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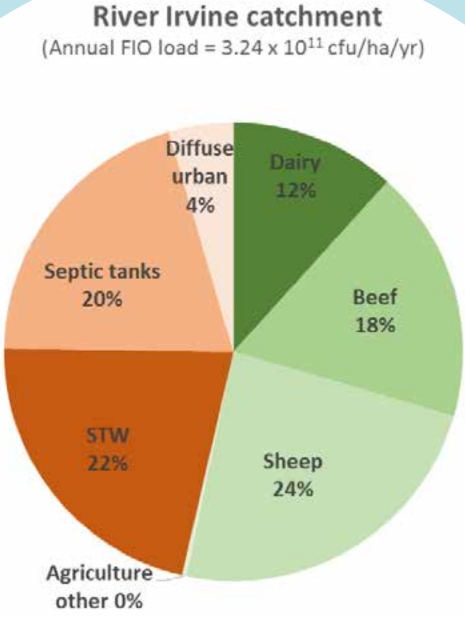
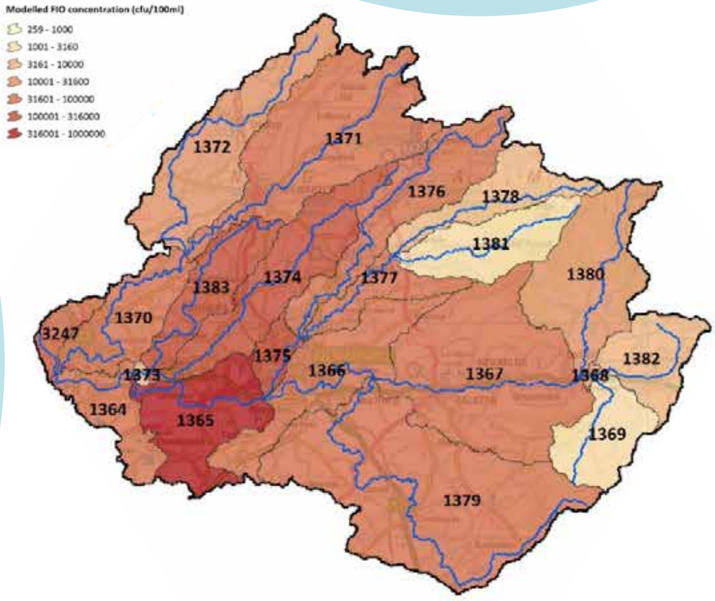
Developing a methodology for screening and identifying potential sources of bacteria to improve bathing, shellfish and drinking water quality

Phase 1: To design and scope a suitable methodology





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[1] The actual methodology will be developed in Phase 2 of the project.
[2] All abbreviations and acronyms used in this report are listed in Appendix 1.
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Executive summary[1]

1 Background

Although the quality of water in Scotland is generally very good, "bacteria can pose a risk to human health via shellfish, bathing and drinking water quality issues" (Project Specification). Faecal indicator organisms (FIOs) are of primary concern, since they are the key microbial water quality compliance parameters – specifically, *Escherichia coli* (EC) and intestinal enterococci (IE) under the revised Bathing Waters Directive (rBWD; Council of the European Communities (CEC), 2006a) and Shellfish Waters Directive (SWD; CEC, 2006b). These bacteria, which are generally non-pathogenic, are excreted by all warm-blooded animals and their presence indicates an environmental pathway contaminated with faecal waste which may be contributed to by a pathogen carrier(s). In order better inform policy development and the targeting of resources and investment to address microbial pollution, data are ideally needed on:

- FIO concentrations in near-shore coastal waters and at drinking water abstraction points (here collectively referred to as 'receptor waters')
- FIO loadings in waters discharging to coastal waters
- Source apportionment of FIO load inputs to receptor waters from catchment sources – these being moderated through natural die-off, which affects the 'zone of influence' of individual pollutant sources
- Effectiveness of individual agricultural mitigation actions in reducing FIO fluxes from agricultural sources
- Effectiveness of improvements in sewerage infrastructure.

Scotland, through the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) programme, has already invested substantially in the development of a process-based screening tool[2] to generate such data: an initial diffuse pollution screening tool (DPST; ADAS *et al*., 2006), which has subsequently been updated and extended to include the effectiveness of implementing different remedial actions to reduce fluxes from agricultural land ('Effectiveness of Measures' (EoM) Project; ADAS, 2014). The current version of the FIO tool (here termed 'EoM-FIO') has been used to generate data on the annual 'FIO' (actually faecal coliform (FC)) loads, expressed as colony-forming units (cfu)/ha)) delivered to watercourses within each of the Water Framework Directive (WFD) catchments in Scotland, with load apportionment to particular agricultural and sewerage-related sources and pathways. EoM-FIO is based on an exceptionally large environmental/hydrological/farm characterisation/farm management database, and undoubtedly has considerable potential. In discussions with SEPA staff it would seem that the sheer complexity of the underlying database and associated issues of 'accessibility/utility' may limit SEPA's ability to capitalise fully on its potential. It is also apparent that EoM-FIO does not meet all the requirements identified above, specifically in relation to FIO concentration data; level of temporal resolution (lack of seasonal and, more critically, low- and high-flow separation); and the incorporation of die-off along watercourses – the latter being critical in affecting the 'zone of influence' of individual sources. Clearly, any further development of EoM could potentially enhance its utility not just in relation to FIOs, but also the range of other pollutants that are covered by the EoM database. Cognisance also has to be taken of the fact that SEPA has adopted a SIMCAT/SAGIS[3] framework for catchment-scale water quality modelling; and that only a limited budget (presently *c.* £70k) and timescale (*c.* 6 months) is envisaged from the development of an agreed methodology in Part 2 of the project.

It is vital to note that model-based screening tools can only provide estimates of the 'norms' that might be expected under a particular set of circumstances – e.g. they can be used to identify areas ('expected hotspots') within the catchment of a receptor water that are likely to generate higher FIO loadings, such as areas of more intensive livestock farming or urbanisation. They cannot, in themselves, identify 'rogue' locations where much higher than normal FIO loadings are likely to be generated – e.g. a combined sewer overflow (CSO) that regularly exceeds its consented discharge; a leaking septic tank close to a stream; or a livestock farm where General Binding Rules (GBRs) and codes of practice are regularly breached, allowing, for example, relatively fresh livestock wastes to enter a watercourse. Clearly, such rogue hotspots may have a significant impact in terms of microbial water quality impairment. Supplementary techniques, such as field walking, use of thermal imaging, stream ecology assessments or, *in extremis*, empirical microbial studies need to be employed to identify these.

2 Principal objectives

The project had two key objectives:

- To evaluate, within the existing Scottish context (as outlined above), the types of modelling and other approaches that might be most readily and effectively be adopted.
- To recommend and scope an approach which seems most suitable to meet the needs of the project.

3 Evaluation of possible approaches

In terms of modelling, two types of approach could be adopted:

- **Generic 'black box' regression models** – In this case, empirical data from previous detailed catchment investigations are used to develop regression models of the relationship between low- and high-flow FIO concentrations in watercourses

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[1] The specifications for Part 1 included providing reviews/advice on various matters which CREH consider to be peripheral to developing a screening methodology. These aspects, which are not considered in the Executive Summary, are presented in the appendices: (Appendix 4) Natural FIO inputs from wildlife; (5) Effectiveness of actions for reducing FIO fluxes from agricultural sources; (6) Effectiveness of methods for reducing FIO fluxes from sewerage sources; (7) Use of MST and other faecal typing approaches in FIO source apportionment; and (8) Near-shore coastal dynamic modelling.

[2] While this screening tool covers all of the main agriculture-derived pollutants, only the FIO component is considered here.

[3] SIMulation of CATchments model/Source Apportionment Geographical Information System.

(dependent variables) and key catchment characteristics (independent 'predictor' variables; e.g. stocking density, residential density, land use, soil hydrological properties, catchment size, etc.). These models are then used to predict FIO concentrations in other watercourses from their catchment characteristics. Such data can then be combined with actual flow records to estimate FIO fluxes under low- and high-flow conditions. Such an approach, using models developed by CREH, is currently being used to underpin the catchment-based FIO modelling work being undertaken by the Environment Agency (EA) in England and Wales.
- **Process-based models/tools** – This approach (as used in DPST and EoM-FIO) attempts, in so far as is possible, to model the fate of FIOs derived from individual faecal inputs (fresh and/or stored/treated) as they move from the original input location to the catchment outlet, principally along hydrological flow paths.

The strengths and weaknesses of these two approaches in meeting the project aims are presented, based on recent detailed literature reviews. Both are identified as having significant strengths and it is proposed that they are employed as complementary components, along with others, in the proposed screening methodology. The potential of using existing CREH regression models and EoM-FIO, together with the results of recent CREH work on T_{90} values in watercourses (as used by EA), is explored with reference to two catchments selected by SEPA as being representative of two key catchment types in Scotland:

- **R. Irvine catchment** – a simple riverine catchment with substantial areas urbanisation (principally Irvine and Kilmarnock) and intensive livestock farming, which discharges to designated coastal bathing waters
- **Loch Etive (shellfish water) catchment** – a large and complex west coast catchment (with multiple catchment inputs, many via Loch Awe) dominated by upland sheep farming.

4 Proposed screening methodology

This comprises five key, interlinked, components[4], each of which could potentially be developed further in Phase 2:

I. Generic black-box regression models of FIO concentrations
- **a.** To estimate FIO concentrations and loadings in riverine inputs to Scottish coastal waters and other receptor waters – enabling such waters to be ranked according to their risk of impairment
- **b.** To estimate FIO concentrations and loadings for individual subcatchments within catchments identified as being at greatest risk – enabling the more critical subcatchments to be identified for closer investigation

II. EoM-FIO screening tool
To further help identify the more critical catchments/subcatchments and, crucially, enable the:
- **a.** Identification of key source(s) – through source apportionment
- **b.** Estimation of impact of remedial measures

III. Models of FIO die-off along watercourses/zones of influence
To provide insight into the zone of influence of individual FIO pollutant sources within the catchment of a receptor water

IV. Site-specific investigative methods/tools
To help identify rogue FIO hotspots within catchments

Rogue agricultural hotspots
Farm inspections/field walking
Field-based water quality surveys
Use of Farmscoper (ADAS)
Thermal imaging

Rogue sewerage-related hotspots
Regular monitoring and evaluation of WwTW/CSO performance
Field-based water quality surveys

V. Integration of outputs of Components I-IV within a catchment GIS framework
The data/outputs from components I-IV need to be integrated within a GIS system such as the SIMCAT/SAGIS framework, so that potential users of the FIO screening methodology, from government agencies to catchment field officers, can easily access the various layers of information in order to assess the weight of evidence and make better-informed judgements.

5 Recommendations for development of proposed methodology in Phase 2

In total 19 recommendations (labelled i-xix) are made, covering each of the five components. These are classed as being of high [***], moderate [**] and low [*] priority, with the key organisations responsible for undertaking the work being identified:

Component I: Generic black-box regression models of FIO concentrations
- **i.** Inclusion of sheep as a predictor variable in all models [*** CREH]
- **ii.** Inclusion of Scottish data in present model database [** CREH/SEPA]
- **iii.** Enhancement of database for England and Wales [* CREH/SEPA]
- **iv.** Development of 'winter' models [*** ADAS/CREH]
- **v.** Application of resulting models all to Scottish WFD catchments and the catchments of receptor waters [*** CREH/SEPA]

Component II: EoM screening tool (FIOs and other pollutants)
- **vi.** Simplification of accessibility of WFD catchment data [*** ADAS/SEPA]
- **vii.** Quantification of seasonal variations in load [*** ADAS]
- **viii.** Quantification of low- and high-flow loads [*** ADAS]
- **ix.** Enhancement of database on sewerage sources [*** SEPA]
- **x.** Updating of FIO database for sewerage-related FIOs [*** CREH]
- **xi.** Incorporation of FIO die-off along watercourses [* ADAS/CREH]
- **xii.** Enhancement of data on stocking density [*** SEPA]
- **xiii.** Enhancement of data on proximity and connectivity of grazed fields directly to watercourses [** SEPA]
- **xiv.** Generation of summary statistics for individual landscape types [** SEPA]
- **xv.** Enhancement of data on livestock and waste management practices [*** SEPA]
- **xvi.** Enhancement of data on soils and drainage [** SEPA]

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[4] A further component (Near-shore coastal dynamic modelling – see Appendix 8) would need to be included in order to model FIO concentrations in coastal waters, but this is outside scope of the present project.

xvii. Development of Farmscoper-v3 (ADAS) for Scottish farms [*** ADAS]

Component III: Models of FIO die-off along watercourses/zones of influence

xviii. Establishment of seasonal and diurnal variations in T_{90} [*** CREH]

Component IV: Site-specific investigative methods/tools

Many of the recommendations made in relation to Component II (EoM-FIO), if implemented, will facilitate the identification of potential rogue agricultural and sewerage-related hotspots for more detailed investigation (especially xii–xvii)

Component V: Integration of outputs of I-IV within a catchment GIS framework

Integration of outputs within SIMCAT/SAGIS framework [*** ADAS/CREH/SEPA]

Contents

Tables

Appendices

1. Introduction[5]

1.1 Background[6]

Although the quality of water in Scotland is generally very good, "bacteria can pose a risk to human health via shellfish, bathing and drinking water quality issues" (Project Specification). Faecal indicator organisms (FIOs) are of primary concern, since they are the key microbial water quality compliance parameters – specifically, *Escherichia coli* (EC) and intestinal enterococci (IE) under the revised Bathing Waters Directive (rBWD; Council of the European Communities (CEC), 2006a) and Shellfish Waters Directive (SWD; CEC, 2006b). These bacteria, which are generally non-pathogenic, are excreted by all warm-blooded animals and their presence indicates an environmental pathway contaminated with faecal waste which may be contributed to by a pathogen carrier(s). In order better inform policy development and the targeting of resources and investment to address microbial pollution (both at national and catchment scales), data are ideally needed on:

- FIO concentrations in near-shore coastal waters[7] and at drinking water abstraction points (here collectively referred to as 'receptor waters')
- FIO loadings in waters discharging to coastal waters
- Source apportionment of FIO load inputs to receptor waters: from catchment sources (livestock farming, wildlife, wastewater treatment works (WwTW) effluents, combined sewer overflows (CSOs), septic tanks, etc.) – these being moderated through natural die-off, which affects the 'zone of influence' of individual pollutant sources; and additionally, in the case of coastal waters, direct inputs from birds and other wildlife
- Effectiveness of individual agricultural mitigation actions (e.g. streambank fencing and constructed farm wetlands) in reducing FIO fluxes from agricultural sources
- Effectiveness of improvements in sewerage infrastructure (e.g. increased capacity of storm tanks for WwTWs (also referred to as sewage treatment works (STWs)) and CSOs, and installation of tertiary ultra-violet (UV) disinfection for sewage treatment.

Fluxes of FIOs from catchments typically increase *c.* 100-fold during rainfall as a result of the combined effects of more extensive areas affected by surface flow, increased connectivity between FIO sources and watercourses and greater volumes of flow, thereby greatly increasing the risks of water quality impairment in receptor waters (Crowther *et al*., 2001; Stidson *et al*., 2011, Wyer *et al*., 2013). FIO fluxes will also vary through the year as a result changing weather conditions, livestock management practices, seasonal use of holiday accommodation, etc. It is crucial therefore that the FIO data are of a sufficient temporal resolution to at least allow characterisation of seasonal contrasts in low- and high-flow concentrations/fluxes.

Ideally, long-term, event-focused FIO monitoring would be undertaken at catchment/subcatchment outlets and at key point sources within catchments to enable accurate quantification of FIO fluxes and their source apportionment (perhaps augmented by microbial source tracking (MST) or other faecal typing methods – as outlined in Appendix 7). However, such monitoring is costly, and is only likely to be justified where the situation is judged to be particularly critical.

The alternative, which is the only feasible approach at the national scale and forms the focus of the present study, is to adopt a modelling approach to estimate FIO concentrations, fluxes and source apportionment. Typically this involves the use of generic 'black-box' regression and/or process-based models, and both are evaluated in the present report. Given that the development and application of such models can, in itself, be both time-consuming and expensive, priority here has been given to exploring the extent to which FIO models and databases that already exist for Scottish catchments, together with existing UK generic models/tools, might form the basis for developing a screening tool that meets current requirements.

1.2 Existing FIO screening tool and databases for Scottish catchments

Scotland, through the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) programme, has already invested substantially in the development of a process-based tool[8]: an initial diffuse pollution screening tool (DPST; ADAS *et al*., 2006), which has subsequently been updated and extended to include the effectiveness of implementing different remedial actions to reduce fluxes from agricultural land ('Effectiveness of Measures' (EoM) Project; ADAS, 2014). The current version of the FIO tool (here termed 'EoM-FIO') has been used to generate data on the annual 'FIO' loads (actually faecal coliform (FC)[9]) loads, expressed as colony-forming units (cfu)/ha)) delivered to watercourses within each of the *c.* 3,300 inland and *c.* 15,400 coastal Water Framework Directive (WFD) catchments in Scotland, with load apportionment to particular agricultural and sewerage-related sources and pathways. In light of the large and complex environmental/hydrological/farm characterisation/farm management database that underpins EoM-FIO, and the resources that have already been invested in its development, the present project includes a full exploration (undertaken in collaboration with ADAS) as to the extent to which EoM-FIO already meets some the requirements identified above and to which it might be further extended, specifically in relation to the level of temporal resolution and the

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[5] All acronyms and abbreviations used in this report are listed in Appendix 1.

[6] The wider research and regulatory/policy contexts within with the present investigation is set is presented in Appendix 2.

[7] FIO concentrations in near-shore coastal waters are dependent upon input loadings, rates of die-off and degree of dilution within the waterbody (see Appendix 8) – the modelling of which is beyond the scope of the FIO screening methodology being considered here.

[8] While this screening tool covers all of the main agriculture-derived pollutants, only the FIO component is considered here.

[9] All the data used in the modelling relate to FC. Some EC data were used in the source FIO-Farm project (Defra WQ0111), but that was mainly for validation and corroboration.

incorporation of die-off along watercourses – the latter being critical in affecting the 'zone of influence' of individual sources. Clearly, any further development of EoM could potentially enhance its utility not just in relation to FIOs, but also the range of other pollutants that are covered by the EoM database. Cognisance also has to be taken of the fact that SEPA has adopted a SIMCAT/SAGIS[10] framework for catchment-scale water quality modelling. Ideally, therefore, the methodology developed will produce outputs in a form that can be readily input to SIMCAT/SAGIS.

In addition, Centre for Research into Environment & Health (CREH) has undertaken detailed empirical studies of FIO concentrations, loadings and source apportionment in 10 Scottish catchments over the past two decades (as detailed in Table 1), and these could form a valuable basis for developing simple regression models to predict FIO concentrations in Scottish catchments or in providing 'ground truth' data against which the outputs of other models might be evaluated.

1.3 Limitation of modelling: 'expected' (cf. 'rogue') hotspots

It is vital, at the outset, to stress that model-based screening tools can only provide estimates of the 'norms' that might be expected under a particular set of circumstances – e.g. they can be used to identify areas ('expected hotspots') within the catchment of a receptor water that are likely to generate higher FIO loadings, such as areas of more intensive livestock farming or urbanisation. They cannot, in themselves, identify 'rogue' locations where much higher than normal FIO loadings are likely to be generated – e.g. a CSO that regularly exceeds its consented discharge; a leaking septic tank close to a stream; or a livestock farm where General Binding Rules (GBRs) and codes of practice are regularly breached, allowing relatively fresh livestock wastes to enter a watercourse. Clearly, such rogue hotspots may have a significant impact in terms of microbial water quality impairment. Supplementary techniques, such as field walking, use of thermal imaging, stream ecology assessments or, *in extremis*, empirical microbial studies need to be employed to identify these. This distinction between 'expected' and 'rogue' hotspots is absolutely critical in the development of an effective screening methodology.

1.4 Wildlife inputs

Natural wildlife within the catchments of receptor waters (including birds, seals, etc. in the estuarine/coastal zone) undoubtedly represent a potential source of microbial pollution. However, as highlighted in Appendix 4, very few data are available on the FIO loadings generated by wildlife (cfu/mammal or bird/day). Equally, there are few data on the numbers of mammals/birds present in individual catchments across Scotland, and even less on the spatial patterns of defecation (e.g. what proportion of defecation is direct to watercourses or waterbodies). It is therefore impossible, on present evidence, to meaningfully model wildlife sources. In the majority of catchments, wildlife inputs are likely to relatively small, and are best considered as contributing to background levels of microbial pollution. In situations where field observations suggest that wildlife inputs may a potential cause for concern then these will need to be investigated on a case-by-case basis.

1.5 Aims and objectives

1.5.1 Aims

To design an effective FIO screening methodology for Scotland that could be developed quickly and at a reasonable cost, that will enable, within acceptable limits:

a. Prediction of current FIO loadings (ideally concentration & flow) being delivered to specific receptor waters under different flow conditions and in different seasons
b. Source apportionment of overall FIO loadings to sources within catchments
c. Estimation of 'zone of influence' of individual sources within catchments
d. Estimation of impacts of interventions to reduce fluxes from sewerage- and/or agricultural-related sources.

1.5.2 Principal objectives

In order to meet these aims, the following objectives were set:

- To evaluate, within the existing Scottish context (as outlined above), the types of modelling and other approaches that might be most readily and effectively be adopted
- To recommend and scope an approach which seems most suitable to meet the needs of the project.

1.5.3 Subsidiary review/advisory tasks

The following tasks were also completed (as required in the project specification). They are, however, considered by CREH to be peripheral to the principal objectives and the findings are reported in the final appendices of this report:

Appendix 4:	Natural FIO inputs from wildlife
Appendix 5:	Effectiveness of actions for reducing FIO fluxes from agricultural sources
Appendix 6:	Effectiveness of methods for reducing FIO fluxes from sewerage sources
Appendix 7:	Use of MST and other faecal typing approaches in FIO source apportionment
Appendix 8:	Use of near-shore coastal dynamic models of FIOs.

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[10] SIMulation of CATchments model/Source Apportionment Geographical Information System.

2 Design of screening methodology

2.1 Key underlying considerations

Three factors were considered paramount in designing the methodology. Specifically, it should:

- Capitalise on the existing screening tool (EoM-FIO) and the database that underpins this, and on existing generic models that might be readily applied to, or developed for, Scottish catchments
- Be realistic ('honest') in terms of the level of spatial resolution that is achievable
- Be capable of being developed fully in Phase 2 – i.e. within an agreed time-frame (presently 6 months) and budget, which may need to include software licensing costs (a provisional figure of £70k was indicated in earlier documentation).

2.2 Overview of possible modelling approaches

Two types of modelling approach could be adopted: generic 'black box' regression models and process-based models/tools. The strengths and weaknesses of these approaches in meeting the project aims are as follows.

2.2.1 Use of generic 'black box' regression models

In this case, empirical data from previous detailed catchment investigations are used to develop regression models of the relationship between low- and high-flow FIO concentrations in watercourses (dependent variables) and key catchment characteristics (independent 'predictor' variables; e.g. stocking density, residential density, land use, soil hydrological properties, catchment size, etc.). These models are then used to predict FIO concentrations in other watercourses from their catchment characteristics. Such data can then be combined with actual flow records to estimate FIO fluxes under low- and high-flow conditions. Such an approach, using models developed by CREH, is currently being used to underpin the catchment-based FIO modelling work being undertaken by the Environment Agency (EA) in England and Wales – e.g. modelling of outputs from the Wyre catchment to the coast at Fleetwood (CREH, 2013; Report to Environment Agency (EA) North West, Project 30506 – outlined in PowerPoint presentation to Start-up Meeting on 13/1/16).

2.2.1.1 Strengths

- Models are based on actual empirical ('ground truth') FIO concentration data – for low- and high-flow conditions during the summer bathing season in the case of the existing CREH/EA models.
- Concentration data can readily be combined with flow data to estimate FIO loads.
- Can be used to identify catchments, and also subcatchments within them, which are likely to be generating greater FIO fluxes.
- Can be used as a basis for evaluating the impact of improvements in sewerage infrastructure/sewage treatment (e.g. installation of UV treatment), provided the number of residences served by the infrastructure and WwTW is known, and estimates can be made of the total FIO loads derived from these sewerage sources before and after improvement.
- Application is very easy, with limited data/computational requirements.

2.2.1.2 Limitations/weaknesses

- Such 'black box' models provide no explicit insight into the processes operating within individual catchments
- Because of issues of multicollinearity they cannot be used with any degree of confidence for source apportionment (e.g. even for basic apportionment of sewerage- and agriculture-related sources), and therefore need to be employed with caution when using the outputs to underpin predictions of the impacts of particular remedial interventions (either sewerage- or agriculture-related).
- Based on the aggregation of empirical data from monitoring studies undertaken in different catchments, over relatively short periods (typically 6–8 weeks), and under sets of conditions that obtained at the time (e.g. antecedent weather conditions, sewerage infrastructure, farm management practices, level of adoption of agricultural mitigation methods, etc.) – as such they are 'locked' in time.
- Insufficient empirical data at present to develop robust models for periods outside the summer bathing season (bathing water quality has been the main driver of most empirical studies over the past two decades) – this issue is particularly important for shellfish waters.
- The latest generic models for the UK were developed by CREH in collaboration with the EA (CREH, 2010) and are based on (thermo-tolerant) FC and faecal streptococci (FS) enumerations, rather the latest rBWD compliance parameters (EC and IE) – for which some, but more limited, data are currently available; and on data for catchments in England and Wales (i.e. they are strictly 'England & Wales' models) – though comparable FIO data are available for some Scottish catchments.

2.2.2 Use of process-based models/tools

This approach attempts, in so far as is possible, to model the fate of FIOs derived from individual faecal inputs (fresh and/or stored/treated) as they move from the original input location to the catchment outlet, principally along hydrological flow paths. While many process-based hydrological models have been developed for sediment and nutrient fluxes within catchments, the application of such models to FIOs is very much in its infancy.

Oliver *et al*. (2011), as part of a Defra-funded project, presented a very detailed review of catchment modelling strategies for FIOs. This identified the following criteria as being critical in assessing the suitability of individual modelling platforms:

- **Hydrological representation**: Important to focus on the potential of models to simulate the capture of faecally-derived microbial pollutants via hydrological processes and their subsequent routing through the catchment drainage network.
- **Time-step**: The temporal resolution ('time-step' in the models) for FIOs is governed by the likely duration of likely water

quality impairment, which can be very short for bathing waters and shellfish harvesting waters. Hourly resolution would be the ideal.

- **Spatial-scale**: A catchment-based/-scale approach is needed, but within this consideration needs to be given to the importance of arbitrary 1 km^2 gridded-distributed models versus models that delineate hydrological response units (HRUs) or the equivalent based on common landscape functionality.
- **Diffuse- and point-source contributions**: In addition to diffuse-source FIO inputs to stream loadings there will need to be some consideration of how point-source FIO inputs are accounted for within the catchment context – the latter including WwTW discharges, CSOs, leaking septic tanks, farmyard runoff, etc.
- **Ability to represent lifecycle/storage and release processes within model parameterisation**: FIO modelling needs to be able to account for cell die-off and regrowth potential within different catchment matrices, and also storage/release within the catchment (e.g. on ground surfaces and within stream bed sediments).
- **Ability to account for mitigation impacts:** Models need to be able to take into account changes in catchments that relate to management interventions through the alteration of parameter values.
- **Licensing (cost)**: Licensing requirements may present a significant hindrance to the model adoption of models which do not use open-source web-based platforms.

Evaluations were made of 16 different modelling platforms, the results of which are summarised in Table 2. These findings will certainly need to be taken into account if a decision is ultimately taken to develop a completely new screening tool in Phase 2. Kay *et al*. (2012), as part of the same project, presented a detailed overview of the parameterisation requirements of such models; and, more recently, Oliver *et al*. (2016) have reviewed the issues and underlying questions that need to be addressed in developing models to underpin the management of microbial water quality risks in agricultural catchments. Not included in the above reviews is the EA's process-based Fieldmouse model for diffuse pollutants (the latest version (v3) of which is held by SEPA). This is evaluated in Section 2.3. Some observations on SIMCAT/SAGIS, which is currently used as SEPA's corporate modelling framework, are presented in Section 2.4.

2.2.2.1 Strengths

- Models individual FIO inputs within catchments and the ways in which their movement to the catchment outlet is affected by processes of die-off (within stored livestock wastes, on ground surfaces, within soils, along watercourse, etc.) and transport, with hydrological flowpaths (and associated degree of connectivity to watercourses) being particularly critical.
- The fluxes from derived from different sources are estimated separately (i.e. sources are apportioned) and summed to give the total load.
- The models have the potential to generate real-time estimates of fluxes under different hydrological conditions (low- and high-flow) at specific times of the year (i.e. taking into account seasonal variations in farm management practices, holiday accommodation occupancy, FIO die-off rates, etc.).
- The effectiveness of particular mitigation actions upon catchment fluxes of FIOs can be evaluated – by taking into account not only the degree of attenuation achieved by a particular intervention (e.g. constructed farm wetland for yard runoff), but also the FIO loads actually affected by the intervention.
- Models are very adaptable and can be readily updated as new empirical data on source strengths, die-off rates, etc. become available.
- Supporting tools are increasingly being developed that generate data suitable for input to such models (e.g. InfoWorks[11] for sewerage sources).

2.2.2.2 Limitations/weaknesses

The empirical database on the dynamics of die-off processes and transport of FIOs and their controlling factors within catchments is less well developed than for other diffuse agricultural pollutants (e.g. nutrients).

The databases required parameterise and drive such models are inevitably very large and complex, and require a substantial computer capacity and level of expertise to run them effectively.

While some of the models are open-source and freely available, in other cases license fees are payable.

2.3 Fieldmouse model[12]

2.3.1 Background

(with contribution by C. Burgess and J.M. Douglass, EA)

As noted above, SEPA presently have a copy of Fieldmouse v3[13] and asked for this to be explicitly considered in this report. Fieldmouse has been developed by the EA to model concentrations of diffuse agricultural pollutants (including FIOs) and their source apportionment within catchments, initially to inform the targeting of agricultural interventions in the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) catchments. Fieldmouse itself is primarily a tool for routing water and associated pollutants (derived using the EA's Catchment Change Matrix (CCM; which is broadly equivalent to ADAS's Farmscoper)) through a catchment from the point of pollutant input to the catchment outlet or intermediate receptor point. It uses the Soil and Water Assessment Tool (SWAT) to model flow and route FIO movement within the landscape. The Continuous Estimation of River Flows (CERF) model is used to give long-term average quick flow and slow flow outputs (Griffiths *et al*. 2008). Fieldmouse is designed primarily to be employed at the subcatchment and farm scale, rather than at the larger catchment or national scale. Technically, it could be used at the field or even more local scale (provided input data of a sufficiently high resolution were available), but this has not been tested. It is still in the early stages of development, testing

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[11] Innovyze Ltd., Howbery Park, Wallingford, Oxfordshire OX10 8BA, UK: Latest version: InfoWorks ICM (Integrated Catchment Modelling) http://www.innovyze.com/products/infoworks_icm/ (this has replaced InfoWorks CS).

[12] Fieldmouse is hosted by the Catchment-Based Approach (CaBA) organisation, but only very brief information is presented on CaBA website (http://www.catchmentbasedapproach.org/best-practice/use-data/fieldmouse; last accessed on 4/3/16). It is presently available free-of-charge (without a licence), and requires ArcGIS 9.3 (or greater) with the spatial analyst extension.

[13] It should be noted that Fieldmouse v3 includes MONTE-CARLO sampling and the ability to run with the Glue Framework. However, it does not include the CREH-modelled FIO T_{90} die-off component (as outlined in Appendix 9), which is in a 'forked' version of Fieldmouse v2, but this could be added.

and evaluation, and the EA recognise that work still has to be undertaken on the FIO component.

