CREW CENTRE OF EXPERTISE FOR WATERS

Developing a probabilistic risk model to estimate phosphorus, nitrogen and microbial pollution to water from septic tanks

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Full Report

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Hydro Nation International Centre

The James Hutton Institute

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Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes supported by MASTS. The Centre is funded by the Scottish Government.

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Please reference this report as follows: Glendell, M., Gagkas, Z., Richards, S., Halliday, S. (2021) Developing a probabilistic model to estimate phosphorus, nitrogen and microbial pollution to water from septic tanks. CRW2018_12. Scotland's Centre of Expertise for Waters (CREW). Available online at: crew.ac.uk/publications

ISBN Number: 978-0-902701-84-7

Dissemination status: Unrestricted

Acknowledgements: The authors would like to thank the project steering group: Graeme Cameron (SEPA), Brian McCreadie (SEPA), Fiona Napier (SEPA) and Ewan Lawrie (SNH) for valuable advice, guidance and data. Prof Marc Stutter from the James Hutton Institute who contributed thoughts to model construction and paramterisation.

Cover photographs courtesy of: Samia Richards (JHI).

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Executive Summary

Research questions

1. What factors contribute to the risk of phosphorus (P) pollution from septic tank systems (STS)?
2. Can a probabilistic risk model informed by expert knowledge be applied on a national scale, given available data?
3. What factors would need to be considered to apply the model to nitrogen (N) and microbial (FIOs) pollution risk?

Background

Septic tanks are private sewage treatment facilities which typically serve the population not connected to main sewer networks. There is substantial uncertainty about the impact of septic tanks on water quality, primarily because of a lack of information about the location, number, condition, specific pollutant pathways, pollutant attenuation and inadequate monitoring of the effects of septic tank discharges to surface water and groundwater.

Under the requirements of the Water Framework Directive, there is a need for SEPA to identify pressures contributing to water quality downgrades and to put in place appropriate and feasible measures to return waters to good status. SEPA currently use the SAGIS model to identify major pollutants including phosphorus (P) loads and concentrations at the waterbody scale.

A number of assumptions are currently made regarding the parameterisation of the SAGIS model including input loads, on-site pollutant removal efficiency and connectivity to surface water to generate export loads from septic tanks. At the waterbody scale it is not uncommon for SAGIS to simulate a septic tank P contribution of 20 - 30% of the total load, this figure is greater (up to 65%) in rural catchments. However, it is also known that in these areas, model outputs are uncertain, making it difficult to quantify the sources of phosphorus from septic tanks. A new approach to modelling the contribution of P is therefore required to inform the development of specific strategies or implementation of measures for mitigative purposes.

This project provides evidence to inform policy makers on options to address pollution from septic tanks. Results feed directly into the EU WFD, Bathing Water and Shellfish Directives. More specifically new information generated from the project will provide evidence on the location and type of watercourses most likely to be impacted by P export from septic tanks so SEPA (and potentially Scottish Water) can target measures to improve the water quality to good status.

Research undertaken

This study identified a method and data requirements for a model to estimate soluble reactive phosphorus (SRP) losses to water from STS, initially for seven pilot catchments and then at a national scale. The new methodology includes a representation of processes responsible for SRP leaching from STS. Model assumptions are transparent and based on literature, data and expert opinion.

Key findings

- The literature review indicated that the risks of phosphorus pollution to watercourses from STS are associated with STS density, location and proximity to watercourses. Poor performance of a large proportion of septic tanks and hence the risk of phosphorus leaching to water bodies are related to the lack of proper soakaway system, poor soil quality, undersized STS and lack of maintenance.
- Using the risk criteria identified in section 3.1 and spatial data described in section 3.2.2, a risk model of soluble reactive P (SRP) pollution from STS based on BBNs was successfully constructed and parameterised at a Scotland-wide scale.
- Sensitivity analysis has shown that STS effluent concentration (linked to STS treatment type and condition), STS density and STS connectedness (linked to STS distance and the presence/absence of direct discharge to watercourse) were the most important risk factors related to SRP pollution losses.
- Overall, simulated SRP losses at both catchment and national scale were comparable with previous estimates, indicating that the model simulates plausible losses within the right order of magnitude.
- Six modelled scenarios demonstrated that upgrading STS treatment to secondary or tertiary level, improving STS maintenance status and/or disconnecting STS direct discharges to watercourses would all result in reduced SRP losses. Tertiary treatment and absence of direct

discharge resulted in greatest reductions of SRP emissions at catchment and national scales. Further evaluation and selection of these potential mitigation measures could be informed by cost benefit analysis.

- Literature review suggested that incorporating FIO's and N within the STS risk modelling framework developed for phosphorus would be achievable, as the risk factors for different pollutants are comparable. Although in this project, the FIO model was not implemented and FIO loadings were not calculated, this would be feasible in a follow-up project.
- This would represent an advancement on the currently adopted modelling approaches as it would include a probabilistic dimension, which would address some of the uncertainties around STS use, condition and maintenance (Bergion et al., 2017).
- Probabilities in Gill and Mockler (2016) could inform BBN model paramterisation for N.

Recommendations

1. To improve the estimation of STS P contribution in water quality models, multiple risk factors contributing to STS pollution risk need to be considered.
2. A detailed catchment-based survey of STS condition would be beneficial to test model parameterisation. This could include a survey of STS age and maintenance, coupled with targeted effluent and water quality monitoring to get as good an understanding as possible of ST loads in a small catchment with limited other P inputs.
3. Simulations indicate that several mitigation strategies could reduce SRP losses from STS at both catchment and national scales. Fitting all STS with tertiary treatment or disconnecting STS from direct discharges to watercourses could reduce SRP emissions from STS in Scotland by cca. one half. Fitting all STS with secondary treatment may reduce SRP losses in Scotland by cca. one third.

4. Extending the BBN risk model for SRP losses from STS to FIOs and nitrogen pollutant losses would be achievable and relatively straightforward.

1. Introduction

1.1 Background and scope

Septic tank systems (STS) are private sewage treatment facilities which typically serve the population not connected to main sewer networks. There is substantial uncertainty about the impact of STS on water quality, primarily because of a lack of information about the location, number and condition and inadequate monitoring of the effects of septic tank discharges to surface water and groundwater.

Under the requirements of the Water Framework Directive, there is a need for SEPA to identify pressures contributing to water quality downgrades and to put in place appropriate and feasible measures to return waters to good status. SEPA currently use the SAGIS model to identify major pollutants including phosphorus (P) loads and concentrations at the waterbody scale.

A number of assumptions are currently made regarding the parameterisation of the SAGIS model including input loads, on-site pollutant removal efficiency and connectivity to surface water to generate export loads from septic tanks. At the waterbody scale it is not uncommon for SAGIS to simulate a septic tank P contribution of 20 – 30% of the total load, this figure is greater (65%) in rural catchments. However, it is also known that in these areas, model outputs are uncertain, making it difficult to quantify the sources of phosphorous from septic tanks. A new approach to modelling the contribution of P is therefore required to inform the development of specific strategies or implementation of measures for mitigative purposes.

Previous related work

The James Hutton Institute and UK Centre for Ecology and Hydrology have considerable research experience in understanding the sources, controls, and pathways of P, Nitrogen (N) and Faecal Indicator Organisms (FIO) from septic tanks. Examples include 'Factoring Ecological Significance of Sources into Phosphorus Source Apportionment' (Stutter et al., 2014), 'Assessing the potential risks to water quality from phosphate leaching' (Sinclair et al., 2012), 'Simple indicators to assess the role of soils in determining risks to water quality CREW report' (Lilly and Baggaley, 2014), 'Septic tank discharges as multi-pollutant hotspots in catchments' (Richards et al., 2016), 'Modelling of phosphorus pollution risk to watercourses in Scotland using Bayesian Belief Networks' (Glendell et al., 2018) and 'The impact of phosphorus inputs from small discharges on designated freshwater sites' (May et al., 2015), 'Development of framework for a Red-Amber-Green assessment on phosphorus application to land' (Gagkas et al., 2019).

This project provided evidence to inform policy makers on options to address pollution from septic tanks. Results feed directly into the EU WFD, Bathing Water and Shellfish Directives. More specifically new information generated from the project will provide vital evidence on the location and type of watercourse most likely to be impacted by P export from septic tanks so SEPA (and potentially Scottish Water) can target measures to improve the water quality to good status.

1.2 Project objectives

The key aims of this project were to:

1. Review factors that contribute to the risk of P pollution from STS.
2. Develop a method and identify data requirements for a probabilistic risk model to estimate pollutant loads to water from septic tanks at a national scale.
3. Develop a simple rule base for the export of N and FIOs from septic tanks to watercourses to inform future model development.

1.3 Outline of the report

This report is structured in three parts. Firstly, in section 3.1 we present an overview of risk factors related to P losses from STS. These risk factors are then included in the probabilistic risk-based model of P pollution presented in section 3.2. Section 3.3 provides a review of risk factors related to N and FIO loss from STS to inform future model development for these pollutants.

2. Research undertaken

This study identified a method and data requirements for a model to estimate SRP losses to water from septic tanks, initially for 7 pilot catchments and then at a national scale. The new methodology includes a representation of processes responsible for SRP leaching from STS. Model assumptions are transparent and based on literature, data and expert opinion. The methodology included the following steps.

A. SEPA's methodology for modelling the location of septic tanks was reviewed.
B. Assumptions, parameterisation, and process representation of a Septic Tank P loading model were reviewed and implemented in a probabilistic model based on Bayesian Belief Networks (BBNs).

The model considered connectivity to watercourses, taking into account:

- Distance of septic tank to stream network
- Slope of septic tank
- Soil P sorption effect on leachfield
- Soil hydrological properties affecting likely P leaching from leachfield
- Presence/absence of direct STS discharge to watercourse
- Risk of P leaching to watercourse based on above connectivity criteria
- STS treatment type and condition/ maintenance were also included.

C. The new understanding (point B) was implemented in a risk-based model in 7 pilot river catchments at a 100m^2 scale and then aggregated on a national scale, using a 1km^2 grid provided by SEPA.

3. Findings

3.1 Factors contributing to risk of phosphorus pollution from Septic Tank Systems (STS) to waterbodies (Samia Richards)

Risk factors that contribute to STS impact were reviewed at catchment and site-specific level. The likelihood of STS to cause pollution depends on their density, location, condition and maintenance.

At a catchment level, risk factors include soil hydrological characteristics, topography, depth to water table, STS density, STS location, proximity to watercourses and the connectivity of effluent discharge (direct discharge to streams or discharge to soakaway). These factors provide an initial screening system to allow the identification of STS that are most likely to cause pollution due to their location.

At a site-specific level, the potential for an individual STS to cause water pollution is related to septic tank size, design, condition and age, the number of users, STS maintenance (e.g. frequency of desludging), effluent P concentration and whether the effluents are treated with tertiary treatment such as constructed wetland, aerobic treatment unit or sand filter system unit. However, this site-specific information is difficult to obtain and is not readily available, although it can be obtained through a questionnaire-based survey to determine local factors that affect P discharge and transport. Such survey-based approaches have been used successfully in some studies (Arnscheidt et al., 2007; EPA Ireland, 2003; Patrick, 1988; Selyf consultancy, 2002).

