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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

farmers attending a local catchment forum and a series of outputs were generated for their own farm enterprises as means of a demonstration. These outputs were then scrutinised by the farmers, thus providing an effective qualitative 'on-the-ground' evaluation of the DST. Such an approach has been recognised as a useful step to assure that a DST is operational among end-users (Kerselaers et al., 2015).

3. The ViPER approach

Beyond simply developing a GUI, the intention was to create a web-based platform for the DST. The rationale for a web-based client server approach was based on a number of factors which included accessibility across different desktop operating systems (Windows, Linux, OSX), no installation of programmes being required, the underpinning model always being up-to-date because data are kept centrally, and potential to share data with other users via online permissions. Conversion of the conceptual basis for the ViPER DST to a procedural DST required server hardware and software development. On the server side this included a spatial database to store farm field definitions, and a FIO modelling tool, and for the interactive web client included map editing and reporting tools. It is not the purpose of this paper to detail the software coding process that enabled functionality within the ViPER DST, but rather explore how it was built using both local knowledge and scientific expertise. The ViPER DST portal is accessible via www.nercviper.co.uk taking the user to the DST front page (Fig. 1), from here the user can view details about the toolkit and explore three distinct farm-based tools: 1) a demonstration farm environment; 2) a basic *E. coli* calculator; and 3) a spatial and temporal *E. coli* risk-mapping tool.

3.1. A demonstration farm environment (visual interaction)

The ViPER demonstration farm provides an interactive drag-and-drop environment whereby end-users can vary livestock grazing regimes and explore 'what-if?' scenarios for generating *E. coli* loading to pasture. Essentially, the demonstration farm represents a conceptual model of a very simple farm system, allowing end-users to engage with the basic premise of the DST (Fig. 2). The rationale for inclusion of this 'virtual' demonstration farm was based on its perceived usefulness for the farm advisor community as an engagement tool to help facilitate discussion with farmers about how and why *E. coli* risks might materialise and change in a generic farm system. Through being quick and easy to use it was seen as a conversation starter and, due to its simple design, required no training but offered a 'playful' interface. Further, given that no association was made with a real farm enterprise it removed any suggestion of 'blame' attributable to a particular identifiable farm unit, and allowed visualisation of grazing scenarios and their corresponding *E. coli* burden risks, without the farmer feeling that their own farm was under scrutiny. The suggestion by the end-user community to include this drag-and-drop interface complements findings from wider national surveys of farmer perceptions of DSTs within which there were calls for increased visualisation of information, more maps, and less text (Rose et al., 2016).

The need for speed was another key issue in the development of the demonstration farm environment. It was therefore considered essential to make this run entirely in the client web browser thereby removing any processing demands on the server during end-user interactions with this component of the DST. To meet this design objective for real time 'playful' interaction it was necessary to constrain how end-users were able to interact with the demonstration farm environment. Thus, the farm environment comprised four simple fields, restricted to either 5, 10 or 20 ha in area (two fields are 10 ha to allow direct comparison of different scenarios). End-users could choose to populate these fields with grazing livestock attributed to the five aforementioned categories but only in multiples of 10 cows/calves or 25 sheep/lambs. Stocking densities were then converted into a gradient of risk of *E. coli* loading to land (CFU ha^{-1}), from low to high, colour-coded green to red, respectively. Restricting the field sizes and grazing livestock numbers meant that the DST could calculate *E. coli* loading very quickly from a pre-determined matrix of calculations that was developed to account for every possible permutation of livestock grazing per field. Findings from a recent survey of farmers in England and Wales concerning on-farm decision-making and DSTs further reinforce the importance of 'instantaneous information' being delivered from DSTs as a pivotal factor influencing uptake (Rose et al., 2016). The demonstration farm environment was therefore considered an important preliminary tool for capturing a farmer's interest, which would then enable further discussion and their continued engagement with the DST.

3.2. A basic *E. coli* calculator (time series plots)

The *E. coli* calculator provides a useful tool for estimating *E. coli* loads (CFU ha^{-1}) on pasture, and in contrast to the demonstration farm environment, allows for flexibility in user-defined scenarios (e.g. specific livestock numbers on fields of an exact size defined by the user). This was welcomed by stakeholders as a logical progression from the demonstration farm environment, while at the same time representing a tool that was equally useful as a stand-alone component within the ViPER DST. The use of custom-built scenarios, such as that available within the basic *E. coli* calculator, open up opportunities for end-users to experiment and explore the relative impacts and consequences of the decision-making process (Lacoste and Powles, 2016). To our knowledge, the basic *E. coli* calculator is the only freely available tool for calculating *E. coli* burden on pasture from grazing livestock as governed by faecal excretion and *E. coli* die-off. The contribution of the total *E. coli* load to pasture is apportioned according to each livestock category