2.3.1.1 Inputs to model/data requirements

Pollutant inputs are derived using the EA's CCM. This uses farm-specific data on land use, stocking levels, etc. (which the EA hold for each of the 100,000+ farms in England) and on land parcel attributes to model pollutant losses to watercourses per farm. Pollutant inputs from other sources (e.g. point source inputs from sewerage-related sources) can also be added. The following data are required:

- **Spatial estimate of FIO load inputs to watercourses** – EA use the CCM to model these, based on holding-scale data mapped to the Rural Payment Agency's (RPA) Customer and Land Database (CLAD) parcels. However, outputs such as those generated by EoM-FIO could be employed. Fieldmouse doesn't require any particular input format – just something that can be read by ArcMap. A 1 km dataset would work fine, so long as the load is converted to be the load per digital terrain model (DTM) cell. Thus, if a 10 m DTM is used, the input load is estimated per 10 m cell. The FIO loading data that EA use are for FC and FS. In the forked version of Fieldmouse v2[14], CREH models for EC and IE die-off have been used to estimate FC and FS die-off along watercourses.
- **Digital terrain model** – ideally 10 m or finer, filled to remove sinks. EA currently use a 10 m LIDAR DTM from their Geomatics division.
- **Digitised river network with flow direction and connectivity defined** – EA use the 'Detailed River Network' (DRN) which encodes flow direction by way of FROM and TO nodes.
- **Spatial estimate of flow generation** – Fieldmouse isn't a hydrological model and never will be. EA use 1 km run off generated by the CERF model, which splits flow into slow flow and quick flow, which are treated differently in terms of FIO decay. The flow data doesn't need to be a 1 km dataset – flow generation aggregated to WFD catchment boundaries would suffice. The only flow calibration parameter in Fieldmouse is a simple correction factor. EA have found that CERF represents the spatial diversity of flow generation fairly well for most catchments, and a single correction factor has worked well.
- **Spatial point-source loads and flows** (optional) – e.g. WwTW consented dry-flow discharges, WwTW storm tank overflows (STOs), CSOs, etc.
- **Catchment boundaries**
- **Water quality (FIO) monitoring data for calibration**
- **River flow monitoring data for calibration**

2.3.1.2 Modelling FIO die-off

In contrast to other agricultural pollutants, attenuation of FIOs (through die-off) on ground surfaces and along the watercourse is a potentially significant factor affecting pollutant loadings and, accordingly, Fieldmouse incorporates estimates of FIO die-off rates. The exported FIO load from the CCM is transported to the river, accumulated and decayed within the Fieldmouse framework (Hankin & Douglass 2012). In the forked version of v2 exponential decay ($\lambda = 10$ for the slow flow element and $\lambda = 0$ for the quick flow part of the flow) is used, with load apportioned by the ratio of the two. Estimates of die-off along watercourses has been derived using a CREH model of the relationship between T_{90} and irradiance and water turbidity (see further discussion in Section 4.3.1, below). The EA modelling is currently based on the following: 12 hours of daylight, with the average number of sun hours per day derived from a 1 km Meteorological Office dataset per catchment; and long-term average turbidity data from across the catchment being modelled. Further details of the methods employed and assumptions made are given in an internal EA document on *FIO time of travel and decay estimates* – presented here in Appendix 9.

2.3.1.3 Model outputs

At present the outputs for FIOs all relate to conditions during the summer bathing season, and the model has been run using long-term average flow data sets. Hitherto, the model has been used primarily to estimate annual loadings delivered to coastal catchment outlets, though it could equally be applied to any receptor water. Technically, it would be possible to extend the application to generate estimates of low- and high-flow concentrations and loads. These, however, would need to be calibrated using catchment-specific FIO monitoring data.

2.3.2 Evaluation

Fieldmouse and its associated input databases seems to incorporate all of the key factors and processes which are likely to affect the FIO loadings delivered to catchment outlets and other receptor sites. A potential weakness would appear to lie in the application of a simple exponential function to model die-off on ground surfaces and within soils as FIO inputs are transported from land to the adjacent watercourse. However, as the EA acknowledge, Fieldmouse is still very much in the early stages of development, and this aspect would certainly seem to merit further investigation. Also, while technically capable of delivering estimates of FIO concentrations and loads under low- and (more critically) high-flow conditions, the EA have not yet developed and run the model in this way, and at present there is no basis for assessing how successful this will prove to be.

2.4 SIMCAT/SAGIS framework

According to the Project Specification, SIMCAT/SAGIS[15] is of critical importance since in Phase 2: "…. the successful contractor would develop the methodology and mechanics of a simple model to allow SEPA/SW/DWQR to effectively build and run the model (within SEPA's corporate modelling SIMCAT/SAGIS framework)". It should be noted that SIMCAT/SAGIS is not designed to be used to predict short-term (typically rainfall-driven) episodes of adverse microbial water quality which typically characterise FIO fluxes in river systems, and commonly present the main reasons for regulatory failures at receptor sites such as bathing and shellfish waters (Crowther *et al*., 2001; Stidson *et al*., 2011, Wyer *et al*., 2013). Thus, while present versions of SIMCAT/SAGIS might be used to model background/aggregate FIO fluxes, this is unlikely to meet the key information requirements of the regulators and/or downstream water users. If, therefore, consideration were given to using SIMCAT/SAGIS for modelling purposes, then some

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[14] It should be noted that in the forked version of v2 exponential decay to is used to represent die-off in the landscape, rather than the SWAT-derived landscape retention/loss factors.

[15] For a description of SAGIS/SIMCAT and its applications see: https://connect.innovateuk.org/documents/2779724/7364681/jenny+grubb+paper.pdf/0761c608-92f0-46d3-8f84-5f45fdb6e7dd;jsessionid=7f06dc2095706f7ba0dea02fd4f6e623.1.

redesign would be required to ensure the operational utility of this platform.

One strength of the SIMCAT/SAGIS system is that it allows the overlay of multiple data layers, thus enabling geo-referenced, externally generated spatial data (empirical data, modelled data, field observations, etc.) to be incorporated as layers within a single interrogable framework.

3 Proposed screening methodology

In view of the short time-frame and relatively limited resources available, the development of a completely 'new' set of process-based models for Scotland would seem totally impractical and unjustifiable. Instead, it is recommended that a screening methodology is developed which capitalises on the considerable investments that have already been made in EoM (FIOs and other pollutants) and in the various empirical FIO source-apportionment studies that have been undertaken in Scotland. What is proposed is a composite ('mashup') screening methodology which integrates and develops further the existing approaches/databases, and provides a framework within which more detailed, site-specific investigative work might be undertaken by staff in the field. The proposed screening methodology comprises five key, interlinked, components[16], each of which could potentially be developed further in Phase 2:

I. **Generic black-box regression models of FIO concentrations**
    a. To estimate FIO concentrations and loadings in riverine inputs to Scottish coastal waters and other receptor waters – enabling such waters to be ranked according to their risk of impairment
    b. To estimate FIO concentrations and loadings for individual subcatchments within catchments identified as being at greatest risk – enabling the more critical subcatchments to be identified for closer investigation

II. **EoM-FIO screening tool**
    To further help identify the more critical catchments/subcatchments and, crucially, enable the:
    a. Identification of key source(s) – through source apportionment
    b. Estimation of impact of remedial measures

III. **Models of FIO die-off along watercourses/zones of influence**
    To provide insight into the zone of influence of individual FIO pollutant sources within the catchment of a receptor water

IV. **Site-specific investigative methods/tools**
    To help identify rogue FIO hotspots within catchments

V. **Integration of outputs of Components I-IV within a catchment GIS framework**
    Consideration needs to be given to the incorporation of outputs from Components I-IV within a GIS system (SEPA currently used the SIMCAT/SAGIS framework), so that potential users of the FIO screening methodology, from government agencies to catchment field officers, can easily access the various layers of information in order to assess the weight of evidence and make better-informed judgements.

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[16] A further component (Near-shore coastal dynamic modelling – see Appendix 8) would need to be included in order to model FIO concentrations in coastal waters, but this is outside scope of the present project.

4 Scoping of proposed screening methodology in two 'trial' catchments

Here, Components I–III have been further explored using two 'trial' catchments, various approaches that might be adopted in Component IV are outlined, and the importance of integrating these within SIMCAT/SAGIS is emphasised. The catchments selected by SEPA for this scoping assessment are representative of two key catchment types in Scotland:

- **R. Irvine[17] (here termed 'Irvine') catchment** – a simple riverine catchment with substantial areas urbanisation (principally Irvine and Kilmarnock) and intensive livestock farming which discharges to designated coastal bathing waters (Figure 1)
- **Loch Etive ('Etive') catchment[18]** – the large and complex west coast catchment (with multiple catchment inputs, many via Loch Awe) of the Loch Etive shellfish water, dominated by upland sheep farming (Figure 2).

In this these trial investigations, attention is focussed on the FIO concentrations and loads generated within the various 'confluence'[19] catchments identified in Figures 1 and 2, and ignores the issues of die-off within waterbodies, either within the Irvine or Etive[20] catchments. 15-minute flow data for the Irvine catchment outlet (at Shewalton) over a typical month in the summer bathing season (July 2015) were used, in combination with the modelled FIO concentrations, to illustrate the way in which real-time estimates of FIO loads can be generated.

4.1 Component I: Use of generic regression models of FIO concentrations

The only black box regression models for UK conditions are the England & Wales models that have been developed by CREH for conditions during the summer bathing season, the latest versions of which were developed in collaboration with the EA (CREH, 2010). These are used here to illustrate the potential of this approach, which could be developed further in Phase 2 of this project.

4.1.1 Development of the CREH (summer bathing season) models

The modelling undertaken was based on low- and high-flow geometric mean (GM) FC and FS concentrations recorded during the summer bathing season in 13 catchments in England and Wales (8 CREH catchment studies and 5 ECSFDI catchments) over the period 1995–2010. Within each of these, water quality was monitored for a series of subcatchments which encompassed the range of land use present within the catchments. In total, 151 subcatchments were included at low flow and 133 at high flow. Data on the following catchment characteristics were included as predictor variables in the regression models: catchment area (km^2), Base Flow Index (BFI), land cover (% of different land cover types), residences (km^2) and livestock densities (km^2). The resulting regression models for FC and FS have explained variances (adjusted r^2 values) of 0.627 and 0.648, respectively, which are particularly high for environmental models of this type; whereas the corresponding low-flow values are rather lower (0.458 and 0.360). Further details are presented in Appendix 2. It should be noted that the current low-flow models do not include sheep as a predictor variable. While this may not be particularly problematic in many catchments in England and Wales, or the Scottish lowlands, where sheep stocking densities often correlate with other livestock (e.g. with cattle), it is likely to be an issue in some of the more extensive catchments in the Scottish highlands, where sheep are overwhelmingly dominant.

4.1.2 Trial application of regression models

4.1.2.1 Characteristics of the two trial catchments

Data for the key catchment parameters used in the modelling of the confluence catchments within the Irvine and Etive catchments are presented in Tables 3 and 4, respectively. These reveal very marked differences both between the two catchments and within each catchment. The Irvine catchment as a whole has an area of 481.41 km^2 and has quite a high population density (117.47 residences/km^2). Its land use is dominated by improved grassland (55.4%), and the stocking densities are correspondingly high – e.g. dairy cattle 41.05/km^2 and sheep 112.07/km^2. Some of the smaller confluence catchments are particularly heavily urbanised (e.g. 1579.06 residences/km^2 in catchment 1375, which includes part of Kilmarnock; and 1552.39 residences/km^2 in 3247, which includes parts of Irvine). Notably high stocking densities occur in some of the more rural catchments (e.g. 142.37/km^2 dairy cattle in 1365 and 204.71/km^2 sheep in 1382. By comparison, the Etive catchment is much larger (1329.64 km^2) and has a very low population density (1.56 residences/km^2). Only 3.8% of the land is improved grassland, and sheep are the only significant livestock present, with an average stocking density of 31.11/km^2.

4.1.2.2 Predicted summer bathing season FC concentrations in watercourses draining the confluence catchments

For illustrative purposes, attention here focuses on the application of the FC models to the trial catchments. Two key

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[17] CREH undertook a detailed empirical FIO source-apportionment investigation in Irvine catchment in 1998 – CREH, 1999; and investigated the impacts of various agricultural interventions in the Killoch Burn subcatchment of the R. Irvine in 2002/4 – CREH, 2006).

[18] CREH undertook a detailed empirical FIO source-apportionment investigation of Loch Etive in 2006/7 – Stapleton *et al*., 2011).

[19] 'Confluence' catchments, defined by SEPA, comprise a combination of tributary catchments limited downstream by their confluence with a larger watercourse, and short sections along the major watercourses. While they account for all the land within the catchment as a whole (e.g. within the R. Irvine catchment), data generated for the output locations along the main watercourse(s) need to be regarded with caution, since they do not include all of the land upstream of the catchment outlet point. This issue will need to be addressed in Phase 2 of the project.

[20] It should be noted that there will inevitably be substantial attenuation of FIOs as a result of die-of, predation and sedimentation within Loch Awe, and this issue will be fully addressed in Phase 2 (if the decision is made to adopt the proposed methodology).

points must be borne in mind in interpreting these data: (a) only the data for the discrete tributary catchments actually reflect water quality at the catchment outlet (data for entire upstream catchments would be needed for catchment outlets along the main watercourses); and (b) no account has been taken of die-off within waterbodies (lakes and reservoirs) – which is a major issue with Loch Awe and its associated confluence catchments in the Etive catchment.

The predicted summer bathing season GM FC concentrations under low- and high-flow conditions in the confluence catchments of Irvine and Etive are presented in Figures 3 and 4 (and Tables 3 and 4), respectively. The predicted GM FC concentration at the Irvine catchment outlet at Shewalton (based on aggregated catchment data) increases from 1.1 x 10^4 cfu/100 ml at low flow to 6.9 x 10^4 cfu/100 ml at high flow (i.e. a *c.* 6-fold increase), whereas the corresponding figures for the Etive catchment as a whole are 8.1 x 10^2 and 2.5 x 10^3 cfu/100 ml (i.e. a *c.* 3-fold increase). These results clearly illustrate the differences in FIO concentrations that can be encountered between two markedly contrasted catchments, with much high levels of microbial pollutants being present in the Irvine, with its much higher population density and stocking levels. They also illustrate the way in which FIO concentrations increase at times of high flow. Within the Irvine catchment there are particularly marked differences between the various confluence catchments (Figure 3) – e.g. predicted GM FC concentrations at high flow range from 1.9 x 10^3 cfu/100 ml in catchment 1369 (Logan Burn) in the eastern headwaters to 7.8 x 10^5 cfu/100 ml in 1365 (R. Irvine @ confluence with Carmel Water – i.e. one of the catchments along the main watercourse), which includes quite extensive areas of urban land and areas of intensive dairy/sheep farming. Such model outputs are clearly going to form an important component of a screening methodology.

Plots of the predicted and actual GM FC concentrations for the five confluence catchments monitored previously by CREH are presented in Figures 5 (low flow) and 6 (high flow). These results clearly need to be interpreted with caution when based on so few catchments. They are, however, are encouraging in revealing a strong underlying relationship between the predicted values and 'ground truth' data, particularly in the high-flow plot, the best-fit line for which reveals a relationship that is not far from 1:1. On this basis, we can have some measure of confidence in the outcomes of the regression modelling.

4.1.2.3 Estimates of FC loads delivered to the outlet of the Irvine catchment in July 2015

Flow data for the Irvine catchment outlet for July 2015 are presented in Figure 7. This period clearly includes several significant rainfall events, with values ranging from 7.6–99.6 cumecs. FC loads have then been estimated by applying a crude low/high-flow separation to the flow records (flows ≥ 12.0 cumec were identified as high flow) and applying the corresponding GM FC concentrations. A plot of variations in the FC load delivered to the coastal bathing water during July 2015 is presented in Figure 8. As would be anticipated, the predicted load increases markedly in response to rainfall events, with values increasing from *c.* 1.0 x 10^9 cfu/s at low flow to between 1.0 x 10^{10} and 1.0 x 10^{11} at high flow (i.e. a 1.0–2.0 $\log_{10}$ increase in magnitude). Modelled FIO concentrations, when combined in this way with flow records, can be readily used to estimate the microbial pollutant loadings impacting coastal bathing and shellfish waters, drinking water abstraction points and other receptor waters.

4.1.3 Potential further development of regression modelling (in Phase 2)

The above trial application has clearly demonstrated the utility of this approach in rapidly generating estimates of FIO concentrations (and loads) for catchments and their subcatchments. In developing this approach further, the following points will need to be borne in mind:

a. Sheep not a predictor variable in existing low-flow FC model
b. Lack of Scottish data in present model database
c. Lack of 'winter' models
d. Changed microbial compliance parameters (under rBWD and SWD).

4.2 Component II: Use of EoM-FIO

4.2.1 Key features/limitations of EoM-FIO

(with contribution by S. Anthony and R. Gooday, ADAS)

EoM-FIO, which was developed as an integral component of the EoM Project (ADAS, 2014) is based on a large and complex environmental/hydrological/farm characterisation/farm management database. ADAS recognise that EoM-FIO cannot, in itself, meet the all requirements of the present project – it was not designed to do so! It is important at the outset therefore to identify the key features/limitations that have a bearing upon the development of the present screening methodology.

4.2.1.1 Issues of spatial resolution

The EoM database summarises calculated pollutant loads at WFD waterbody scale (inland and coastal). The method of calculating the waterbody-scale pollutant loads is based on an integration of 1 km^2 'export coefficients' (derived from more detailed process and statistical modelling) with summary waterbody-/farm-scale measures of the inputs at risk of becoming pollutants (such as livestock excreta) that were derived from the June Agricultural Survey (JAS) and practice data. While, technically, it would be possible to generate FIO pollutant load data on a 1 km^2 grid, the degree of uncertainty in locating the animal numbers, etc. based on the JAS is such that the apparent spatial resolution would not be 'honest'. If the location of animals and farm boundaries could be obtained from the Cattle Tracing Service and EU Integrated Administration and Control System (IACS), then then this would facilitate the generation of more local pollutant input loadings. However, the detail of how the inputs are managed (as slurry or manure, number of days at grazing, etc.) would still largely be downscaled from regional- and national-scale farm practice surveys and not reflect the operations of individual farms. Clearly, this is particularly problematic in cases where an individual 1 km^2 might be occupied by only 1 or 2 farms.

While outputs at the scale of the individual WFD inland river catchments (which average *c.* 20 km^2) can be generated with some degree of confidence (as in the EoM Project), the results generated for smaller areas (e.g. coastal WFD catchments) must be regarded with utmost caution. ADAS have concerns about the use of the WFD or General Binding Rule (GBR) database results for the individual coastal catchments in any screening process for targeted action on FIOs in designated bathing or shellfish waters. For this type of activity it is critical that the FIO inputs are accurately located. However, there are often marked changes in land use mosaic in coastal regions, e.g. settlement often hugs the coastline and that means less space for livestock. As is illustrated in Figure 9, the coastal WFD catchments are very small in comparison to the JAS parishes for which livestock numbers, etc. were made available for inclusion in EoM-FIO – with these data being downscaled using landcover data, but assuming constant stocking rates within each parish.

4.2.1.2 Issues of temporal resolution: Seasonality

At present EoM-FIO is designed only to generate estimates of the mean annual FIO load delivered to watercourses within each WFD catchment (i.e. seasonal and flow-driven variations in load are not quantified). However, there is an element of seasonality in the annual load calculations, both in the magnitude of source strengths and in the die-off rate and likelihood of runoff to carry the FIOs to the watercourse. The source apportionment in the EoM database gives the best and most easily accessible indicator of base- and high-flow load contributions and their seasonality. For example, losses from cattle excreta from fields grazed in summer from surface/drainflow (source-area-pathway apportionment) represent the losses in event drainage that would correspond to high-flow conditions during summer months. In principle it would be possible to return to the source models and explicitly calculate seasonal loads. However, it would not be possible to move to a monthly or weekly resolution as the critical source model (FIO-FARM) is a stochastic representation of runoff risk that is driven by climate parameters.

4.2.1.3 Issues of low/high flow concentrations

FIO concentrations in the runoff event water could be extracted from the source FIO-FARM model, but unfortunately this is not readily available in the version of the model that was scaled up for the EoM database – which only tracks the number of FIOs. Technically, it would be possible to develop EoM-FIO in such a way as to separate the flow volume and concentration components.

4.2.1.4 Die-off along watercourses

For a crude verification of the EoM, ADAS did incorporate a die-off algorithm to estimate the proportion of inputs that would be delivered 'alive' to the coast. It should be noted that this algorithm was based only on information on lake residence times and took no account of water temperatures or turbidity. Again, EoM-FIO could be developed to incorporate more explicit modelling of the 'river transport', taking into account key factors such as irradiance and turbidity (see Section 4.3).

4.2.1.5 Outputs generated

For each of the WFD catchments, data have been generated on:

- Mean annual FIO (actually, FC) loads (expressed as cfu/ha) delivered to watercourses under present conditions derived from three separate sources (Figure 7-10, ADAS, 2014):
  a. 'Other point' (i.e. STWs and septic tanks[21] – but not CSOs or STOs at STWs)[22] or discharges direct to the coastal zone
  b. 'Other diffuse' (i.e. diffuse inputs from wildlife in non-agricultural landscapes and from urban areas)
  c. 'Agriculture'
- Estimates of the percentage reductions in load that would be achieved as a result of different levels of intervention to mitigate fluxes from agricultural sources.

CSOs and STOs were not included in the EoM database (simply because the primary focus in the EoM Project was on nutrients), and losses for the majority of the STWs were only based on consented dry-weather flows. This is unfortunate from the point of view of FIOs and means that the sewerage-related component is currently underestimated.

4.2.2 Assessment of utility of EoM-FIO output in trial catchments

The WFD catchments in the Irvine Etive catchments are presented in Figures 10 and 11, respectively, and estimated annual FIO loads delivered to watercourses in these catchments are presented in Figures 12 and 13.

4.2.2.1 Inter-catchment comparisons

The total annual FIO load/unit area within the Irvine catchment (3.24×10^{11} cfu/ha/yr) is about four times that of the Etive catchment (8.58×10^{10} cfu/ha/yr). As would be anticipated, the source-apportionment plots (Figure 14) reveal marked contrasts between the two. In the Irvine catchment the loadings derived from agricultural (54%) and non-agricultural sources (46%) are very similar. The agricultural component is derived from dairy (12%), beef (18%) and, particularly, sheep (24%); and the non-agricultural component is dominated by the two sewerage-related inputs: STWs (22%) and septic tanks (20%). In contrast, in the Etive catchment, agricultural sources are dominant (72%), with the majority (63%) being from sheep and the remainder from beef (9%).

4.2.2.2 Intra-catchment variations

Data on the annual FIO loads of the individual WFD catchments and their source apportionment are presented in Tables 5 (Irvine) and 6 (Etive). As is evident from Figures 12 and 13, there is quite marked variability in the loads derived from individual WFD catchments, and these EoM-FIO data readily enable catchments with the higher loadings to be identified for closer investigation. In the Irvine, for example, WFD catchment 10394 has the highest load (6.90×10^{11} cfu/ha/yr), of which the majority (65%) is derived from STW sources (Figure 15). WFD catchment 10927, by comparison, has a lower loading (2.82×10^{11} cfu/ha/yr), which is close to the average for the Irvine catchment as a whole, and in this case 83% is estimated to be derived from agricultural sources: dairy (21%), beef (28%) and sheep (34%). In the case of the Etive catchment, WFD catchments 10792 and 10285 have broadly similar overall loads and apportionment between agricultural and sewage-related sources, but show a marked difference in the specific apportionment of the sewage sources – with STW discharges being absent in the former catchment and accounting for 25% of the load in the latter (Figure 16).

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[21] Based on SEPA licensing records, the number of consented septic tank discharges in Scotland is 51,700, and this figure has been used in the EoM database. It should be noted, however, that this is likely to be an underestimate due to unlicensed tanks. It is noted in ADAS (2014, p. 52) that from previous ADAS work (in 2006) from comparison of the Ordnance Survey Postcode Address Points register with the number of households charged for drainage services by Scottish Water, an estimated 184,320 properties were on septic tanks.

[22] Industrial discharges are also included in the EoM database, but these are not considered as sources of FIOs.

4.2.3 Potential for further development of EoM-FIO (in Phase 2)

EoM-FIO provides valuable insight into the likely total annual loads of FIOs delivered to watercourses and, most importantly, their source apportionment (aim (b) of this project). It also provides estimates of the impacts of interventions to reduce FIO fluxes from agricultural sources (aim (d)). However, it does not presently address the other two aims, namely:

a. **Prediction of current FIO loadings** (ideally concentration and flow) being delivered to specific receptor waters under different flow conditions and in different seasons
b. **Estimation of 'zone of influence'** of individual sources within catchments.

EoM-FIO could certainly be developed further to help meet these two aims, but this would require substantial investment in time and resources, especially in relation to (a). It should be noted that (a), at least for the summer bathing season, is being addressed separately through Component I (the regression modelling); and (b) through Component III. It may well be that further development of EoM-FIO is not required, or that it be targeted to address any outstanding concerns that are identified by the stakeholders in their evaluation of the proposed screening methodology. As noted in the introduction, any further development of EoM could potentially enhance its utility not just in relation to FIOs, but also the range of other pollutants that are covered by the EoM database.

4.3 Component III: Models of die-off along watercourses/zones of influence

4.3.1 Existing CREH database for modelling T_{90} values in UK watercourses

CREH is involved in an on-going set of microcosm experiments to investigate rates of die-off of FIOs in freshwaters draining to the R. Ribble – using methods initially developed to investigate T_{90} values in estuarine and marine samples from the Severn Estuary (Kay *et al*., 2005). CREH (2014) reported on an analysis of the interim results (up to end of 2013) and the development of preliminary models of T_{90} variations under different levels of solar irradiance and turbidity, and these findings now underpin the EA's modelling of die-off along watercourses (as detailed in Appendix 9). For illustrative purposes in the present scoping study, the following three representative T_{90} values have been used:

- Day time/Sunny conditions/Low turbidity* in watercourses: $T_{90} = 3$ h
- Day time/Sunny conditions/High turbidity* in watercourses: $T_{90} = 20$ h
- Night time/Dark conditions: $T_{90} = 50$ h

* The low and high turbidity values are applied to low- and high-flow conditions, respectively.

4.3.2 Trial application of representative T_{90} values to establish zones of influence

For the purposes of this trial, typical low- and high-flow velocities of 0.1 and 1.0 m/s, respectively, have been assumed. These figures, in combination with the representative T_{90} values have been used to calculate the extent of FIO die-off (expressed here as $\log_{10}$ die-off) over different flow distances under the following four different scenarios:

i. Low flow/Low turbidity/Day time/Sunny conditions
ii. High flow/High turbidity/Day time/Sunny conditions
iii. Low flow/Night time/Dark conditions
iv. High flow/Night time/Dark conditions.

By combining the flow velocity and T_{90} data, the flow distances required to produce a particular level of die-off have been calculated for each of these scenarios (Table 9).

4.3.2.1 Zones of influence affecting catchment outlets

For illustrative purposes, results have been generated just for the Irvine catchment and from the perspective of the catchment outlet (i.e. discharge to the coast). The estimated flow distances required for a specified die-off to occur under each scenario are presented in Table 7. Plots are presented for the four different scenarios: Figure 17 – Day time/Sunny scenarios (i and ii); and Figure 18 – Night time/Dark scenarios (iii and iv). These show the distance upstream from the outlet over which there will have been particular rates of die-off, shown here as: < 0.50 $\log_{10}$, 0.50–1.00 $\log_{10}$, 1.00–1.50 $\log_{10}$, 1.50–2.00 $\log_{10}$ and > 2.0 $\log_{10}$ (1.00, 2.00 and 3.00 $\log_{10}$ are equivalent to 90, 99 and 99.9%, respectively). The effect of flow conditions upon the zone of influence under sunny conditions is clearly shown in Figure 17. The calculated zone of influence is very short in Scenario i (Low flow), when there will be an estimated 1.0 $\log_{10}$ die-off within 1.08 km of the outlet, and 2.0 $\log_{10}$ within 2.16 km. These figures compare with 72 and 144 km respectively, in Scenario ii (High flow). In the case of the Irvine, the maximum river flow length from outlet to headwater source is < 40 km and therefore under high-flow conditions the entire catchment falls into the < 0.50 $\log_{10}$ category. At night time the T_{90} values increase to 50 h, thereby extending the zone of influence much further up the catchment (Figure 18). At low flow (Scenario iii), for example, the critical 1.0 and 2.0 $\log_{10}$ die-off distances increase to 18 and 36 km, respectively. These results clearly demonstrate the impact that changes in irradiance, turbidity and flow velocity have upon the zone of influence.

4.3.2.2 Zones of influence of individual FIO sources within catchments

It should be noted that plots of the type present in Figures 17 and 18 could, just as easily be presented 'in reverse' to delineate the zone of influence of a hypothetical FIO source within the catchment – i.e. to show the distance downstream from an individual source over which there will be particular rates of die-off. For example, in the case of an hypothetical point-source input at Darvel (*c.* 25 km from the coast) the plots would show that at low flow in sunny conditions, there would be a 2.0 $\log_{10}$ die-off over a distance of 2.16 km downstream, whereas at high flow in sunny conditions there would be a < 0.5 $\log_{10}$ die-off before the input load reached the coast.

4.3.3 Potential for developing models of die-off (in Phase 2)

In the present trial investigation, four extreme sets of conditions were used to illustrate the potential utility of this approach for estimating zones of influence of individual FIO inputs to watercourses. CREH's existing models could be used to investigate variations in die-off rates across a wide range of solar irradiance and turbidity conditions, and the utility of applying these models could be explored, e.g. to model the effects of diurnal and seasonal patterns in irradiance upon T_{90} values.

4.4 Component IV: Site-specific investigative methods/tools to help identify rogue FIO hotspot sources within catchments

As noted above, predictive models provide insight into FIO concentrations and loads that would be 'expected' in a given catchment/subcatchment, given its land use, stocking levels, degree of urbanisation/residential density, etc. In order to identify rogue hotspots (i.e. where FIO loadings to streams significantly exceed these norms), then a variety of site-specific methods/tools can be employed. In addition to agricultural and sewerage-related sources, brief consideration is given to wildlife sources.

4.4.1 Rogue agricultural hotspots

Rogue agricultural hotspots are most likely associated with the presence of either a livestock farm(s) which is at the top end of the range in terms of FIO generation for their type (e.g. have higher than normal stocking levels or where farming practices, while within existing GBRs/codes of practice, are at the riskier end of the range); or a farm(s) where GBRs/codes of practice are regularly being breached. Such hotspots can only be identified on a farm-by-farm basis using a combination of methods/tools, including the following.

4.4.1.1 Farm inspections/field walking

Farm facilities and/or management practices that are actually causing high levels of microbial water pollution or present high risks of pollution can usually be identified quite readily from farm visits undertaken by catchment officers. The qualitative water pollution risk assessment for livestock-related FIO pollution presented in Appendix 5 (Table A5-1) provides a useful guide.

4.4.1.2 Field-based water quality surveys

Visual inspections of watercourses, especially ditches located close to farm hardstandings, can often reveal locations where water quality impairment is occurring. Simple macro-invertebrate surveys (kick sampling) and in-field specific conductance measurements may further help to identify more heavily polluted waters which could well include microbial pollutants.

4.4.1.3 Use of Farmscoper (ADAS)

Farmscoper is a decision support tool[23] that has been developed over recent years by ADAS to estimate the likely pollutant loads generated on individual farms and the impacts of mitigation. It takes into account factors such as stocking density, slurry storage, soil characteristics, climatic factors, etc. Version 3, which has recently been released by Defra, includes (for the first time) FIOs. Although based on the profiles of specific farm types in England, it could be used in its present form by catchment officers to help identify individual farms within Scottish catchments that are likely represent key sources of microbial pollution.

4.4.1.4 Thermal imaging

Thermal imaging, currently being pioneered by APEM Ltd[24], can be used to locate areas of greater heat (e.g. grazing livestock, manure heaps, etc.) within catchments. While such technology may well be effective, it is potentially quite costly when deployed over large areas and it would seem unlikely to generate much information that will not be evident from farm inspections/field-walking.

4.4.2 Rogue sewerage-related hotspots

These will be locations where the FIO load being discharged to a watercourse considerably exceeds the 'norm' for a particular type of discharge, either because of greater than expected flows (consented discharge in many cases) and/or higher than typical FIO concentrations – as, for example, would occur if a WwTW was under-performing in terms of FIO attenuation.

4.4.2.1 Regular monitoring, inspection and evaluation of performance of WwTWs/CSOs/septic tanks (including those associated with small caravan parks and other tourist-related facilities)

Monitoring of FIO concentrations and load inputs to watercourses from individual WwTWs under low- and high-flow conditions, combined with flow data from key CSOs, will enable many of the potentially key sewerage-related sources to be assessed, and their performance evaluated against 'norms' and consented discharges. Regular inspections should also be made of the wastewater treatment and disposal facilities associated with individual caravan parks, etc.

4.4.2.2 Field-based water quality surveys

In addition, visual inspections of watercourses downstream of sewerage-related (including septic tank) discharges can often reveal locations where water quality impairment is occurring. In serious cases, sewage fungus can often be observed. Simple macro-invertebrate surveys (kick sampling) and in-field specific conductance measurements taken upstream and downstream of a discharge point may further help to identify inputs of polluted waters which could well include microbial pollutants.

4.4.3 Rogue wildlife hotspots

Field walking and local knowledge of the catchments of receptor waters should readily reveal areas where wildlife sources may be making a significant contribution to microbial pollutant loadings – examples of which are presented in Appendix 4.

4.5 Component V: Integration of outputs of Components I-IV within a catchment GIS framework

If the proposed methodology is accepted then, to be fully effective, the outputs from all four components need to be integrated (very much as a 'data repository') within a GIS framework, in a form in which key data layers can be readily accessed and interrogated. The potential of using SEPA's current SIMCAT/SAGIS framework for this purpose will need to be explored.