3.1.1 STS impact at catchment level

Soil hydrological characteristics

Soil hydrological characteristics are an important factor for STS effluent rate of infiltration (movement of effluent into the soil) and percolation (movement of effluent through the soil) and P removal before discharging to the environment. The more permeable the soil, the greater the seepage and therefore lower effluent/soil contact time, risking the untreated effluent reaching groundwater (Table 1). Thus, highly drained, coarse subsoils (coarse, medium and fine gravel) are very permeable and are deemed unsuitable for subsurface effluent disposal (Gill et al., 2004). Conversely, very fine-textured, poorly drained subsoils (fine silt and heavy clay) have low permeability, risking effluent pooling on the soil surface and therefore are unsuitable for subsurface effluent disposal. Discontinuities in the subsoil (fissures and cracks) also provide preferential flow pathways of the untreated effluent (Gill et al., 2005), increasing the risk of contamination. Thus, the leach field is required to have certain hydrological properties that are assessed during site soil percolation tests before system installation is approved (Building Regulation, 2000).

Even with suitably drained soils, the capacity of the soil to retain pollutants and sustain the treatment can diminish with time as identified by Dawes and Goonetilleke (2003). The authors reported significant changes in soil characteristics and the performance of subsurface effluent disposal areas due to effluent application which affected subsurface drainage characteristics. Beala et al. (2006) investigated the long-term acceptance rate of the effluent treatment area from prolonged application of STS effluent. The authors reported that soil absorption system can fail following long-term application of STS effluent as a low permeable biomat zone can develop and reduce the hydraulic conductivity of the soakaway.

Table 1. Soil permeability rates, hydraulic conductivity and the anticipated risk factor ratings for STE movement without sufficient treatment (British Geological Survey, 2006; Shwetha and Varija, 2015; Tarboton, 2003).

Soil texture type	Hydraulic conductivity (cm/h)	Permeability rate cm/hour	Permeability class	Risk factor	Risk rating
Gravel	>100	>5	Very rapid	Very high	5
Sand	63.36	5	Rapid	High	4
Sandy loam	12.49	2.5	Moderately rapid	Moderate	2
Loam	2.50	1.3	Moderate	Low	1
Clay loam	0.882	0.8	Moderate	Low	1
Silty clay	0.371	0.25	Slow	Moderate	4
Heavy clay, clay	<0.3	0.05	Very slow	Very high	5

Soil phosphorus sorption potential

Soil ability to remove P from ST effluent and to lock it within the soil system varies according to its P adsorption capacity, which depends on iron (Fe) and aluminium (Al) concentrations in the soil and is calculated from oxalate extractable Fe and Al. Table 2 illustrates the risk factors associated with soakaway soil P sorption capacity, evaluated from Stutter et al. (2014).

Table 2. The risk factors associated with soil P sorption capacity (Stutter et al., 2014).

Soil sorption potential (mg P/kg soil)	Risk Factor	Risk rating
>6000	Very Low	1
3400-6000	Low	2
1800-3400	Moderate	3
900-1800	Moderately High	4
<900	High	5

Topography

Topography is a key factor in determining whether a site is suitable for implementing STS effluent drainage system. The slope of STS site influences the success of STS operation and affects the drainage field function as it is difficult to ensure that wastewater stays in the soil that has an extreme slope (EPA Ireland, 2000). The ideal scenario of STS site is on a level surface or on land with a gradient of <5% (Canter and Knox,1985). As the gradient increases, larger plot area is required to contain the effluent and STS on steeper slopes are more likely to produce contaminated runoff (May et al., 2015). Table 3 present risk factors associated with the topography of STS sites.

Table 3. STS sites topography and associated risk factor ratings (May et al., 2015; May et al., 2016; Stutter et al., 2014) .

Slope	Risk Factor	Risk rating
0-<5%	Very Low	0
5-<15%	Low	1
15-20%	Moderate	3
20-25%	Moderately High	4
>25%	High	5

Water Table

For STS to function successfully, it is necessary to provide a sufficient surface area and underground vertical depth for the reduction of pollutants in the soil system. High water table can hinder the drainage fields' ability to treat sewage effluent as the drainage field becomes saturated, waterlogged or flooded, reducing its ability to adsorb contaminants from the effluent (Canter and Knox, 1985; May et al., 2016; May et al., 2015). The risk of water contamination when installing STS on a site with shallow water table is very high (Table 4).

Table 4. Risk factor of STS to contaminate water associated with water table depth from the base of effluent treatment surface evaluated from May et al. (2016) and Stutter et al. (2014).

Water table depth	Risk Factor	Risk rating
>2.5 m	Very Low	0
2.0-<2.5 m	Low	1
1.5-<2.0 m	Moderate	2
1.0-<1.5 m	Moderately High	3
0-<0.5 m	High	5

Septic Tank Density

Increased number of STS have an adverse and cumulative effect on water quality within a catchment, posing pollution risks to local watercourses (May et al., 2015). Areas with high STS density are more prone to bacterial groundwater contamination (Meeroff et al., 2008). In addition, a positive relationship between median TP concentration in streams and the number of STS within catchments (r = 0.59) was reported in northern Ireland (Arnscheidt et al., 2007). Table 5 contains the suggested risk rating for different STS densities in rural areas (May et al., 2015).

Table 5. Risk rating for STS density in one hectare, evaluated from May et al. (2015) and (2016).

Density of ST (hectare)	Risk Factor	Risk rating
<2	Very Low	1
2-3	Low	2
4-7	Moderate	3
8-15	High	4
>25	Very High	5

Septic tank location and the nature of discharge

The most important criterion for preventing the contamination of water resources due to sewage effluent disposal is to ensure the appropriate setback distances from watercourses are observed. By observing the setback distance required between STS and surface and ground waters, the risk of contamination is greatly reduced. In many countries including the UK, planning regulations require a minimum vertical setback distance of 1.2 m of undisturbed soil between the base of the soakaway or trench system and the bedrock/or the highest water table level (Environment Agency, 2008; EPA Ireland, 2000). As for horizontal setback distance, the UK regulations require a minimum of 10 m from the STS and watercourses, 50 m from water abstraction points and lakes and 15 m from buildings (Building Regulation, 2000 and 2010). However, many older septic systems do not comply with these regulations and many systems were designed to discharge their effluent directly to watercourses. In Scotland, 21% of STS discharge their effluent directly to water bodies (O'Keeffe et al., 2015). Table 6 illustrates the STS risk factors associated with setback distance from watercourses.

Table 6. Risk factors associated with various horizontal setback distances of STS to water courses.

Distance from water body	Risk Factor	Risk rating
>500 m	Very Low	1
100-500 m	Low	2
25-100 m	Moderate	3
<25 m	High	4
0 m	Very High	5

Septic tank failure

STS continue to have a mixed reputation for 'unpredictable' variable treatment efficiency and failure rates (Beal et al., 2005). Some STS operate successfully for many years while others fail within months of installation. At a catchment scale, the percentage of septic tanks operating below designed performance specifications and continuing to deteriorate in efficiency is estimated at 50% (May et al., 2015) and >80% in some catchments in Ireland (Gill et al., 2007). Therefore, when considering STS impact on a catchment, STS failure rate should be considered. Table 7 illustrate the risk factors associated with failing tanks within a catchment the risk rating is based on the expert's opinion.

Table 7. Risk factors associated with STS failure within a catchment.

Failing ST (%)	Risk Factor	Risk rating
0%	Very Low	0
5%	Low	1
10%-20%	Moderate	2
30-40%	High	4
>40	Very High	5

3.1.2 STS impact at site specific level

More detailed information on STS impact on water quality is in most cases not available and can only be obtained through site-specific investigations. Detailed site-specific information such as tank size, age, condition, management and number of users may exert a more localized impact on adjacent water bodies.

Tank size and number of tank users

STS size is crucial to the success of effluent primary treatment and the overall tank performance. Tank size should be proportional to the number of users and provide sufficient storage capacity to meet the users' water demand. Thus, the rate of sludge accumulation and effluent quality are directly related to the number of occupants and the number of bedrooms in the household. An undersized STS fills up rapidly, resulting in reduced effluent residence time and discharging insufficiently treated effluent to the soakaway system (Seabloom et al., 2005). A study by Richards et al. (2016) suggested a correlation between microbial population, P and N concentration in the effluent and the number of STS users. Table 8 illustrates the risk factors related to undersized STS.

Table 8. The risk factors associated with STS size in relation to effluent retention time (after May et al., 2015; Stutter et al., 2014).

Tank size	Risk Factor	Risk rating
Large	Low	1
Medium	Moderate	3
Small	High	5

Septic tank age and condition

Older STS are more susceptible to failure as they were not designed to meet current levels of water use, including frequent bathing, power showers, washing machines and dishwashers (May et al., 2015). It is understood that the current amount of daily water of approximately 150-180 L/ person/day far exceeds the estimated water use 25 years ago, with the average family using 500 L/day (Environment Agency, 2012). May et al. (2015) suggested that over 80% of STS in the UK are probably working inefficiently, and their significant impact as a source of phosphorus to nearby waters is underestimated. In addition, aging STS affects the ability of the drainage field to remove P from the effluent as the soil becomes saturated with P over time, risking P leaching to ground and surface waters. Older STS (over 30 years old) are more likely to cause water pollution issues than those under 10 years old (CMHC, 2006). Table 9 illustrates the risk factors associated with tank age.

Table 9. The risk factors associated with STS age evaluated from Stutter et al. (2014).

Tank age (years)	Risk Factor	Risk rating
1-10	Low	1
10-30	Moderate	2
30-40	High	4
>40	Very High	5

STS management and desludging

Management and regular emptying of domestic sewage sludge play an important role in maintaining STS performance. Infrequent emptying leads to sludge accumulation, reduction in the available tank volume leading to shorter effluent retention time. Withers et al. (2012) inspected 50 STS in a UK catchment and found that 70% of STS were not emptied in >5 years, while 40% of STS were located within 50 m of water bodies. In a Scottish catchment survey by Brownlie et al. (2015), it was revealed that 17% of respondents had never desludged their tanks. Table 10 illustrates the risk factors associated with infrequent desludging of the tank.

Table 10. The risk factors associated with tank desludging frequency evaluated from May et al. (2015).

Tank desludging frequency	Risk Factor	Risk rating
Yearly	Very Low	1
1-2 years	Low	2
2-5 years	Moderate	3
>5 years	High	5

Phosphorus concentration and additional treatment of STS effluent

Septic tank effluents contain variable levels of phosphorus, which depend on a number of factors including household habits, water use, number of STS users, presence of a soakaway soil treatment system and additional tertiary effluent treatment. Phosphorus concentration is reduced and effluent quality is improved when additional treatment is present (Brownlie et al., 2015; Gill et al., 2005) as phosphorus can be taken up by plants or assimilated by microorganisms or filtered out during different tertiary treatments. Table 11 illustrates the rating of risk factors associated with effluent treatment and P concentrations. The estimated effluent concentration of soluble reactive phosphorus (SRP) that is expected after the different effluent treatment is estimated as <10% in primary treatment, 20% in secondary treatment and >80% when tertiary treatment is applied to the effluent (Brownlie et al., 2015).

Table 11. The risk factors associated with effluent P concentration resulting from various effluent treatment.

Effluent treatment	P concentration (SRP mg/l)	Risk Factor	Risk rating
Primary, secondary and tertiary treatment	Very low (2.0)	Very Low	1
Primary and secondary treatment	Low (5.0)	Low	2
Only primary treatment	High (10.0)	High	3
Not sufficient primary treatment	Very High (>10.0)	Very High	5

Summary

This literature review indicates that the risks from STS contamination and the risks of effluent phosphorus transport to watercourses are associated with STS density, inadequate location and close proximity to watercourses.

Poor performance of a large proportion of septic tanks and hence the risk of phosphorus leaching to water bodies are related to the lack of proper soakaway system, poor soil quality, undersized STS and lack of maintenance.