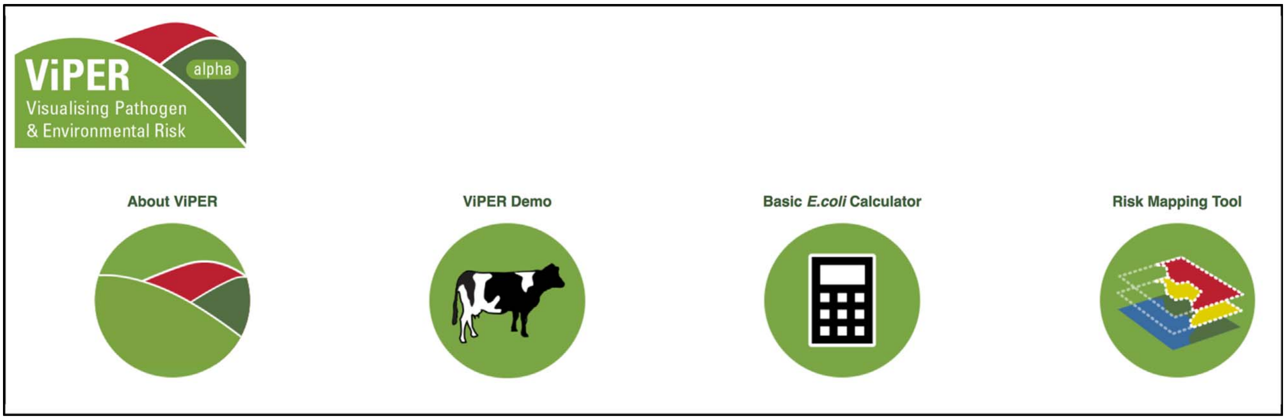
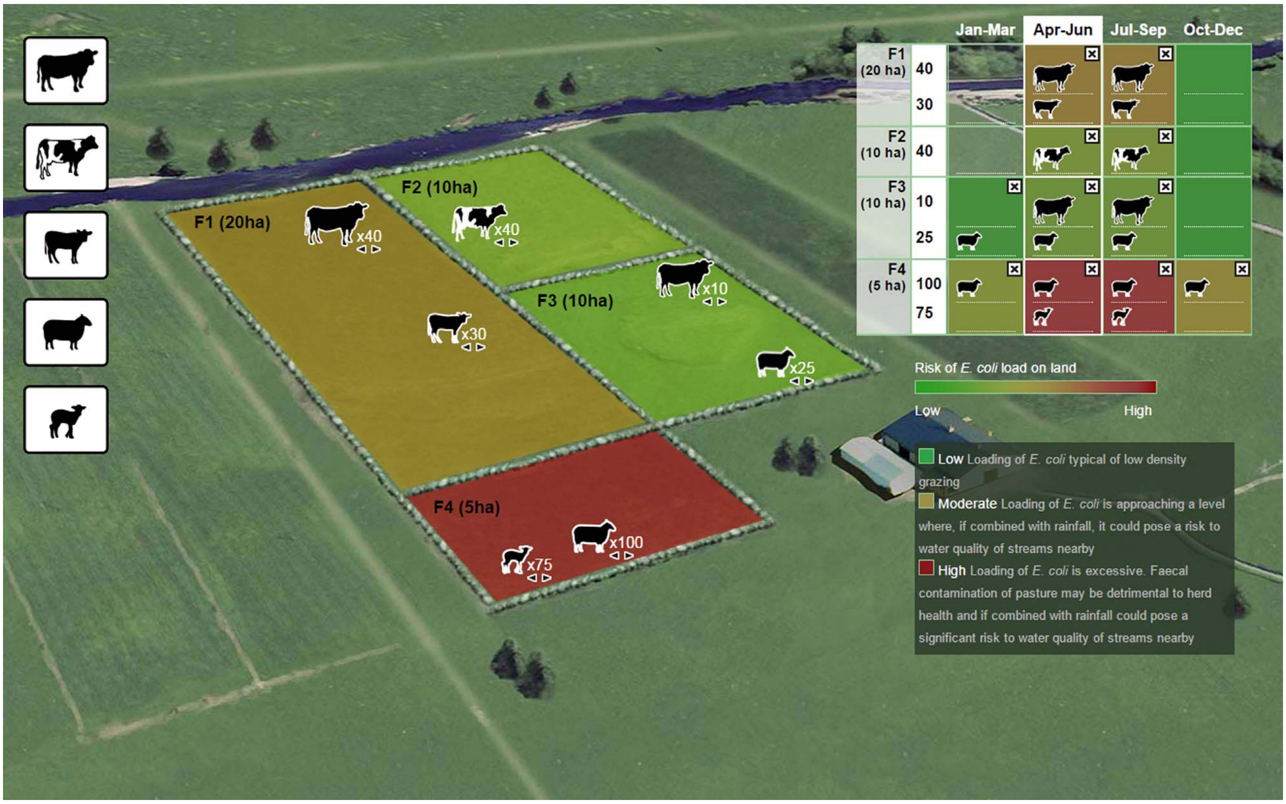


Fig. 1. Screenshot of the ViPER DST front page available at www.nercviper.co.uk.