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[23] Available free-of-charge from ADAS (http://www.adas.uk/Service/farmscoper).

[24] Contact details: APEM, Ltd., Riverview, A17, Embankment Business Park, Heaton Mersey, Stockport SK4 3GN (http://www.apemltd.co.uk/).

5 Recommendations (provisional)

The following section is currently provisional, since it assumes that SEPA and other stakeholders feel that the proposed screening methodology is capable, with further development (within the timeframe and budget envisaged for Phase 2), of meeting the aims of the present project. If this is not the case, then other approaches will need to be evaluated.

5.1 Proposed screening methodology for further development in Phase 2

On the basis of the above review and the generally satisfactory outcomes of the scoping investigations undertaken, it is recommended that the screening methodology outlined in Section 3 be adopted for further development. This will involve the following five components:

I. Generic black-box regression models
II. EoM-FIO screening tool
III. Models of FIO die-off along watercourses
IV. Site-specific investigative methods/tools
V. Integration of outputs of Components I-IV within a catchment GIS framework.

5.2 Recommended development of proposed screening methodology in Phase 2

Before being deployed at a national scale, it is recommended that each component of the study is developed further. In total there are 19 recommendations, which for ease of reference are labelled i-xix. These have been classed as being of high [***], moderate [**] and low [*] priority, with the key organisations responsible for undertaking the work being identified.

5.2.1 Component I: Generic black-box regression models

i. Inclusion of sheep as a predictor variable in all models [* CREH]** – In the existing models, sheep stocking density is not a predictor variable in the low-flow models for FC or FS. In view of the overwhelming dominance of sheep in some Scottish catchments, it is vital that the existing models are developed further to ensure that sheep are included.

ii. Inclusion of Scottish data in present model database [CREH/SEPA]** – The present models are based on data from England and Wales. Comparable FIO data are available for several Scottish catchments (from previous CREH studies), though it should be noted that many of these were undertaken in the period 1998–2007 (Table 1). If the necessary catchment (predictor) data, could be generated for these (ideally with stocking data and residence data for *c.* 2002), then it would be possible to develop new sets models that include Scottish data in the modelling database, e.g.

- **'UK' models** – incorporating the full set of catchment data;
- **'Scottish environment-focused' models** – excluding data sets from what are essentially lowland arable catchments in southern England (e.g. Holland Brook, Essex and R. Avon, Hampshire); or possibly
- **'Scottish' models** – provided the database for Scottish catchments is sufficient to allow this.

iii. Enhancement of database for England and Wales [* CREH/SEPA] – CREH have undertaken further FIO monitoring studies (including some outside the summer bathing season) in various catchments across England and Wales since the current generic models were developed, and these could be included to further enhance the database. It should be noted that the present models are based on FC and FS enumerations, rather the rBWD compliance parameters (EC and IE). Recent empirical catchment investigations have switched to EC and IE. Unfortunately, there are at present insufficient data available to establish a clear relationship between the two different data sets. The differences, however, are undoubtedly relatively small compared with magnitude of spatial and temporal variability that is commonly encountered within and between catchments, and CREH would advocate combining data from the two data sets in order to extend the data base.

iv. Development of 'winter' models [* ADAS/CREH]** – This is likely to prove more problematic because many fewer empirical data exist for periods outside the summer bathing season. If EoM-FIO is the extended to include seasonal components (vii, below), then priority should be given to exploring ways in which these seasonal load data might be used to provide a basis for estimating FIO concentrations outside the bathing season.

v. Application of resulting models all to Scottish confluence and WFD catchments and the catchments of receptor waters [* CREH/SEPA]** – The resulting models will need to be applied to catchments across the whole of Scotland, which will necessitate the generation of data for the predictor variables for each catchment. For many of receptor water catchments this will require an aggregation of data for all upstream catchments. In cases where lakes and reservoirs are present along a watercourse, then the catchments of such waterbodies will need to be delimited and data for the predictor variables be generated for areas of catchments downstream of these.

5.2.2 Component II: EoM screening tool (FIO plus other pollutants in the database)

While the following sections are written from the perspective of FIOs, points vi–ix should be extended to cover the other pollutants.

vi. Simplification of accessibility of WFD catchment data [* ADAS/SEPA]** – EoM-FIO has been designed to generate data on overall annual FIO loadings at the WFD catchment scale, with apportionment according to different sources, pathways, etc. The underlying database is vast, and CREH has gained the impression from discussions with Jonathan Bowes (SEPA), that they find EoM somewhat overwhelming. If this is the case, then basic information on loads and source apportionment for individual WFD catchments (as presented in Figures 15 and 16 and Tables 5 and 6), and aggregated data for the catchments of particular receptor waters (as in Figure 14), needs to be made more immediately accessible.

vii. **Quantification of seasonal variations in load [*** ADAS]** – In view of the much more limited empirical data are available on FIO loadings in streams outside the summer bathing season, seasonal apportionment of the annual loads derived from the three source types (agricultural, other point-source and other non-point source) is a key priority, and could potentially be used, in conjunction with existing regression modelling, to provide a basis for estimating low- and high-flow FIO concentrations outside the summer bathing season (see iv, above).

viii. **Quantification of low- and high-flow loads [*** ADAS]** – Estimates of FIO load inputs to watercourses from the three source types at high flow are critical to gaining a better understanding of the most likely causes of water impairment in receptor waters.

ix. **Enhancement of database on sewerage sources [*** SEPA]** – At present CSOs and STOs, STW flows that exceed consented dry-weather flows and sewerage-related point-source inputs to the coastal zone are not included in the database; and there is reason to doubt the extent to which licensed septic tanks are representative of the total number of septic tanks present. These data gaps will need to be filled in order to ensure that the sewerage components are fully represented in the database.

x. **Updating of FIO database for sewerage-related FIOs [*** CREH]** – At present, present EoM-FIO uses the FIO concentration data for untreated sewage and treated effluents presented in the review by Kay et al. (2008b) as the basis for estimating FIO loadings from sewerage-related discharges to watercourses. Since the publication of this paper, CREH have undertaken monitoring of many additional WwTWs in the UK, and it is recommended that in Phase 2 the earlier database be updated by incorporating data from these additional CREH studies and other sources.

xi. **Incorporation of FIO die-off along watercourses [* ADAS/CREH]** – While this is a possibility, it is felt that this issue is best addressed separately through in Component III.

xii. **Enhancement of data on stocking density [*** SEPA]** – These need to be generated at a higher level of spatial resolution than at present so that stocking densities and locations of livestock on individual farms and/or within relatively small defined areas of land (e.g. the coastal WFD catchments) can be established more readily and accurately for use by Field Officers. ADAS strongly recommend that records are obtained from the Cattle Tracing Service to accurately locate herds (especially within the coastal catchments), rather than relying on down-scaling of aggregate parish JAS records. For sheep, it will be necessary to use holding level data from the JAS, but it might be possible to use movement-off records from the Animal Movement Licensing System (AMLS) to get a better view of sheep numbers, especially where there is temporary grazing on rented land or the marshes. Furthermore, these records should be integrated with IACS field-parcel ownership data and vector mapping of landcover to place the stock on the appropriate grazing land. It is suggested that the 1988 Land Cover Scotland (LCS) dataset is used in place of the LCM 2007 as, despite the age, it was based on air-photo interpretation and is therefore likely to be better able to delineate the areas of rough grazing and grazed salt marshes. Different grass types are likely to be associated with different levels of fencing, etc.

xiii. **Enhancement of data on proximity and connectivity of grazed fields directly to watercourses [** SEPA]** – This would be best assessed by integration with Ordnance Survey (OS) 1:25,000 or 'blue line' maps of river/drain networks, supported by an analysis of the EU Land Use/Cover Area frame Survey (LUCAS) field boundary survey dataset. The latter is sampled at a density of one point per 3–5 km in Scotland and provides considerably more resolution than the Centre for Ecology and Hydrology (CEH) Countryside Survey.

xiv. **Generation of summary statistics for individual landscape types [** SEPA]** – These could be generated by creating a simple landscape typology based on soil type and landcover, and then extracting summary statistics from LUCAS for each landscape type. This would preserve the continuity of field boundary features associated with distinctive means of landscape management in Scotland – which may be particularly important in coastal zones. The Scottish National Heritage (SNH) Landscape Character Assessments (LCAs) may be a start for this.

xv. **Enhancement of data on livestock and waste management practices [** SEPA]** – Insight into key risk factors such as months at grazing, type of manure management practiced, etc. could potentially be gained by linking the JAS holding locations directly to the holding level records from the 2010 EU Survey of Agricultural Production Methods (SAPM). The SAPM was based on 4,400 returns (out of 34,000 commercial holdings) and could again be used with a landscape typology to provide some regional/robust farm type data on some key management risk factors, that could be downscaled to smaller land areas (e.g. the coastal WFD catchments).

xvi. **Enhancement of data on soils and drainage [** SEPA]** – The GIS database needs to be linked to the best available soils map and conceptual model of drainage pathways: the James Hutton Institute (JHI) 1:25,000 scale map for central and eastern Scotland, and the 1:250,000 map only where necessary. The EU Surface water/groundwater contribution (SUGAR) index FOOTPRINT MAP might also help as a readily available product.

xvii. **Development of Farmscoper-v3 (ADAS) for Scottish farms [*** ADAS]** – Currently, Farmscoper is based on detailed profiles of farms of particular types in England. As part of the recent EoM project (ADAS, 2014), detailed profiling has been undertaken of the key farm types in Scotland, and it is recommended that ADAS are commissioned to develop a Scottish version of Farmscoper-v3 to better inform Field Officers.

5.2.3 Component III: Models of FIO die-off along watercourses/zones of influence

xviii. **Establishment of seasonal and diurnal variations in T_{90} [*** CREH]** – The scoping studies have clearly demonstrated the impact of extreme T_{90} (and flow) conditions upon the zone of influence of individual FIO pollutant sources. Clearly, the irradiance received by watercourses will exhibit underlying seasonal, diurnal and cloud cover-related variations which could be modelled fairy readily to generate more realistic estimates of T_{90} values.

5.2.4 Component IV: Site-specific investigative methods/tools

Many of the recommendations made in relation to Component II (EoM-FIO), if implemented, will facilitate the identification of potential rogue agricultural and sewerage-related hotspots for more detailed investigation (see especially recommendations xii–xvii, above).

5.2.5 Component V: Integration of outputs of Components I-IV within a catchment GIS framework

xix. Integration of outputs within SIMCAT/SAGIS framework [* ADAS/CREH/SEPA]** – The fact that it was felt necessary to commission the present project, when so much resource has previously been invested in the development of FIO screening tools for Scotland, suggests that the EoM-FIO screening tool is judged to produce outputs that are either 'unreliable' and/or difficult to access and utilise. Clearly, the former cannot be properly assessed until the underlying database is used and the outcomes tested – but it is difficult to envisage a more detailed and comprehensive database being constructed to underpin such modelling. From discussions with Jonathan Bowes (SEPA) it would seem that the overwhelming complexity of the database and associated issues of 'accessibility/utility' are the main reason why the seemingly enormous potential of the EoM-FIO screening tool has not been fully capitalised upon. If this is the case, then it is vital to consider the extent to which the key components of the EoM-FIO database and its outputs, along with those relating to Components I, III and (to some extent) IV, can be incorporated as layers within SEPA's existing corporate modelling framework (SIMCAT/SAGIS) – i.e. using SIMCAT/SAGIS as a 'data repository'. It is envisaged that this would be interrogable at both the level of the individual WFD catchments and (aggregated) for catchments discharging to the coast and other receptor waters (e.g. for drinking water supply).

5.3 Time-scale and budget for completion of Phase 2

In the Project specification it is suggested that Phase 2 be undertaken over a 6-month period (April–September 2016). In view of the large number of separate elements, many involving inputs from more than one organisation, that need to be completed before the proposed methodology can be fully operationalised, it is highly unlikely that Phase 2 can be completed in 6 months. One year would seem much more realistic, even if only the high priority recommendations (above) were taken forward. Clearly, the amount of funding required will depend upon how the Project Steering Group decide to take things forward in light of the outcomes of Phase 1. It should be borne in mind that SEPA staff will need to be engaged in many elements of the proposed development.

5.4 Research agenda for Scotland (outside scope of Phase 2)

The wider research and regulatory/policy contexts within which the present investigation is set is presented in Appendix 2 (from PowerPoint presentation prepared for the project Start-up Meeting). Here various research priorities are identified in terms FIO modelling, both within catchments and near-shore coastal waters. It is recommended that these research needs are borne in mind by SEPA and other Scottish Government agencies as future research agendas are set. It is perhaps worth noting that implementation of water quality improvements via agricultural BMPs could have been seen earlier had water quality considerations been higher in the list of drivers for farm support payments.

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Figures

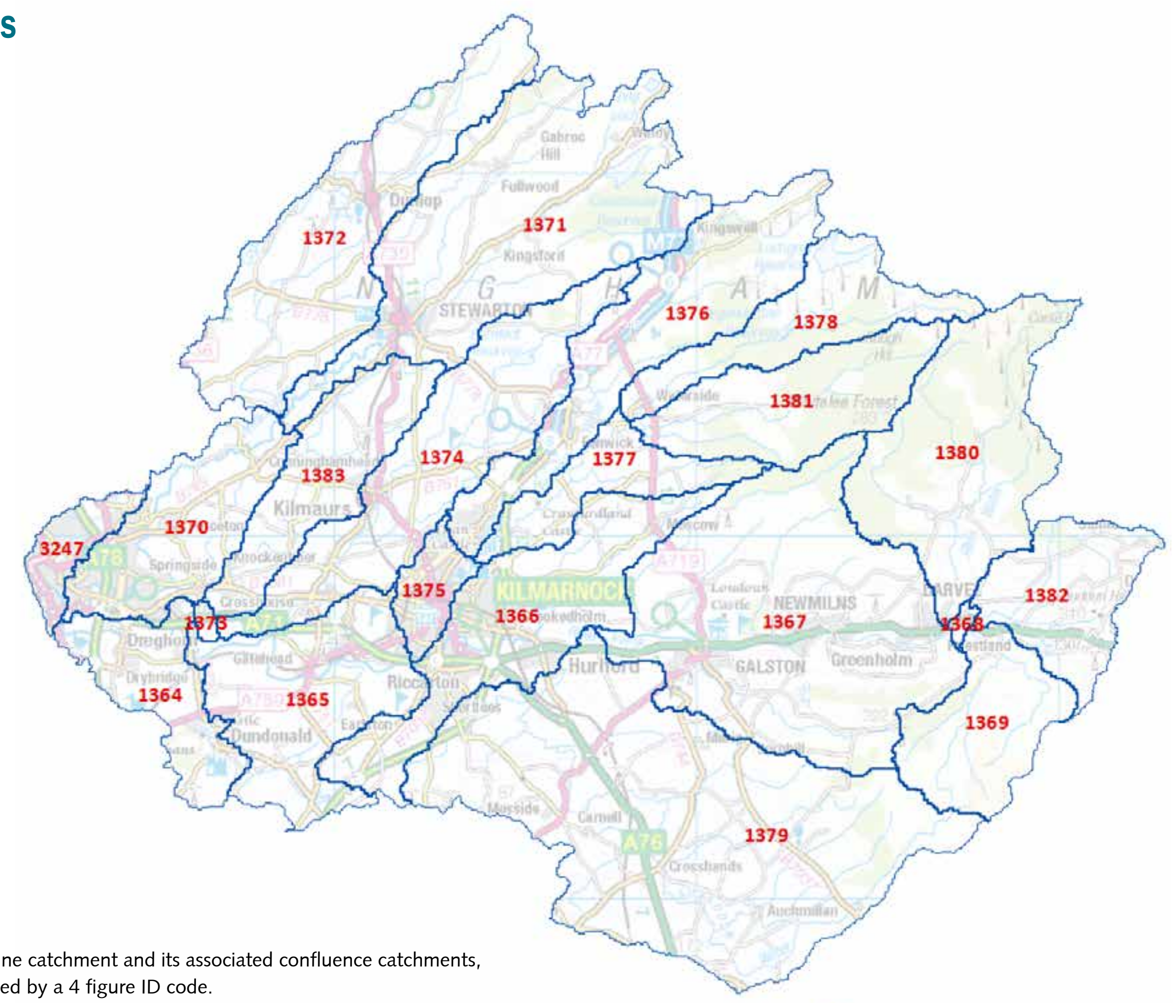


Figure 1 Irvine catchment and its associated confluence catchments, each identified by a 4 figure ID code.

Figure 2 Etive catchment and its associated confluence catchments, each identified by a 4 figure ID code.

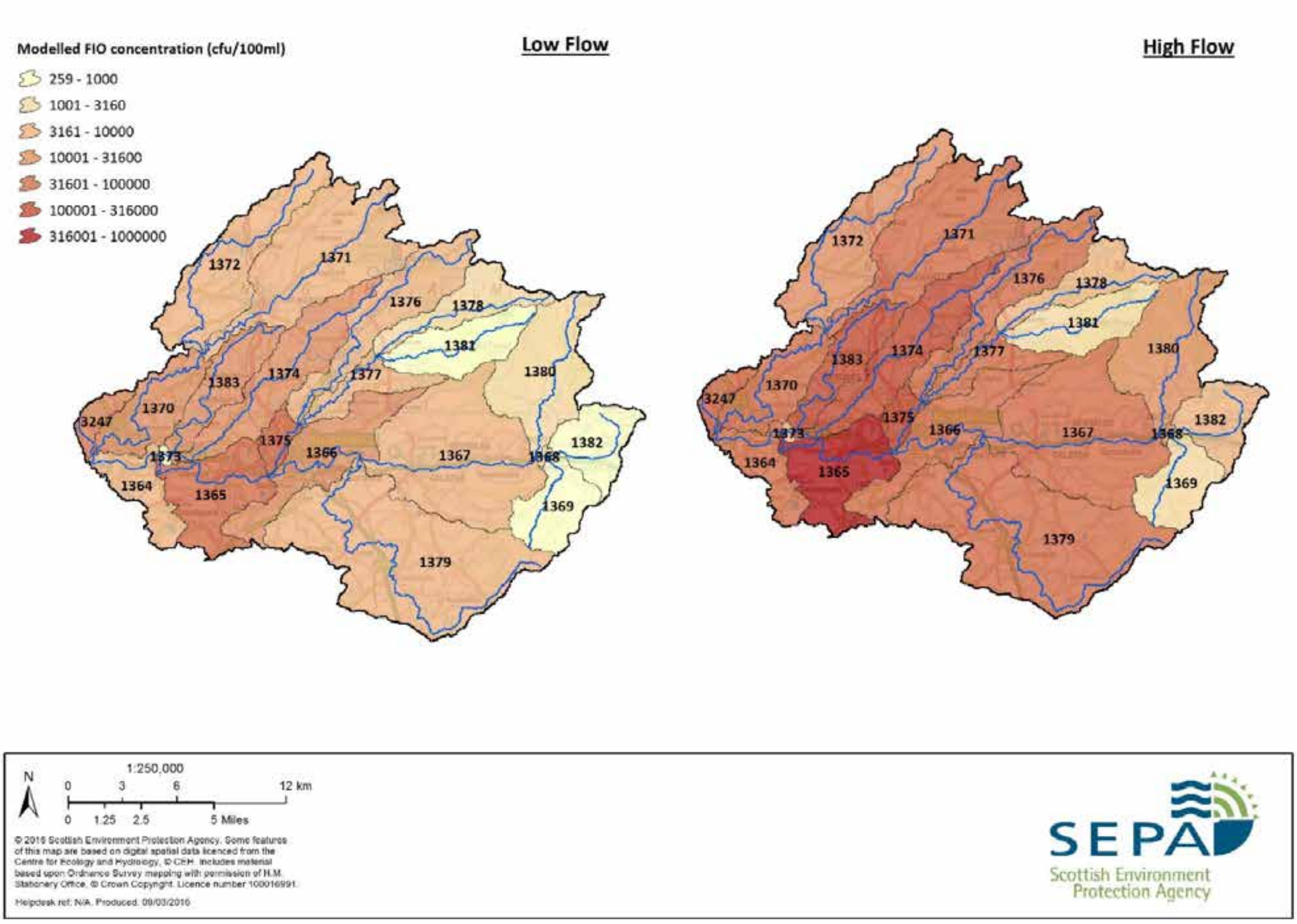


Figure 3 Component I (regression modelling) – Irvine catchment: Modelled geometric mean FC concentrations derived from the various confluence catchments under low- and high-flow conditions during the summer bathing season.

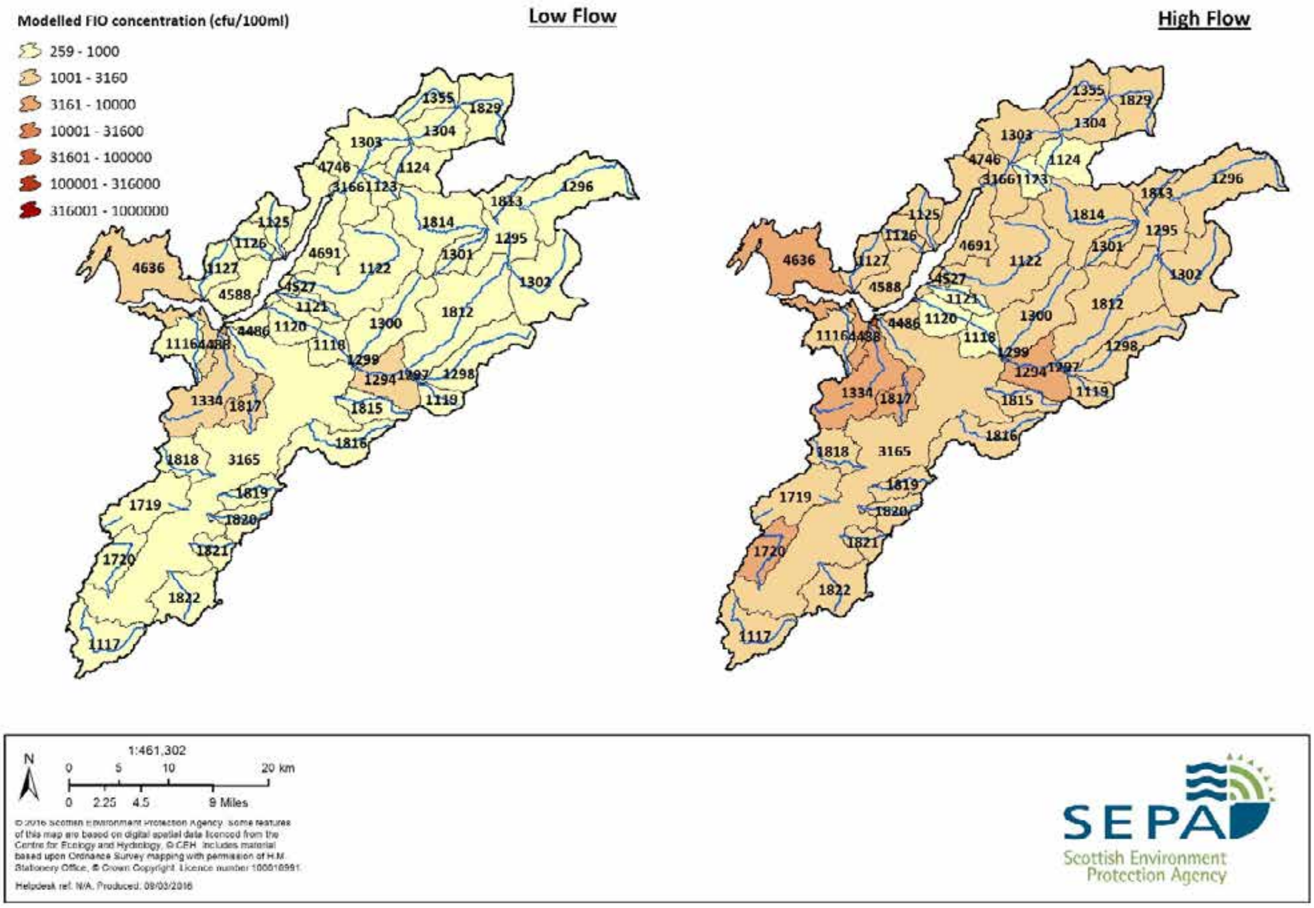


Figure 4 Component I (regression modelling) – Etive catchment: Modelled geometric mean FC concentrations derived from the various confluence catchments under low- and high-flow conditions during the summer bathing season.

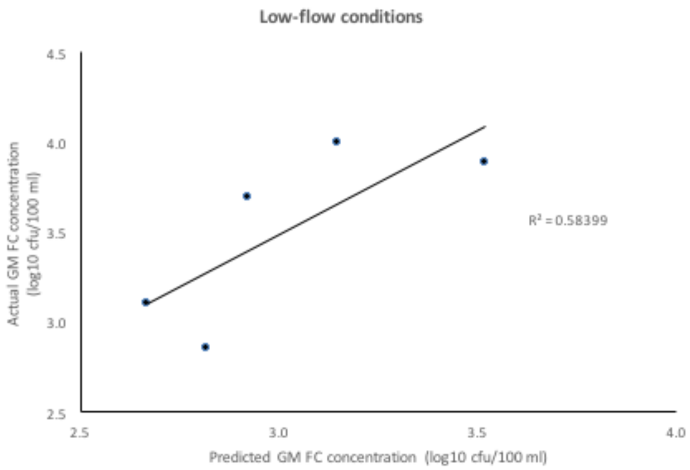


Figure 5 Component I (regression modelling): Relationship between predicted and actual geometric mean faecal coliform concentrations at low flow for the five confluence catchments for which empirical data are available from previous CREH studies (as identified in Tables 3 and 4).

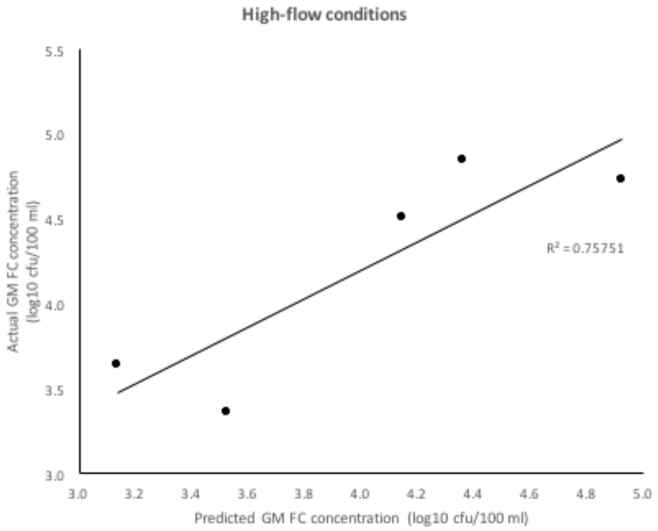


Figure 6 Component I (regression modelling): Relationship between predicted and actual geometric mean faecal coliform concentrations at high flow for the five confluence catchments for which empirical data are available from previous CREH studies (as identified in Tables 3 and 4).

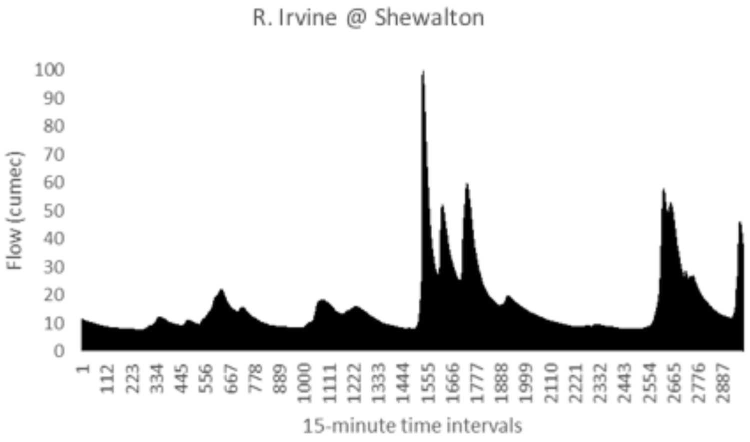


Figure 7 R. Irvine: Flow data for the outlet of the catchment at Shewalton in July 2015 (from 09:00 1/7/15 to 09:00 1/8/15).

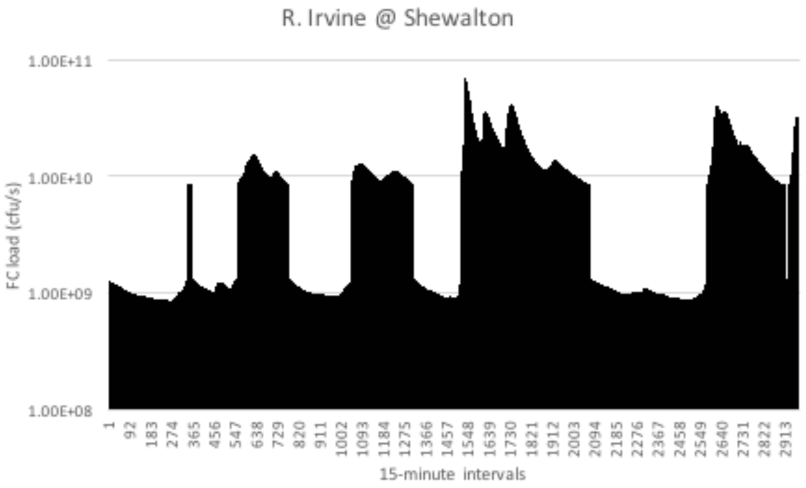


Figure 8 Component I (regression modelling) – R. Irvine: Estimated FC load delivered to the catchment outlet at Shewalton in July 2015.

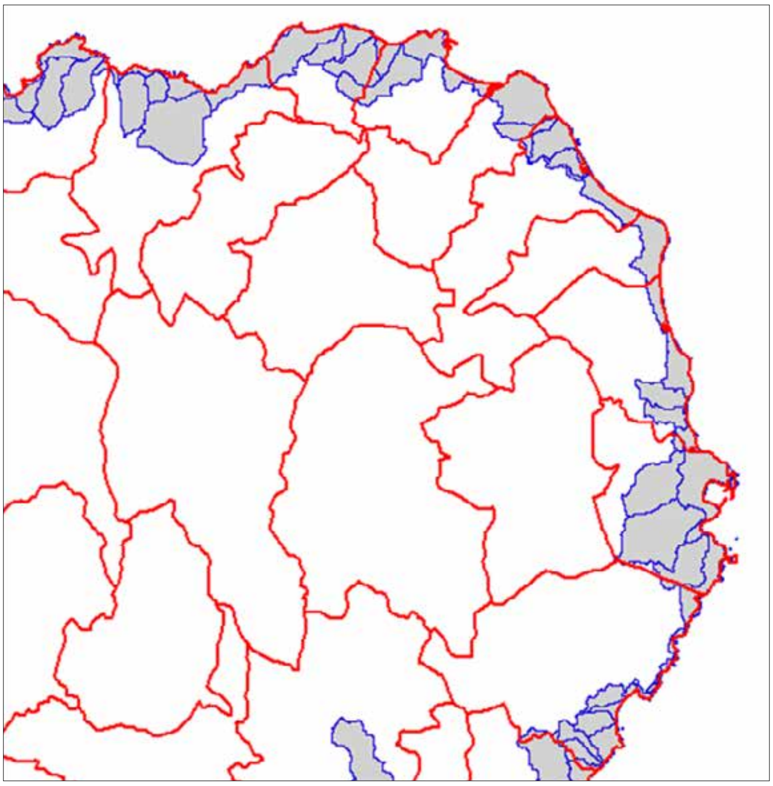


Figure 9 Component II: Illustration of the relationship between coastal WFD catchments (blue polygons) and the June Agricultural Survey (JAS) parishes (red polygons) for which livestock numbers are available.