To improve the estimation of STS P contribution, multiple factors contributing to STS pollution risk need to be considered. A detailed catchment-based survey of STS location, size, age, management and condition would be beneficial.

3.2 Probabilistic risk-based septic-tank phosphorus pollution model (Miriam Glendell and Zisis Gagkas)

Phosphorus (P) pollution risk factors relating to STS outlined in section 3.1 above were used to develop a conceptual risk model based on Bayesian Belief Networks (BBN) (Figure 1). BBNs are probabilistic graphical models that allow the integration of both quantitative and qualitative information, with a transparent representation of model uncertainty (Forio et al., 2015). BBNs allow system-level thinking, revealing possible causal relationships between controlling factors that may not be apparent otherwise and in situations where controlled experiments are not possible (Pearl and Mackenzie, 2018), such as complex river catchments. The intuitive graphical structure of BBNs allows the involvement of stakeholders in model development and helps to build credibility of model simulations. The model allows to integrate disparate data sources, including observational data (e.g. concentration of pollutants), GIS data, literature and expect opinion in a single framework, and is therefore well suited to situations where data is sparse or uncertainty is high.

Figure 1 illustrates the process of BBN model development. In this study, the model was parameterised (i.e. Conditional Probability Tables were populated) using a literature review (see section 3.1), GIS data (see section 3.2.2) and expert elicitation (see section 3.2.3). Model structure is shown in Figure 4 and detailed model description is presented in Appendix 1.

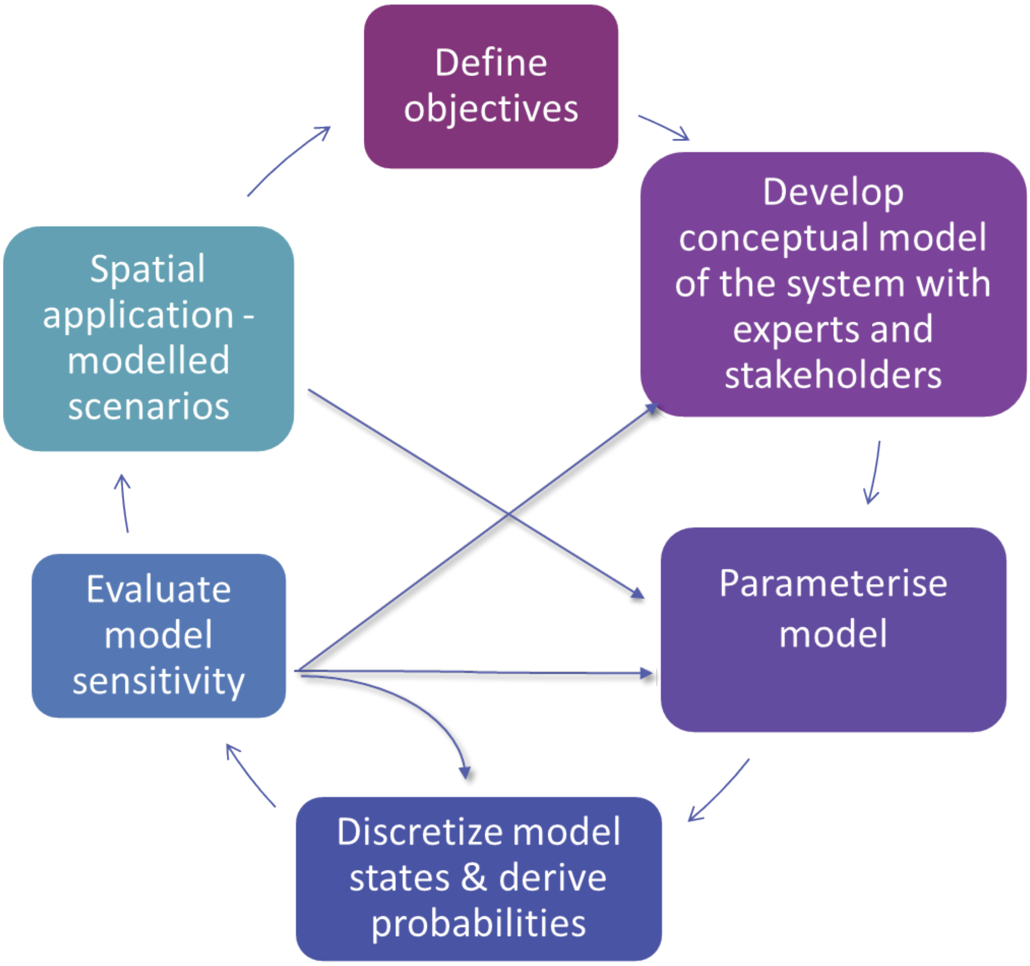

Figure 1. Steps in BBN model development. Adapted from Pollino and Henderson (2010).

The model was initially applied to seven pilot catchments, whereby the 'Catchment' variable was set as 'hard evidence' using spatial data. At the national scale, the same model parameterisation was used, except the 'Catchment' variable was not set as hard evidence, which means that conditional probabilities were 'marginalised' over the catchment variable (Fenton and Neil, 2013) for 'ST treatment' and 'Direct Discharge presence/absence' variables.

3.2.1 Selection of pilot study catchments

Figure 2. Selected study catchments for model development and testing.

Seven study catchments were chosen for model parametrisation and initial testing of model simulations (Table 12). Fernie Burn, Linkwood Burn and Rough Burn water bodies were selected because private sewage discharges have been previously identified by SEPA (based on SAGIS modelling) as a predominant pollution pressure (> 50% load) (McCreadie, 2019) and recent water quality data for these catchments was available. Lunan, Tarland, Cessnock and Mein catchments are part of ongoing research by the James Hutton Institute and thus water quality monitoring and other supporting data was available. The selected catchments were representative of Scottish land use and soils conditions and provided a good geographical coverage (Figure 2).

3.2.2 Spatial data used for model paramterisation

The open-source software QGIS 3.12 was used for import, analysis and visualisation of spatial datasets (i.e. septic tank locations, elevation and soils and land use layers) and R packages *raster* and *rgdal* were used for importing and processing rainfall grids. The following spatial data were used in model paramterisation:

Modelled STS locations

Modelled STS locations were provided by SEPA and were based on the 'postcode' method (May et al., 2015) for the identification of STS locations.

Elevation grid

The BBN model outputs were deployed spatially at a grid cell resolution of 100m that was based on the Ordnance Survey digital terrain model at 50m grid resolution (OSDTM50) and was generated by reclassifying OSDTM50 to 100m grid (Gagkas and Lilly, 2019). The 100m grid DTM was used to calculate slope (in percent) for the extent of Scotland.

Soil properties

Information on soils was derived from the Soil Map of Scotland (partial cover) Phase 6, which gives the distribution of Scottish soils at a 1:25,000 scale and covers cultivated land in Scotland. Information on soil type (Major Soil Subgroups/MSSG), the soil's natural drainage class and the associated Hydrology of Soil Types (HOST) class for each soil type was derived (Boorman et al., 1995). Dominant soil types (i.e. MSSG) within the study catchments were brown earths and humus-iron podzols apart from Cessnock where noncalcareous gleys covered most of the catchment's area (Table 12). Most soils in Cessnock, Linkwood Burn and Lunan catchments were (naturally) imperfectly or poorly drained, while freely or relatively freely drained soils covered most of the remaining catchment area.

Rainfall

HadUK (Hollis et al., 2019) gridded climate observations (monthly rainfall grids) at 1kmx1km grid resolution for the 1981-2010 period were used for calculating monthly and annual rainfall averages for the study catchments and for Scotland. Rainfall grids were downloaded from the Natural Environment Research Council's Data Repository for Atmospheric Science and Earth Observation (in NetCDF format) and contained monthly rainfall values (January to December) at the centroids of each 1kmx1km grid square.

Soil hydrological characteristics

For the purpose of this project, Hydrology of Soil Types (HOST) classes (Boorman et al., 1995) of individual soils were translated to risk factors of septic tank effluent movement given in Table 1 (Table 12). This was done by considering the HOST conceptual models of water movement (Figure 3) that provide an integrated assessment of soil texture and soil hydrological properties (soil infiltration and percolation) based on soil morphological characteristics (presence of a gleyed layer, a slowly permeable layer or peaty topsoil) and the presence of an aquifer or groundwater. Thus, this classification also provides a general assessment of water table contamination risk as in Table 4. Most HOST classes were assigned a high or very high risk factor due to high potential for surface runoff and/or low permeability, while HOST classes of low and moderate risk rating represented relatively free-draining soils with no presence of an aquifer or groundwater or with aquifers at depth greater than 2 metres (Tables 1 and 4). We extracted HOST class information at the location of each modelled septic tank from the Soil Map of Scotland (partial cover) Phase 6 (1: 25,000 scale) at the catchment scale and from the National Soil Map (1: 250,000 scale) for the areas not covered by the detailed partial cover Soil Map at the national scale.

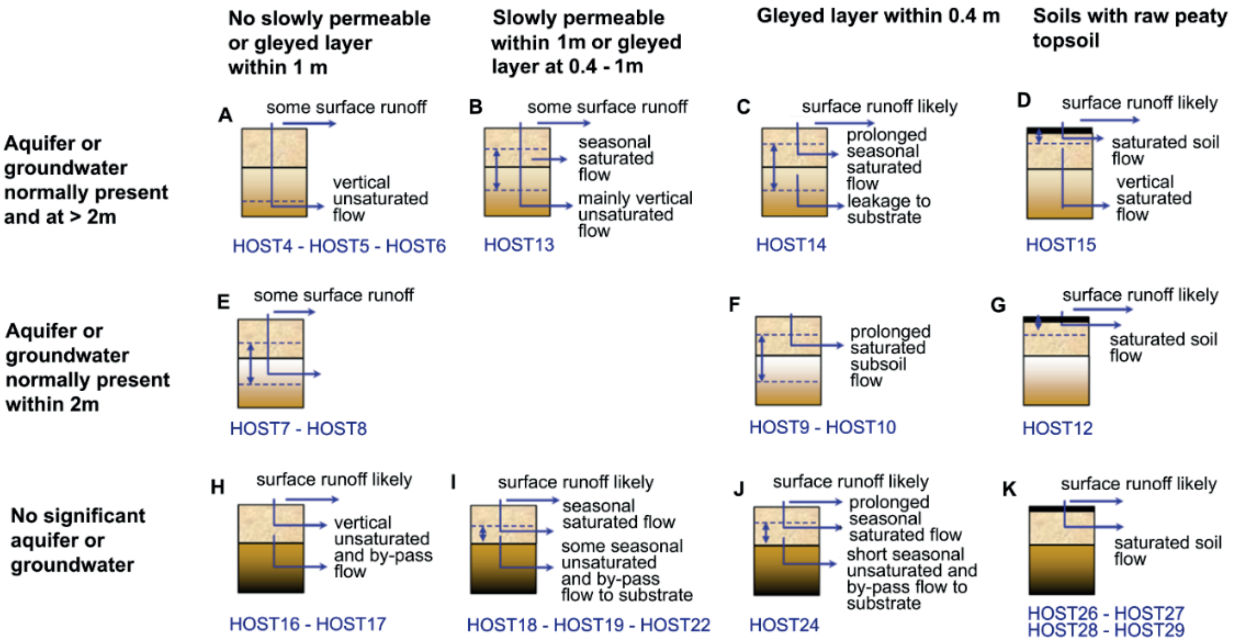

Figure 3. Hydrology of Soils Types (HOST) conceptual models and associated classes (modified by Gagkas and Lilly, 2019).