🟩 **Low** Loading of *E. coli* typical of low density grazing

🟨 **Moderate** Loading of *E. coli* is approaching a level where, if combined with rainfall, it could pose a risk to water quality of streams nearby

🟥 **High** Loading of *E. coli* is excessive. Faecal contamination of pasture may be detrimental to herd health and if combined with rainfall could pose a significant risk to water quality of streams nearby

Fig. 2. Screenshot of the 'drag-and-drop' interface of the demonstration farm environment available at www.nercviper.co.uk – for interpretation of colour in this figure, the reader is referred to the web version of the article.

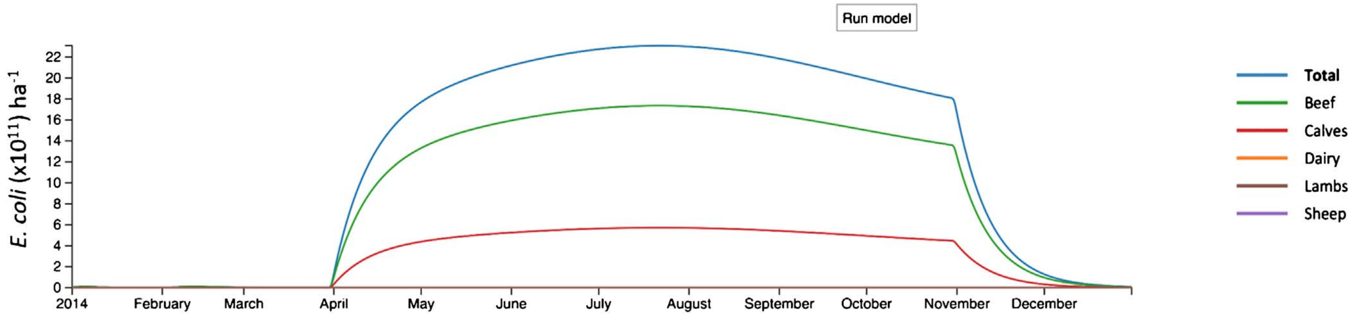


Fig. 3. Typical time-series of *E. coli* burden associated with different grazing livestock. Available at www.nercviper.co.uk – for interpretation of colour in this figure, the reader is referred to the web version of the article.

(beef and dairy cows, calves, sheep and lambs) to identify which animals are contributing higher *E. coli* burden to land relative to others for any given livestock grazing scenario. Fig. 3, for example, shows the resulting *E. coli* burden following the reintroduction of 25 beef cows and 15 calves to 10 ha of pasture following the winter housed period typical for the northern hemisphere. This output is particularly helpful in targeting on-farm advice to reduce *E. coli* burden for scenarios where multiple livestock types are present. As with the demonstration farm environment, the calculator does not need to associate with a geo-referenced farm location and thus represents another tool in the ViPER DST package that can help to raise awareness among farming communities about how, where and when *E. coli* accumulation on pasture can occur, but without any specific scrutiny of a particular farm enterprise.

3.3. A spatial and temporal E. coli risk-mapping tool

The original objective for the ViPER DST was to deliver a spatially-explicit risk-mapping tool to identify relative differences in *E. coli* burden on land associated with different grazing scenarios. The demonstration farm environment and the *E. coli* calculator were not originally considered as components necessary for the ViPER DST and without stakeholder engagement and a participatory approach to DST design these important components of the ViPER DST would not have been developed. While this highlighted a clear mismatch between the developer and end-user vision for the DST the advantage was that this mismatch was identified *and acted upon* in the early stages of the DST evolution. Failure to engage with the end-users at project inception would therefore have likely reduced the relevance of the resulting DST for the end-user communities because of misdirected efforts by the development team (Lacoste and Powles, 2016). The expertise and experience of the stakeholder group in advising and engaging with farmer communities recognised that these additional functions would provide a potential mechanism to familiarise members of the farming community with the risk mapping tool, and serve to not just develop an understanding of *E. coli* risks in agricultural systems but also a rapport between the farmer and the advisor while exploring the toolkit.