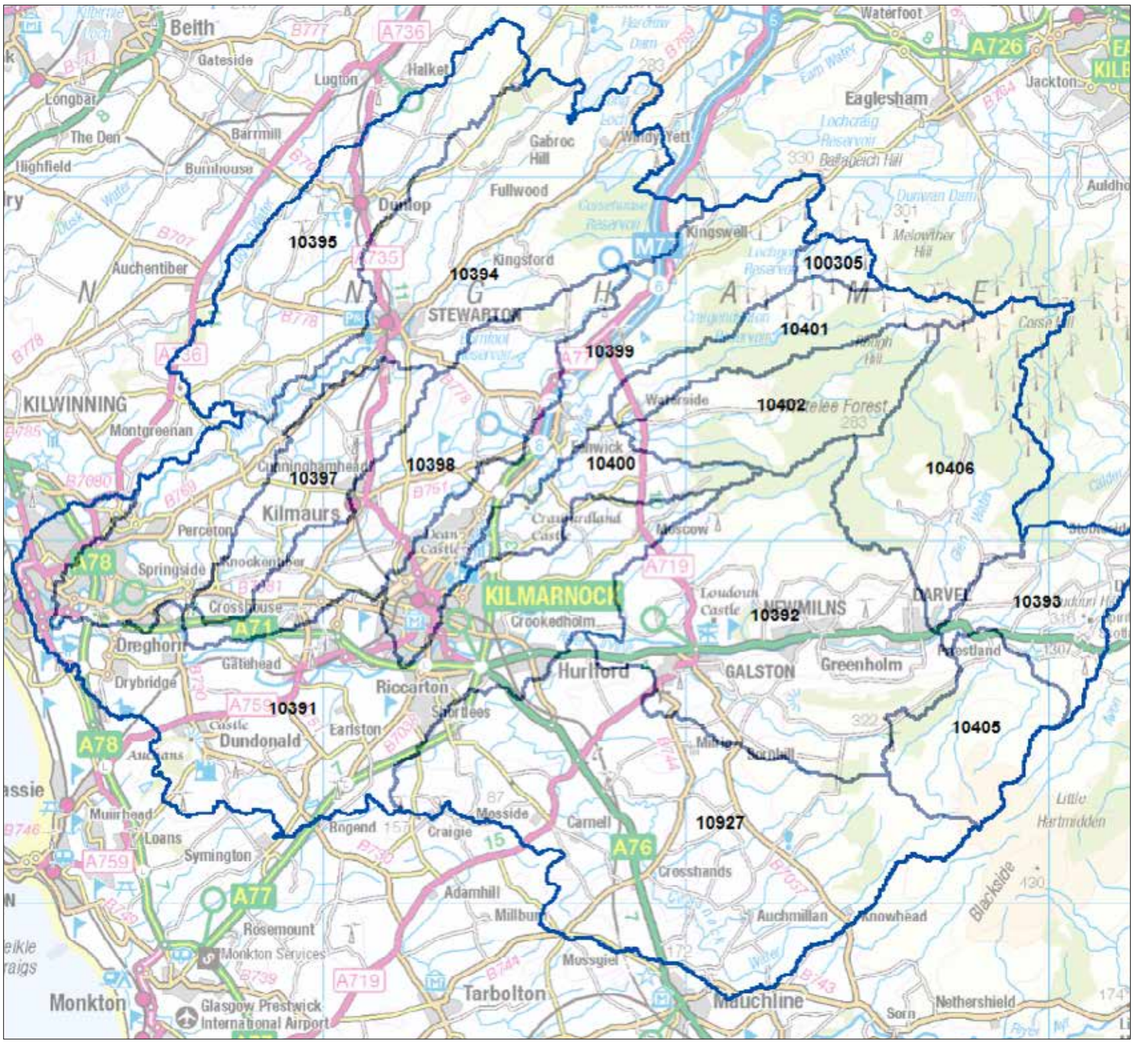


Figure 10 Irvine catchment and its associated WFD inland catchments, each identified by a 5 or 6 figure ID code.

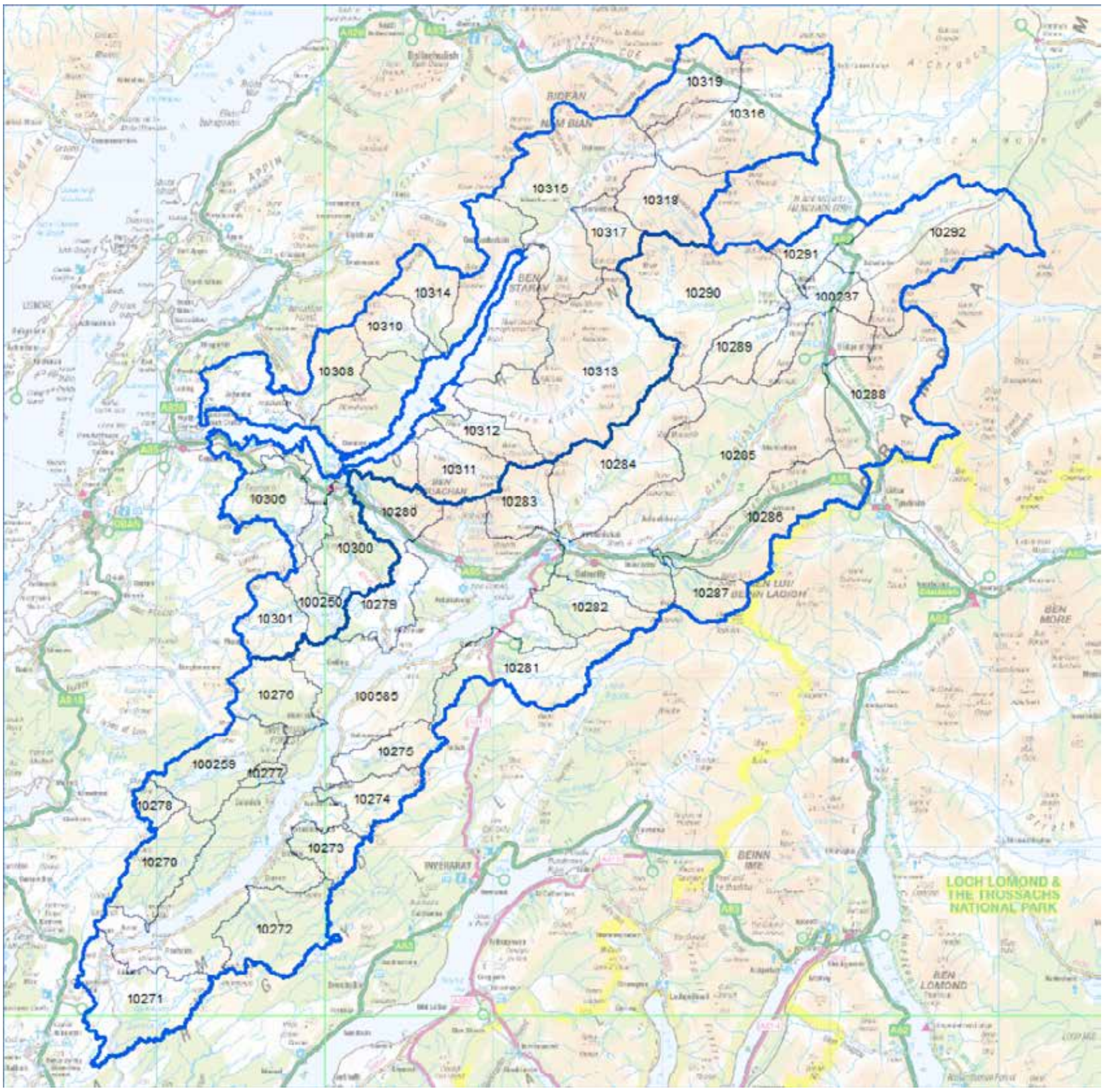


Figure 11 Etive catchment and its associated WFD inland catchments, each identified by a 5 or 6 figure ID code.

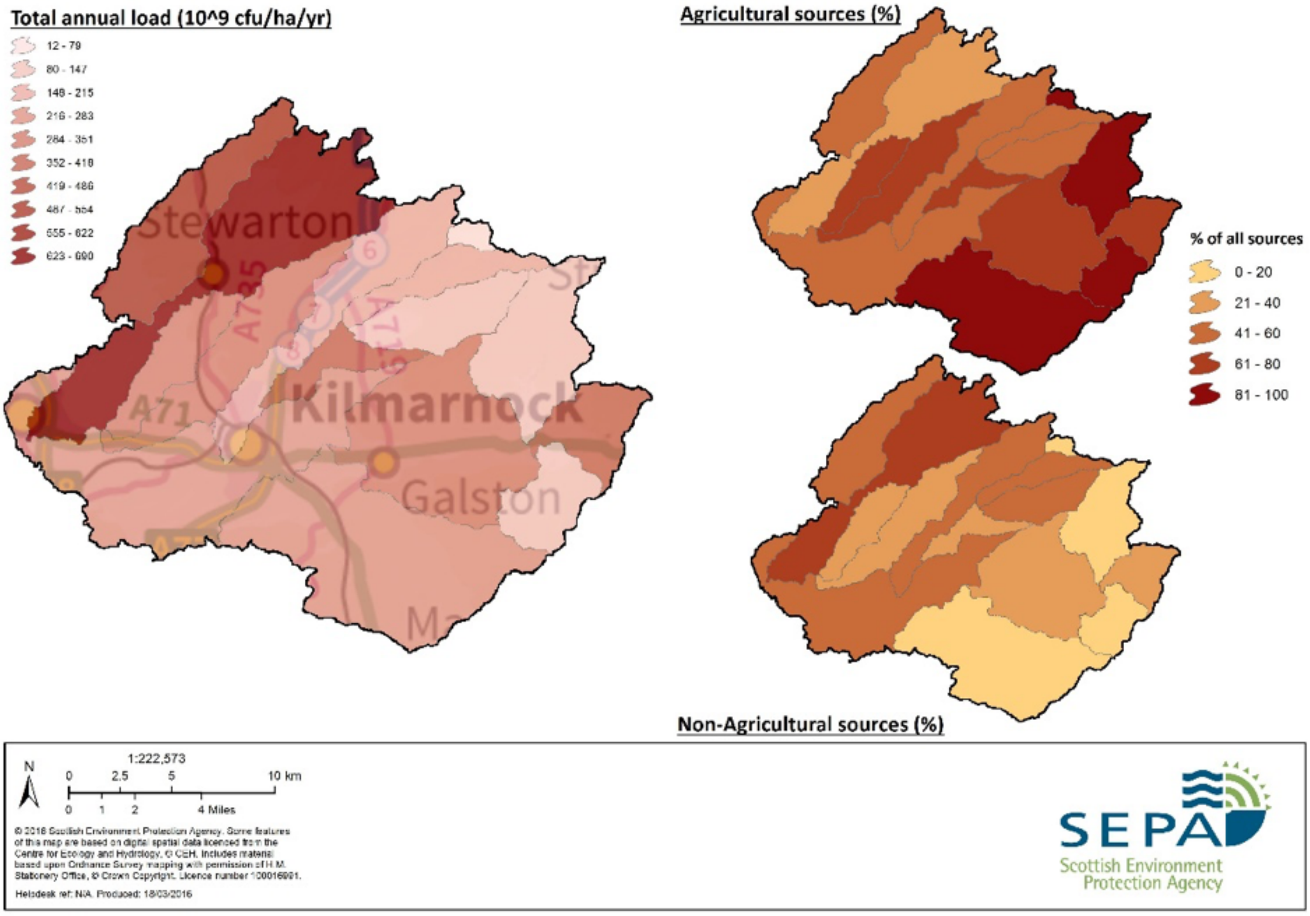


Figure 12 Component II (EoM-FIO): Irvine catchment – variations in annual FIO loads (cfu/ha/yr) delivered to watercourses in the individual WFD catchments and apportionment to agricultural and non-agricultural sources.

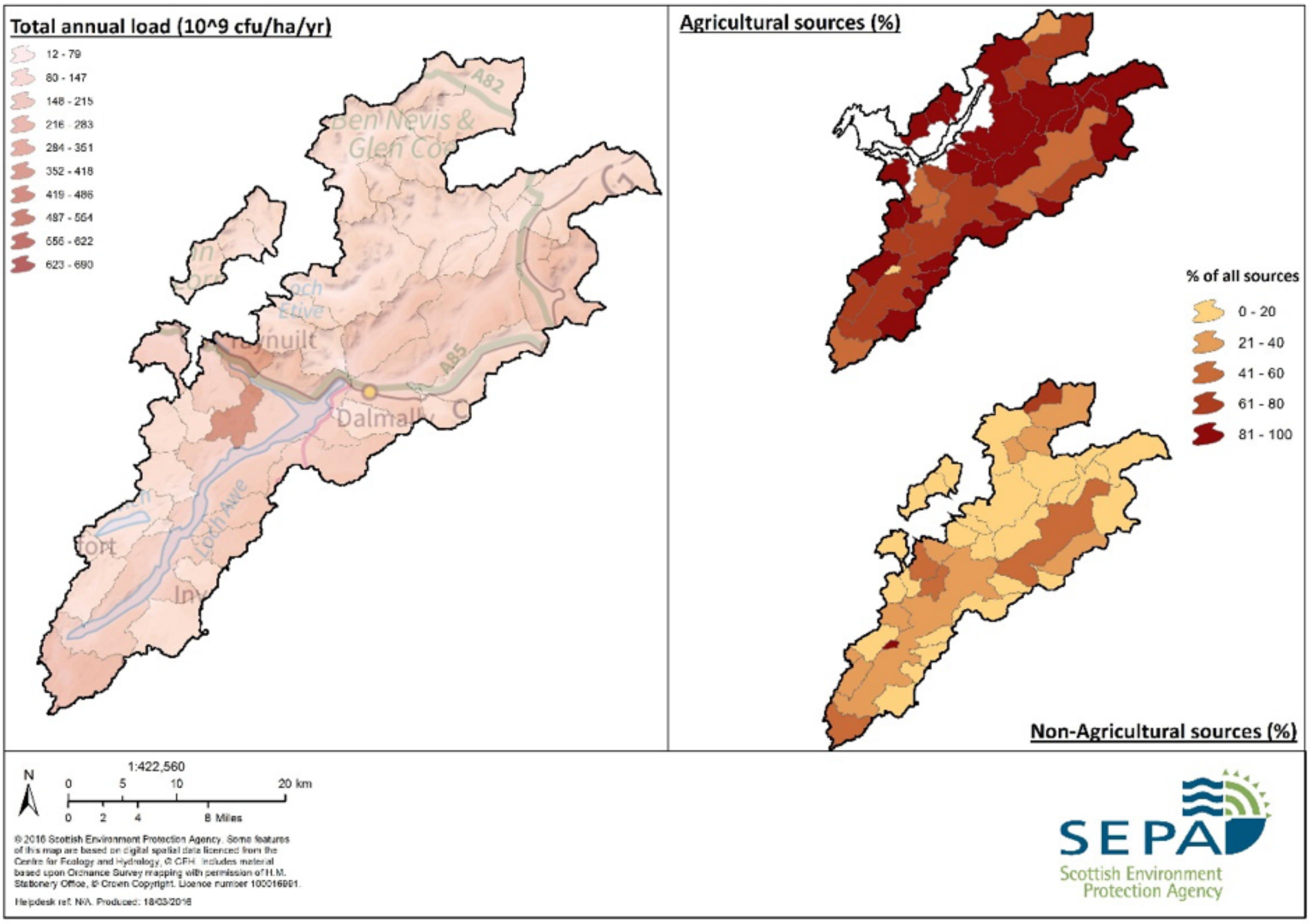
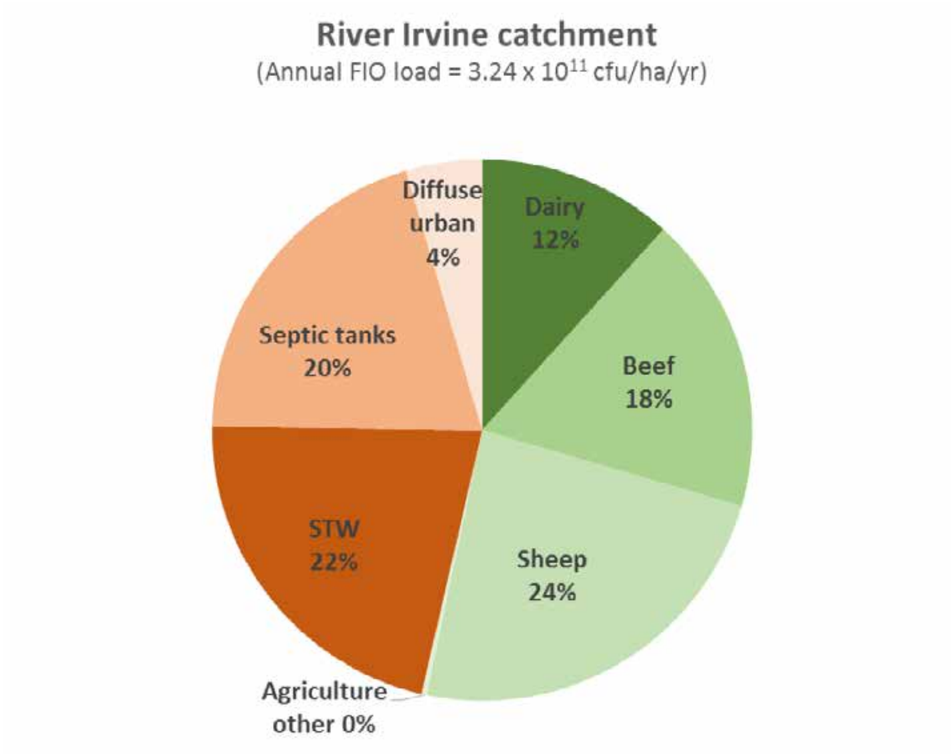


Figure 13 Component II (EoM-FIO): Etive catchment – variations in annual FIO loads (cfu/ha/yr) delivered to watercourses in the individual WFD catchments and apportionment to agricultural and non-agricultural sources.



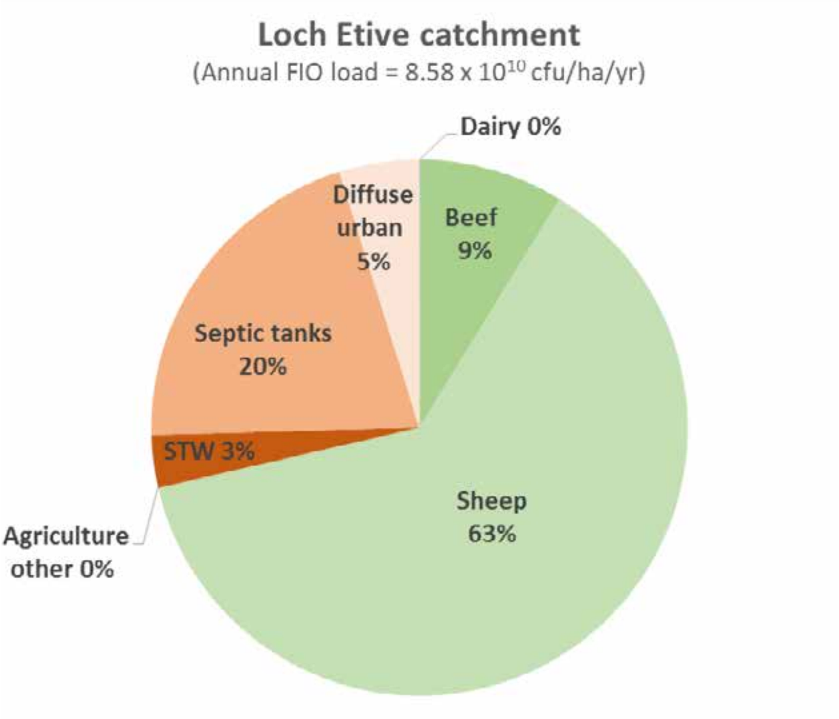
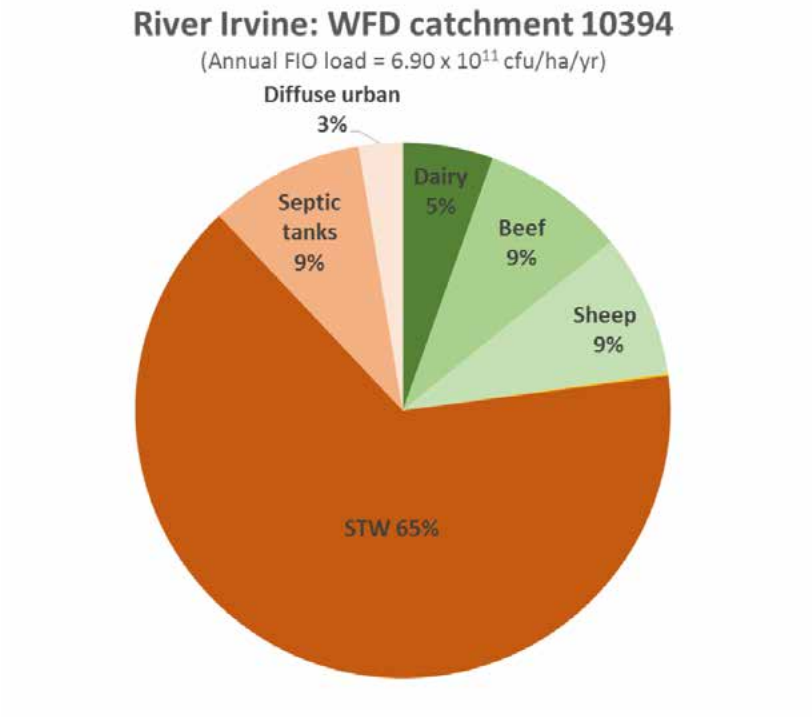


Figure 14 Component II (EoM-FIO): Source apportionment of the total loads delivered to watercourses in the Irvine and Etive catchments.



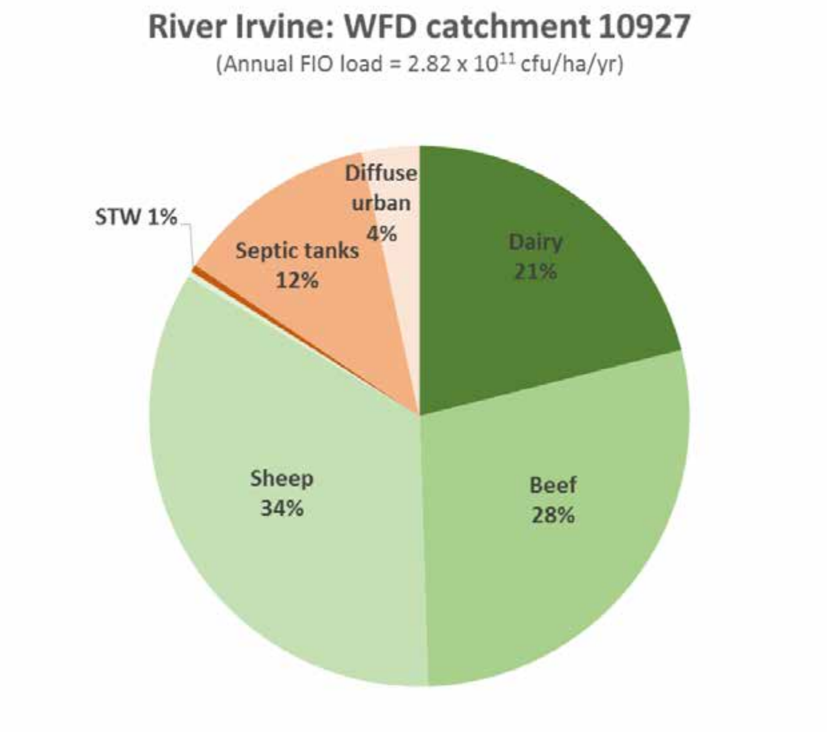
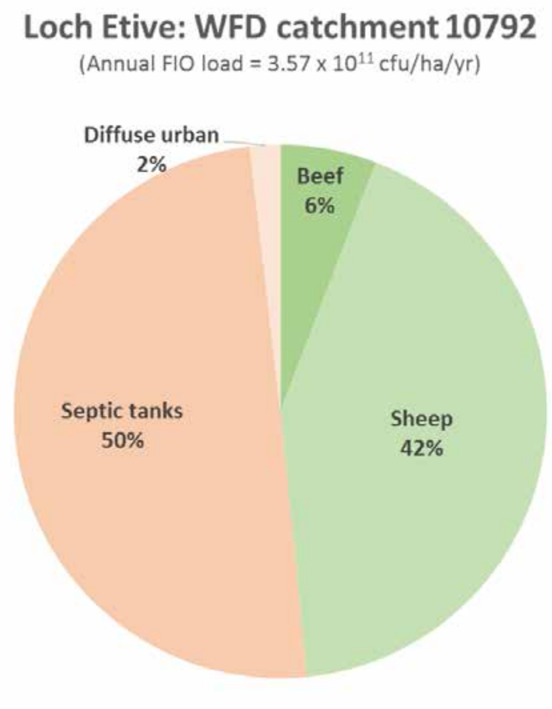


Figure 15 Component II (EoM-FIO): Source apportionment of the total loads delivered to watercourses in two contrasting WFD catchments in Irvine catchment with relatively high FIO loadings.



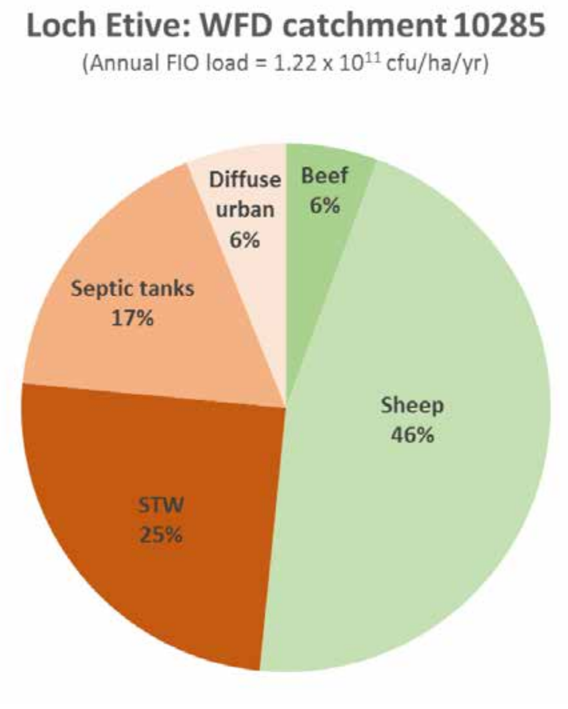


Figure 16 Component II (EoM-FIO): Source apportionment of the total loads delivered to watercourses in two contrasting WFD catchments in Etive catchment with relatively high FIO loadings.

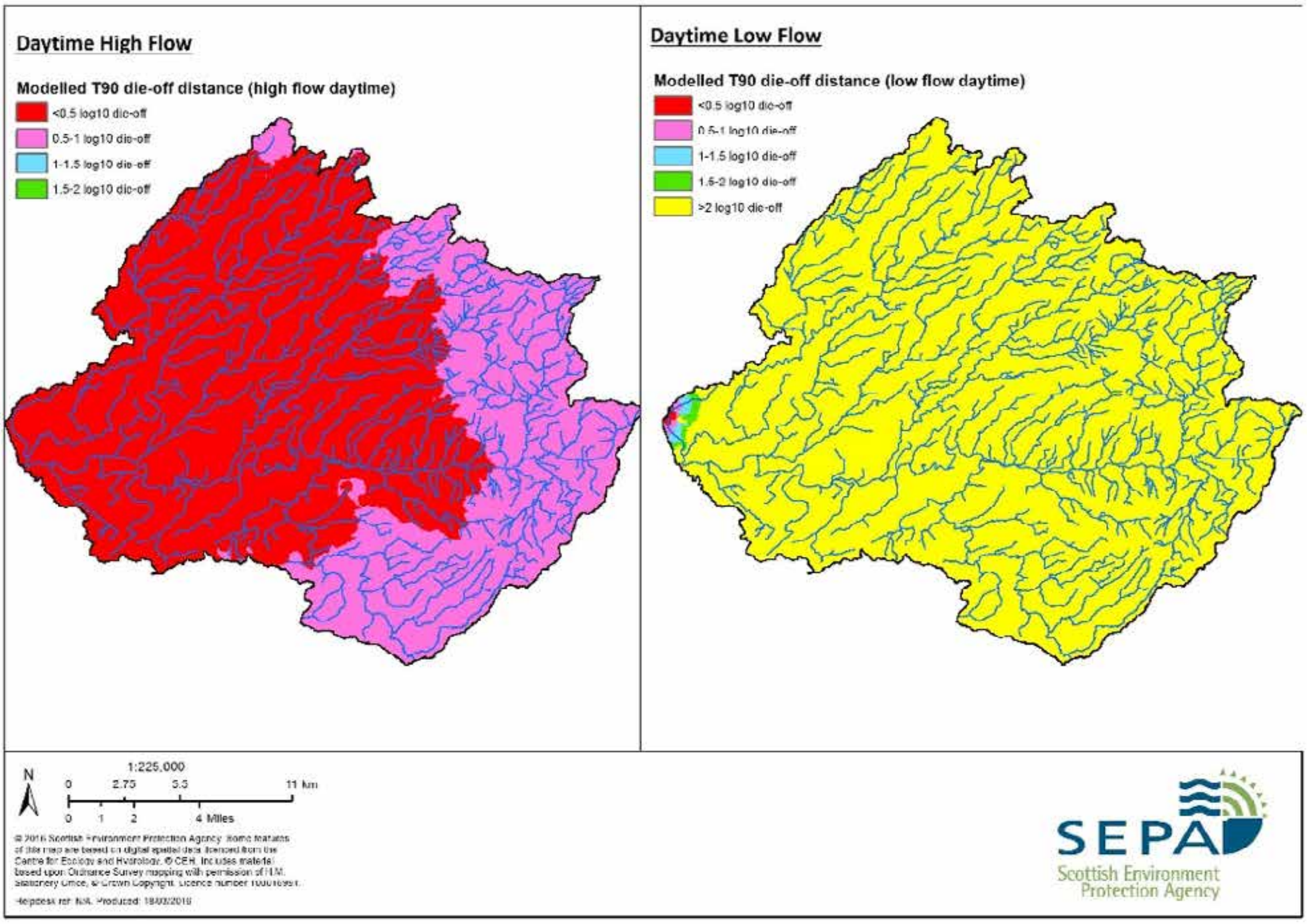


Figure 17 Component III (T_{90} modelling): Zone of influence of FIO sources within the Irvine catchment upon FIO loadings delivered to the catchment outlet (i.e. to coastal waters) under daytime/sunny conditions at times of (i) Low flow/low turbidity and (ii) High flow/high turbidity – plots show distance upstream (plots currently in reverse order).

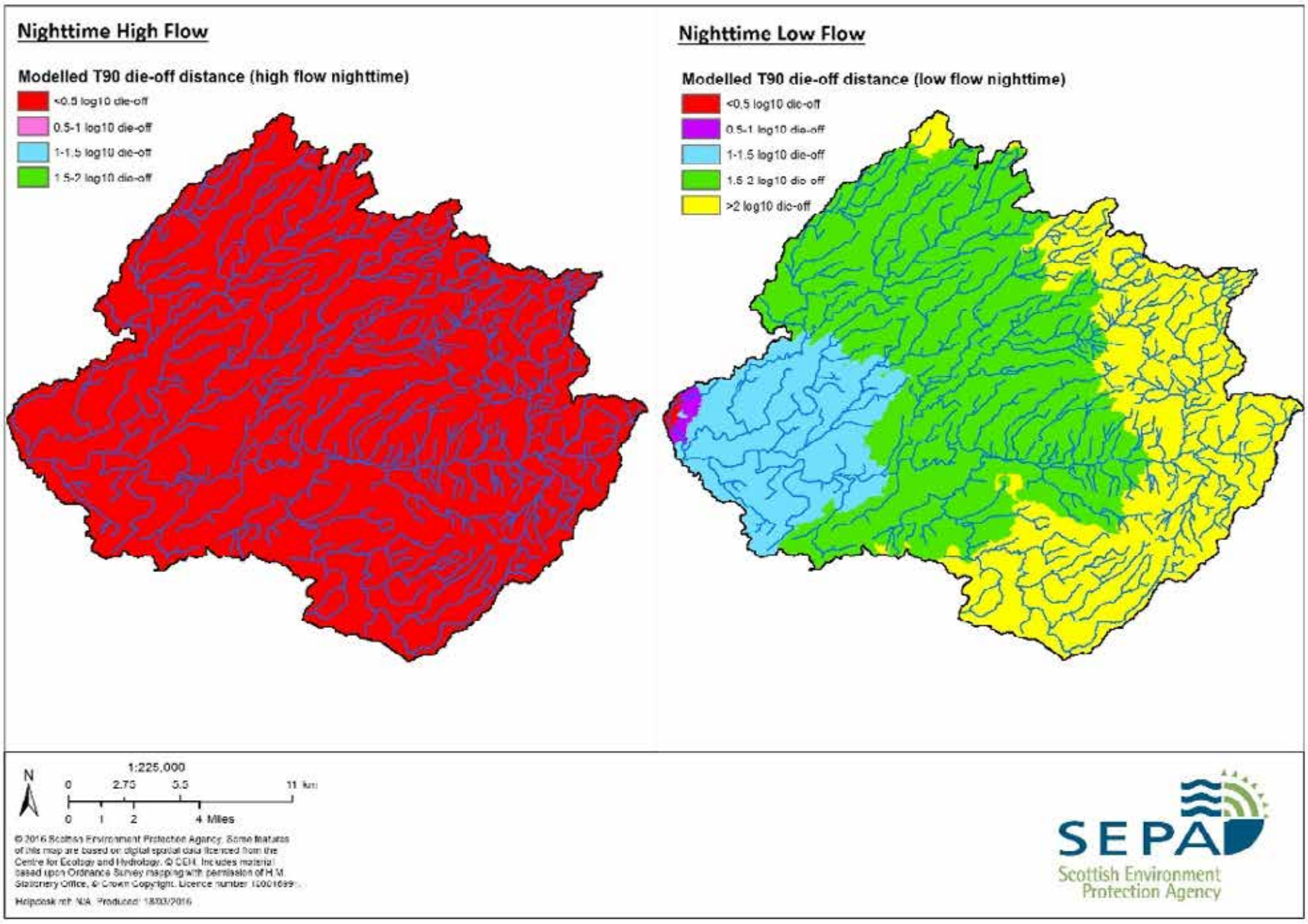


Figure 18 Component III (T_{90} modelling): Zone of influence of FIO sources within the Irvine catchment upon FIO loadings delivered to the catchment outlet (i.e. to coastal waters) under night time/dark conditions at times of (iii) Low flow and (iv) High flow – plots show distance upstream (plots currently in reverse order).