Majority of septic tanks located within the study catchments were classified as having a high-risk factor (n=1590), followed by those having a moderate risk factor (n=284). Most septic tanks in the Linkwood Burn and Lunan catchments had a high-risk factor (82% and 66%, respectively) while 64% of septic tanks located within Tarland had a moderate risk factor for hydrological leaching risk.

Table 12. Translating HOST classes to risk factors of septic tank effluent movement

HOST class	Risk factor
HOST16	Low
HOST6, HOST13, HOST17, HOST19, HOST22	Moderate
HOST5, HOST14, HOST15, HOST18, HOST24, HOST27	High
HOST4, HOST7, HOST8, HOST9, HOST10, HOST12, HOST26, HOST28, HOST29	Very high

Soil phosphorus sorption potential

The information on phosphorus sorption capacity of soils at the modelled septic tank locations was derived from the Map of soil Phosphorus Sorption Capacity (PSC) at 1: 250,000 scale, which gives the inherent ability of soil to retain P and depends on soil chemistry, texture, pH and organic matter content. (SRUC, 2015). In that study, soil properties including pH, organic carbon content, clay content and oxalate extractable iron and aluminium concentrations were determined from a dataset of 399 soils samples from 38 different soil associations. Topsoil samples from the National Soil Inventory of Scotland (2007-9), from other research projects and from the National Soils Archive were used to estimate the PSC of each soil association using a model. The values were then grouped into 3 categories of PSC index from 1 (Low) to 3 (High). Where no data were available, the areas were mapped as "not determined".

Overall, most septic tanks within the study catchments included in this study had a Low PSC index (n=1402), indicating a high potential for P leaching, followed by septic tanks that had a Moderate PSC index (n=713). Most septic tanks had a Low PSC index in all study catchments apart from Fernie Burn where most septic tanks had a moderate PSC index.

Topography

Slope (in percent) was calculated using the 100m grid DTM and intersected with modelled septic tank locations to obtain slope values. Thereafter, mean septic tank slope was calculated for each 100x100m grid cell and individual grid cells we assigned a corresponding risk rating as defined in Table 3.

Most septic tanks located within the study catchments (n=1,708 or 73%) had slopes equal or less than 5%, indicating a very low risk factor, while we found only 59 septic tanks with slope greater than 15% indicating moderate to high risk factors.

Septic Tank Density

The number of septic tanks located within each 100x100m grid cell (1 ha area) was counted to derive septic tank density. Highest counts of septic tanks within each grid cell within the study catchments were between 3 to 6 in Cessnock, Lunan, Mein and Rough Burn, 12 to 14 in Tarland and Fernie Burn, respectively, while 32 septic tanks were counted in just one grid cell in Linkwood Burn. Overall, mean septic tank density (calculated only for those cells that contained septic tank locations) was similar for all study catchments and ranged between 1 and 3 septic tanks/ha.

Septic tank location and the nature of discharge

The distance of individual septic tanks to surface watercourses was calculated by measuring the horizontal distance from the septic tank location to the nearest water body in the SEPA detailed stream network (using the distance to nearest hub tool in QGIS 3.12.0). The mean distance of septic tanks to the nearest water body was calculated for each 100x100m grid cell and individual grid cells we assigned a corresponding risk rating as in Table 6.

Of the 2,338 septic tanks located within the study catchments, 637 were located within 100m from the nearest watercourse, indicating a moderate to very high risk, mainly in Linkwood Burn (n=153), Lunan (n=225) and Tarland (n=114). More than half of septic tanks (n=1,306) were located at distances greater than 200m from the nearest stream that indicates a low to very low risk factor.

3.2.3 Elicitation of delivery coefficients for ‘Septic Tank Connectedness’

Delivery coefficients or the proportion of SRP load that might be delivered to the freshwater system given a certain degree of STS connectedness were specified as probability distributions which allow to represent a degree of uncertainty regarding delivery ratios. A statistical beta distribution on a 0-1 scale was fitted using percentiles (5th, 50th = median, 95th) estimated by expert opinion (Prof Marc Stutter, James Hutton Institute) (Table 13).

Table 13. Delivery coefficients of SRP load proportions given degree of STS connectedness based on expert elicitation.

	Illustrative descriptions for each level of STS connectedness	Lowest estimated fraction to be delivered (5th percentile)	Median estimated fraction to be delivered (50% percentile) Assumed the median values approximate the expected plume migration in the subsoil for the 20 yr age scenario in mineral soils (~1m/year as estimate)	Maximum likely fraction to be delivered to the stream (95% percentile)	All answers based on a 20-year-old STS, not broken or leaking, with a standard design of pipe exit at ~1m depth into a leachfield as per Scottish Planning regulations
Very high	Low leachfield removal due to low soil P sorption (index 1) and high soil infiltration over 750mm/year; ST within 10m distance of stream or with direct discharge to stream on a steep slope over 25%	0.5	0.8	1	Answered as if all mineral soil risk scenarios.
High	Low leachfield removal due to low soil P sorption (index 1) or high soil infiltration over 500m/year; ST within 25m distance of stream on a slope over 20%	0.3	0.6	0.9	
Medium	Medium leachfield removal due to medium soil P sorption (index 2) and medium soil infiltration over 250mm/year; ST within 100m distance of stream on a slope over 15%	0.1	0.3	0.6	
Low	High leachfield removal due to high soil P sorption (index 3) and low soil infiltration < 250mm/year; ST over 100m distance of stream on a slope < 15%	0	0.1	0.3	
Very low	High leachfield removal due to high soil P sorption (index 3) and low soil infiltration < 250mm/year; ST over 500m distance of stream on a slope < 5%	0	0.05	0.1	

3.2.4 Model structure and sensitivity analysis

Detailed model description is provided in Appendix 1. Figure 4 shows the structure of the risk-based model and the most influential variables, based on sensitivity analysis, that contribute to the STS pollution risk. Deeper red indicates greater sensitivity and hence greater influence of a variable on modell simulation outcomes. It is apparent that STS effluent concentration (and hence treatment type), condition, density, distance to watercourse and presence/absence of direct discharge (the latter two contributing to the STS connectedness) have the strongest influence on the SRP pollution risk.

In addition, P losses per STS for different levels of risk factors for which GIS data was available were compared (Figure 5). The results support the conclusions from the sensitivity analysis and indicate that STS density, distance to watercourse and to a lesser degree HOST risk factor, that represents soil hydrological characteristics and depth to water table, are most important variables that influence the scale of P losses from individual STS.

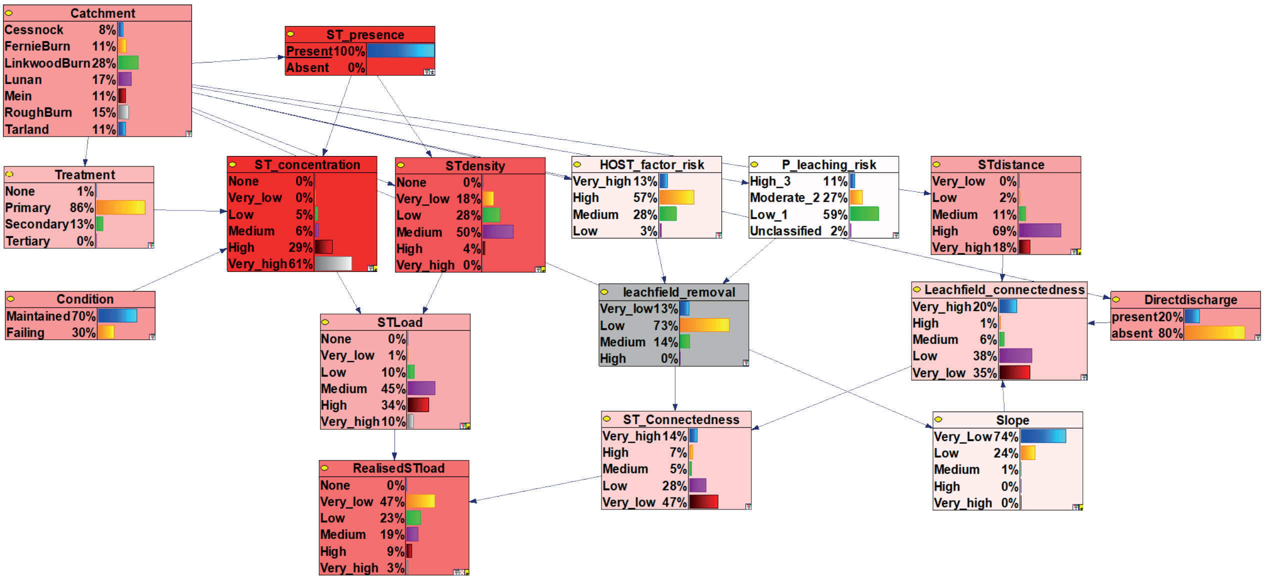

Figure 4. Structure of the conceptual risk-based model of phosphorus pollution from STS. The degree of red shading indicates most sensitive variables (deeper red) with a strongest influence on P pollution risk based on sensitivity analysis. Thickness of arrows indicates the 'strength of influence' or correlation between variables. (HOST factor risk represents both soil hydrological characteristics and depth to water table risk factors).

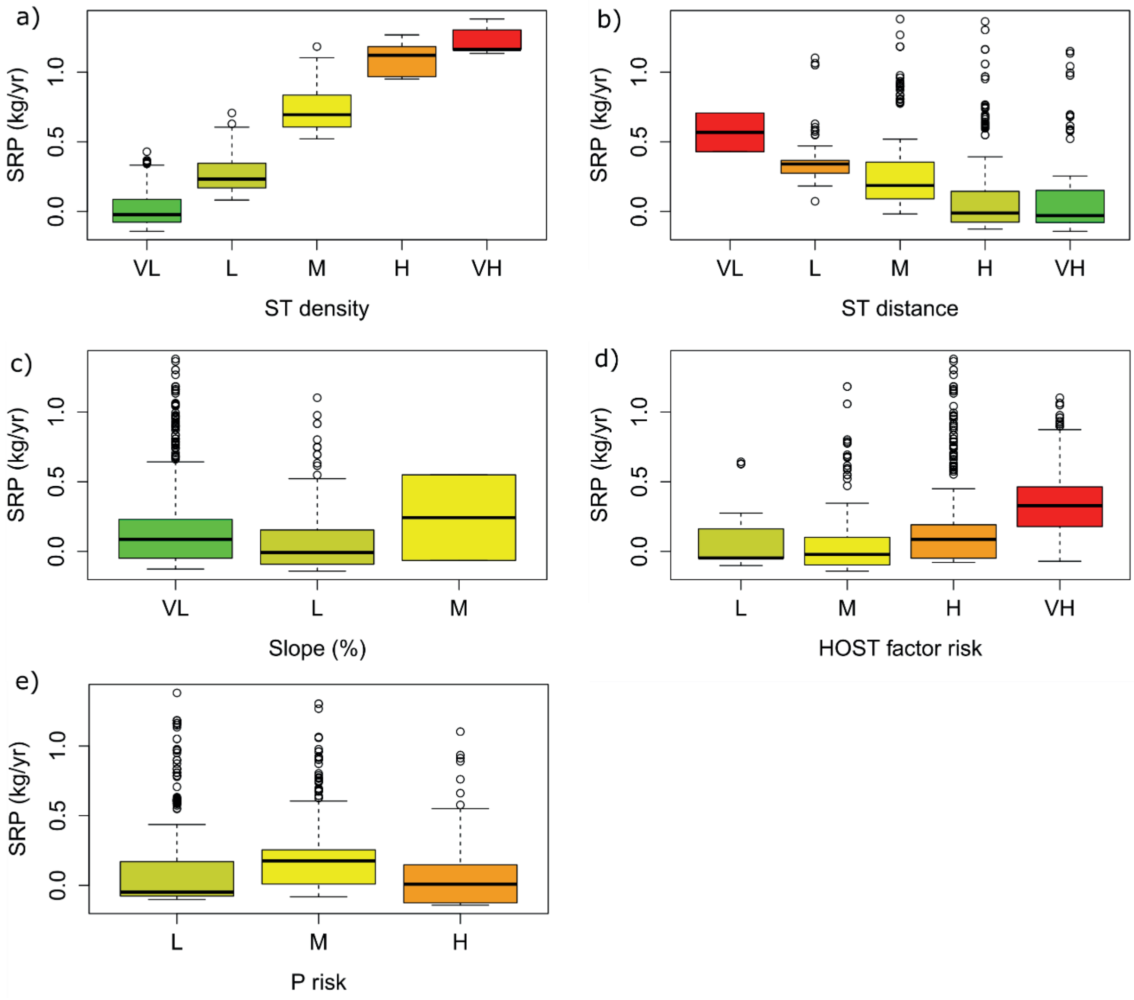

Figure 5. Simulated phosphorus losses per STS for different levels of risk factors that were represented as spatial GIS layers. Factor levels are: VL=Very Low; Low=Low; M=Moderate; H=High; VH=Very High (see Chapter 3.1 for explanation).