The third and most sophisticated tool associated with the ViPER DST was a risk-mapping tool that combines elements of the demonstra-

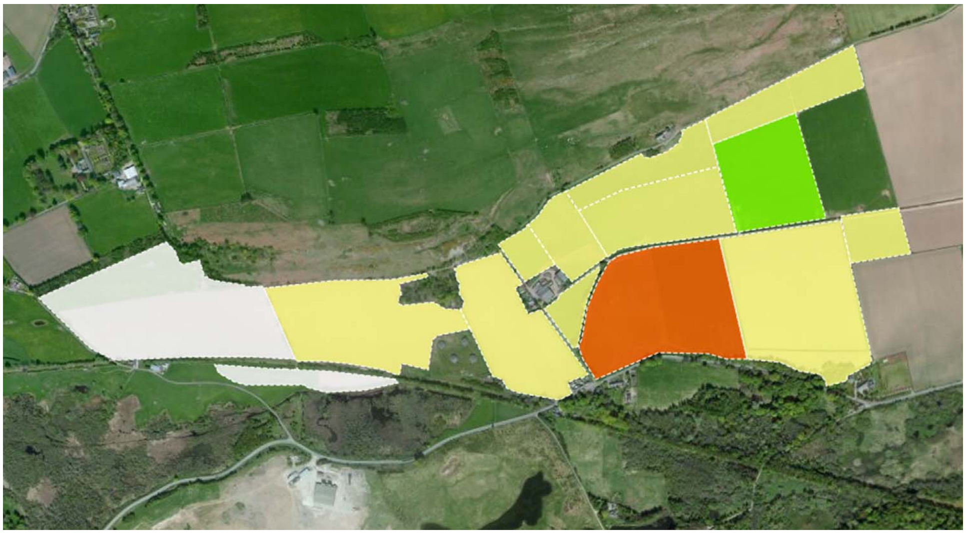


Fig. 4. Spatial risk map for a point in time across a farm boundary to identify where *E. coli* burden is greatest. Available at www.nercviper.co.uk – for interpretation of colour in this figure, the reader is referred to the web version of the article.

tion farm environment and the *E. coli* calculator to generate risk maps for geo-referenced fields and farms (Fig. 4). It can operate as a standalone product or complement the other two tools if they are considered appropriate for building a level of understanding about *E. coli* dynamics on pasture prior to generating a farm risk map. The farm risk map details how spatial and temporal patterns of *E. coli* risk accrue across a defined farm boundary using a map-based format that is both familiar and preferable to farmers for the production of other risk assessment management strategies, e.g. manure and soil management plans (Rose et al., 2016; Oliver et al., 2010a). Unlike the other two components, the risk mapping tool (Fig. 4) is a password protected area of the ViPER DST requiring registered log-in details. Users can sign up for free access, and the server records their subsequent activity. This risk mapping tool converts modelled time-series predictions of the accumulation of *E. coli* on pasture (calculated as a dynamic function of livestock numbers, their faecal excretion and bacterial shedding capacity, and bacterial die-off rates as determined by environmental drivers such as temperature and level of UV radiation) into a more accessible format (e.g. a colour coded spatial risk map) at the field, farm or catchment-scale.

4. Evaluating the co-design process

Workshop attendance captured a strong representation from a range of different end-user typologies (see Table 1). Some examples of common issues associated with stakeholder engagement and participatory processes did emerge. For example, one of the larger end-user organisations opted to send a different person to each of the two stakeholder workshops, most likely in an effort to spread the distribution of person time spent in this process. Some might argue that this is a disadvantage because it could expose variability in stakeholder perspectives within a particular organisation. In the co-design of the ViPER DST we considered it an advantage because we were able to capture greater breadth of viewpoints to help strengthen the wider applicability of the resulting DST. Furthermore, the enthusiasm of different stakeholders during participation suggested they were not simply ‘towing the party line’ associated with their organisations, but instead provided constructive criticism and feedback that was central to their area of expertise, and which ultimately led to a credible DST. The enthusiasm and willingness to participate through the DST development contradicts some suggestions of difficulties to engage participants because of stakeholder fatigue (Voinov et al., 2016). One explanation for this may be associated with the short timeframe of the development process (six months) because the underpinning science was already fairly well developed. The six-month process did not impose heavy time commitments on stakeholders and ensured that clear progress was recognisable between one stakeholder meeting and the next.

The DST development team used an inception workshop (12 participants) to outline the principle of the toolkit and our participatory approach, and to solicit early input from stakeholders to help shape the design of the ViPER DST. An immediate observation was the need to manage stakeholder expectations of how advanced the ViPER DST could become within the funding timeframe of six months. This is perhaps not surprising given that different groups of stakeholders will accommodate vested interests and varying expectations (Voinov and Bousquet, 2010); however, despite the cohort being aware of the relatively short time-frame available to the developer team, the stakeholder wish-list of ViPER DST functionality for enabling on-farm microbial risk assessment was extensive (see Table 2). The colour coding in Table 2 relates to the relative timeframe considered possible for implementation of each desired feature and was used to communicate to stakeholders the likelihood of inclusion of different requests in early stages of DST development, which helped to manage expectations. The process of identifying the requirements of an idealised DST was nonetheless important in helping to prioritise development tasks, and a combination of technical expertise and end-user insight allowed for a ranking of those priorities. The finalised table was communicated to participants after the workshop and approved by all.