Tables

Table 1 Catchment scale FIO monitoring studies undertaken by CREH in Scotland

Catchment	Study year	Season	Subcatchments[a] (*n*):	
			Base flow	High flow
River Irvine	1998	Summer	23	23
River Girvan	1989	Summer	1	1
Troon	2000	Summer	1	1
Brighouse Bay	2003	Autumn	1	1
Brighouse Bay	2004	Summer	1	1
Ettrick Bay	2002	Autumn	1	1
Ettrick Bay	2004	Summer	1	1
Killoch Burn	2002	Autumn	2	2
Killoch Burn	2004	Summer	2	2
Sandyhills	2002	Autumn	5	5
Sandyhills	2004	Summer	5	5
River Nairn	2003	Winter	8	-
River Nairn	2004	Summer	8	8
Loch Etive	2006/7	Summer	8	8
Strathclyde Loch	2013	Summer	8	8

[a] Only subcatchments ≥ 5 km^2 and with ≥ 5 samples at base or high flow are included.

Table 2 is on the following page.

Table 3 Component I (Regression modelling) – Irvine catchment: Values of predictor variables for the confluence catchments and the resulting predicted low- and high-flow geometric mean faecal coliform concentrations

Confluence ID[a]	Catchment area (km^2)	Baseflow index (BFI)	Residences (#/km^2)	Improved grassland (%)	Dairy cattle (#/km^2)	Sheep (#/km^2)	GM FC concentration (cfu/100 ml):	
							Low flow	High flow
1367	54.75	0.382	98.80	58.3	29.87	111.22	7.2 x 10^3	3.8 x 10^4
1369	15.50	0.483	2.06	24.2	14.38	124.48	5.4 x 10^2	1.9 x 10^3
3247	5.07	0.359	1552.39	18.0	0.00	18.09	2.4 x 10^4	9.8 x 10^4
1379*	75.92	0.311	10.84	75.0	65.37	120.73	4.9 x 10^3	3.2 x 10^4
1373	0.60	0.332	3.35	71.8	0.00	125.91	8.9 x 10^2	3.6 x 10^3
1380	30.72	0.318	12.73	20.6	10.69	117.50	2.2 x 10^3	1.0 x 10^4
1376*	26.75	0.277	88.04	37.4	25.94	154.08	9.8 x 10^3	7.0 x 10^4
1375	4.82	0.282	1579.06	6.0	0.00	0.00	3.4 x 10^4	1.5 x 10^5
1372	33.00	0.345	23.03	75.2	41.96	106.01	4.4 x 10^3	2.4 x 10^4
1368	0.59	0.508	100.85	75.6	0.00	344.71	3.0 x 10^3	2.6 x 10^4
1364	12.88	0.349	123.14	43.4	0.00	203.74	5.8 x 10^3	3.8 x 10^4
1381	18.66	0.256	0.70	20.4	9.87	51.40	8.7 x 10^2	3.1 x 10^3
1377	10.35	0.276	20.20	77.2	59.30	139.18	7.4 x 10^3	5.5 x 10^4
1371	46.56	0.346	70.31	56.9	51.50	66.94	9.5 x 10^3	5.1 x 10^4
1370	18.33	0.368	404.04	58.0	0.00	62.60	1.1 x 10^4	4.5 x 10^4
1374	29.21	0.326	125.53	67.6	62.62	90.23	1.7 x 10^4	1.2 x 10^5
1365	24.43	0.342	134.67	65.6	142.37	154.30	5.9 x 10^4	7.8 x 10^5
1382	14.92	0.522	2.08	65.7	33.08	204.71	6.6 x 10^2	3.2 x 10^3
1383	16.36	0.326	67.18	76.0	84.03	91.40	1.7 x 10^4	1.2 x 10^5
1378	15.48	0.277	4.13	18.0	10.43	80.66	1.5 x 10^3	6.1 x 10^3
1366	26.51	0.350	399.77	59.4	0.00	138.77	1.1 x 10^4	6.4 x 10^4
Whole catchment*	**481.41**	**0.340**	**117.47**	**55.4**	**41.05**	**112.07**	**1.1 x 10^4**	**6.9 x 10^4**

[a] * Indicates catchments for which actual GM FC concentration data are available for summer 1998 (CREH, 1999).

Table 2 Summary of review by Oliver *et al*. (2011) of platforms for catchment modelling of FIOs – copy of Table 1 from original report

	PSYCHIC	INCA	SWAT	HSPF	SCIMAP	ANSWERS	PEDAL2	MHTracking	MIKE SHE	AGNPS	DWSM	SIMCAT	EG / E2	PAMIMO-C	WATFLOOD	Pathogen budget
Original Author	Davidson *et al*	Whitehead	Arnold	Johanson	Lane	Beasley	Beven/ Heathwaite	O'Donnell	Refsgaard & Storm	Young *et al*	Borah	Anglian Water		Lewis & Duncan	Kouwen	Ferguson
Year	2008	1998	1998	1980		1980			1995	1987	2001	1970s		2003	1988	2004
Model type	PB	PB	PB	PB	RB	PB	GB	PB	PB	PB	PB	Stochastic	PB	PB	PB	PB
Timestep	M	D	D	SD		SE	V	V (SD)	V (SD)	V (SE or M)	SE	M (need to check)	SD or D		SD	D
Continuous?	✔	✔	✔	✔				✔	✔				✔		✔	
Spatial scale	Field-catchment	Catchment	Catchment	Catchment	Catchment	Catchment	Headwater	Catchment	Plot to catchment	Catchment	Catchment	Catchment	Catchment	Catchment	Catchment	Catchment
Soil characteristics	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔			✔		
Met inputs	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔		✔		✔	✔
Hydrological subroutine	✔	✔	✔	✔	✔	✔		✔	✔		✔	✔	✔		✔	✔
Bacterial submodel?			✔	✔			✔				✔		✔	✔	✔	✔
Point source input?	✔	✔	✔	✔		✔		✔	?	✔		✔	✔		✔	✔
Land management/cover	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔			✔	✔	✔	✔
Nutrient submodel	✔	✔	✔	✔	✔	✔	✔		✔	✔	✔	✔	✔		✔	
In-stream component?		✔	✔	✔				✔	✔	?		✔		✔	✔	✔
Account for Mitigation	✔		✔	✔		✔	✔	✔	✔			✔	✔	✔		
GIS output?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	✔	✔	✔	
Freely available?			✔	✔	✔		✔	in put		✔			in part		in part	ICMS software

Table 4 Component I (Regression modelling) – Etive catchment: Values of predictor variables for the confluence catchments and the resulting predicted low- and high-flow geometric mean faecal coliform concentrations

Confluence ID	Catchment area (km^2)	Baseflow index (BFI)	Residences (#/km^2)	Improved grassland (%)	Dairy cattle (#/km^2)	Sheep (#/km^2)	GM FC concentration (cfu/100 ml): Low flow	GM FC concentration (cfu/100 ml): High flow
1121	10.62	0.325	0.00	0.1	0.00	0.85	3.9 x 10^2	9.3 x 10^2
3166	24.29	0.297	0.33	0.5	0.00	0.00	5.2 x 10^2	1.3 x 10^3
1355	18.53	0.238	0.05	0.0	0.00	8.54	6.3 x 10^2	1.8 x 10^3
1818	17.78	0.289	0.28	1.7	0.00	75.53	5.3 x 10^2	1.8 x 10^3
1301	12.32	0.221	0.24	0.0	0.00	0.00	7.6 x 10^2	2.3 x 10^3
4527	2.56	0.284 [b]	0.39	3.2	0.00	0.00	5.7 x 10^2	1.5 x 10^3
1300	41.21	0.267	0.12	1.6	0.00	7.83	5.5 x 10^2	1.5 x 10^3
1122	71.72	0.312	0.04	0.3	0.04	0.02	4.3 x 10^2	1.0 x 10^3
1822	26.66	0.220	0.11	1.1	0.00	42.00	7.2 x 10^2	2.4 x 10^3
1817	15.16	0.294	3.56	13.3	0.00	43.00	1.1 x 10^3	3.5 x 10^3
1304	21.80	0.261	0.00	0.0	0.00	5.65	5.3 x 10^2	1.5 x 10^3
3165	200.21	0.299	2.11	7.3	0.00	52.10	8.5 x 10^2	2.7 x 10^3
1819	12.95	0.231	0.15	0.8	0.00	63.11	6.8 x 10^2	2.4 x 10^3
1299	1.29	0.301	1.54	9.2	0.00	8.50	7.5 x 10^2	2.0 x 10^3
4488	7.52	0.284 [b]	11.17	20.2	0.00	32.03	2.0 x 10^3	6.9 x 10^3
1821	10.01	0.205	0.00	2.1	0.00	66.76	7.5 x 10^2	2.9 x 10^3
1293	0.01	0.268	0.00	57.8	0.00	77.94	5.1 x 10^2	1.8 x 10^3
4588	21.28	0.284 [b]	1.69	1.9	0.00	14.71	8.4 x 10^2	2.4 x 10^3
1303	31.20	0.291	0.10	0.3	0.05	3.24	4.8 x 10^2	1.2 x 10^3
1294	26.01	0.263	6.61	10.9	0.00	62.63	1.7 x 10^3	6.5 x 10^3
1118	14.84	0.391	0.00	0.5	0.01	77.78	3.0 x 10^2	8.5 x 10^2
4691	23.53	0.284 [b]	0.04	0.0	0.00	0.00	4.9 x 10^2	1.2 x 10^3
1298	36.07	0.252	0.25	0.1	0.00	0.96	6.4 x 10^2	1.8 x 10^3
4486	6.24	0.284 [b]	0.48	3.5	0.00	39.14	5.9 x 10^2	1.8 x 10^3
1126	12.16	0.311	0.00	0.0	0.00	14.71	4.2 x 10^2	1.1 x 10^3
1116 [a]	18.46	0.316	1.57	9.6	0.12	62.92	7.1 x 10^2	2.3 x 10^3
1812	70.97	0.262	0.08	0.6	0.00	19.90	5.5 x 10^2	1.6 x 10^3
1302	46.15	0.274	0.09	0.5	0.00	60.23	5.2 x 10^2	1.7 x 10^3
1295	29.36	0.266	0.58	0.1	0.00	6.31	6.8 x 10^2	1.9 x 10^3
1814	50.09	0.295	0.04	0.0	0.00	0.01	4.6 x 10^2	1.2 x 10^3
4495	6.39	0.284 [b]	12.21	29.9	0.00	44.23	2.1 x 10^3	7.6 x 10^3
4600	0.71	0.284 [b]	0.00	0.0	0.00	14.71	4.7 x 10^2	1.3 x 10^3
1297	0.37	0.259	5.41	6.7	0.00	66.23	1.6 x 10^3	6.1 x 10^3
1815	15.95	0.284 [b]	0.13	1.8	0.00	30.94	5.1 x 10^2	1.5 x 10^3
4508	1.51	0.284 [b]	0.66	5.4	0.00	17.39	6.4 x 10^2	1.8 x 10^3
1296	51.80	0.245	0.08	0.6	0.00	0.87	6.1 x 10^2	1.7 x 10^3
1813	10.24	0.238	0.10	0.0	0.00	0.00	6.4 x 10^2	1.8 x 10^3
1119	10.86	0.282	0.37	0.5	0.00	3.02	5.7 x 10^2	1.5 x 10^3
1719	32.53	0.270	0.43	4.1	0.00	79.87	6.3 x 10^2	2.2 x 10^3
1127	15.63	0.301	0.19	2.8	0.04	14.71	4.8 x 10^2	1.3 x 10^3
1123	11.06	0.360	0.09	0.0	0.00	0.00	3.6 x 10^2	8.1 x 10^2
1816	30.70	0.232	0.49	3.8	0.00	45.63	7.9 x 10^2	2.7 x 10^3
1720	20.41	0.207	0.34	2.1	0.00	67.52	8.7 x 10^2	3.4 x 10^3
1120	17.41	0.438	0.00	1.2	0.06	48.05	2.6 x 10^2	6.2 x 10^2
1829	30.18	0.233	0.27	0.0	0.00	0.09	7.2 x 10^2	2.1 x 10^3
1334 [a]	45.02	0.324	6.40	3.1	0.02	64.93	1.3 x 10^3	4.3 x 10^3
1124	22.13	0.432	0.05	0.0	0.00	0.00	2.7 x 10^2	5.5 x 10^2
4482	0.53	0.284 [b]	114.63	70.7	0.00	72.53	7.4 x 10^3	3.4 x 10^4
1125	14.69	0.302	0.00	0.0	0.00	8.75	4.3 x 10^2	1.1 x 10^3
1117	31.32	0.376	2.39	13.0	0.00	64.41	6.5 x 10^2	1.9 x 10^3
1820	13.28	0.204	0.08	5.4	0.00	78.44	7.8 x 10^2	3.1 x 10^3
4746	18.50	0.284 [b]	0.11	0.3	0.00	0.00	5.0 x 10^2	1.3 x 10^3
4636	47.41	0.284 [b]	13.31	24.4	0.00	58.29	2.2 x 10^3	8.4 x 10^3
Whole catchment*	**1329.64**	**0.286**	**1.56**	**3.8**	**0.01**	**31.11**	**8.1 x 10^2**	**2.5 x 10^3**

[a] Indicates catchments for which actual GM FC concentration data are available for summer 2006/7 (Stapleton *et al*., 2011).

[b] Indicates catchments for which no BFI data were supplied – the mean BFI for the remaining Etive catchments has been inserted.

Table 5 Component II (EoM-FIO) – Irvine catchment: Estimated annual FIO loads delivered to watercourses in the various inland WFD catchments and their source apportionment

WFD Catchment	FIO load (10^9 cfu/ha/yr)	Agricultural (%):				Non-agricultural (%):		
		Dairy	Beef	Sheep	Other	STWs	Septic tanks	Diffuse urban
10391	241.6	15.0	18.5	11.2	0.3	3.1	38.8	13.2
10392	311.4	8.4	15.8	54.2	0.3	0.0	17.2	4.0
10393	350.7	8.5	17.9	50.6	0.3	0.0	20.0	2.6
10394	689.6	5.5	8.7	8.6	0.1	65.0	9.4	2.7
10395	515.3	8.6	17.9	20.2	0.7	23.3	27.2	2.0
10397	311.8	26.8	32.4	10.4	0.6	0.0	24.7	5.1
10398	310.8	18.6	24.5	18.9	0.4	0.0	32.6	5.1
10399	173.9	13.9	22.9	21.9	0.1	0.0	26.0	15.2
10400	383.7	16.8	23.4	20.5	0.3	0.0	36.0	3.1
10401	152.2	9.2	16.3	22.4	0.0	0.0	51.1	1.0
10402	103.8	10.8	18.7	25.9	0.0	0.0	43.4	1.2
10405	138.5	10.3	24.2	52.5	0.3	0.0	11.7	0.9
10406	114.6	8.6	18.1	61.4	0.3	0.0	9.5	1.9
10927	282.2	21.1	28.4	34.2	0.3	0.4	12.1	3.4
100305	30.8	8.3	28.5	62.8	0.1	0.0	0.0	0.4

Table 6 Component II (EoM-FIO) – Etive catchment: Estimated annual FIO loads delivered to watercourses in the various inland WFD catchments and their source apportionment

WFD Catchment	FIO load (10^9 cfu/ha/yr)	Agricultural (%):				Non-agricultural (%):		
		Dairy	Beef	Sheep	Other	STWs	Septic tanks	Diffuse urban
10270	19.7	0.0	9.3	68.3	0.0	0.0	20.8	1.5
10271	200.2	0.0	11.7	45.4	0.0	0.0	41.5	1.5
10272	21.3	0.0	13.2	86.0	0.0	0.0	0.0	0.9
10273	66.0	0.0	5.9	81.2	0.0	0.0	12.7	0.1
10274	108.9	0.0	8.4	79.7	0.0	0.0	11.6	0.2
10275	102.8	0.0	6.4	80.7	0.0	0.0	12.6	0.3
10276	56.0	0.0	4.8	60.9	0.0	0.0	33.8	0.5
10277	31.2	0.0	0.0	0.2	0.0	0.0	99.8	0.0
10278	76.4	0.0	9.9	66.0	0.0	0.0	20.9	3.1
10279	356.9	0.0	5.8	42.6	0.0	0.0	49.7	1.8
10280	236.6	0.1	14.5	55.5	0.0	0.0	23.1	6.7
10281	111.9	0.0	9.5	76.2	0.0	0.0	12.2	2.1
10282	59.0	0.0	8.4	82.2	0.0	0.0	8.9	0.4
10283	42.2	0.0	6.4	90.9	0.0	0.0	0.0	2.7
10284	82.4	0.0	8.1	88.4	0.0	0.0	2.4	1.0
10285	122.4	0.0	5.6	46.0	0.0	24.9	17.4	6.1
10286	43.2	0.0	3.6	59.6	0.0	0.0	16.0	20.8
10287	34.6	0.0	3.7	92.9	0.0	0.0	0.0	3.4
10288	114.8	0.0	5.9	75.5	0.0	0.0	7.9	10.7
10289	28.2	0.0	0.0	96.4	0.0	0.0	0.0	3.6
10290	53.4	0.0	2.7	96.9	0.0	0.0	0.0	0.4
10291	78.0	0.0	3.7	87.2	0.0	0.0	0.0	9.1
10292	69.4	0.0	7.6	81.1	0.0	0.0	0.0	11.4
10300	144.3	0.1	9.5	47.1	0.0	0.0	40.1	3.1
10301	40.5	0.0	6.1	93.9	0.0	0.0	0.0	0.0
10306	104.3	0.4	21.7	60.9	0.1	0.0	13.1	3.8
10308	58.2	0.3	19.7	78.6	0.1	0.0	0.0	1.3
10310	11.6	0.0	0.0	100.0	0.0	0.0	0.0	0.0
10311	77.6	0.3	17.5	82.1	0.0	0.0	0.0	0.0
10312	37.3	0.0	11.2	88.8	0.0	0.0	0.0	0.0
10313	48.5	0.2	13.0	86.8	0.0	0.0	0.0	0.0
10314	14.2	0.0	0.0	100.0	0.0	0.0	0.0	0.0
10315	50.4	0.2	14.5	67.9	0.0	0.0	12.0	5.3
10316	24.7	0.0	0.0	61.8	0.0	0.0	6.5	31.6
10317	24.7	0.0	6.0	61.7	0.0	0.0	30.7	1.6
10318	15.8	0.0	0.0	74.9	0.0	0.0	24.0	1.0
10319	25.4	0.0	0.0	32.5	0.0	0.0	17.8	49.7
100237	60.0	0.0	3.8	76.3	0.0	0.0	0.0	19.9
100250	14.1	0.1	8.8	91.1	0.0	0.0	0.0	0.0
100259	30.0	0.0	10.7	73.2	0.0	0.0	11.4	4.7
100585	139.4	0.0	9.6	54.9	0.0	0.0	31.9	3.5

Table 7 Component III: Flow distances (km) required for a specified die-off to occur under different scenarios

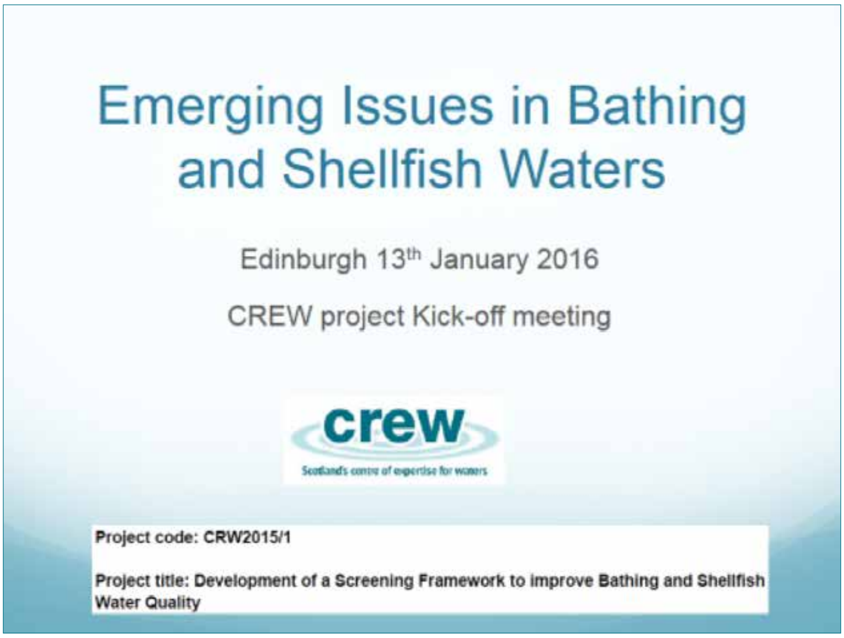
Scenario			Flow distance (km) required for specified die-off:				
	Flow velocity (m/s)	T_{90} (h)	Die-off 0.5 $\log_{10}$	Die-off 1.0 $\log_{10}$	Die-off 1.5 $\log_{10}$	Die-off 2.0 $\log_{10}$	Die-off >2.0 $\log_{10}$
i Low flow/Low turbidity/Day time/Sunny	0.1	3	0.54	1.08	1.62	2.16	>2.16
ii High flow/High turbidity/Day time/Sunny	1.0	20	36	72	108	144	>144
iii Low flow/Night time/Dark	0.1	50	9	18	27	36	>36
iv High flow/Night time/Dark	1.0	50	90	180	270	360	>360

Appendices

Appendix 1: Acronyms and abbreviations used in report

ADAS	Agricultural Development and Advisory Service
AMLS	Animal Movement Licensing System
BFI	Base Flow Index
CaBA	Catchment-Based Approach (organisation)
CCM	Catchment Change Matrix (EA)
CEC	Council of the European Communities
CEH	Centre for Ecology and Hydrology
CERF	Continuous Estimation of River Flows (EA)
cfu	Colony forming units
CLAD	Customer and Land Database (Rural Payment Agency)
CSF	Catchment sensitive farming
CSO	Combined sewer overflow
CREH	Centre for Research into Environment and Health (Aberystwyth University)
cumec	Cubic metre/second
Defra	Department for Environment, Food and Rural Affairs
DPI	Diffuse pollution inventory (Defra manual)
DPST	Diffuse pollution screening tool for Scotland – developed by ADAS (2006)
DRN	Detailed river network (EA)
DTC	Demonstration test catchment (England)
DTM	Digital terrain model
EA	Environment Agency (England & Wales)
EC	*Escherichia* (or *E.*) *coli*
ECSFDI	England Catchment Sensitive Farming Delivery Initiative
EoM-FIO	Effectiveness of Measures Project (ADAS, 2014) – FIO modelling tool component
EU	European Union
FIO	Faecal indicator organism
FC	Faecal coliforms
FS	Faecal streptococci
FYM	Farmyard manure
GBRs	General Binding Rules (Scotland)
GM	Geometric mean
ha	Hectare
HMSO	Her Majesty's Stationery Office
HOST	Hydrology of soil types
HRU	Hydrological response unit (in modelling)
IACS	Integrated Administration and Control System (EU)
IE	Intestinal enterococci
JAS	June Agricultural Survey
JHI	James Hutton Institute
km	Kilometre
LCA	Landscape Character Assessment (SNH)
LCM	Land Cover Map (CEH)
LCS	Land Cover Scotland
LUCAS	Land Use/Cover Area frame Survey (EU)
MarCon	MarCon Computations International (Co. Galway, Ireland)
MarGIS	EA's coastal model (of Morecambe Bay) developed by MarCon
m	metre
min	minute (time)
NVZ AP	Nitrate Vulnerable Zone Action Programme
OS	Ordnance Survey
PYSCHIC	Process/hydrological model of P and susp sed transport
RPA	Rural Payments Agency
rBWD	Revised Bathing Water Directive
s	Second (time)
SAGIS	Source-apportionment geographical information system
SAPM	Survey of Agricultural Production Methods (EU one-off survey 2010)
SBF	Streambank fencing
SCA	Standing Committee of Analysts
SEPA	Scottish Environment Protection Agency
SIMCAT	SIMulation of CATchments model
SNH	Scottish National Heritage
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SRDP	Scotland Rural Development Programme
STO	Storm tank overflow at WwTWs
STW	Sewage treatment works
SUGAR	SUrface water/GroundwAter contRibution index
SWAT	Soil and Water Assessment Tool (hydrological model)
SWD	Shellfish Water Directive
TMDL	Total maximum daily load
UK	United Kingdom
USEPA	United States Environmental Protection Agency
UV	Ultraviolet (disinfection)
VBS	Vegetated buffer strip
WFD	Water Framework Directive
WwTW	Wastewater treatment works

Appendix 2: Emerging issues in bathing and shellfish waters
(from PowerPoint presentation prepared by CREH for project start-up meeting (13 January 2016))



Emerging Issues in Bathing and Shellfish Waters

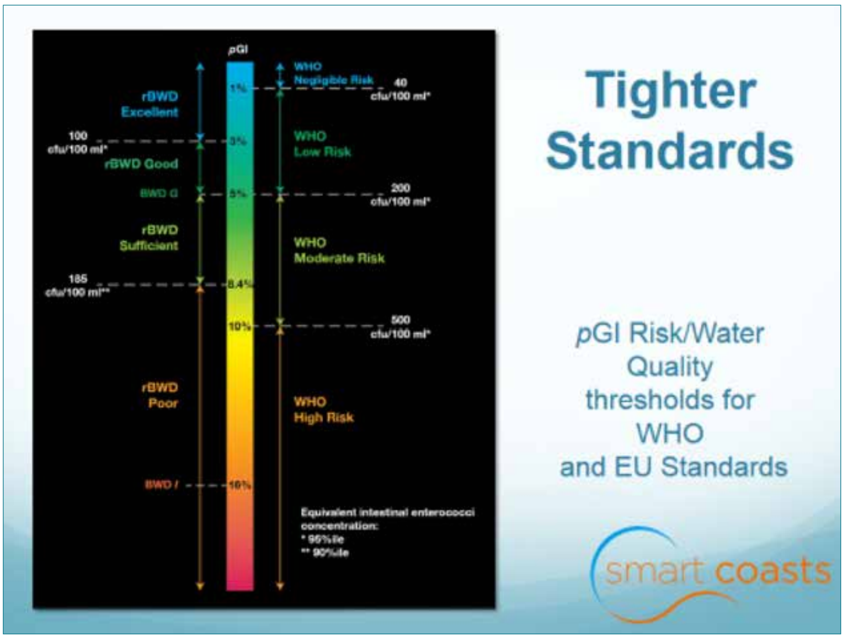
Edinburgh 13th January 2016

CREW project Kick-off meeting

crew
Scotland's centre of expertise for waters

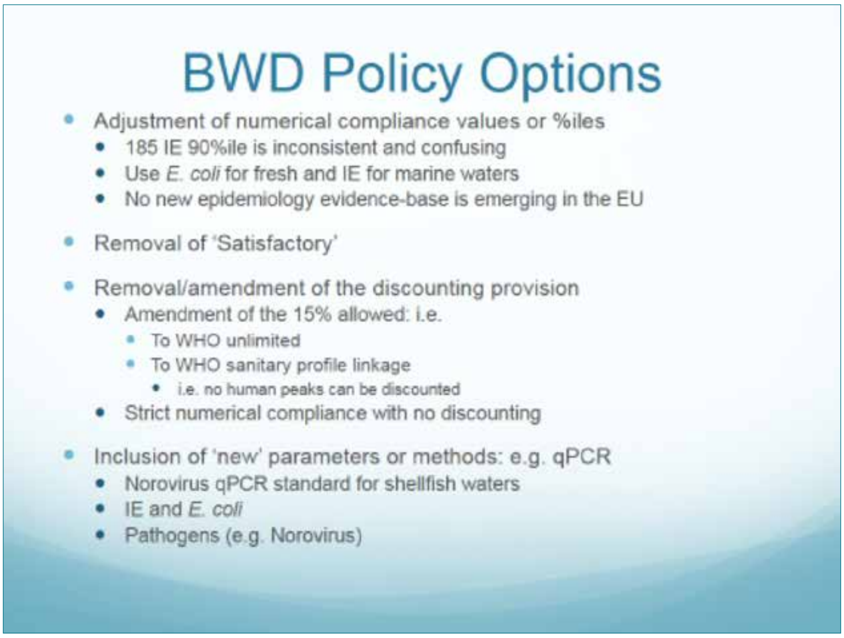
Project code: CRW2015/1

Project title: Development of a Screening Framework to improve Bathing and Shellfish Water Quality



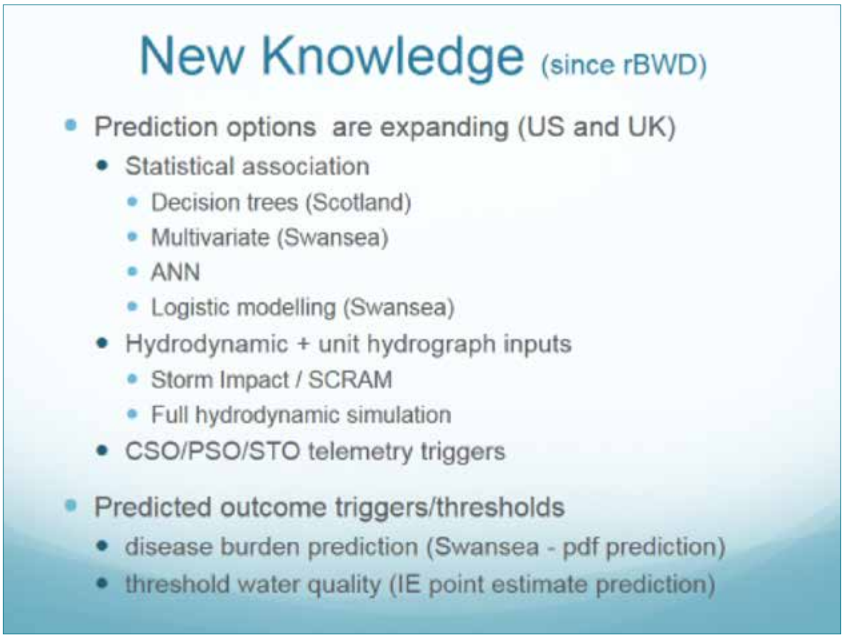
Tighter Standards

pGI Risk/Water Quality thresholds for WHO and EU Standards



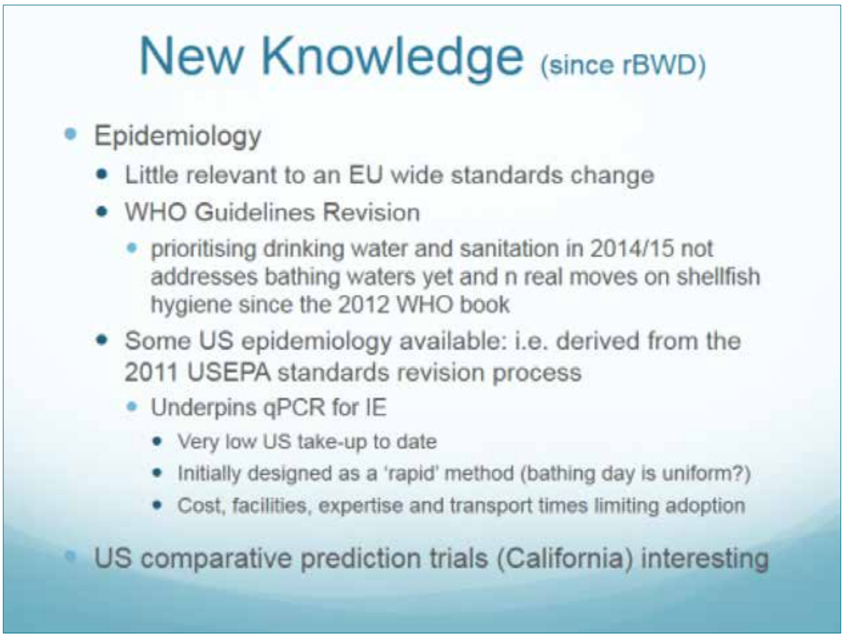
BWD Policy Options

- Adjustment of numerical compliance values or %iles
  - 185 IE 90%ile is inconsistent and confusing
  - Use *E. coli* for fresh and IE for marine waters
  - No new epidemiology evidence-base is emerging in the EU
- Removal of 'Satisfactory'
- Removal/amendment of the discounting provision
  - Amendment of the 15% allowed: i.e.
    - To WHO unlimited
    - To WHO sanitary profile linkage
      - i.e. no human peaks can be discounted
  - Strict numerical compliance with no discounting
- Inclusion of 'new' parameters or methods: e.g. qPCR
  - Norovirus qPCR standard for shellfish waters
  - IE and *E. coli*
  - Pathogens (e.g. Norovirus)