3.2.5 Simulation outcomes

National scale

The parameterised model was applied at a Scotland-wide scale and modelled losses were aggregated from 100m to 1km grid cell scale to match the spatial resolution required by SEPA. Phophorus losses were only simulated where STS are expected to occur (Figure 6).

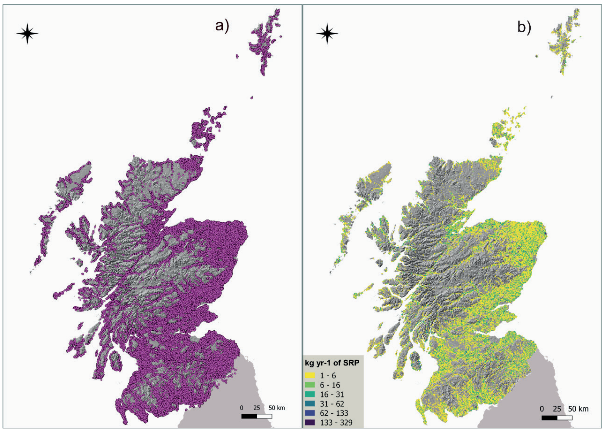

Figure 6. a) modelled ST locations based on assumptions from SEPA; **b)** simulated losses of SRP from the risk-based BBN at 1 km^2 grid squares.

Six hypothetical management scenarios were simulated. These included a) baseline, b) all STS fitted with primary treatment, c) all STS fitted with secondary treatment, d) all STS fitted with tertiary treatment, e) no STS directly connected to streams and f) all STS well maintained. Results presented in Figure 7 show that with the exception of all STS being fitted with just primary treatment (Figure 7b), all other interventions would result in the reduction of SRP losses from STS, as compared to the baseline (Figure 7a). The greatest impact, demonstrated as an increased probability of 'very low' SRP losses can be seen in scenario d) where all STS are fitted with tertiary treatment.

Figures 8 and 9 show the difference in mapped SRP losses at 1km^2 spatial resolution for two example study catchments under the six management scenarios. Table 14 shows that under the most effective scenario d) whereby all STS are fitted with tertiary treatment, total SRP losses in Scotland would be reduced by approximately one half. Fitting all STS with secondary treatment (scenario c) or avoiding any direct discharge to watercourses (scenario e) would reduce national losses by approximately one third. The total estimated SRP losses from STS in Scotland of 214 t yr^{-1} under the baseline scenario are higher than a previously reported estimate of 142 t yr^{-1} (May et al., 2015). However, the scale of these previously estimated national losses of SRP are approximated in scenario c) (fitting all STS with secondary treatment) and scenario e) (avoiding direct discharge to watercourses) (Table 14).

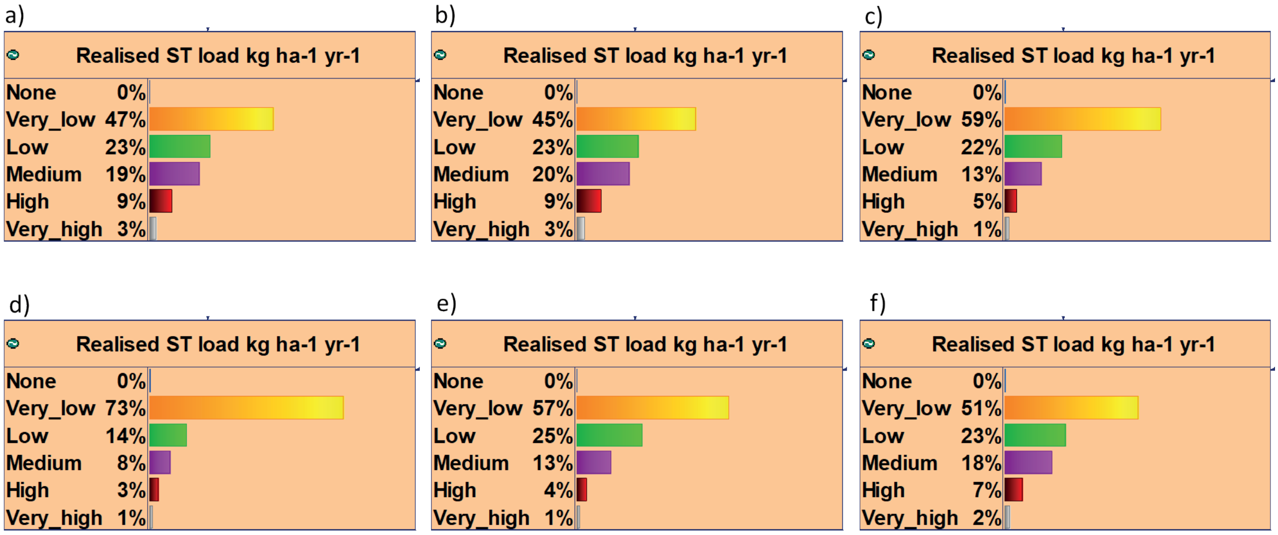

Figure 7. Six potential management scenarios demonstrate the change in risk of SRP losses from STS a) baseline, b) all STS fitted with primary treatment, c) all STS fitted with secondary treatment, d) all STS fitted with tertiary treatment, e) no STS directly connected to streams and f) all STS well maintained.

Table 14. Comparison of SRP losses from 1km^2 grid cells and estimated total annual loss for Scotland under six management scenarios.

Scenario	SRP losses from 1km^2 grid cells				Total annual SRP losses in Scotland
	Min	Median	Mean	Max	
	kg yr^{-1}	kg yr^{-1}	kg yr^{-1}	kg yr^{-1}	t yr^{-1}
National Baseline	0.72	4.12	7.36	328.80	213.88
National Primary Treatment	0.74	4.27	7.70	346.47	223.71
National Secondary Treatment	0.53	2.74	4.66	182.18	135.22
National Tertiary Treatment	0.50	2.24	3.80	123.08	110.47
National No Direct Discharge	0.47	2.49	4.64	198.48	134.56
National ST Maintained	0.65	3.59	6.28	305.93	182.45

Figure 8. A comparison of simulated SRP losses from STS in the Linkwood Burn catchment a) modelled location of STS, b) baseline scenario, c) all STS fitted with primary treatment, d) all STS fitted with secondary treatment, e) all STS fitted with tertiary treatment, f) no STS directly connected to streams and g) all STS well maintained.

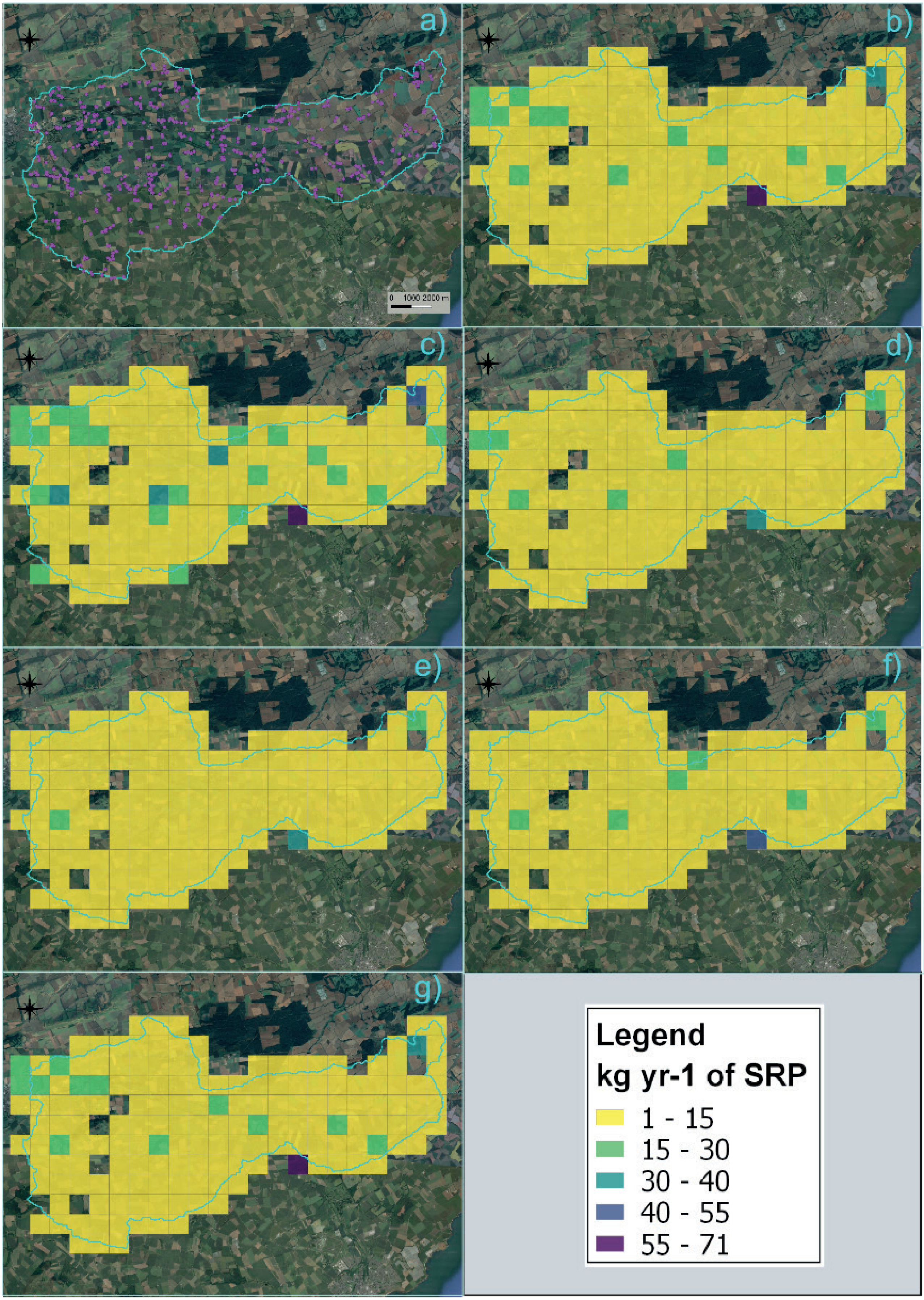

Figure 9. A comparison of simulated SRP losses from STS in the Lunan catchment from the a) modelled location of STS, b) baseline scenario, c) all STS fitted with primary treatment, d) all STS fitted with secondary treatment, e) all STS fitted with tertiary treatment, f) no STS directly connected to streams and g) all STS well maintained.