A second workshop was used to reconvene stakeholders to evaluate progress and evolution of the DST. Representatives from the same stakeholder organisations listed in Table 1 were present. This workshop also served to ensure that the original conceptual understanding and ideas of the stakeholders, recorded at the inception workshop, were being genuinely translated into a procedural DST based on user-orientated needs (c.f. Lacoste and Powles, 2016; Reed et al., 2014). The participatory nature of this workshop centred on stakeholders simultaneously testing the DST environment in real-time. In total, 16 participants (12 common to the first workshop + 4 additional invitees) interacted with the ViPER DST in a preliminary assessment of how the server would cope with concurrent users and server sided processing queues. Although this represented a small number of users as part of a system stress-test, it did enable a pilot scale evaluation of multi-user demands in an attempt to expose any issues in DST operation, none of which were identified from the perspective of operability of the server system.

Unsurprisingly, a number of issues were identified with the operability of the GUI and DST and the intention of the workshop was to

Table 2
Desirable features of ViPER identified by end-users (light grey – a priority to include within ViPER; hollow – to explore where possible; black – important as a more holistic assessment of *E. coli* risk but beyond the remit of the initial ViPER project.

Desired feature	Timeframe
Output that is robust rather than precise	░
Design to be implemented by catchment officer not farmer	░
Output at farm & catchment level (multiscale)	░
GUI environment that tells a 'story' to farmers & stakeholders	░
Traffic-light system for communicating risks	░
Link to catchments/postcode ID, not 'zoom in' map	░
Needs to be an engagement tool – modify with user – identify win-win scenarios	░
Pictorial & map based outputs	░
Coupling of risk categories with rules (e.g. if high risk & within Xm of watercourse then ……	░
Continue interaction with stakeholders for development	░
No specialist software, not tied to an operating system	░
Clicking & dragging interface – a 'play' environment function	░
Consider help as info buttons/hover over info tabs/side panels/utilize 'test-users' at later stages	░
Front page overview for the GUI	░
How would a mitigation measure impact on risk?	□
Risk map banding relative to watercourse	□
Load in/export data in standard formats (e.g. CSV output, input)	□
Model farm environment function	□
Identification of timing of pathogen/*E. coli* mobilisation	■
How risk varies with climate, time of FIO travel, hydrology,	■
How will risk vary during high & low flow events	■
Could be multi-issue in future (P, N, too): be aware of other tools	■
Link to Hydrological connectivity	■

capture common concerns among end-users with regard to how intuitive the GUI system was. It also identified where 'bugs' in underpinning code were generating errors in DST function, and provided general perceptions of what was working well versus what was frustrating or confusing. Feedback forms were used to capture views from the stakeholders, with particular attention paid to how user-friendly the system was. Ease-of-use was agreed universally at the inception workshop as a core criteria to consider at the forefront of DST development and also ranked as one of the most influential factors in governing DST uptake in a survey of farmer perceptions of decision support (Rose et al., 2016).

In the latter stages of the development of the ViPER DST two demonstration events were used to trial the outputs and gauge end-user responses to the alpha version release prior to transitioning it to a beta version DST. This also enabled a qualitative verification of the risk maps that were being produced (Oliver et al., 2012a). It has been suggested that anecdotal evidence can contribute an important qualitative component of the verification of outputs from such tools (Sandink et al., 2016). Anecdotal evidence was provided by our stakeholder cohort in this respect, for example one stakeholder commented that the proposed *E. coli* risk patterns in space and time were consistent with how he would intuitively have estimated *E. coli* burden based on livestock grazing densities, but that the framing of the *E. coli* burden as a relative risk map made that information appear more accessible and easier to act upon because it provided a formal record. Further, by testing the DST output at catchment forums involving an engaged farmer community we were able to ascertain farmer perceptions of the DST and gauge levels of acceptance versus distrust in outputs among the farming community. The fact that the tool had been developed using a multi-actor approach did appear to put the ViPER DST in a good light among the farming participants but there was still an element of scepticism regarding the contribution of FIOs from agriculture versus wildlife and avian populations. These remain valid points, and such sources can contribute towards a proportion of *E. coli* pollution in surface waters (Guber et al., 2015; Muirhead et al., 2011). However, the demonstration event alone generated discussion and KE across different communities, and thus demonstrated the types of conversations likely to be generated between farm advisors and the farming community if and when deployed.