New Knowledge (since rBWD)

- Prediction options are expanding (US and UK)
  - Statistical association
    - Decision trees (Scotland)
    - Multivariate (Swansea)
    - ANN
    - Logistic modelling (Swansea)
  - Hydrodynamic + unit hydrograph inputs
    - Storm Impact / SCRAM
    - Full hydrodynamic simulation
  - CSO/PSO/STO telemetry triggers
- Predicted outcome triggers/thresholds
  - disease burden prediction (Swansea - pdf prediction)
  - threshold water quality (IE point estimate prediction)



New Knowledge (since rBWD)

- Epidemiology
  - Little relevant to an EU wide standards change
  - WHO Guidelines Revision
    - prioritising drinking water and sanitation in 2014/15 not addresses bathing waters yet and n real moves on shellfish hygiene since the 2012 WHO book
  - Some US epidemiology available: i.e. derived from the 2011 USEPA standards revision process
    - Underpins qPCR for IE
      - Very low US take-up to date
      - Initially designed as a 'rapid' method (bathing day is uniform?)
      - Cost, facilities, expertise and transport times limiting adoption
- US comparative prediction trials (California) interesting

New Knowledge (since rBWD)

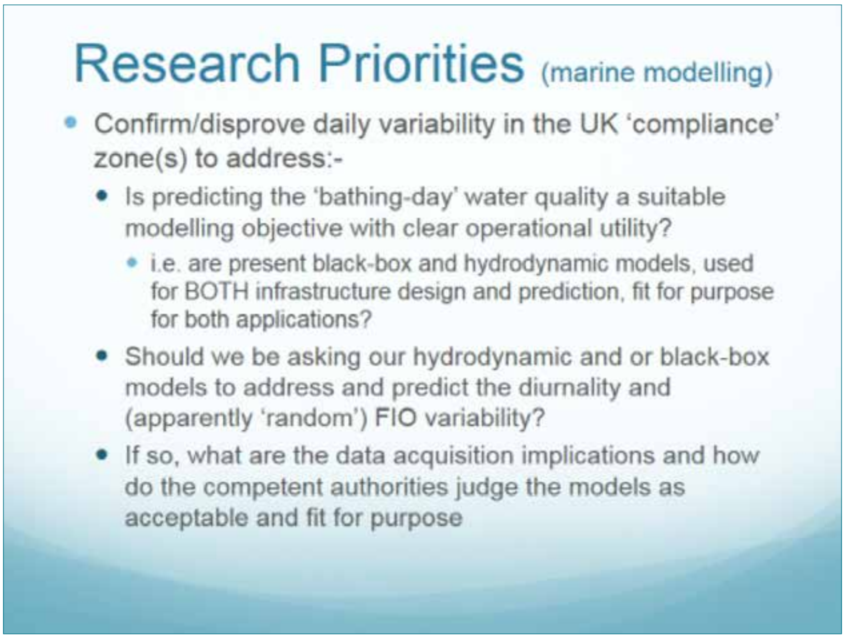
- Source tracking
  - USA/Canada/EU (Kate Field's bacteriodales)
    - Significant development of markers
    - Concern at qualitative nature and apparent poor reproducibility is limiting support:
    - Work on genomic profiling of the FIOs is 'expected' to indicate source (NERC EHH programme UK), but:
      - Will this be library independent?
      - Will it be quantitative?
      - Will it be affordable as an operational tool?
  - EU (Rosina Girones Barcelona/Viroclime)
    - Species/specific viral MST markers
      - Appears 'quantitative' on the 'paddling pool' test
      - Library independent
        - Inter-lab trials needed to define precision and reproducibility

New Knowledge (since rBWD)

- 'Normal' variability of FIOs in environmental waters
  - commonly 100 fold each bathing day more if the 'day' is 24hours and distinct diurnality is often apparent
    - Swansea Smart Coasts
    - California
    - Guernsey
    - UK Tracer investigation sites
  - Implications for compliance assessment
    - EU/WHO longer data sequence is justified
    - Sampling regimes are important (though the bathing day) compliance increases significantly in the early afternoon
  - Implications for modelling
    - Compliance data are inappropriate for model calibration/validation
      - Prediction of 'Bathing-Day' water quality may be of little operational value

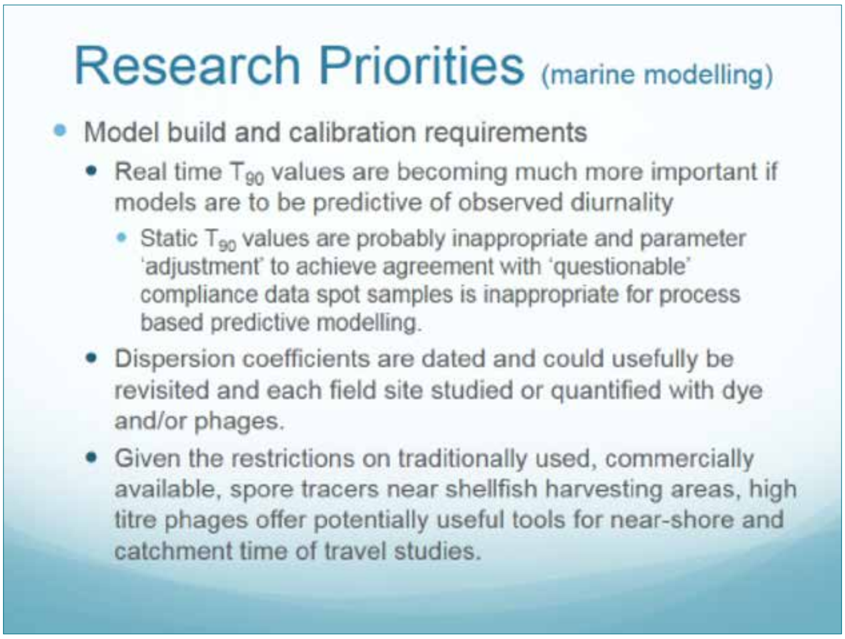
Research Priorities (methods)

- Review of epidemiological research (Defra, RAND review)
- Review of qPCR as an operational tool (NERC Healthy Water (David Oliver-Stirling)
    - Shellfish standards still an issue (EU-level initiative CEFAS leading)
- Operational community requirements of new methods, i.e. precision, cost and reproducibility
  - qPCR MST
  - qPCR FIOs
  - Genomics
- The Barcelona virology approach looks promising and worth a UK trial/proof of concept investigation (Water Research paper accepted for publicatioin)
- UKWIR/UKTAG involvement: i.e. watching brief, on UK genomics profiling of relevance to BW and SHW



Research Priorities (marine modelling)

- Confirm/disprove daily variability in the UK 'compliance' zone(s) to address:-
  - Is predicting the 'bathing-day' water quality a suitable modelling objective with clear operational utility?
    - i.e. are present black-box and hydrodynamic models, used for BOTH infrastructure design and prediction, fit for purpose for both applications?
  - Should we be asking our hydrodynamic and or black-box models to address and predict the diurnality and (apparently 'random') FIO variability?
  - If so, what are the data acquisition implications and how do the competent authorities judge the models as acceptable and fit for purpose



Research Priorities (marine modelling)

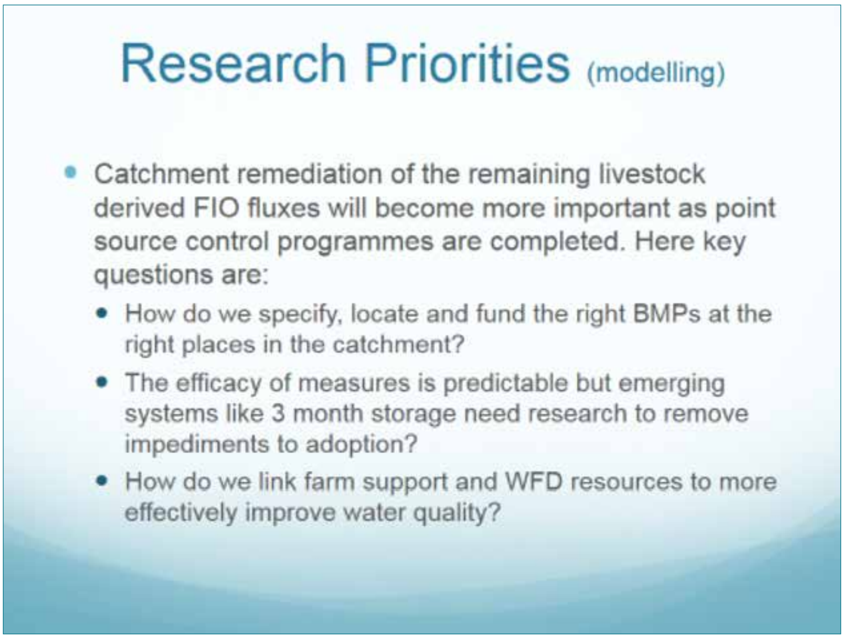
- Model build and calibration requirements
  - Real time T_{90} values are becoming much more important if models are to be predictive of observed diurnality
    - Static T_{90} values are probably inappropriate and parameter 'adjustment' to achieve agreement with 'questionable' compliance data spot samples is inappropriate for process based predictive modelling.
  - Dispersion coefficients are dated and could usefully be revisited and each field site studied or quantified with dye and/or phages.
  - Given the restrictions on traditionally used, commercially available, spore tracers near shellfish harvesting areas, high titre phages offer potentially useful tools for near-shore and catchment time of travel studies.

Research Priorities (marine modelling)

- Cal/Val data must not be only derived from regulatory compliance data sequences, acquisition of: (i) higher precision and (ii) intensive data is important in this regard given the magnitude of related infrastructure expenditure decisions.

Research Priorities (modelling)

- Catchment and river models need parameterisation data for
  - Riverine FIO decay coefficients (T_{90} values)
    - Water
    - Sediment (NB regrowth may be a factor here)
  - Catchment FIO export coefficients
    - Only one paper world-wide – i.e. a huge deficit compared to nutrients and sediment parameters, much EA modelling using this source but it increasingly dated
  - Process model development (e.g. Basins C2C: Inca (Oxon); Pedal (Lancaster) will be constrained by these parameterisation data deficits



Research Priorities (modelling)

- Catchment remediation of the remaining livestock derived FIO fluxes will become more important as point source control programmes are completed. Here key questions are:
  - How do we specify, locate and fund the right BMPs at the right places in the catchment?
  - The efficacy of measures is predictable but emerging systems like 3 month storage need research to remove impediments to adoption?
  - How do we link farm support and WFD resources to more effectively improve water quality?

Appendix 3: Details of the CREH (2010) regression modelling

1 CREH and catchment sensitive farming (CSF) catchments used in the modelling

The eight CREH and five ECSFDI catchments in England and Wales that were used in developing the models used in the present study are listed in Tables A3-1 and 2, respectively, together with information on the numbers of subcatchments used and (in case of CREH catchments) the year when the study was undertaken. The locations of the catchments are shown in Figure A3-1.

2 Comparability of FIO data sets for ECSFDI and CREH catchments

As at the CREH monitoring points, samples at 33 of the 39 ECSFDI monitoring points were all taken aseptically, i.e. manually and immediately stored in cool dark conditions prior to analysis. At six ECSFDI sites, however, manual sampling was supplemented by some automated sampling during 35 high-flow events. Such sampling risks cross contamination in the auto-sampler and is likely to have allowed greater opportunities for die-off prior to analysis. In both sets of investigations presumptive EC (or FC) and IE (or FS) concentrations were measured using standard UK methods based on membrane filtration, which have not changed substantially since 1995 (HMSO, 1994; Environment Agency, 2000). For the CREH sites, base-/high-flow separation of samples was undertaken by visual inspection of hydrographs, whereas an automated procedure was adopted by the EA for the ECSFDI catchments. In undertaking the modelling it was been assumed that the resulting FIO data from the ECSFDI and CREH catchment studies are directly comparable.

3 Catchments that include reservoirs/lakes

Unfortunately, a number of the ECSFDI monitoring points have reservoirs/lakes within their catchments. Because of die-off and sedimentation of FIOs within reservoirs and lakes, waters leaving such waterbodies typically have very low FIO concentrations which may poorly reflect upstream land use, stocking levels, the effects of best management practices (BMPs), etc. within the contributing catchment (Kay and McDonald, 1980). FIO data for such sampling points therefore need to be interpreted with caution, especially in cases where land upstream of lakes/reservoirs occupies a relatively high proportion of a catchment. In the present study, two sets of FIO data are presented: the actual concentrations recorded and the estimated concentrations in runoff from the ‘non-waterbody’ part of the catchment (i.e. land downstream of all reservoirs/lakes) – the latter being referred to here as ‘reservoir-adjusted’ concentrations. The reservoir-adjusted concentrations are derived on the basis of the following assumptions: (i) the volume of flow derived from waterbodies is proportional to the area their contributing areas occupy within the subcatchment; and (ii) geometric mean (GM) EC and IE concentrations in output waters from such waterbodies are as reported in Table A3-3. Using these assumptions, the GM FIO concentrations recorded at the subcatchment monitoring point can be separated into two components: (i) the concentration in waters issuing from waterbodies and (ii) that (i.e. the reservoir-adjusted concentration) from the rest of the subcatchment. While the reservoir-adjusted concentrations are estimates, this procedure is considered preferable to excluding from analysis all subcatchments (both ECSFDI and CREH) containing reservoirs/lakes.

4 Data describing subcatchment characteristics

The following data were generated for the various CREH and ECSFDI catchments. For each subcatchment, the data are expressed on the basis of either the total subcatchment area or, where reservoirs and/or lakes are present, the reservoir-adjusted area (i.e. the non-reservoir part).

- **Base flow index (BFI)** – The mean BFI for the reservoir adjusted catchments has been derived from the Hydrology of Soil Types (HOST) database.

- **Land cover data** – The land cover data have mostly been synthesised from the Centre for Ecology and Hydrology (CEH) Land Cover Map (LCM) 2000, with the various classes amalgamated (as detailed in Table A3-4). In addition, Ordnance Survey (OS) Meridian 2 digital ‘developed land use’ (DLU) boundary data have been used to provide an additional, independent urban data set. The land cover variables were all expressed as a percentage of the land area.

- **Residential data** – The residential address database was used to determine the density of residences within each subcatchment, expressed as number/km^2.

- **Livestock data** – Agricultural census data for 2009 were used for the ECSFDI catchments and for 2000 for the CREH catchments to determine stocking levels (dairy cattle, beef cattle, sheep, pigs, poultry and other) within each reservoir-adjusted subcatchment, expressed as number/km^2. Because of the relatively low resolution of these data, they are considered unreliable when calculated for areas of < 3 km^2.

5 Statistical methods

Standard methods of statistical analysis were undertaken using SPSS v15.0 for Windows (SPSS Inc., 2006). Multiple regression techniques, using a stepwise selection procedure, were used to model the relationships between GM FIO concentrations at base and high flow (the dependent variables, *y*) and the various catchment variables (independent variables, *x*). Log$_{10}$ transformations were applied to those independent variables for which skewness exceeded 1.00. In the regression analysis, relationships of the following form were generated: $y = a + b_1x_1 + b_2x_2 + \ldots.. + b_ix_i + e$ where *a* is the intercept (y at $x = 0$), *b* is the slope (change in *y* per unit change in *x*) and *e* is a random error term. Independent variables with a variance inflation factor > 2 (i.e. tolerance, 0.500) were excluded to minimise multicollinearity (Rogerson, 2001); probability of *F* for a variable to enter was set at 0.05; the level of explained variance was assessed using the coefficient of determination (r^2), adjusted for degrees of freedom; and the normal probability plot of standardised residuals was examined to confirm the validity of each model. All statistical tests were assessed at $\alpha = 0.05$ (i.e. 95% confidence level).

6 Regression models

The independent variables used in the regression modelling are identified in Table A3-5 and summary data for the resulting regression models are presented in Table A3-6.

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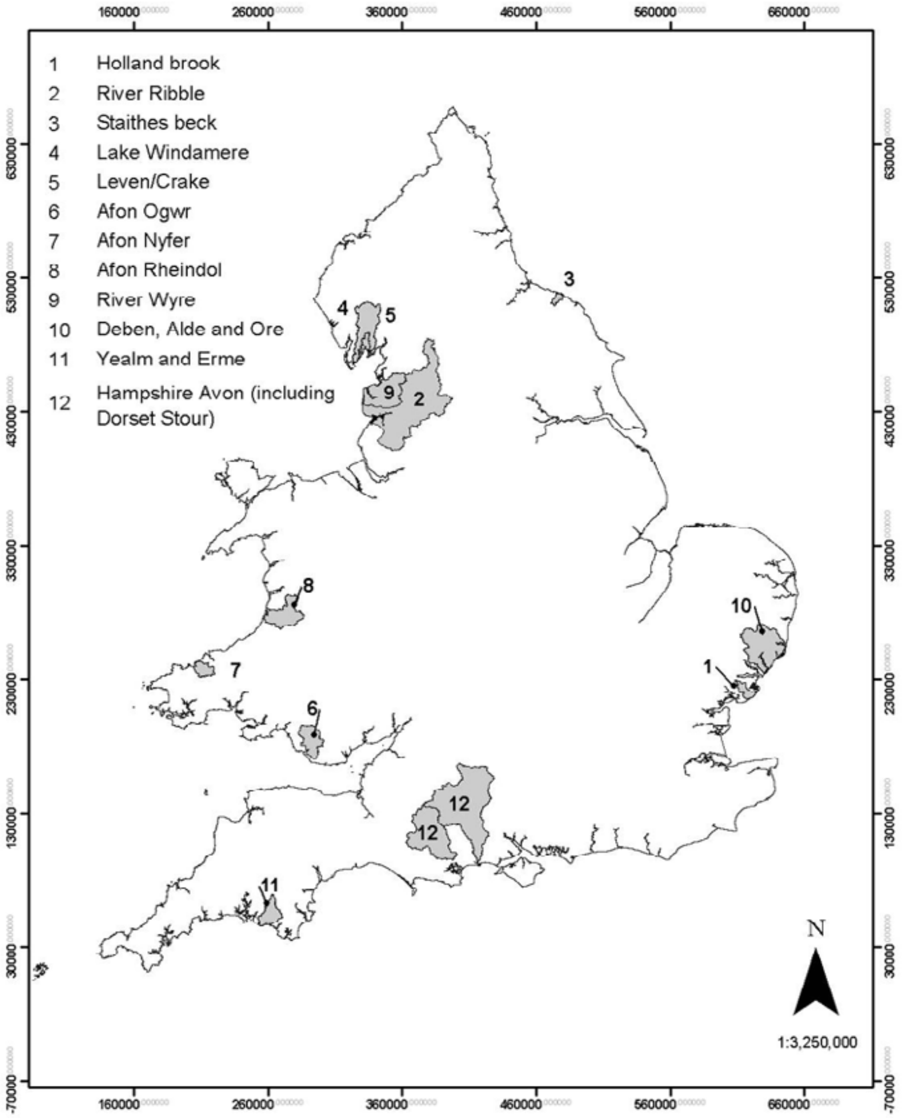

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Figure A3-1 Location of the eight CREH and five ECSFDI catchments and in England and Wales used in developing the generic models.

Table A3-1 CREH catchments/subcatchments[a] used (in combination with the ECSFDI catchments) in developing generic regression models

	Catchment	Study year	Subcatchments (*n*):	
			Base flow	High flow
England				
1	Holland Brook	1998	10	10
2	River Ribble	2002	37	37
3	Staithes Beck	1995	6	2[c]
4	Lake Windermere inputs	1999	3	3
5	River Leven/Crake	2005	16	16
Wales				
6	Afon[b] Ogwr	1997	14	14
7	Afon Nyfer	1996	17	2[c]
8	Afon Rheidol/Ystwyth	1999	12	12
	Total		115	96

[a] Only subcatchments ≥ 5 km^2, with reservoir catchments of < 50% and with ≥ 5 samples at base or high flow are included in present analysis.

[b] 'Afon' (Welsh) = 'River'.

[c] There was very little rainfall during these studies, and ≥ 5 samples were only obtained two sites.

Table A3-2 ECSFDI catchments used in generic modelling

Catchment	Subcatchments (*n*)	Subcatchments used in modelling[a]:	
		Base flow (*n*)	High flow (*n*)
Deben	7	6	7
Avon	11	11	11
Stour	1	1	1
Yealm	10	8	8
Wyre	10	10	10
Total	39	36	37

[a] Only subcatchments ≥ 5 km^2, with reservoir catchments of < 50% and with ≥ 5 samples at base or high flow are included in present analysis.

Table A3-3 Geometric mean FIO concentrations (cfu 100 ml^{-1}) in waters issuing from lakes and reservoirs[a]

	Base flow	High flow
FC	26	83
IE	5	16

[a] Based on data from Nant-y-Moch and Cwm Rheidol Reservoirs in Afon Rheidol/Ystywyth study, Lake Windermere in the Windermere study, and Fewston and Thruscross Reservoirs in Yorkshire – the latter from Kay (1979).

Table A3-4 Derivation of LCM 2000 land cover variables used in regression modelling

LCM Code	Description	Classification for independent variables used in regression analysis
11	Broad-leaved woodland/ mixed woodland	Woodland
21	Coniferous woodland	Woodland
41	Arable cereals	Arable
42	Arable horticulture	Arable
43	Arable non-rotational	Arable
51	Improved grassland	Improved grassland
52	Setaside grass	Arable
61	Neutral grass	Rough grazing
71	Calcareous grass	Rough grazing
81	Acid grassland	Rough grazing
91	Bracken	Rough grazing
101	Dense dwarf shrub heath	Rough grazing
102	Open dwarf shrub heath	Rough grazing
111	Fen marsh swamp	Rough grazing
121	Bog (deep peat)	Rough grazing
131	Inland water	Other
151	Montane habitats	Rough grazing
161	Inland bare ground	Other
171	Suburban/rural development	Urban
172	Continuous urban	Urban
181	Supra-littoral rock	Other
191	Supra-littoral sediment	Other
201	Littoral rock	Other
211	Littoral sediment	Other
212	Saltmarsh	Other
221	Sea/Estuary	Other

Table A3-5 Catchment (predictor) variables used in multiple regression analyses

Variable type	Variable[a]
Catchment size	Subcatchment area (km^2)
Catchment hydrology	Base flow index (BFI)
Land cover	Urban (OS Meridian) (%)
	Urban (%)
	Improved grassland (%)
	Rough grazing (%)
	Arable/set-aside (%)
	Woodland (%)
Human population	Residences (km^{-2})
Stocking densities	Dairy cattle (km^{-2})
	Beef cattle (km^{-2})
	Total cattle (km^{-2})
	Sheep (km^{-2})
	Pigs (km^{-2})
	Poultry (km^{-2})

[a] Log_{10} transformations were applied in cases where skewness ≥ 1.00. Except for BFI, 1.00 was added to data values prior to transformation in order to eliminate zero values.

Table A3-6 Summary of stepwise multiple regression models of relationship between SUMMER bathing season mean $\log_{10}$ faecal coliform and enterococci concentrations at base and high flow and the catchment variables listed in Table A3-5

Step Variable	Sign of *b*	Adjusted r^2	Sig level (p)
Base-flow models (n = 151)			
Faecal coliforms			
1. Residences ($\log_{10}$, km^{-2})	+	0.321	
2. BFI ($\log_{10}$)	-	0.407	
3. Dairy cattle (km^{-2})	+	0.458	< 0.001
Intestinal enterococci			
1. Residences ($\log_{10}$, km^{-2})	+	0.204	
2. BFI ($\log_{10}$)	-	0.305	
3. Area ($\log_{10}$, km^2)	-	0.347	
4. Rough grazing (%)	-	0.360	< 0.001
High-flow models (n = 133)			
Faecal coliforms			
1. Residences ($\log_{10}$, km^{-2})	+	0.182	
2. Sheep (km^{-2})	+	0.448	
3. BFI ($\log_{10}$)	-	0.573	
4. Dairy cattle (km^{-2})	+	0.627	< 0.001
Intestinal enterococci			
1. Residences ($\log_{10}$, km^{-2})	+	0.199	
2. Sheep (km^{-2})	+	0.461	
3. BFI ($\log_{10}$)	-	0.576	
4. Total cattle (km^{-2})	+	0.613	
5. Area ($\log_{10}$, km^2)	-	0.637	
6. Pigs ($\log_{10}$, km^{-2})	+	0.648	< 0.001

Appendix 4: Natural FIO inputs from wildlife

Although research is currently being undertaken in Scotland on various specific pathogens in wildlife (including deer, rabbits and seals), it seems from discussions and correspondence with Dr Mark Dagleish, Prof. Lee Innes, and Dr Beth Wells (all at Moredun Research Institute) and with Prof. Davy McCracken (Scotland's Rural College) that no work has been undertaken on FIO load inputs to catchments and estuarine/coastal waters. In fact, relatively few studies have been undertaken on FIOs derived from wildlife. Data from CREH's existing database on FIO loadings from wildlife are presented in Table A4-1. Brief notes are presented here on the contributions of FIOs to estuarine/coastal waters from seals and birds, and on other observations on the impacts of birds.

1 Seals

In the case of seals, it should be noted that Lisle *et al*. (2004) report some quite high concentrations of FIOs in faecal samples from Weddell seals (*Leptomychotes weddellii*) in Antarctica – EC: range 0–1.21 x 10^4 cfu/g dry weight (dw), FC: 3–1.40 x 10^4 cfu/g dw, and enterococci 1.21 x 10^4 cfu/g dw, though no estimates are given of the daily loads; and harbour seals (*Phoca vitulina*) are reported to be contributing to the contamination of a number of US shellfish waters (Nash *et al*., 2000). Seals therefore represent a potential source of FIOs in estuarine and coastal waters, especially where they are present in large numbers.

2 Birds

Birds often gather in quite large numbers in estuarine/coastal zones and around inland water bodies to feed, roost and/or breed. Several studies have shown birds to be a significant source of faecal pollution in surface waters – e.g. Kirschner *et al*. (2004), Levesque *et al*. (1993), Suprihatin *et al*. (2003), Ricca & Cooney (1998), Wakelin *et al*. (2003). Wither *et al*. (2005), for example, in studies along the Fylde coast have highlighted the effects of up to *c*. 30,000 starlings that roost on the piers at Blackpool from late summer onwards, with seasonal variations in FIO concentrations in the adjacent bathing waters being correlated with the number and distribution of birds.

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Table A4-1 FIO inputs to catchments and estuarine/coastal waters from wildlife

Source[a]	Animal/bird type	*E. coli* (cfu/animal/day)	Faecal coliform (cfu/animal/day)	Intestinal enterococci (cfu/animal/day)	Faecal streptococci (cfu/animal/day)
Animals					
USEPA (2006)	Deer		5.00 x 10^8		
Birds					
Gould & Fletcher (1978)	Duck		1.10 x 10^{10}		1.80 x 10^{10}
Moriarty (2014)	Duck	3.18 x 10^{10}			
Moriarty (2014)	Canada goose	9.03 x 10^6		6.25 x 10^6	
Moriarty (2014)	Gull	9.35 x 10^8			
Gould & Fletcher (1978)	Black-headed gull (*L. ridibundus*)		3.00 x 10^8		2.00 x 10^6
Gould & Fletcher (1978)	Common gull (*L. canus*)		6.20 x 10^8		1.00 x 10^6
Gould & Fletcher (1978)	Lesser black-backed gull (*L. fuscus*)		5.00 x 10^9		1.50 x 10^7
Gould & Fletcher (1978)	Herring gull (*L. argentatus*)		1.80 x 10^9		2.00 x 10^7
Moriarty (2014)	Black swan	7.98 x 10^8			
Wither *et al*. (2005)	Starling	4.80 x 10^8			

[a] **Sources:** Gould, D. J. & Fletcher, M.R. (1978) Gull droppings and their effects on water quality. *Water Research*, 12, 665-672.
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Appendix 5: Agricultural mitigation actions and their effectiveness

Extensive reviews undertaken for SEPA by CREH (2006, 2012; Kay *et al*., 2012) have provided detailed syntheses and evaluations of the attenuation rates resulting from individual mitigation actions (i.e. a, above), specifically covering actions to: reduce FIO numbers at source within catchments; attenuate FIO transfers from ground surfaces to adjacent watercourses; and treat dirty water from farm hardstandings. Although there have been a several more recent studies, the outcomes of these do not markedly affect the previous findings – a summary of which is presented in Sections 1 and 2 (below). At time of these reviews, very little was known about the likely numbers of FIOs that would be affected by particular actions (i.e. b, above), and so there was no real basis for assessing the impacts that the implementation of remedial actions would have upon catchment fluxes. Fortunately, this knowledge gap has now been addressed for Scotland through the EoM project (ADAS, 2014), thus enabling meaningful estimates to be made of the likely impact actions at a catchment scale. The key findings from this are summarised in Sections 3 and 4 (below).

This section is based largely on an extensive detailed review undertaken for SEPA (CREH, 2012). Although there have been a several more recent studies, the outcomes of these have do not markedly affect the previous findings.

1 FIO risk assessment

A qualitative assessment of magnitude and frequency of water pollution risk for livestock-related FIO pollution from farmstead and field sources is presented in Table A5-1.

2 Range of measures

Three groups of measures can be identified:

2.1 Reduction of FIO numbers at source within catchments

Reductions could be achieved, for example, by imposing restrictions on stocking densities within catchments or by incineration of livestock wastes. However, the most practicable approach is to maximise the opportunities for die-off of FIOs in fresh faeces, farmyard manure and slurry before and after they are disposed of to land. Typical rates of attenuation are presented in Figure A5-1. These highlight: the importance of preventing livestock having access to watercourses in order to ensure that there is no direct input of fresh faeces; the quite rapid attenuation of FIOs during slurry and FYM storage over 3 months (e.g. 90% for slurry), even with daily inputs of fresh faeces; and the very rapid attenuation of FYM and slurry following application to land (either broadcast or by injection). Most striking, however, is the very high attenuation achieved where FYM and slurry are stored without further fresh inputs (e.g. a 99.99% reduction in stored slurry after a median storage time of 69 days). This suggests that an increase of storage capacity to enable slurry storage without fresh addition for 2–3 months prior to disposal to land would greatly reduce FIO pollution from this source.

2.2 On-farm treatment of dirty water from farm hardstandings

This generally takes two forms: ponds and constructed farm wetlands, which often include one of more ponds. Summary data (Figure A5-2) indicate typical rates of attenuation in the order of 90%, and maximum recorded rates of 99.9% for ponds and 99.99% for constructed wetlands.

2.3 Attenuation of FIO transfers to watercourses

This encompasses various measures, including: containment of runoff from hardstandings for storage and/or treatment and safe disposal; control of livestock on farmland (streambank fencing and bridging, minimising runoff from tracks, minimising livestock congregation areas and soil poaching, and woodchip corrals); control of manure/slurry application to land; vegetated buffer strips (VBSs) (including riparian buffer strips); and grassed waterways ('swales'). Median rates of FIO attenuation reported for woodchip corrals, grassed swales and VBSs are all in the order of 90% (Figure A5-2).

3 Effectiveness of actions for reducing FIO fluxes from agricultural sources in Scotland: recent insight gained from the EoM project (ADAS, 2014)

The effectiveness of interventions in reducing agriculture-related FIO fluxes within catchments is dependent not only upon the attenuation (percentage or $\log_{10}$ reduction) in FIO concentration/load that occurs as a result of a particular mitigation action (as reviewed above); but, equally importantly upon the number of FIOs within a catchment that are directly affected a particular action. The previous CREH (2012) review highlighted a lack of empirical data or models to characterise FIO transport/flow pathways within agricultural landscapes and the limited data on impacts of multiple mitigation interventions upon FIO fluxes at a catchment-scale. The EoM now provides unique insight into both these for Scottish WFD catchments.