Catchment scale

SRP losses from STS were calculated for all seven study catchments (Table 14). The estimated losses per STS are comparable with P losses between 0.6-1.7 kg yr^{-1} reported in May et al. (2015), while the losses for each study catchment (between 0.94 and 1.26 t yr^{-1}) are at the lower end of estimates (between 0.02 and 56 t yt^{-1}) reported for a range of UK water bodies by May et al. (2015). This indicates that the new risk model is predicting credible losses within the right scale of magnitude.

In further work funded by the Scottish Government RESAS programme, the simulated STS losses will be included with other P losses from diffuse agricultural sources, farm yards and sewage treatment works using a fuller phosphorus pollution risk model to calculate source apportionment for a catchment outlet. This will allow validation of simulated SRP concentrations at the catchment outlet against water quality monitoring data and compare SRP source apportionment from the full BBN model with source apportionment from the existing model used by SEPA.

Table 15. SRP losses from 1km² grid cells and estimated total annual loss for each catchment under six management scenarios.

Study catchments	Min kg yr^{-1}	Median kg yr^{-1}	Mean kg yr^{-1}	Max kg yr^{-1}	Sum kg yr^{-1}	STS number	SRP loss per STS t yr^{-1}
Cessnock	0.84	1.40	2.24	8.18	75.99	71	1.07
Fernie Burn	0.83	1.50	2.58	20.11	404.28	321	1.26
Linkwood Burn	0.80	1.48	3.54	24.06	619.71	659	0.94
Lunan	0.79	1.20	1.57	11.61	972.88	853	1.14
Mein	0.98	1.40	1.59	8.60	49.47	38	1.30
Rough Burn	0.80	0.90	1.56	9.29	104.55	110	0.95
Tarland	0.72	0.85	1.62	15.26	315.70	286	1.10

3.2.6 Conclusions

Using the risk criteria identified in section 3.1 and spatial data described in section 3.2.2, this project constructed and parameterised a new risk model of SRP pollution from STS based on BBNs at a Scotland-wide scale. Sensitivity analysis has shown that STS effluent concentrations (linked to STS treatment type and condition), STS density and STS connectedness (linked to STS distance to watercourse and the presence/absence of direct discharge to watercourse) were the most important risk factors related to SRP pollution losses. Overall, simulated SRP losses at both catchment and national scale were comparable with previous estimates and hence within the right order of magnitude. The six modelled scenarios demonstrated that upgrading STS treatment to secondary or tertiary level, improving STS maintenance and/or disconnecting STS direct discharges to watercourses (by re-routing the discharge to a soakaway system) would all result in reduced SRP losses. Tertiary treatment and absence of direct discharge resulted in greatest reductions of SRP emissions at catchment and national scales. Further evaluation and selection of these potential mitigation measures could be informed by cost benefit analysis.

3.3 Review of modelling FIO and nitrogen export from Septic Tank Systems (STS) (Sarah Halliday)

This section provides an overview of key processes related to nitrogen (N) and faecal indicator organism (FIO) export from septic tank systems (STS) and how these are represented in modelling frameworks.

Understanding the sources of N and FIOs within a catchment, and the relative contribution of each independent source to the total nutrient/contaminant load delivered to the freshwater system, is vital to ensuring effective management of water quality. FIO sources can broadly be divided into two categories: human faecal sources, generally considered as point source contamination (i.e. sewage treatment works/storm overflows); and animal faecal sources, generally considered as a diffuse source (Oliver et al., 2016). Nitrogen sources can also be broadly classified as either point source (i.e. sewage treatment work) or diffuse sources (i.e. fertiliser applications).

Although some detailed process based models of STS exist (e.g. Pang et al., 2006), process-based modelling of STS is challenging as there is typically little information of the scale of STS use within a catchment, although this can be estimated from information on sewage network or detailed mapping exercises, there generally remains limited information of the operational capacity of the systems, its age/condition and maintenance; critical factors in determining the operational efficiency of STS (Ferguson et al., 2007; Haydon and Deletic, 2006; Hernandez-Suarez et al., 2019; Pang et al., 2006; Siegrist et al., 2005). In terms of catchment-scale modelling, disaggregation within the broad source categories (point/diffuse) is variable. Although work has been undertaken to develop models specifically focused on STS loadings (Gill and Mockler, 2016; McCray et al., 2005; Pang et al., 2006; Siegrist et al., 2005); many models do not identify loadings from STS as a distinct pollution source (Cho et al., 2016; Kay et al., 2008).

3.3.1 STS Discharge pathways

As stated, sources of contamination within catchments are generally assumed to be either point sources, such as a sewage treatment work discharge point, or diffuse source, such as fertiliser applications. However, STS are not straightforward to classify (Edwards and Withers, 2008). Substantial evidence exists from monitoring surveys that often STS owners are not undertaking the required maintenance to ensure the STS work effectively (in some cases homeowners can even be unaware that they have a STS); on inspection systems are not sited in appropriate locations; and the capacity of the system is being exceeded (Dudley and May, 2007; Withers et al., 2011). Therefore, although STS should be operating as a diffuse pollution source, often as a result of these factors they are actually point sources.

Consequently, some modelling frameworks have treated STS as point sources and under these simulations the output loadings from the tank are directly routed to the river systems without any additional load reductions (Parajuli, 2007). This would be an appropriate representation of STS which have direct discharges or where the separation distance is insufficient to permit effective additional FIO/N reductions. However, other modelling frameworks have opted to treating STS as diffuse sources, and assumed the loadings are applied to land (Bergion et al., 2017; Cho et al., 2016; Haydon and Deletic, 2006; Siegrist et al., 2005). This would be an appropriate representation of STS which are discharging to effective soakaway systems.

Some research has suggested that septic tanks can act as both point and diffuse sources depending on flow conditions (Edwards and Withers, 2008). Models have captured this by linking assumptions about percentage of STS connectivity to the river system depending on flow conditions (Ferguson et al., 2007).

3.3.2 Process understanding and conceptual approaches

Faecal indicator organisms

FIO modelling focuses largely on total coliforms, faecal coliforms and *E. coli*. If STS are explicitly incorporated as a distinct FIO source, load estimations are generally made using a conceptual approach (Bergion et al., 2017; Parajuli, 2007; Reder et al., 2015). Under this approach a series of assumptions are made about the scale of STS use; the average property occupancy; the rate of effluent production associated with the population and the effluent FIO concentration (Table 16). These values are then used to estimate the average FIO loading entering STS (Figure 10). The FIO load discharged from the STS is then estimated based on percentage reductions applied to the input loadings linked to the assumed level of treatment provided by the system. It is generally assumed that STS have no better than secondary treatment, however if STS are working effectively, secondary treatment is believed to reduce FIO loadings by 95% or more (Reder et al., 2015).

Some models have considered failing sites by defining a set percentage of septic tanks as failing and assuming that 100% of the input load would be transferred to the river system. Failure rates adopted in the literature range from 12-36% (Coffey et al., 2010; Hernandez-Suarez et al., 2019; Parajuli, 2007). However, other work has highlighted that although not all systems may be classed as completely failing, a high percentage > 80% may be working ineffectively (Ahmed et al., 2005; Arnscheidt et al., 2007; Carvalho et al., 2005; May, 2015). The percentage of failing sites was identified as a key factor in determining the importance of STS FIO loadings to the overall catchment budget (Parajuli, 2007).

As outlined, the models largely assume STS to be either point sources of contamination, in which case no additional FIO reductions would occur, or they are considered as diffuse sources and the discharge is applied to land. If discharge is applied to land, FIO transport to the freshwater environment is dependent on how well they are attenuated by die-off, physical straining, or by adsorption to soil surfaces.

If treated as diffuse sources, research has highlighted that the importance of STS FIO loadings to the overall catchment budget diminished due to additional soil processing (Parajuli, 2007).

Table 16. Modelling Assumptions (Bergion et al., 2017; Cho et al., 2016; Ferguson et al., 2007; Gill and Mockler, 2016; Hernandez-Suarez et al., 2019; Kay et al., 2008; McCray et al., 2005; Parajuli, 2007; US EPA, 2001; Valiela et al., 1997).

Factor	Standard approach to estimation	
The number of STS in a catchment	Based on property connectivity to the sewer network, or detailed catchment survey work	
The number of people per property	2.4 – 3.14	
Average rates of effluent production (m^3 person^{-1} day^{-1})	0.15 – 0.31	
Average FIO concentrations in wastewater (cfu 100 ml^{-1})	Total coliforms	3.9 x 10^7
	Faecal coliforms	6.3 x 10^6 - 1 x 10^7
	E. coli	1 x 10^7
Human TN production (g N person^{-1} day^{-1})	11.4 – 13.3	

Nitrogen

A significant body of work has been undertaken to understand and model N catchment dynamics, with a range of process-based models and export coefficient approaches implemented (Edwards and Withers, 2008; Johnes, 1996; Kaste and Skjelkvale, 2002; Tian et al., 2012; Wade et al., 2002; Worrall et al., 2012). However, as noted above, STS are not always considered as a distinct nutrient source, with effluent modelling largely focused on sewage treatment work exports. Where STS are considered, most modelling approaches follow the same principles adopted in the FIO modelling, with estimated effluent loads received by the STS based on a series of assumptions about property occupancy; effluent production rates; and the effluent N concentrations. (Anderson, 2006; Kroeger et al., 2006; Siegrist et al., 2005; Valiela et al., 1997).

Conventional STS are not traditionally designed for nitrogen removal. However, due to the anaerobic condition within the tank and microbial activities, organic N is converted to inorganic N (largely ammonium-N) with no reduction in total nitrogen (TN). A large range in total nitrogen concentrations 10 – 210 mg l^{-1} have been recorded in septic tank discharges (Edwards and Withers, 2008; Humphrey et al., 2013; Katz et al., 2010; Lusk et al., 2017; Valiela et al., 1997). This has been attributed to the variability in daily water usage which directly influences dilution capacity of the tanks as well as dietary differences in population utilising the system.

Ammonium (NH_4) is normally the dominant nitrogen species released from STS (>70%) (Gill et al., 2009; Katz et al., 2010; Lusk et al., 2017). However, the importance of organic-N has also been highlighted, normally accounting for between 10-30% of TN, although some studies have found it to be the dominant N species (O'Driscoll et al., 2014).

N speciation in the soakaway is heavily dependent on the site conditions. When STS operate efficiently, almost all the TN discharged from the tank is converted to NO_3 by nitrification in the soakaway (94-99%) (De and Toor, 2017; Gill et al., 2009; Katz et al., 2010; O'Driscoll et al., 2014). However, where the soakaway is not operating effectively, NH_4 and organic-N can account for a significant proportion of the drainfield TN (> 40%). Many studies have identified separation distance as key factor in determining the efficiency of the nitrification process in the drainfield (De and Toor, 2017; O'Driscoll et al., 2014). This specification is critical considering the mobility of N species in groundwater systems; whereas NO_3 has the potential to denitrify in sediments, organic-N does not (Humphrey et al., 2013). This is an important consideration as the bioavailability of dissolved organic N (DON) has been recognised in recent studies (Pellerin et al., 2006).

Key processes for reducing NO_3 concentrations in the drainfield are denitrification, dilution/dispersion and plant uptake (Beal et al., 2005). The extent of any of the processes is dependent on subsurface soil conditions, including the redox status, microbial composition and labile carbon source. Due to the complexity of factors affecting this processing, a range of N reduction rates have been observed within drainfields 0-50% (Gill et al., 2009; Valiela et al., 1997), although some studies have reported reductions of over 80% (Aley et al., 2007; Humphrey et al., 2013; O'Driscoll et al., 2014). Most models use the same approach as the FIO modelling and assumed a set percentage reduction (US EPA, 2013). Work has been undertaken to determine different attenuation factors for N based on subsoil permeability (Gill and Mockler, 2016).