5. Future development & opportunities

The beta version of the ViPER DST represents a feature-complete credible and reliable approach for mapping where and when *E. coli* accumulates on pasture, and in what quantity, and converts this *E. coli* burden to an appropriate level of risk with regard to source loading. New features and functionality are expected to be continually incorporated into the beta version of the ViPER DST prior to establishing a firm "final" release, not least with respect to the additional requests listed in Table 2 that were beyond the scope of the original DST development phase. It should be possible to add elements to ViPER which could better characterise: (i) the episodic nature of *E. coli* delivery from catchment systems driven principally by rainfall; (ii) inclusion of pollutant hot-spots such as farm hard-standings, stream crossing and watering/wading locations and in-field stock congregation for feeding and watering; and (iii) slurry spreading practice and areas. In a similar manner, pollutant attenuation strategies such as integrated constructed wetlands, slurry storage and treatment should be capable of integration. In the development of the ViPER DST, one end-user highlighted the potential opportunity to include the ViPER DST within a farmer training package for the more effective treatment of livestock related FIOs impacting on protected areas (e.g. bathing and shellfish harvesting waters) in catchment systems. The inclusion of the any DST within such a package would embed the underlying research and KE into the everyday practice of catchment management communities and facilitate extension of the research to the large customer base of farmers engaged with these end-users, thus providing a measure of success. Clearly this would represent an ultimate goal in transitioning the ViPER DST to a ready-to-use toolkit.

5.1. Crowd-sourced E. coli maps of UK regions

The password-protected environment of the risk mapping tool facilitates the collation of livestock data within the ViPER DST. Spatial data such as this, often collated via agricultural census returns, is often difficult to obtain at the field level because of confidentiality issues (Winter et al., 2011). However, should farmers and farm advisors voluntarily upload data into ViPER to generate *E. coli* risk maps it would remove the barrier of accessing livestock data from a third party. The password protected nature of the DST prevents an individual's data being shared to another user (unless authorisation is given within the DST) but within the stored database of the DST a collated map of *E. coli* risk, generated from a series of inputs from different users, would gradually accrue. Caveats on the use of such crowd-sourced are important and so clarity on the levels of consent required from end-users with respect to how the information might be used would be essential. While crowd-sourced data offers an exciting opportunity for deriving a large-scale (e.g. UK-wide) risk map of *E. coli* loading to agricultural land, a suite of ethical issues regarding access to that data and how it is used would need to be considered and addressed (Bronson and Knezevic, 2016).

5.2. An app-based format

An app-based format of the ViPER DST, usable on smart phones and tablet devices would provide an attractive addition to the ViPER platform. Developing a parallel app-based format would potentially increase visibility and accessibility of ViPER, and advances in software development are enabling portable technologies such as smartphones and tablets to accelerate the development of 'smart agriculture' (Delgado et al., 2013). However, the challenges for implementation are not trivial, for example, ensuring consistency of app function across the many operating systems currently available to end-users would be time consuming. Interestingly, none of the stakeholders proposed an app format as an essential component of the DST development. Furthermore, 'habit' (in this case, habit of not using new technologies) was recorded as a popular response with respect to influential factors governing a lack of uptake of new technology, such as apps, within decision support in a recent farmer survey, with examples of 'being old-fashioned', 'not liking new technology' and 'not owning a phone' quoted (Rose et al., 2016). The authors of the same survey did recognise that younger farmers were more likely to be exposed to, and accepting of, new technology and smartphone software.

5.3. Towards a hydrologically connected risk mapping tool

A suggestion echoed by many of the stakeholders was the linking of the ViPER DST with a model of hydrological connectivity (e.g. Lane et al., 2009) to enable prediction of *E. coli* risk to watercourses rather than just mapping spatial variations of where and when *E. coli* accumulated on land. This is a valid point, though it should be noted that the latter is consistent with other risk management approaches that identify low to high vulnerabilities on pasture associated with, for example, manure loading, nutrient status or soil erosion potential (Withers et al., 2000). However, the linking with hydrological transfer would elevate the DST to a more sophisticated system for informing on microbial risks to waterbodies. This is especially true given that diffuse microbial pollution can originate from critical source areas within agricultural landscapes, whereby high source loading coincides with an opportunity for connectivity to a watercourse (Heathwaite et al., 2005).

6. Conclusion

Involving stakeholders within all stages of DST design, from inception and idea formulation through to testing, is critically important. It can help to promote enthusiasm for the end-product, instil trust and understanding in the DST through demonstrating transparency in approach, and deliver added-value from the identification of different objectives associated with deployment of such DSTs, often not considered by technical development teams. To this end, ViPER represents one of the first freely-available decision support tools to visualise and communicate *E. coli* risks on agricultural land and to our knowledge the first freely-available *E. coli* burden calculator applicable to multiple scales of agricultural systems. The evolution of the ViPER DST benefitted from adaptations directly informed by our stakeholder cohort, which will hopefully contribute to preventing an implementation gap in the future when a final release of the DST is made available. Both co-design and co-production should be considered a valuable, if not essential, process in the formalisation of DSTs for improved environmental management.

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References

Bechmann, M.E., Stålnacke, P., Kværnø, S.H., 2007. Testing the Norwegian phosphorus index at the field and subcatchment scale. Agric. Ecosyst. Environ. 120, 117–128.