3.1 Source apportionment of agriculture-derived FIO inputs in Scotland

It is estimated (Figure 9-4 in ADAS, 2014) that nationally virtually the entire loss (*c.* 95%) of FIOs to watercourses under current agricultural practice is attributable to voiding by livestock in fields and watercourses, with the remainder being largely attributable to stored livestock wastes (slurry and farmyard manure) and dirty water (yard runoff/washings – some of which may be stored prior to disposal to land). This finding is especially significant in that it suggests that, because of the significant die-off of FIOs that occurs in manure heaps, slurry tanks, etc., current practices relating to the storage of livestock wastes and their subsequent disposal to land are not a major source of FIO loadings in streams. The results also show (Figure 9-4) that of the FIO inputs to watercourses, by far the greatest proportion (87%) are derived from surface runoff, with the remainder being via preferential flow (8%), which is primarily including drain flow, and direct defecation to watercourses (5%). Clearly, given the complexity of factors and processes that are operative within catchments, and that underpin this modelling, these precise figures need to be regarded with some degree of caution. Assuming, however, that they broadly correct, then these finding have substantial implications for the targeting of remediation actions. For example, priority should be given to seeking way of reducing the pollutant fluxes derived from faeces voided when livestock are outdoors, both direct to water, but perhaps more importantly in fields. Effective mitigation actions might include the creation of riparian buffer strips (to prevent cattle access to watercourses and ask as a 'filter' to trap FIOs in surface runoff), minimising areas of soil compaction by trampling in cattle congregation areas (which favour surface runoff from areas where large quantities of voided faeces are likely to be present), minimising runoff from tracks frequently used by livestock (e.g. diverting runoff through grass swales).

3.2 Effectiveness of remedial actions upon catchment fluxes of FIOs in Scotland

In the EoM report (ADAS, 2014), estimates were made of the effectiveness of different intervention scenarios in reducing the FIO loads presently being delivered to watercourses in the WFD catchments. These range from 100% compliance with the Nitrate Vulnerable Zone Action Programme (NVZ AP) measures, many of which have already been implemented and their impact therefore largely accounted for within the 'present' FIO loadings; to 100% compliance with the NVZ AP and the GBRs and 100% implementation of the Scottish Rural Development Programme (SRDP) options. The former gives estimated reductions in FIO loads of < 5% within most of the NZVs (Figure 9-2(a) in ADAS, 2014), whereas under the latter scenario, the majority of catchments across the whole of Scotland have reductions of between 20 and 60% (Figure 9-8(a), ADAS, 2014). In reality, 100% implementation of the SRDP options is regarded as unrealistic. In a much more realistic scenario of what might be achieved by *c*. 2027 assuming there is 100% compliance with the GBRs and NVZ AP and SRDP funding rates and priorities remain the same as now[1], the estimated reductions in FIO loads from agriculture are < 40%, with most being < 20% (Figure 9-10(a), ADAS, 2014). In microbial terms, such reductions are relatively small and are likely to have only a limited impact in reducing levels of microbial impairment in receptor waters.

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[1] Assumes actions associated with the SRDP options are implemented according to the 'long term' rates in Tables 6-9 and 6-10 (ADAS, 2014), with no implementation of SRDP options outside of the priority catchments.

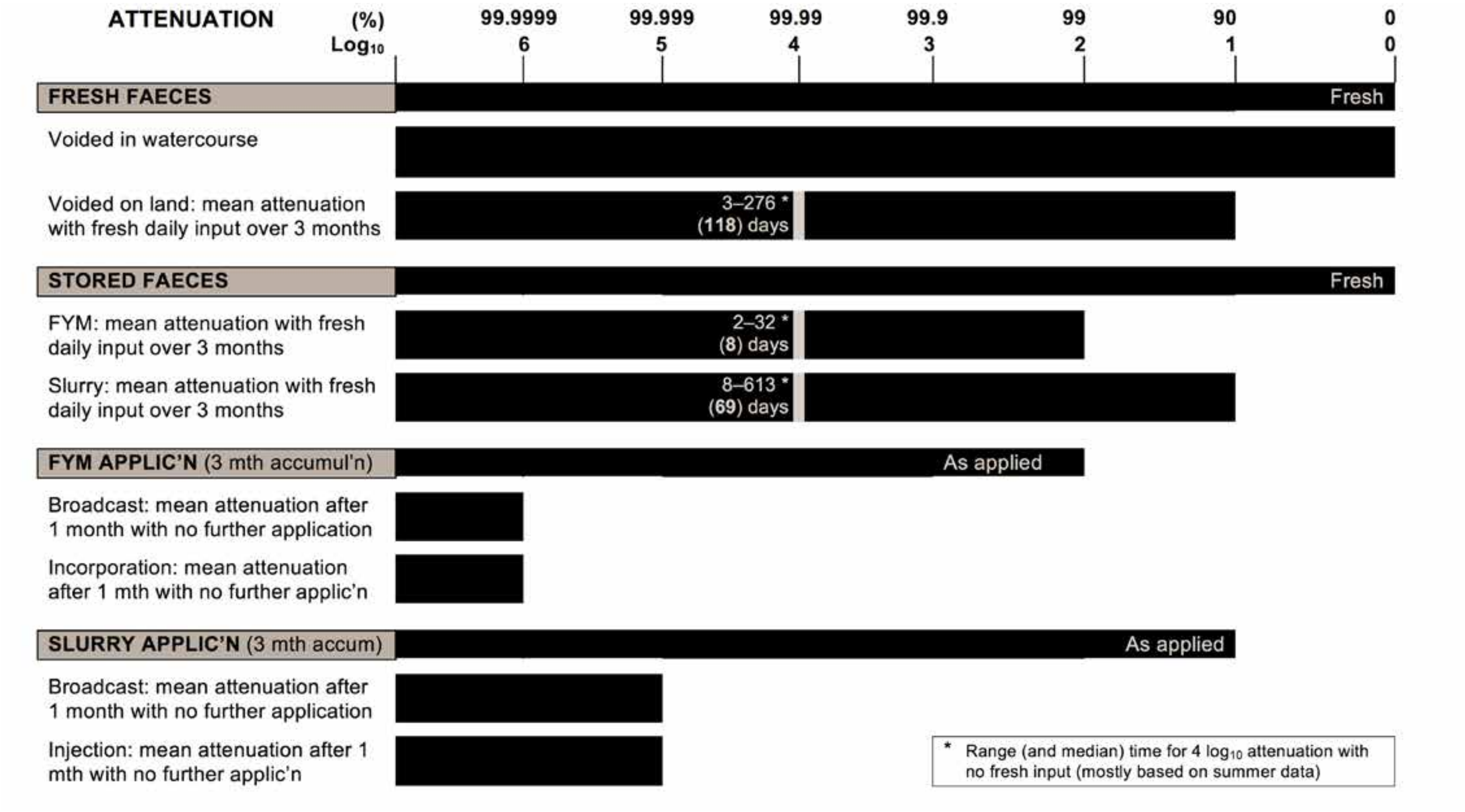

Figure A5-1 Rates of FIO/pathogen attenuation (to nearest $\log_{10}$) associated with faeces and manure/slurry.

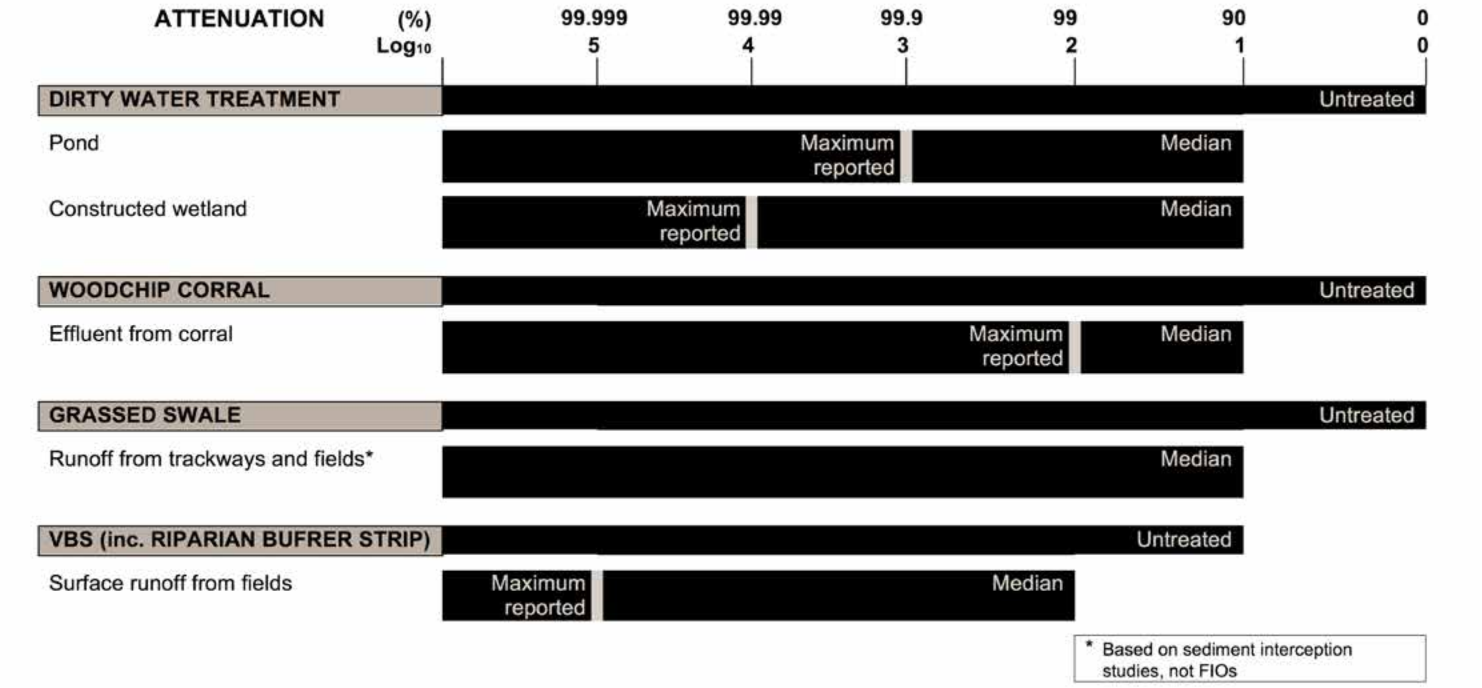

Figure A5-2 Typical rates of FIO attenuation (expressed to nearest $\log_{10}$) in runoff from yards and agricultural land as result of specific measures.

Table A5-2 Qualitative assessment of magnitude and frequency of water pollution risk for livestock-related FIO pollution from farmstead and field sources

POLLUTANT SOURCE/CONNECTIVITY:				**RISK ASSESSMENT:**	
Source	Classification criteria for different sources	Classification[a]	Connectivity to watercourse[b]	**MAGNITUDE** Risk of water pollution during a potentially polluting 'event')[c]	**FREQUENCY** Likelihood of occurrence of a pollution 'event'[c]
FARMSTEAD SOURCES:					
Hardstanding	Amount of faecal material on hardstanding surface:	0	0-High	0	0
		Low-High	0	Low	Low
		Low	Low	Low	Low
		Moderate	Low	Moderate	Moderate
		High	Low	Moderate	**High**
		Low	High	Moderate	**High**
		Moderate	High	**High**	**Very high**
		High	High	**Very high**	**Very high**
Slurry store	Risk of slurry leakage:	Low	0	Low	Low
		Moderate	0	Low	Moderate
		High	0	Low	**High**
		Low	Low	Moderate	Low
		Moderate	Low	Moderate	Moderate
		High	Low	Moderate	**High**
		Low	High	**Very high**	Low
		Moderate	High	**Very high**	Moderate
		High	High	**Very high**	**High**
Manure store			0	Low	Low
			Low	Low	Moderate
			High	**High**	**Very High**
Milking parlour spillages and washings			0	Low	Low
			Low	**High**	**High**
			High	**Very high**	**Very high**
Roof runoff			0-High	Low	Low
FIELD SOURCES:					
Fields (including animal congregation areas), but exc. riparian area	Amount of faeces present on ground surface from grazing animals and/or animal waste applics:	0	Low-High	0	0
		Low	Low	Low	Low
		Moderate	Low	Moderate	Low
		High	Low	Moderate	Low
		Low	High	Low	**High**
		Moderate	**High**	**High**	**High**
		High	**High**	**Very high**	**High**
Riparian areas	As above:	0	High	0	0
		Low	High	Low	**High**
		Moderate	High	**High**	**High**
		High	**High**	**Very high**	**Very high**
Tracks/roads	Degree of faecal contamination by farm animals:	0	0-High	0	0
		Low	Low	Low	Moderate
		Moderate	Low	Low	Moderate
		High	Low	Moderate	Moderate
		Low	High	Moderate	**Very high**
		Moderate	**High**	**High**	**Very high**
		High	**High**	**Very high**	**Very high**
Animal access to watercourses	Number of animals:	0	Direct	0	0
		Low	Direct	Moderate	Moderate
		Moderate	**Direct**	**Very high**	**High**
		High	**Direct**	**Very high**	**Very high**

---

[a] Classification of sources: The classification for a particular source might vary markedly through the year (e.g. on a beef farm there may be little, if any, faecal input to the hardstanding during the summer, but quite a high input over winter when cattle are housed).
[b] Connectivity to watercourse: 0 = total containment, Low = No flow path (i.e. runoff from yards, roads etc. forms a diffuse input to adjacent land or in case of fields there is little surface runoff), High = Hydrological pathway that is directly connected to nearby watercourse (i.e. concentrated runoff from yards, roads, etc. or riparian areas that become are activated at times of high flow).
[c] Potentially polluting events include times of active surface runoff, dairy/yard washing, cattle fording streams, etc. The risk of water pollution during an event and the likelihood of an event are dependent upon the both the nature (i.e. classification) of the source and the degree of connectivity to a receiving water.

Appendix 6: Effectiveness of methods for reducing FIO fluxes from sewerage sources

Compared with the typically diffuse and unregulated/unmonitored agricultural FIO sources, much more is known about point-source sewerage discharges to watercourses, with the majority having discharge consents. Typical FIO concentrations of FIOs in untreated sewage (as in CSO and STO discharges) and the effectiveness of various types of sewerage treatment in the attenuation of FIOs are quite well documented. Kay *et al*. (2008b), for example, reviewed data from 162 sewerage discharge sites in the UK that CREH had monitored over the period 1995–2007, covering untreated sewage (*n* = 69) and primary , secondary- and tertiary-treated effluents (*n* = 12, 67 and 14, respectively); and this database has since been augmented by subsequent studies. Such data, combined, with known (or modelled) discharge volumes can be readily used to estimate the impact of specific improvements in sewerage infrastructure (increasing storage capacity of storm tanks, reducing magnitude and frequency of CSO discharges, etc.) and treatment (e.g. installation of tertiary treatment: UV disinfection, reedbeds, etc.).

Appendix 7: Use of microbial source tracking (MST) and other faecal typing approaches in FIO source apportionment

In recent years, MST has emerged as an operational tool. This offers the potential to provide quantitative estimates of the contributions of human and animal pollution in regulated waters at monitored receptor sites. Early developments used the ratio of faecal coliform and faecal streptococci in surface waters as a source indicator (Faechem, 1975; Geldreich 1965: Geldreich & Kenner, 1969). The ratio FC/FS > 4 = Human; <0.7 = Non-human was suggested. However, this approach proved unreliable, probably due to differential, but largely unknown, die-off of the two indicators once outside the gut (Lalor, 1994). More recently, both library- dependent and library-independent methods have been developed. The former '*match genetic or phenotypic patterns of FIO isolates from a known source to that of isolates in an ambient sample*' (Boehm *et al*., 2013), whilst the latter use species-specific genetic markers which do not require costly library construction describing genetic profiles of all suspected sources of pollution. A useful recent study reported by Boehm *et al*. (2013) examined 41 library- independent MST methods in a multi-laboratory trial. These were generally found to give good binary presence or absence assessment in prepared and faecally seeded matrices, but the quantitative contribution components proved less reliable and resilient to sample concentration factors. Thus, the available tools fall short of the evaluation criteria for operation application established by Santo Domingo *et al*. (2007). They were addressing the requirements of the US Clean Water Act for MST tools to quantify the different sources of FIOs at a catchment scale, thus, to inform remedial measures following Total Maximum Daily Load (TMDL) estimates (the parallel UK process is the design of Programmes of Measures under the EU Water Framework Directive (Article 11)). They suggested that any operational tool needs three test or characteristics, namely:

> 1. *The most critical issue in MST is the lack of performance standards to evaluate the accuracy of any of the existing and emerging methods (as originally noted by Stoeckel and Harwood 2007).*
>
> 2. *To fully validate the potential of MST, long-term, large-scale field studies need to be conducted with the methods that meet standardized performance criteria.*
>
> 3. *Ultimately, quantitative assays will be needed for the TMDL process to establish fecal allocations and to predict the levels of reduction that can be achieved by targeting particular sources. Such assays are also needed to further evaluate the efficacy of management practices at temporal and spatial scales.*
>
> (from Kinzelman *et al*., 2011)

The work of Boehm *et al*. (2014) provides a test of performance standards but it would be difficult to conclude that the latest approaches have yet passed this test and this work, although excellent, did not address 2 or validate the utility of any approach against 3.

In the UK, an assessment of the principal UK water sector MST approach using species-specific markers with *bacteriodales* (a common gut bacteria) was managed by UKWIR with inputs and laboratory testing by the UK regulators. The work was formally published as a journal paper (Stapleton *et al*., 2009) and as an UKWIR report (Davies *et al*., 2007). The approach, here, was to select a catchment and associated recreational water where the source apportionment was well understood, and overlay MST sampling of multiple inputs and at marine regulatory bathing water compliance sites. Intensive hourly sampling at both inputs and receptor sites provided data on the underlying patterns of FIOs and MST markers. This work demonstrated the utility of the MST markers in giving 'qualitative' estimates of the relative human and animal (principally ruminant) contributions to FIO loadings. However, two observation are worthy of note in the consideration of MST as an operational tool in this area. The first is that the MST marker is not attenuated through UV disinfection of treated sewage effluents. Figure A7-1 illustrates this observation. The operational implication of this observation is that the application of the MST approach will over-predict the human component at sites where the human sewage is disinfected, as is the case at most UK sites where a treated sewage is discharged in the vicinity of a bathing or shellfish water. The second observation of concern was very wide swings in the contributions of human and ruminant markers in sea water which were sampled at regular hourly intervals, i.e. >90%:10% to 10%:>90% in adjacent samples. Intuitively this seems improbable in a large volume receiving water (the marine environment) and, given the lack of analytical quality data (criteria 1 above) for the qPCR analyses, then the precision of the numerical values reported for % human and ruminant contributions is certain to be questioned by the operational community. The overall conclusion of this UK work was that quantitative estimates of FIOs derived from MST marker s should be treated with great caution and whist they may be useful it would be unwise to base expenditure decision on this evidence base in the absence of other corroboration.

Most recently, Rusinol *et al*. (2014) have employed species-specific viral pathogens in a novel MST system. These seem to provide credible quantitative assessment of species contribution, but this evidence base is a single paper derived from and EU FP7 research project and further validation and assessment of this approach is needed before its operational deployment could be recommended.

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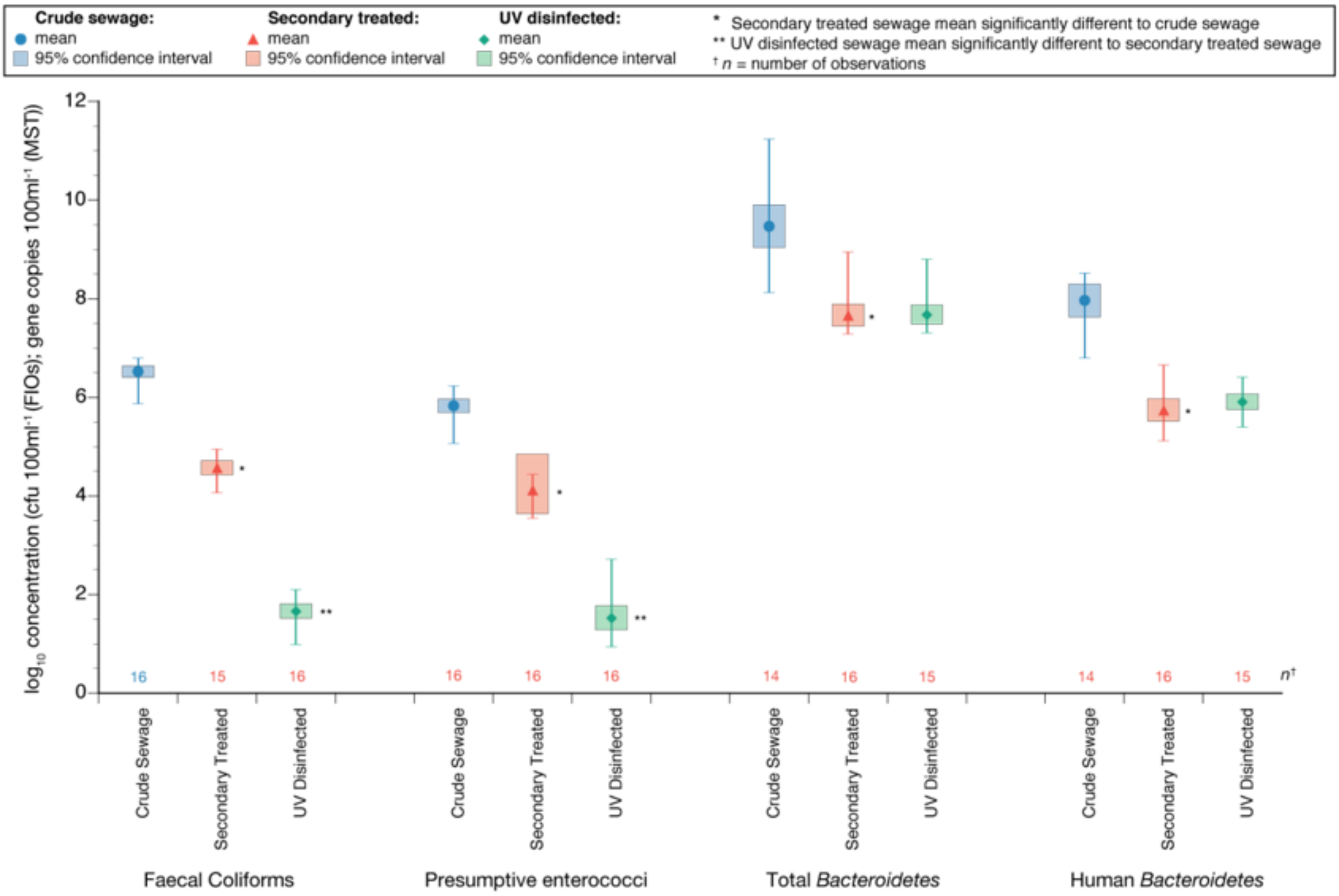

Figure A7-1 Mean, range and 95% confidence intervals of the mean for $\log_{10}$ transformed faecal indicator organism (FIO) concentrations (cfu 100 ml^{-1}) and *Bacteroidales* marker concentrations (gene copies 100 ml^{-1}) in sewage effluent samples (10/3/08–12/3/08) (source: Stapleton *et al*. 2009: Fig. 4).

Appendix 8: Near-shore coastal dynamic modelling

Compared with the typically diffuse and unregulated/In the case of near-shore coastal/estuarine waters, including designated bathing and shellfish waters, the actual FIO concentrations present at any particular point is clearly dependent upon the:

a. magnitude of input loadings – from river catchments, coastal land areas that drain directly to the coast, and direct inputs to the sea from birds, marine mammals, etc.;

b. rates of die-off within the estuarine/coastal waters – which will be affected by factors such as time of day, weather conditions and depth and turbidity of water; and

c. degree of dilution within the waterbody as a result of mixing with 'relatively unpolluted' waters from further offshore.

Location-specific, coastal dynamic models are needed in order to gain insight into the movement and mixing of waters in the near-shore zone. According to Ted Schlicke (SEPA, pers. comm.), all of Scotland's bathing waters have been subject to hydrodynamic/water quality modelling (undertaken by Scottish Water's consultants, primarily Intertek and Atkins) to assess compliance against the rBWD and inform infrastructure improvements needed to ensure compliance. It has also been used to quantify the impact of point-source discharges relative to diffuse impacts. In addition to this, extensive modelling has been carried out in the Clyde Estuary, and at some other locations containing fish farms.

SEPA have recently acquired outputs and model files from the newly-completed Scottish Shelf model. This will need to be taken into account if further near-shore modelling is commissioned around Scotland's coast – e.g. for stretches of coast that include designated shellfish waters.

Appendix 9: Environment Agency internal document (December 2014) on FIO time of travel and decay estimates – as used in Fieldmouse model

FIO time of travel and decay estimates

December 2014

The impact of individual sources of faecal pollution is dependent on how likely live organisms are to reach a sensitive receptor. Here, we outline a method to aid the targeting of interventions in faecal pollution.

The Environment Agency is responsible for two protected areas under the Water Framework Directive that are sensitive to faecal pollution. Bathing waters are designated recreational waters and shellfish waters are designated to protect economically significant species.

- A Bathing Water is a specific lake or beach at the coast that has been designated by government as a bathing water under the EC Bathing Water Directive. These locations are selected because they are sites where bathing is traditionally practised by a large number of people.

- A 'Shellfish Water' is a specific area of coastal water or estuary that requires protection or improvement in order to support shellfish life and growth, therefore contributing to the high quality of shellfish products consumed by humans. Shellfish Waters are designated under the EC Shellfish Waters Directive.

Both designations are designed to protect against excess microbial pollution. Sewage treatment, septic tanks and urban and agricultural run-off are major sources of microbial loads to the river (Defra 2011). This work aims to highlight areas of the catchment where action against microbial load (and monitored proxies collectively known as Faecal Indicator Organism (FIOs)) might be the most valuable, and whether these areas change depending on the season and the climatic conditions, using a robust and data-driven approach.

This short summary provides a brief round of modelling work to estimate the areas of catchments most likely to contribute significant loads of FIOs to the receptor. The analysis is split into two main strands i) how many colony forming units (cfu) are exported from the land each year ii) how much of the exported load survive to the receptor (almost always the estuary or nearby coastal waters).

There are a number of examples of catchment scale microbial pollution modelling using time-series grid based models (Jamieson *et al*. 2004). This type of modelling tends to be complicated and time consuming to implement, making it difficult to adopt widely. The approach presented here uses readily available spatial datasets that allow analysis of large areas to be quickly set-up and run (set-up, run and calibration of the River Eden catchment in Cumbria (> 2500 km^2) was completed in < 2 days). Thus we can provide information to aid the targeting of faecal pollution for much of England.

Method

Annual loads of faecal coliforms and faecal streptococci per 1km grid square were estimated for England using the Catchment

Change Matrix (CCM) model (Burgess 2011). The CCM was developed for the Catchment Sensitive Farming (CSF) project to link agricultural measures to farm scale pollutant losses and evaluate measure effectiveness in reducing agricultural catchment losses. To assess FIOs, it combines farm holding level data with national figures on volumes of excreta produce by livestock, farm practices and physical characteristics of the farmed land to generate a set of FIO export baselines (Lyons 2010). The export baselines indicate which farms produce the greatest FIOs losses, but also what practices (for example grazing sheep or applied cattle slurry) are contributing the greatest losses at the farm and catchment scale. The CCM estimates summer and annual faecal coliforms and faecal streptococci losses, which we assume represents *E-Coli* and intestinal enterococci respectively.

These losses are mapped to the Rural Payment Agency's Customer and Land Database (CLAD) and distributed evenly throughout the land parcels for each farm, meaning that the inputs to the next stage of the assessment represent our best estimate of seasonal and annual FIO losses based on national data.

The exported load from the CCM is transported to the river, accumulated and decayed within the Fieldmouse framework (Hankin & Douglass 2012). Exported loads are converted to a 10m grid and then accumulated per Detailed River Network (DRN) segment catchment; an exponential decay rate is applied to the load to estimate the load reaching the river network.

$$\mathrm{L = L_0\, e^{-\lambda x}}$$

Equation 1

Where L_0 is the load per cell, x is the distance to watercourse per cell and λ is the loss or gain rate used within Fieldmouse derived from runs of the SWAT model (Gasman et al. 2007).

Long term average mean subsurface and overland run off from the Continuous Estimation of River Flows (CERF) model is used to estimate flow accumulation through the catchment (Environment Agency 2008). This is a widely used 1km dataset. Use of the mean flow data may mean that the most frequent or most active (in terms of FIO export) flow conditions are not well represented (Kay *et al*. 2007). The representativeness of mean flow of the entire flow hydrograph will be considered per model implementation.

The empirical Guymer solute transport velocity model is used to derive the time of travel to the receptor. (Guymer 2004).

$$\mathrm{v = \; aQ^b}$$

Equation 2

Where a is fucntion based on the slope (shown in equation 3), which is extracted from a LIDAR derived digital terrain model resampled to 10m resolution. Q is the accumulated flow at the end point of each reach and b is an empirically derived constant set to 0.466. The solute transport velocity per reach is converted to a time of travel in days. This is then accumulated downstream for each reach to give a time of travel in days to the receptor (either an estuary or coastal water).

$$\mathrm{a = 86.4 \times 0.671 \times (s^{0.266})}$$

Equation 3

The constants 0.671 and 0.266 are empirically derived and *s* is slope grade (Guymer 2004). The 86.4 multiplier is used to convert the outputs of equation 2 to kmd^{-1} from ms^{-1}. Slope grades of less than 0.05% are reset to 0.05% and slopes greater than 2.5% are reset to 2.5%.

The within river decay is calculated using a FIO decay model developed by the Centre for Research into Environment and Health (CREH) (CREH 2014). Two models are used, one for *E. coli* and a second for intestinal enterococci.

Equations 4 to 6 describe the decay to *E. coli* due to natural die off and UV-B exposure. Equations 7 to 9 describe intestinal enterococci decay due to natural die off and UV-B exposure.

$$\mathrm{EC\ die\ off\ (log_{10}\ cfu\ hr^{-1}) = 0.0108 + \left(\frac{UVB}{EC\ d}\right)}$$

Equation 4

$$\mathrm{EC\ loss = 10^{0.601\, +\, 0.270\, \times\, (log_{10}\, t\, +\, 1)}}$$

Equation 5

$$\mathrm{EC\ d = \left(\frac{EC\ loss}{(1 - EC\ loss)/_{92.56}}\right) \times 3.96}$$

Equation 6

All constants in equations 4 to 9 are empirically derived (CREH 2014). UVB is incoming UV-B irradiance (kJ m-2 h-1) and t is turbidity (NTU). Three states of UV-B irradiance have been used, clear skies, cloudy and night. The night period lasts for 12 hours and the remaining 12 hours are split between clear skies and cloudy based on LTA annual sunlight hours per catchment. For the night, clear sky and sunny periods UV-B irradiance values of 0, 4 and 0.25 have been used respectively (CREH 2014). Turbidity is LTA monitored turbidity across the catchment.

$$\mathrm{IE\ die\ off\ (log_{10}\ cfu\ hr^{-1}) = 0.0201 + \left(\frac{UVB}{IE\ d}\right)}$$

Equation 7

$$\mathrm{IE\ loss = 10^{0.839\, +\, 0.151\, \times\, (log_{10}\, t\, +\, 1)}}$$

Equation 8

$$\mathrm{IE\ d = \left(\frac{IE\ loss}{(1 - IE\ loss)/_{49.81}}\right) \times 3.96}$$

Equation 9

The CREH FIO decay models assume an angle of incidence of 90° and water temperature of 15°C. The angle of incidence assumption is likely to be violated; as such the decay rates may be over estimated. It is also assumed water has a depth of 20cm and is well-mixed. Again this may lead to an over estimation of in-river decay.

Limitations

This work represents the starting point for modelling FIOs in this way for the Environment Agency and is based on a set of nationally consistent parameters and input data. We see this as an iterative approach and will be making continuing, but not regular updates to the method informed by evaluation of the model implementations, local feedback and improved input data.