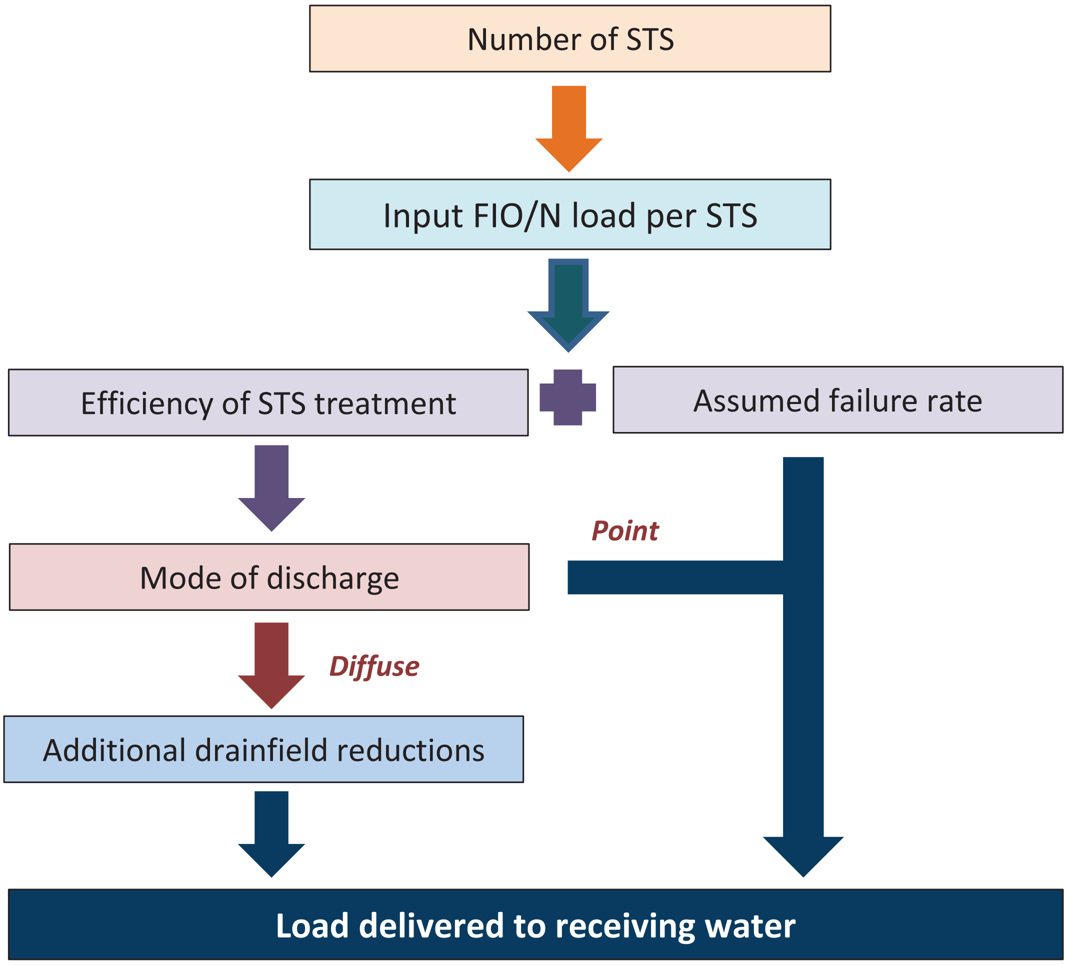

Figure 10. Schematic of the basic process followed to model STS FIO/N loadings.

3.3.3 STS catchment load contribution

In terms of catchment scale FIO loading, some models which have incorporated STS found that they contributed only a small proportion to the total FIO load (<5%); and where this was the case mitigation scenarios targeting STS did not deliver significant reductions in instream FIO concentrations (Bergion et al., 2017; Coffey et al., 2010; Hernandez-Suarez et al., 2019). However, this result is largely dependent on the density of STS within a catchment. In other studies where the density of STS within the catchment is high, providing a significant proportion of the catchment-wide sewage treatment, FIO loads from STS have been found to be significant (Cahoon et al., 2006; O'Keeffe et al., 2015). Within these catchments targeted measures to address failing STS have resulted in significant reductions >80% of FIO loading in the receiving water (Cahoon et al., 2006).

The same findings were found for N. In catchments where the density of STS is high and where they are providing a significant proportion of the catchment-wide wastewater treatment, they can act as a critical N source and account for a high proportion of the total catchment N load (Badruzzaman et al., 2012; Ye et al., 2016).

3.3.4 Critical risk factors for STS

In addition to modelling STS, a significant amount of research has been undertaken to understand the risk factors associated with STS. Key risk factors are largely common for both FIO and N, although for N the conditions in the soakaway are particularly important as these determine the speciation and proportion of N reaching the receiving water (Akoumianaki et al., 2020; Hayes et al., 1990; Oliver et al., 2009; Valiela et al., 1997):

- **STS density**
  The higher the density of STS the greater contribution they are likely to make to the overall FIO/N load. High STS densities have been defined > 20 STS km^{-2}.
- **Population utilising STS**
  All STS have a property occupancy rate at which they were designed to work effectively. If the loading received by the system exceeds the intended capacity, the system efficiency will deteriorate (Richards et al., 2016).

- **Connectivity to receiving water**
  The closer the STS is to the receiving water the higher the risk of contamination or potential for direct discharges (Gill and Mockler, 2016).
- **Separation distance to water table**
  The smaller the separation distance the greater the risk of groundwater contamination; and for N the greater the risk that NH_4 and DON will reach the groundwater (De and Toor, 2017; O'Driscoll et al., 2014).
- **STS condition/maintenance/age**
  Poor maintenance is a high-risk factor for STS failure. However, knowledge on the condition of STS and how well maintained they are is highly limited. In addition, STS have a life-span on installation and work has highlighted the increased likelihood of STS failure after 10 years (Valiela et al., 1997).
- **Soil type and permeability**
  Local soil conditions are critical in determining nutrient/pathogen attenuation (Carvalho et al., 2005). Impermeable soils have been identified as higher risk, as there is less opportunity for percolation and die-off of FIO and less potential for denitrification (Withers et al., 2011). However, a high proportion of sandy soil (>80%) also represent a high risk, due to the reduced adsorption capacity and reduced potential for denitrification (Gill et al., 2009; Lusk et al., 2017). The organic matter content can also be key to determining N processing (Badruzzaman et al., 2012).
- **Other site condition factors**
  The slope on which the STS is sited can also be important, with steeper slopes associated with higher contamination risk.

  Presence of drainage ditches in the STS soakaway can also increase connectivity, creating preferential flow pathways and facilitating direct transfer to the receiving water body (Oliver et al., 2009; Withers et al., 2011).

  Presence of riparian buffer can also be a key factor, especially for N, as it significantly attenuates NO_3 concentrations (Beal et al., 2005; Ferguson et al., 2003).
- **Seasonal factors**
  Areas subject to high levels of seasonal tourism can result in higher risk STS (Cahoon et al., 2006). This is because the efficiency of the STS generally assumed continual use and intermittently used STS with long periods without inflow will not be operating properly. A high degree of variability in water table depths can also influence the efficiency of the STS (O'Driscoll et al., 2014).
- **Climatic factors**
  Rainfall and temperature patterns can impact on the functionality of STS. For example, higher temperatures can increase risk by reducing FIO die-off (Cho et al., 2016); whereas flooding can increase connectivity and increase the FIO/N loading delivered to the receiving waters (Ferguson et al., 2003).

3.3.5 Incorporation within the Bayesian risk-based modelling framework

These findings suggest that incorporating FIO's and N within the STS Bayesian modelling framework adopted for phosphorus would be achievable.

This approach would be an advancement on the currently adopted modelling approaches as it would include a probabilistic dimension, which would address some of the uncertainties around STS use, condition, maintenance, etc. (Bergion et al., 2017). The Bayesian framework would also allow for consideration of additional key risk factors identified in this review. Many of these risk factors have already been incorporated in the P model.

The probabilities used in the work by Gill and Mockler (2016) would be useful in informing the distributions to adopt in a Bayesian framework for nitrogen.

4. Conclusions

- The literature review indicated that the risks of phosphorus pollution to watercourses from STS are associated with STS density, location and proximity to watercourses. Poor performance of a large proportion of septic tanks and hence the risk of phosphorus leaching to water bodies are related to the lack of proper soakaway system, poor soil quality, undersized STS and lack of maintenance.
- Using the risk criteria identified in section 3.1 and spatial data described in section 3.2.2, a risk model of SRP pollution from STS based on BBNs was successfully constructed and parameterised at a Scotland-wide scale.

- Sensitivity analysis has shown that STS effluent concentration (linked to STS treatment type and condition), STS density and STS connectedness (linked to STS distance and the presence/absence of direct discharge to watercourse) were the most important risk factors related to SRP pollution losses.
- Overall simulated SRP losses at both catchment and national scale were comparable with previous estimates, indicating that the model simulates plausible losses within the right order of magnitude.
- Modelled scenarios demonstrated that upgrading STS treatment to secondary or tertiary level, improving STS maintenance status and/or disconnecting STS direct discharges to watercourses by rerouting the discharge to a soil system would all result in reduced SRP losses. Tertiary treatment and absence of direct discharge resulted in greatest reductions of SRP emissions at catchment and national scales. Further evaluation and selection of these potential mitigation measures could be informed by cost benefit analysis.
- Literature review suggested that incorporating FIO's and N within the STS risk modelling framework developed for phosphorus would be achievable, as the risk factors for different pollutants are comparable. Although in this project, FIO model was not implemented and FIO loadings were not calculated, this would be feasible in a follow-up project.
- This would represent an advancement on the currently adopted modelling approaches as it would include a probabilistic dimension, which would address some of the uncertainties around STS use, condition and maintenance (Bergion et al., 2017).
- Probabilities in Gill and Mockler (2016) could inform BBN model parameterisation for nitrogen.

5. Recommendations

1. To improve the estimation of STS P contribution in water quality models, multiple risk factors contributing to STS pollution risk need to be considered.
2. A detailed catchment-based survey of STS condition would be beneficial to test model parameterisation. This could include a survey of STS age and maintenance, coupled with targeted effluent and water quality monitoring to get as good an understanding as possible of ST loads in a small catchment with limited other P inputs.
3. Simulations indicate that several mitigation strategies could reduce SRP losses from STS at both catchment and national scales. Fitting all STS with tertiary treatment or disconnecting STS from direct discharges to watercourses could reduce SRP emissions from STS in Scotland by cca. one half. Fitting all STS with secondary treatment may reduce SRP losses in Scotland by cca. one third.
4. Extending the BBN risk model for SRP losses from STS to FIOs and nitrogen pollutant losses would be achievable and relatively straightforward.

