanism to open-up access to the underpinning science, existing data and the associated model to stakeholders such as policy makers and those with a responsibility for land-based decision-making. The design of a GUI to enable wider access to tools and modelling capability, as has been demonstrated to an extent with nutrient management DSTs (Liu et al., 2014; He et al., 2014), therefore represents a key pathway in helping to convert scientific outputs into real world impact.

Understanding the range and magnitude of *E. coli* sources in a catchment system, in both space and time, helps to identify land considered to be of highest risk of contributing to microbial pollution of water, and can therefore be used to prioritise where management and mitigation should be targeted to deliver maximum benefits for water quality. The aim of this research was to (i) introduce a novel GUI for guiding the spatial mapping of *E. coli* risks in agricultural systems; and (ii) outline the participatory approach that led to the development of the Visualising Pathogen & Environmental Risk (ViPER) DST. The ViPER DST was designed in collaboration with the UK end-user community to specifically address the lack of decision support and advisory tools currently available for informing decision-making with respect to managing microbial risks in agricultural systems.

2. Towards a decision support tool to guide *E. coli* risk mapping

The generation of diffuse microbial pollution links strongly to the well-established concept of critical source areas (CSAs) within agricultural landscapes (Heathwaite et al., 2005) whereby ‘risky’ land is produced when a pollutant source coincides with an opportunity for connectivity to a watercourse. Understanding how, when and where sources of *E. coli* accumulate in agricultural landscapes therefore provides an important first step in identifying potential hotspots of *E. coli* pollution risk. Catchments dominated by agriculture have consistently been shown to be associated with high *E. coli* concentrations in receiving waters (Kay et al., 2010). This is largely because faeces excreted directly onto pasture from grazing animals can contribute a significant burden of faecal bacteria to agricultural land, often in excess of 10^{12} *E. coli* per hectare during each grazing season (Oliver et al., 2012b). Concentrations of *E. coli* present in faeces vary with livestock type and diet and once excreted, *E. coli* populations will begin to die-off at a rate that varies according to the surrounding temperature, season and location. The balance between accumulation and depletion of *E. coli* within land-based reservoirs is dependent on understanding the dynamics of, and subsequent risk from, faecal deposits and, to a lesser extent, land applications of manures and slurries (Vinten et al., 2004).

2.1. An underpinning model

The ViPER DST is underpinned by an empirical model first reported as part of a cross-disciplinary toolkit for assessing farm scale contributions to *E. coli* risk (Oliver et al., 2009), which has since developed and refined (Oliver et al., 2010b; Oliver et al., 2012b). Briefly, this empirical model was constructed using biological parameters of die-off, faecal excretion and *E. coli* shedding rate. Parameter values for daily *E. coli* shedding by dairy cows, beef cows, calves, sheep and lambs are included in the model but can be set to represent local conditions where data are available. The model accounts dynamically for the accumulation and depletion of *E. coli* burden to land at daily time-steps. Full details of how the underpinning model of the DST operates are reported in Oliver et al. (2012b).

2.2. Meeting the needs of end-users (stakeholder engagement)

While the model described above is structurally simple its operation and functionality was not accessible to those who would benefit most from its use (e.g. farm advisors, environmental regulators). The purpose of the ViPER DST was to therefore promote wider access to this model through the development of a user-friendly GUI and web-based format using a participatory approach to its design and evolution. To facilitate joint decision-making in the design process we combined scientific expertise and local knowledge, which in turn helped to maximise the opportunities and multiple-benefits arising from the development of the ViPER DST. A variety of knowledge exchange (KE) mechanisms were adopted and centred on an inception workshop, a ‘stress-testing’ & steering workshop and demonstration events with different end-users. A full list of stakeholder organisations involved in the development of ViPER is provided in Table 1. Establishing a cohesive social infrastructure was critical for the development of the ViPER DST, most notably in the form of an engaged stakeholder group, and this comprised university researchers, environmental regulators from both England and Scotland, farmers, farm advisors, catchment management teams from UK water companies and experts in public health. Critically, stakeholders were involved from project inception, were engaged through to the completion of the DST, and were asked to contribute to strategic decision-making in the design of the DST in an effort to reduce barriers to uptake and future implementation, and move towards a ‘partnership paradigm’ (Matthews et al., 2008). In the final stages of development, the ViPER DST was showcased to a network of

Table 1
Stakeholders involved in the development of the ViPER DST (e.g. participation at workshops).

Stakeholder organization	Role in Project	Description of Organisation
University of Stirling	Project co-ordination	Academic organisation
Lancaster University	Project co-ordination	Academic organisation
Scottish Environment Protection Agency	Participant – advisory	Environmental regulator
Environment Agency	Participant – advisory	Environmental regulator
Catchment Sensitive Farming	Participant – advisory	Farm advisor community
Scottish Water	Participant – advisory	Water industry (Government owned, Scotland)
United Utilities	Participant – advisory	Water industry (Privately owned, England)
Scotland’s Rural College	Participant – advisory	Academic organisation
James Hutton Institute	Participant – access to existing farmer networks	Research institute