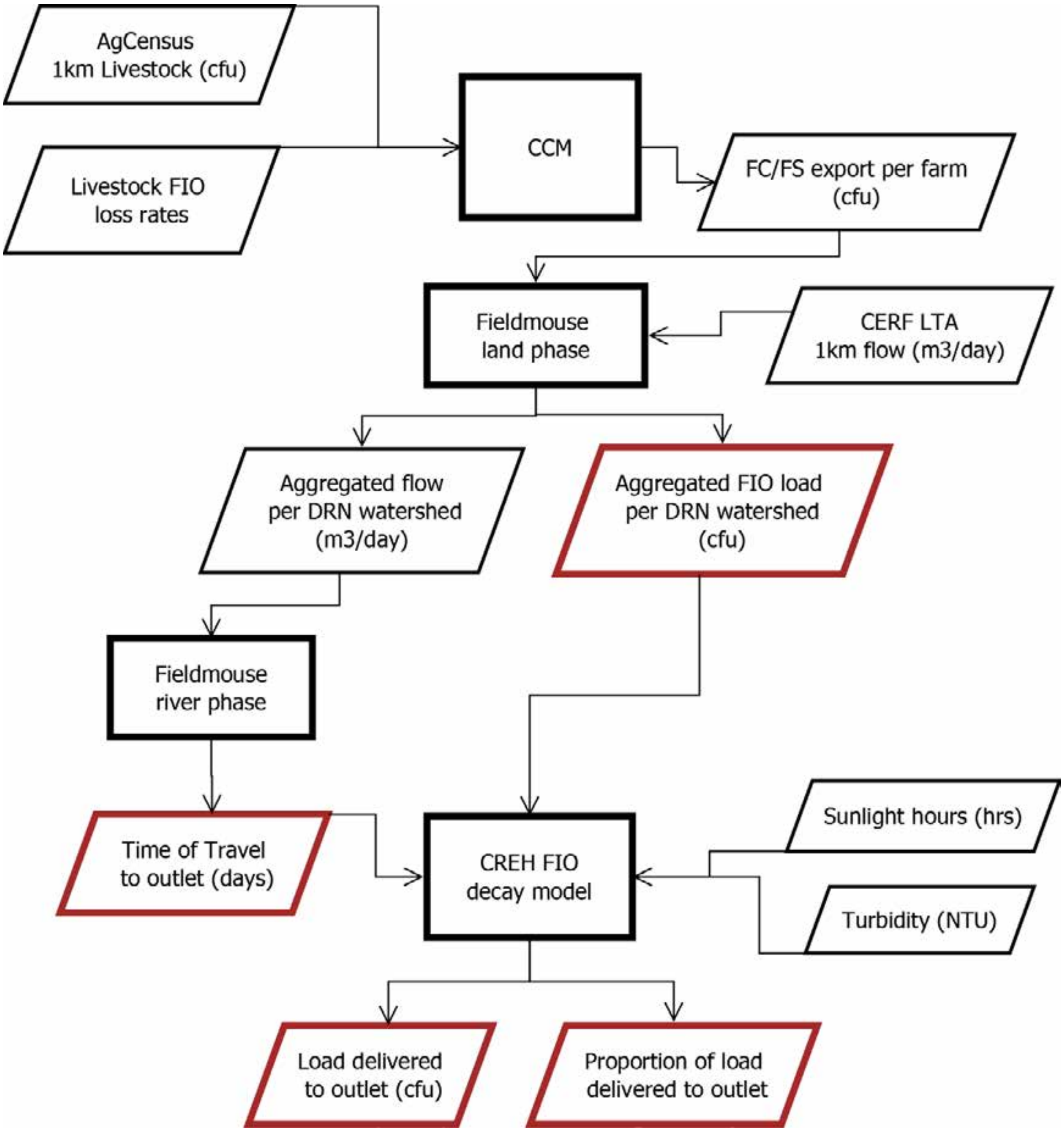

Figure 1 Process diagram for the FIO time of Travel analysis. Red outline indicates interim or final outputs presented here.

For the FIO export phase, run within the CCM, the choice of base bacteria loss rate per animal is critical. We are currently looking at UK alternatives to the current loss rates (largely derived from American studies) and assessing how much difference this would make to our model predictions. The loss rates we currently use estimate relatively low coliform losses per cow compared to sheep, making sheep the dominant catchment scale coliform source. Recent UK-based research (Defra 2011) indicates that E. Coli losses are more similar between the two animals. Should we use the newer loss rates cows would become the dominant catchment source of coliforms.

Model results presented here are based on the average annual flow/estimated summer high flow. Ideally we would have used an additional summer high-flow scenario, however due to data limitations an annual average is the only scenario we are confident using at present. Over time we will develop scenarios based on a range of flow conditions. Bathing waters in particular can fail during low flow conditions as well as high flow so it is important not to consider the maps presented initially as the entire picture.

Both the time of travel and FIO decay models are reductive, potentially important parameters such as water depth or man-made obstructions aren't included, that being said it is felt the below is still a valid attempt to address an important issue.

The Guymer solute time of travel model (equations 2 and 3) was empirically derived using dye-tracing across several UK rivers (Guymer 2004). Dye-tracing is used to represent the travel time of solutes, rather than direct flow velocity measurements. FIOs are conveyed in suspension, either free or bound to other suspended solids rather than in solution. As such the Guymer model is not directly applicable to FIOs, however it should be a good approximation, and probably more useful than using a model based on flow velocities.

Online lakes or other river features that slow flow are not accounted for. Where there are online lakes or multiple flow obstructions the time of travel and subsequently the FIO decay may be underestimated.

No allowances have been made for additional processes occurring below the tidal limit.

Review

What we want from you:

1. Consult with local hydrologists to confirm or challenge the time of travel under average conditions. If this is too slow in our model then headwaters may contribute more than we think
2. Identify any in-river obstacles that will cause the delay of solute travel. On-line lakes and reservoirs will delay the transport of bacteria to the coast and thus allow more die-off to continue. If this is happening a lot in your catchment then this is a critical piece of information that the model is not yet considering.
3. Identify any hotspots where known poor practice is occurring. We could potentially adjust the input losses to reflect this.
4. Where is it most useful for the model to terminate? The tidal limit, or at the estuary/coast as present?

Results

Below are example results from our initial modelling of the Esk Coast WFD management catchment in the North East. Please note that the choice of the Esk Coast catchment is for illustrative purposes here rather than practical use. Though there are multiple bathing waters in the catchment, only Staithes currently fails to achieve rBWD sufficient status. Figure 2 shows the flow duration curve for the flow gauge used to calibrate the model. The first map (figure 3) shows the basic study area, the river network used in the model and how the upstream land links to the downstream bathing waters. Subsequent maps (figure 4–7) shows the time of travel, estimated load input to the river and the load contributed to the catchment outlet. These are the core outputs, which part is most useful to you will depend on the questions you have to answer.

- Figure 2 allows you to place the modelled flow in context of all recorded flows at the calibration gauge. In the case of the Esk Coast model the mean flow is exceeded or equalled only 25% of the time, which is a relatively high flow scenario.
- The basic study area, the river network used in the model and how the upstream land links to the downstream bathing waters.
- The FIO time of travel from each DRN reach to the river outlet in days is shown in figure 4. In general reaches with a longer flow length to the outlet will have a higher time of travel. The time of travel is dependent on flow (equation 2); a higher flow scenario will mean shorter travel times.
- Figure 5 shows the FIO load delivered to DRN segments. This map shows the geographical pattern of FIO export, although it will also be partly affected by drainage patterns.
- The FIO load delivered to the catchment outlet is show in figure 6. This map indicates the DRN segments that deliver the most load to the river outlet.
- Figure 7 is the proportion of the load delivered to the catchment that reaches the catchment outlet. It can be thought of as an input independent version of figure 6. In that no matter how much load is exported from the CCM, the proportion that reaches the outlet will be the same for a given flow, turbidity and sunlight hours inputs.

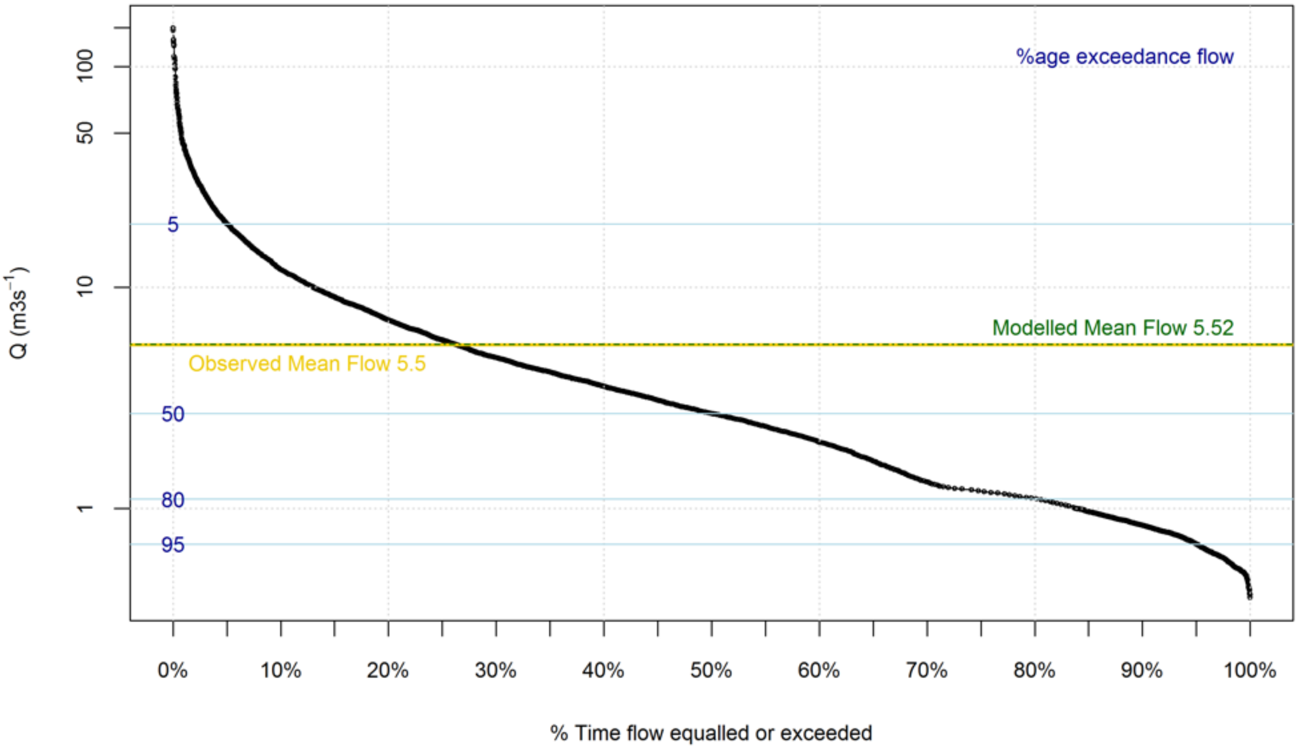

Figure 2 Flow duration curve @Briggswath 02/10/1992 to 25/11/2014.

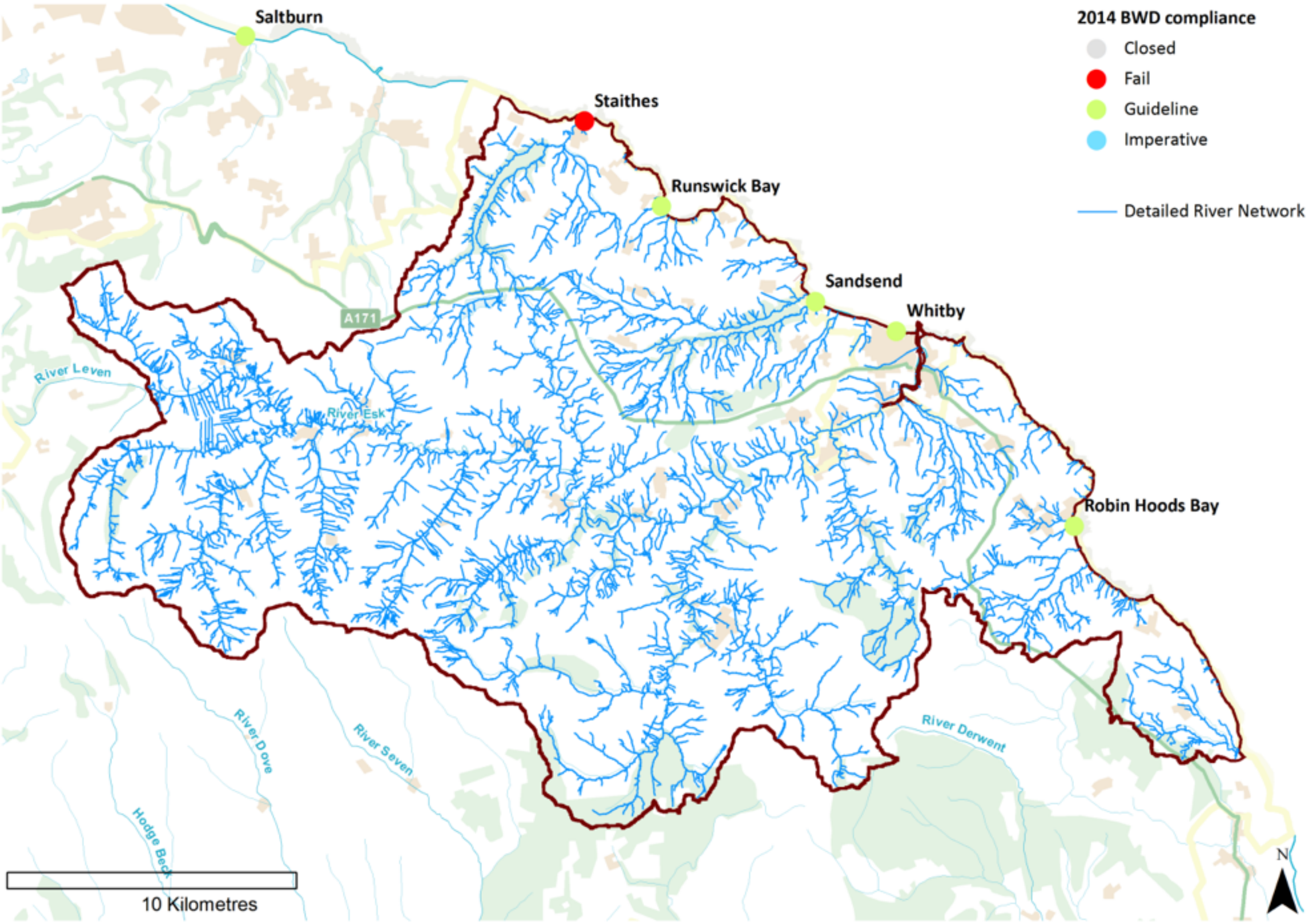

Figure 3 The Esk Coast WFD management catchment and bathing waters.

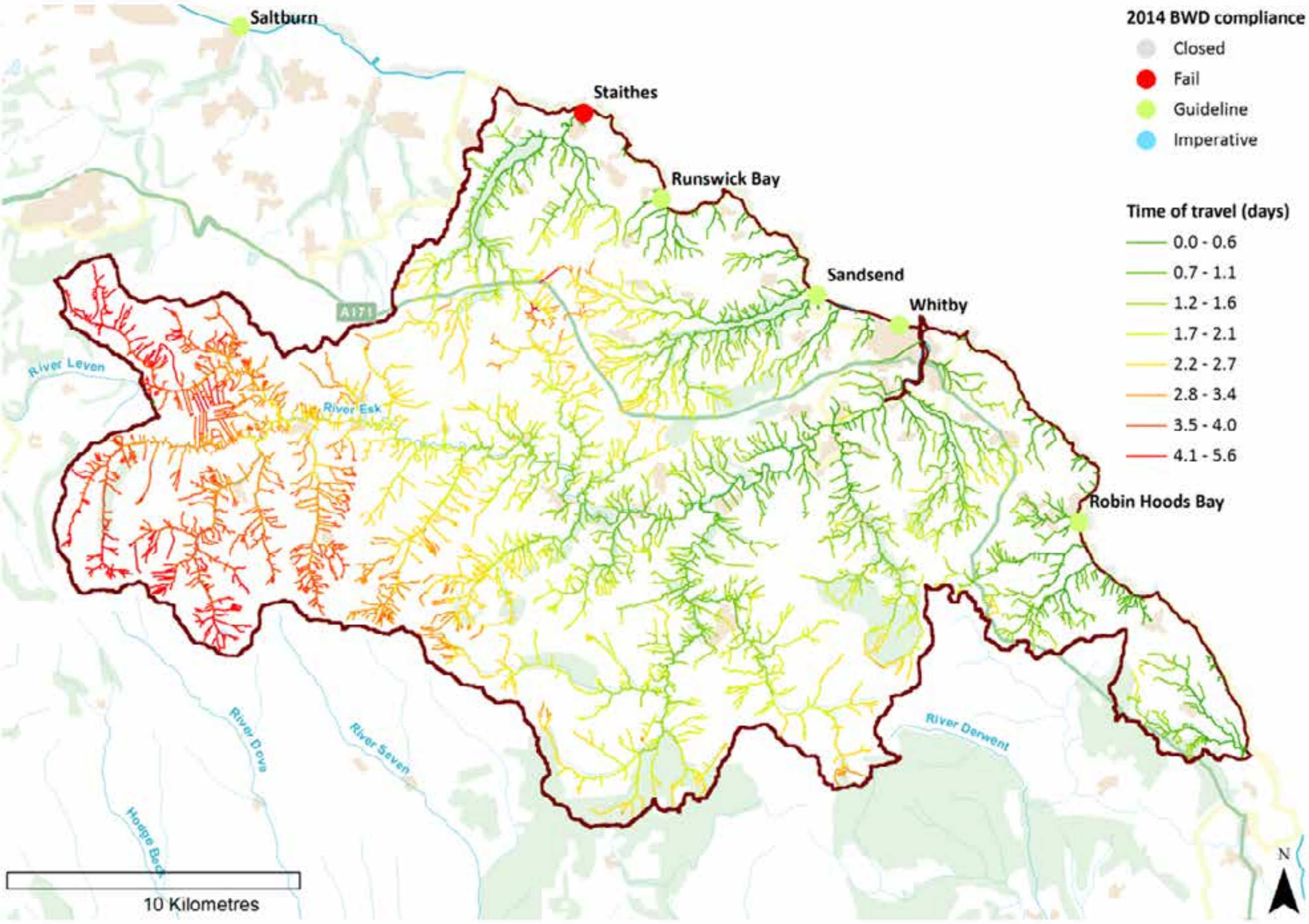

Figure 4 Estimated time of travel to river outlet (in most cases this will be the coast).

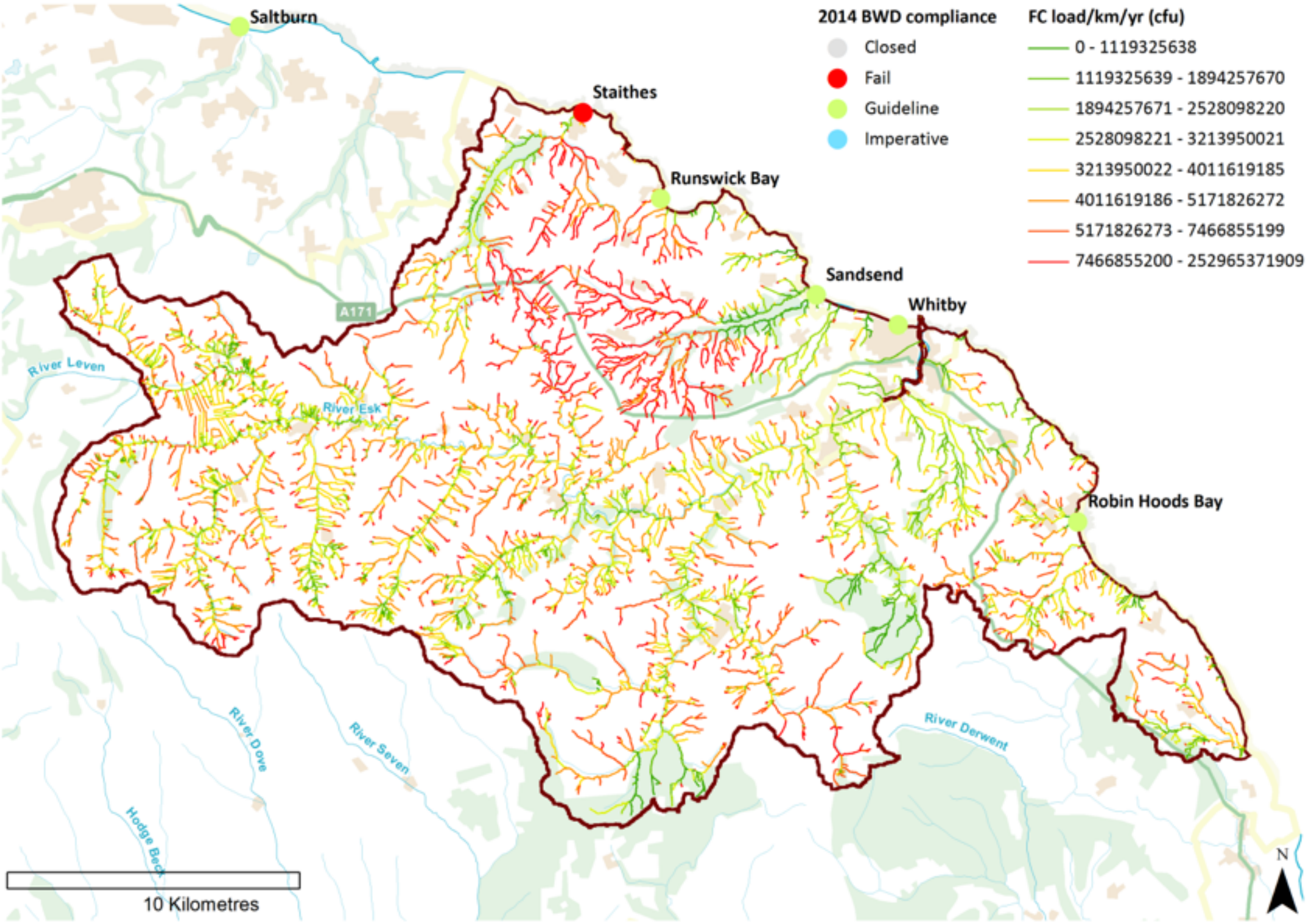

Figure 5 Estimated faecal coliform load (cfu) input to DRN segments per KM per year.

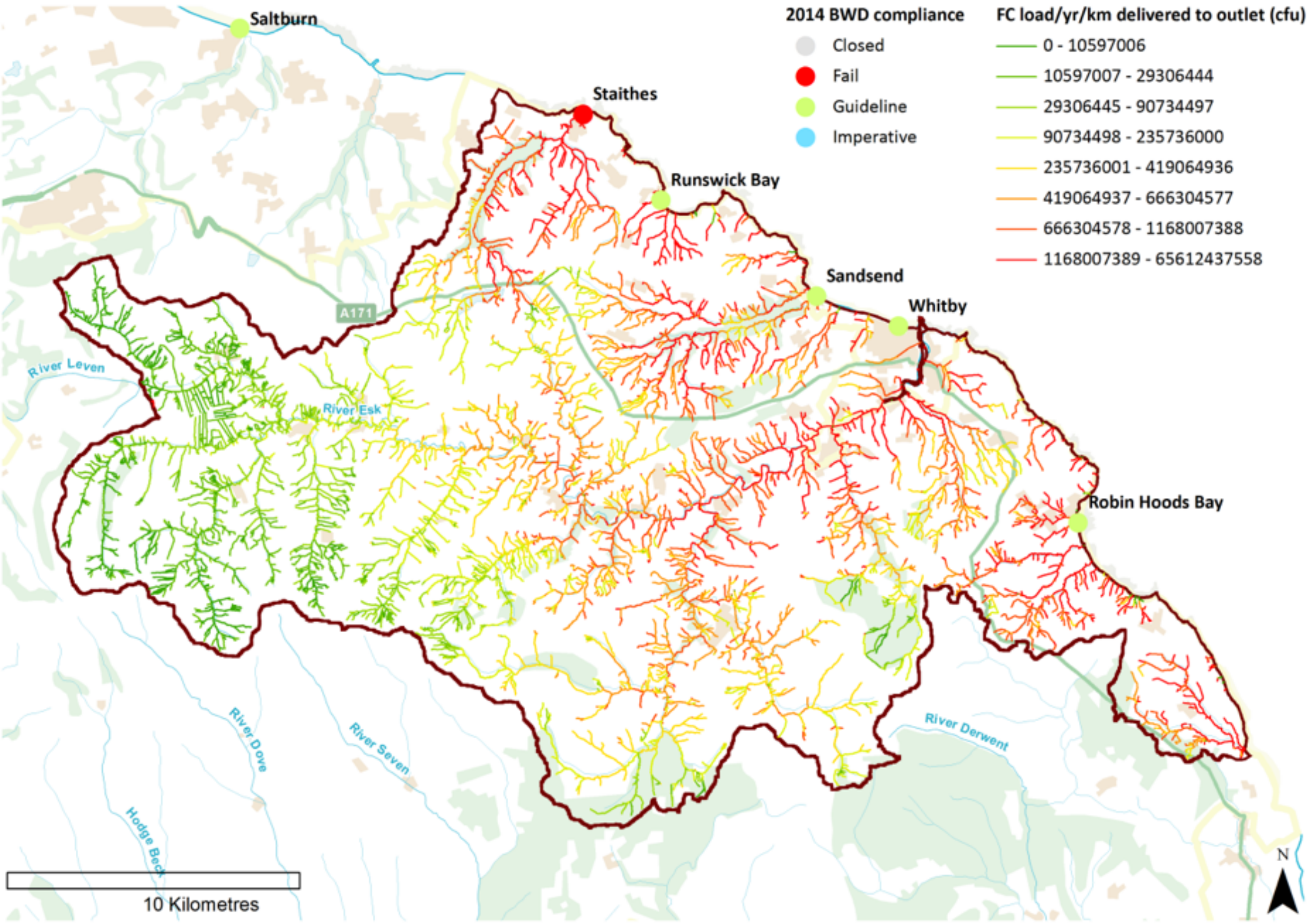

Figure 6 Estimated decayed faecal coliform load (cfu) delivered to the river outlet.

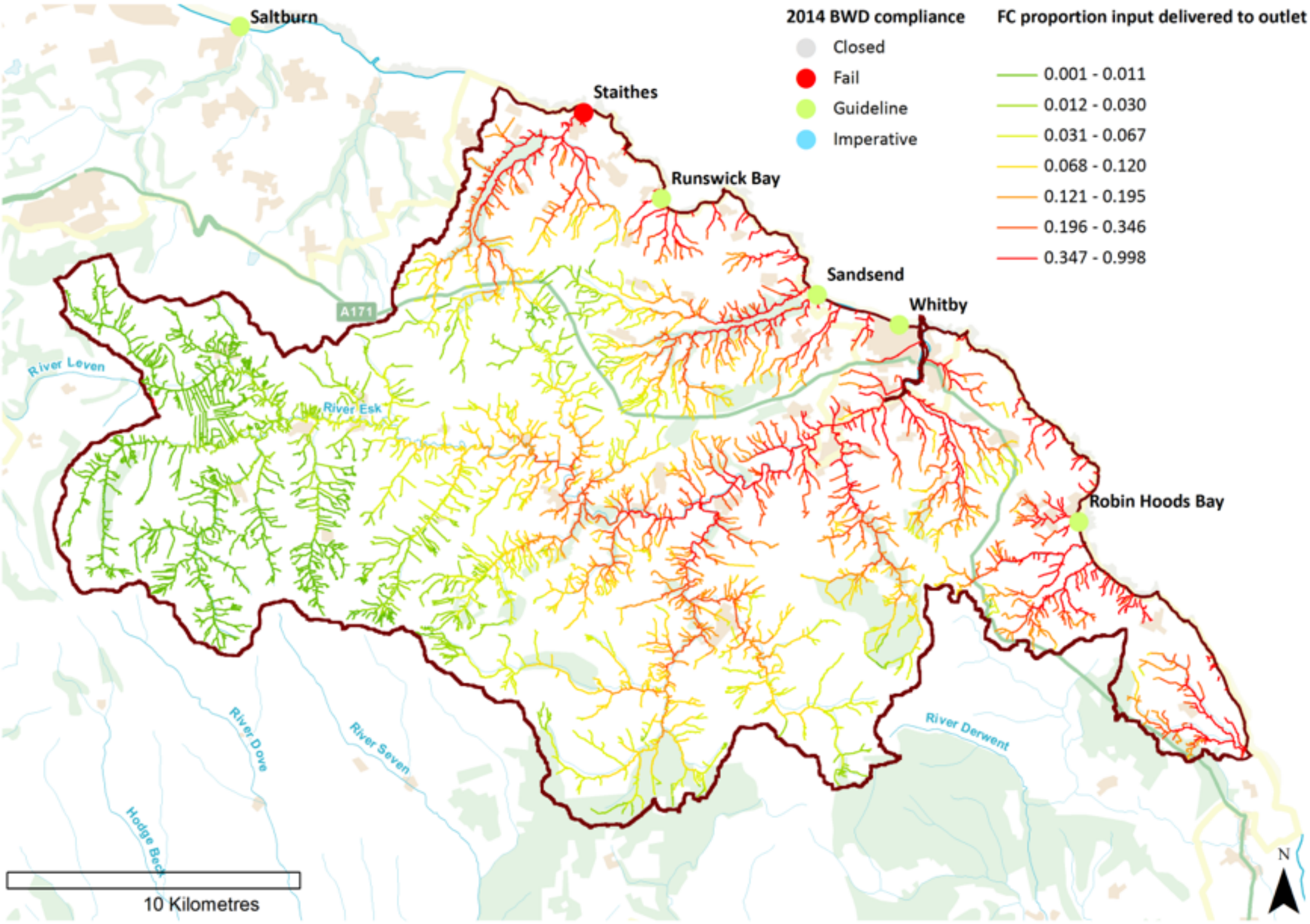

Figure 7 Estimated proportion of faecal coliform load input to DRN segments that is delivered to the catchment outlet.

Using the data

You may of course want to use the output data directly rather than rely on static maps and figures. In which case the table 1, below, provides information of the output data.

The output data would be supplied as a spatial dataset either in an ESRI file geodatabase or as a shapefile. In the case of the geodatabase it would probably contain the input data to run the analysis; the output file name will take the form of '*CATCHMENT_DET*_CERF*flow*_CAL_decay'. With the name of the catchment, the determinand and the flow conditions (most likely 'avg' for mean) replacing the text in italics.

Field name	English translation	Description
DRN_ID... to ... Shp_Lng	Standard DRN fields and Fieldmouse generated fields not needed by the user.	Standard DRN attributes, some of the fields such as those identifying up and down stream reaches are used by Fieldmouse. Some fields are generated by Fieldmouse but again aren't needed to interpret the FIO time of travel and decay analysis.
FIO_L_K	FIO load per day from CCM export estimates (cfu)	FIO load input into DRN reach from local catchment per day (cfu)
Flw_m3_	Flow per day (m^3)	Flow accumulated from local DRN segment catchment in m^3
TFlw_M_	Total accumulated flow (Mld^{-1})	Total flow accumulated from local catchment and upstream area Mld^{-1}
Vlcty_k	IGNORE	IGNORE
Vlcty_1	Velocity km per day - upstream flow	Velocity of FIO transport in km per day, based on local catchment flow and upstream accumulated flow
ToT_dys	Time of travel (days)	FIO time of travel through the DRN segment based on total accumulated upstream flow
accTT_d	Accumulated time of travel (days)	FIO time of travel through DRN segment and summed through all downstream reaches to the receptor. Based on total accumulated upstream flow.
accLng_	Total flow length (km)	Total length of the flow path to the receptor (km)
f_elevt	From node elevation (m above o.d.)	Elevation of the farthest upstream point of the DRN segment. Used to calculate the slope.
t_elevt	To node elevation (m above o.d.)	Elevation of the farthest downstream point of the DRN segment. Used to calculate the slope.
slope	DRN segment slope (degrees)	Slope of the DRN segment (degrees). Used to calculate the time of travel.
dFIO_TLd	Accumulated FIO load per day from diffuse sources (cfu)	FIO load from local catchment summed with load from upstream area from diffuse sources (cfu)
dFIO_TL_	Fieldmouse decayed accumulated FIO load per day from diffuse sources (cfu) - IGNORE	FIO load from local catchment summed with load from upstream area from diffuse sources (cfu). The CREH decay model is currently applied outside of Fieldmouse so this field is identical to dFIO_TLd
dFIO_C_	FIO concentration from diffuse sources (cfu per litre)	FIO load from local catchment summed with load from upstream area from diffuse sources (cfu per litre)
tFIO_TLd	Accumulated FIO load per day from all sources (cfu)	FIO load from local catchment summed with load from upstream area. From all sources. The analysis in currently run with point source inputs turned off so this is equal to the diffuse source field.
tFIO_TL_	Fieldmouse decayed accumulated FIO load per day from all sources (cfu) - IGNORE	FIO load from local catchment summed with load from upstream area. From all sources. The analysis in currently run with point source inputs turned off so this is equal to the diffuse source field. The CREH decay model is currently applied outside of Fieldmouse so this filed is identical to the non-decayed field.
tFIO_C_	FIO concentration from all sources (cfu per litre)	Non-decayed concentration of FIOs. From all sources, currently identical to (cfu per litre)
t_TLd_m	IGNORE.	IGNORE.
t_TLd_D	IGNORE.	IGNORE.
t_Cnc__	IGNORE.	IGNORE.
FIOload	FIO load per year from CCM export estimates (cfu)	FIO load per year input into DRN reach from local catchment per year (cfu)
FIOl_KM	FIO load per year from CCM per km export estimates (cfu)	FIO load per year input into DRN per km of DRN reach from local catchment per year (cfu)
dcFIOld	CREH model decayed FIO load per year from CCM export estimates (cfu)	CREH model decayed FIO load per year input into DRN reach from local catchment per year (cfu)
dFIO_KM	CREH model decayed FIO load per year from CCM per km export estimates (cfu)	CREH model decayed FIO load per year input into DRN per km of DRN reach from local catchment per year (cfu)
prpRmnn	Proportion of original load remaining after decay	dcFIOld / FIOload

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