Bloodworth, J.W., Holman, I.P., Burgess, P.J., Gillman, S., Frogbrook, Z., Brown, P., 2015. Developing a multi-pollutant conceptual framework for the selection and targeting of interventions in water industry catchment management schemes. J. Environ. Manag. 161, 153–162.

Bronson, K., Knezevic, I., 2016. Big data in food and agriculture. Big Data Soc. 1–5.

Brown, L., Scholefield, D., Jewkes, E.C., Lockyer, D.R., Del Prado, A., 2005. NGAUGE: a decision support system to optimise N fertilisation of British grassland for economic and environmental goals. Agric. Ecosyst. Environ. 109, 20–39.

Delgado, J.A., Kowalski, K., Tebbe, C., 2013. The first Nitrogen index app for mobile devices: using portable technology for smart agricultural management. Comp. Electron. Agric. 91, 121–123.

Dupas, R., Parnaudeau, V., Reau, R., Jeuffroy, M.H., Durand, P., Gascuel-Odoux, C., 2015. Integrating local knowledge and biophysical modeling to assess nitrate losses from cropping systems in drinking water protection areas. Environ. Model. Softw. 69, 101–110.

Dymond, J.R., Serezat, D., Ausseil, A.G.E., Muirhead, R.W., 2016. Mapping of *Escherichia coli* sources connected to waterways in the Ruamahanga catchment, New Zealand. Environ. Sci. Technol. 50, 1897–1905.

Goss, M., Richards, C., 2008. Development of a risk-based index for source water protection planning, which supports the reduction of pathogens from agricultural activity entering water resources. J. Environ. Manag. 87, 623–632.

Guber, A.K., Fry, J., Ives, R.L., Rose, J.B., 2015. *Escherichia coli* survival in, and release from: white-tailed deer feces. Appl. Environ. Microbiol. 81, 1168–1176.

He, Z., Hiscock, J.G., Merlin, A., Hornung, L., Liu, Y., Zhang, J., 2014. Phosphorus budget and land use relationships for the Lake Okeechobee Watershed, Florida. Ecol. Eng. 64, 325–336.

Heathwaite, A.L., Fraser, A.I., Johnes, P.J., Hutchins, M., Lord, E., Butterfield, D., 2003a. The phosphorus indicators tool: a simple model of diffuse P loss from agricultural land to water. Soil Use Manag. 19, 1–11.

Heathwaite, L., Sharpley, A., Bechmann, M., 2003b. The conceptual basis for a decision support framework to assess the risk of phosphorus loss at the field scale across Europe. J. Plant Nutr. Soil Sci. 166, 447–458.

Heathwaite, A.L., Quinn, P.F., Hewett, C.J.M., 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. J. Hydrol. 304, 446–461.

Hewett, C.J.M., Quinn, P.F., Whitehead, P.G., Heathwaite, A.L., Flynn, N.J., 2004. Towards a nutrient export risk matrix approach to managing agricultural pollution at source. Hydrol. Earth Syst. Sci. Disc. 8, 834–845.

Hewett, C.J.M., Doyle, A., Quinn, P.F., 2010. Towards a hydroinformatics framework to aid decision-making for catchment management. J. Hydroinfo. 12, 19–139.

Hewett, C.J.M., Quinn, P.F., Wilkinson, M.E., 2016. The decision support matrix (DSM) approach to reducing environmental risk in farmed landscapes. Agric. Water Manag. 172, 74–82.

Karpouzoglou, T., Zulkafli, Z., Grainger, S., Dewulf, A., Buytaert, W., Hannah, D.M., 2016. Environmental virtual observatories (EVOs): prospects for knowledge co-creation and resilience in the information age. Curr. Opin. Environ. Sustain. 18, 40–48.

Kay, D., Anthony, S., Crowther, J., Chambers, B.J., Nicholson, F.A., Chadwick, D., Stapleton, C.M., Wyer, M.D., 2010. Microbial water pollution: a screening tool for initial catchment-scale assessment and source apportionment. Sci. Tolal Environ. 408, 5649–5656.

Kerselaers, E., Rogge, E., Lauwers, L., Huylenbroeck, G.V., 2015. Decision support for prioritising of land to be preserved for agriculture: can participatory tool development help? Comp. Electron. Agric. 110, 208–220.

Lacoste, M., Powles, S., 2016. Beyond modelling: considering user-centred and post-development aspects to ensure the success of a decision support system. Comp. Electron. Agric. 121, 260–268.

Lahr, J., Kooistra, L., 2010. Environmental risk mapping of pollutants: state of the art and communication aspects. Sci. Total Environ. 408, 3899–3907.

Lane, S.N., Reaney, S.M., Heathwaite, A.L., 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index. Water Resour. Res. 45, W08423.

Liu, S., Brazier, R.E., Heathwaite, A.L., Liu, W., 2014. Fully integrated approach: an alternative solution of coupling a GIS and diffuse pollution models. Front. Environ. Sci. Eng. 8, 616–623.

Maskrey, S.A., Mount, N.J., Thorne, C.R., Dryden, I., 2016. Participatory modelling for stakeholder involvement in the development of flood risk management intervention options. Environ. Model. Softw. 82, 275–294.

Matthews, K.B., Schwarz, G., Buchan, K., Rivington, M., Miller, D., 2008. Wither agricultural DSS? Comp. Electron. Agric. 61, 149–159.

Muirhead, R.W., Elliott, A.H., Monaghan, R.M., 2011. A model framework to assess the effect of dairy farms and wild fowl on microbial water quality during base-flow conditions. Water Res. 45, 2863–2874.

Muirhead, R.W., 2015. A farm-scale risk-index for reducing fecal contamination of surface waters. J. Environ. Qual. 44, 248–255.

Oliver, D.M., Fish, R.D., Hodgson, C.J., Heathwaite, A.L., Chadwick, D.R., Winter, M., 2009. A cross-disciplinary toolkit to assess the risk of faecal indicator loss from grassland farm systems to surface waters. Agric. Ecosyst. Environ. 129, 401–412.

Oliver, D.M., Page, T., Hodgson, C.J., Heathwaite, A.L., Chadwick, D.R., Fish, R.D., Winter, M., 2010a. Development and testing of a risk indexing framework to determine field-scale critical source areas of faecal bacteria on grassland. Environ. Model. Softw. 25, 503–512.

Oliver, D.M., Page, T., Heathwaite, A.L., Haygarth, P.M., 2010b. Re-shaping models of *E. coli* population dynamics in livestock faeces: increased bacterial risk to humans? Environ. Int. 36, 1–7.

Oliver, D.M., Fish, R., Winter, M., Hodgson, C.J., Heathwaite, A.L., Chadwick, D.R., 2012a. Valuing local knowledge as a source of expert data: farmer engagement and the design of decision support systems. Environ. Model. Softw. 36, 76–85.

Oliver, D.M., Page, T., Zhang, T., Heathwaite, A.L., Beven, K., Carter, H., McShane, G., O' Keenan, P., Haygarth, P.M., 2012b. Determining *E. coli* burden on pasture in a headwater catchment: combined field and modelling approach. Environ. Int. 43, 6–12.

Oliver, D.M., Porter, K.D.H., Pachepsky, Y.A., Muirhead, R.W., Reaney, S.M., Coffey, R., Kay, D., Milledge, D.G., Hong, E., Anthony, S.G., Page, T., Bloodworth, J.W., Mellander, P.-E., Carbonneau, P.E., McGrane, S.J., Quilliam, R.S., 2016. Predicting microbial water quality with models: over-arching questions for managing risk in agricultural catchments. Sci. Total Environ. 544, 39–47.

Reed, M.S., Stringer, L.C., Fazey, I., Evely, A.C., Kruijsen, J.H.J., 2014. Five principles for the practice of knowledge exchange in environmental management. J. Environ. Manag. 146, 337–345.

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: towards effective design and delivery. Agric. Syst. 149, 165–174.

Sandink, S., Simonovic, S.P., Schardong, A., Srivastav, R., 2016. A decision support system for updating and incorporating climate change impacts into rainfall intensity-duration-frequency curves: review of the stakeholder involvement process. Environ. Model. Softw. 84, 193–209.

Vinten, A.J.A., Douglas, J.T., Lewis, D.R., Aitken, M.N., Fenlon, D.R., 2004. Relative risk of surface water pollution by *E. coli* derived from faeces of grazing animals compared to slurry application. Soil Use Manag. 20, 13–22.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw. 25, 1268–1281.

Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A., Ramu, P., 2016. Modelling with stakeholders—next generation. Environ. Model. Softw. 77, 196–220.

Wilkinson, M.E., Quinn, P.F., Hewett, C.J., 2013. The Floods and Agriculture Risk Matrix: a decision support tool for effectively communicating flood risk from farmed landscapes. Int. J. River Basin Manag. 11, 237–252.

Wilkinson, M.E., Mackay, E., Quinn, P.F., Stutter, M., Beven, K.J., Macleod, C.J., Macklin, M.G., Elkhatib, Y., Percy, B., Vitolo, C., Haygarth, P.M., 2015. A cloud based tool for knowledge exchange on local scale flood risk. J. Environ. Manag. 161, 38–50.

Winter, M., Oliver, D.M., Fish, R., Heathwaite, A.L., Chadwick, D., Hodgson, C., 2011. Catchments, sub-catchments and private spaces: scale and process in managing microbial pollution from source to sea. Environ. Sci. Policy 14, 315–326.

Withers, P.J., Davidson, I.A., Foy, R.H., 2000. Prospects for controlling nonpoint phosphorus loss to water: a UK perspective. J. Environ. Qual. 29, 167–175.