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7. Appendices

<table>
<tr><th colspan="4">Table A1. Model specification</th></tr>
<tr><th>Variable (symbol) [unit]</th><th>States</th><th>Discretisation boundaries</th><th>Description</th></tr>
<tr><td>Site and ST specific variables</td><td></td><td></td><td></td></tr>
<tr><td rowspan="7">Catchment</td><td>Cessnock</td><td></td><td rowspan="7">This variable was set as ‘hard evidence’ using spatial GIS layer for catchment-specific modelling. However, at the national scale, this variable was not set as hard evidence, which meant that marginal distributions were used for the ‘ST Treatment’ and ‘Direct Discharge presence/absence’ at the national scale.</td></tr>
<tr><td>Fernie Burn</td><td></td></tr>
<tr><td>Linkwood Burn</td><td></td></tr>
<tr><td>Lunan</td><td></td></tr>
<tr><td>Mein</td><td></td></tr>
<tr><td>Rough Burn</td><td></td></tr>
<tr><td>Tarland</td><td></td></tr>
<tr><td rowspan="2">ST presence</td><td>Present</td><td></td><td rowspan="2">Probabilities derived for each catchment from GIS data provided by SEPA. In the spatial application of the model, ST presence is set as ‘hard evidence’ using spatial data.
<table>
<tr><th>ST</th><th>Cessnock</th><th>Fernie</th><th>Linkwood</th><th>Lunan</th><th>Mein</th><th>Rough</th><th>Tarland</th></tr>
<tr><td>Present</td><td>0.019</td><td>0.029</td><td>0.07</td><td>0.044</td><td>0.027</td><td>0.037</td><td>0.027</td></tr>
<tr><td>Absent</td><td>0.981</td><td>0.971</td><td>0.93</td><td>0.956</td><td>0.973</td><td>0.963</td><td>0.973</td></tr>
</table>
In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.</td></tr>
<tr><td>Absent</td><td></td></tr>
<tr><td rowspan="2">Condition</td><td>Maintained</td><td>0.7</td><td rowspan="2">Based on literature review (see Chapter 3.1) and expert opinion of the SEPA steering group. The prior distribution is assumed as: 70% maintained, 30% failing.</td></tr>
<tr><td>Failing</td><td>0.3</td></tr>
<tr><td rowspan="4">Treatment</td><td>None</td><td></td><td rowspan="4">Probabilities for each treatment type derived for each catchment from GIS data provided by SEPA. Marginal probability distribution was all treatment types was 1% None, 85% Primary, 14% Secondary, 0% Tertiary for national scale modelling.
<table>
<tr><th>Treatment</th><th>Cessnock</th><th>Fernie</th><th>Linkwood</th><th>Lunan</th><th>Mein</th><th>Rough</th><th>Tarland</th></tr>
<tr><td>None</td><td>0</td><td>0.02</td><td>0.005</td><td>0.01</td><td>0</td><td>0</td><td>0.01</td></tr>
<tr><td>Primary</td><td>0.71</td><td>0.85</td><td>0.85</td><td>0.91</td><td>0.9</td><td>0.86</td><td>0.88</td></tr>
<tr><td>Secondary</td><td>0.29</td><td>0.13</td><td>0.14</td><td>0.07</td><td>0.1</td><td>0.14</td><td>0.11</td></tr>
<tr><td>Tertiary</td><td>0</td><td>0</td><td>0.005</td><td>0.01</td><td>0</td><td>0</td><td>0</td></tr>
</table></td></tr>
<tr><td>Primary</td><td></td></tr>
<tr><td>Secondary</td><td></td></tr>
<tr><td>Tertiary</td><td></td></tr>
</table>

Table A1. Model specification continued

<table>
<tr>
<td rowspan="6">ST concentration
[mg L^{-1}]</td>
<td>None (to represent 0 STs)</td>
<td>0 - 1E-6</td>
<td rowspan="6">Probabilities are conditional on ST presence/absence, ST condition and treatment type. Concentrations for different treatment types were informed by lit. review in Chapter 3.1 (based on Brownlie et al., 2014 and Richards et al., 2016) and were defined as Truncated Normal distribution with a mean for each treatment type, SD at 1/10th of the mean and minimum concentration of 0 mg L^{-1} where ST are absent. For ‘Failing’ STs, ‘None’ treatment was assumed.
<table>
<tr><td colspan="4">ST concentration mg L^{-1}</td></tr>
<tr><td>Treatment type</td><td>Maintained</td><td>Failing</td><td>STs absent</td></tr>
<tr><td>None</td><td>$\mu=14; \sigma=1.4$</td><td>$\mu=14; \sigma=1.4$</td><td>$\mu=0; \sigma=0$</td></tr>
<tr><td>Primary</td><td>$\mu=10; \sigma=1$</td><td>$\mu=14; \sigma=1.4$</td><td>$\mu=0; \sigma=0$</td></tr>
<tr><td>Secondary</td><td>$\mu=5; \sigma=0.5$</td><td>$\mu=14; \sigma=1.4$</td><td>$\mu=0; \sigma=0$</td></tr>
<tr><td>Tertiary</td><td>$\mu=2; \sigma=0.2$</td><td>$\mu=14; \sigma=1.4$</td><td>$\mu=0; \sigma=0$</td></tr>
</table>
Discretisation was based on Brownlie et al. (2014) using boundaries 2,5,8,10,>10 mg L^{-1}. This resulted in plausible probabilities for extreme combinations of factors.</td>
</tr>
<tr><td>Very_low</td><td><2</td></tr>
<tr><td>Low</td><td>2_5</td></tr>
<tr><td>Medium</td><td>4_8</td></tr>
<tr><td>High</td><td>6_10</td></tr>
<tr><td>Very_high</td><td>9_35</td></tr>
<tr>
<td rowspan="6">ST density
[No. ha^{-1}]</td>
<td>None</td>
<td>0-0.99</td>
<td rowspan="6">Mean ST density was calculated for each catchment from GIS data provided by SEPA and was then specified as a Poisson distribution where mean = SD to represent counts per ha^{-1} in each catchment, with a minimum density 1 ST ha^{-1} where ST were ‘Present’. Where STs were ‘Absent’, density was specified as 0. Discretisation was based on literature review in Chapter 3.1.
<table>
<tr><td></td><td>Cessnock</td><td>Fernie</td><td>Linkwood</td><td>Lunan</td><td>Mein</td><td>Rough</td><td>Tarland</td></tr>
<tr><td>Mean ST density ha^{-1}</td><td>1.5</td><td>2</td><td>3.3</td><td>1.4</td><td>1.1</td><td>1.4</td><td>1.4</td></tr>
</table>
Discretisation was based on literature review in Chapter 3.1, (May et al., 2015, 2016). In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.</td>
</tr>
<tr><td>Very_low</td><td>1_2</td></tr>
<tr><td>Low</td><td>2_3</td></tr>
<tr><td>Medium</td><td>3_7</td></tr>
<tr><td>High</td><td>7_15</td></tr>
<tr><td>Very_high</td><td>15_25</td></tr>
<tr><td colspan="4">Connectivity related variables (leachfield removal, topography, distance)</td></tr>
<tr>
<td rowspan="4">HOST factor risk class</td>
<td colspan="2">Very_high</td>
<td rowspan="4">Probabilities for each catchment were derived from spatial GIS data as described in Chapter 3.2.2 above, high risk represents soils with high probability of overland flow generation or high infiltration rate. In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.
<table>
<tr><td>HOST risk class</td><td>Cessnock</td><td>Fernie</td><td>Linkwood</td><td>Lunan</td><td>Mein</td><td>Rough</td><td>Tarland</td></tr>
<tr><td>Very high</td><td>0.33</td><td>0.07</td><td>0.20</td><td>0.07</td><td>0.14</td><td>0.04</td><td>0.10</td></tr>
<tr><td>High</td><td>0.66</td><td>0.50</td><td>0.51</td><td>0.62</td><td>0.74</td><td>0.70</td><td>0.25</td></tr>
<tr><td>Medium</td><td>0.005</td><td>0.41</td><td>0.27</td><td>0.23</td><td>0.12</td><td>0.21</td><td>0.65</td></tr>
<tr><td>Low</td><td>0.005</td><td>0.02</td><td>0.02</td><td>0.08</td><td>0.02</td><td>0.05</td><td>0.00</td></tr>
</table>
In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.</td>
</tr>
<tr><td colspan="2">High</td></tr>
<tr><td colspan="2">Medium</td></tr>
<tr><td colspan="2">Low</td></tr>
</table>

Table A1. Model specification continued

P sorption index	
	High_3
	Moderate_2
	Low_1
	Unclassified

Probabilities of each P sorption class (Sinclair, 2013) were derived for each catchment from mapped GIS data as described in Chapter 3.2.2 above

P sorption index	Cessnock	Fernie	Linkwood	Lunan	Mein	Rough	Tarland
High	0.48	0.00	0.00	0.00	0.24	0.00	0.45
Medium	0.00	0.85	0.025	0.433	0.757	0.062	0.05
Low	0.3	0.142	0.968	0.56	0.00	0.938	0.50
Unclassified	0.22	0.008	0.007	0.007	0.003	0.00	0.00

In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.

Direct discharge	
	Present
	Absent

Probabilities for each catchment were calculated from a national database shared by SEPA.

Direct discharge	Cessnock	Fernie	Linkwood	Lunan	Mein	Rough	Tarland
Present	0.45	0.26	0.12	0.14	0.4	0.15	0.11
Absent	0.55	0.74	0.88	0.85	0.6	0.85	0.89

ST distance [m]		
	Very_low	0_10
	Low	10_25
	Medium	25-100
	High	100-500
	Very_high	500-2000

A normal distribution truncated at the minimum distance observed in each catchment was fitted using summary statistics calculated in GIS for each catchment. Discretisation boundaries were informed by literature review in Chapter 3.1.

	Cessnock	Fernie	Linkwood	Lunan	Mein	Rough	Tarland
Distance	μ=217; σ=146; min=12.1	μ=358; σ=372; min=4.7	μ=202; σ=188; min=5	μ=338; σ=279; min=4.7	μ=198; σ=193; min=29.9	μ=252; σ=298; min=10	μ=241; σ=190; min=3.4

In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.

Slope [%]		
	Very_low	0-5
	Low	1_15
	Medium	2_20
	High	5_25
	Very_high	25-28

A normal distribution truncated at observed minimum slope or a lognormal distribution were fitted using summary statistics calculated in GIS for each catchment. Discretisation boundaries were informed by literature review in Chapter 3.1 (May et al. 2010 and 2016, Stutter et al. 2014).

	Cessnock	Fernie	Linkwood	Lunan	Mein	Rough	Tarland
Slope	μ=3.68; σ=1.54; min=1	μ=1.13; σ=1.04;	μ=1.17; σ=0.538;	μ=1.18; σ=0.764;	μ=1.14; σ=0.751;	μ=2.62; σ=1.-36; min=0	μ=1.78; σ=0.67;

In the spatial application of the model, ST density is set as ‘hard evidence’ using spatial data.

Table A1. Model specification continued

Leachfield removal	Very low Low Medium High	Probabilities are conditional on P sorption index and HOST risk class and always assigned the higher of the combination of the two possible classes. Areas where P sorption index classification was not available were treated as 'Low P sorption index'

P sorption index	High 3				Moderate				Low			
HOST risk	V High	High	Medium	Low	V High	High	Medium	Low	V High	High	Medium	Low
Very Low	1	0	0	0	1	0	0	0	1	0	0	0
Low	0	1	0	0	0	1	0	0	0	1	1	0
Medium	0	0	1	0	0	0	1	1	0	0	0	1
High	0	0	0	1	0	0	0	0	0	0	0	0

Leachfield connectedness	Very_high High Medium Low Very_low	Probabilities are conditional on presence/absence of Direct ST discharge, ST distance and slope. Where Direct discharge is present, connectedness is assumed as 'Very high'. Where Direct discharge is absent, the risk class of the ST distance is assigned but lowered by 10% for each category of decreasing slope risk. The CPT table is too long to reproduce here in full so only two out of four levels of ST distance are presented to illustrate the approach.

ST distance	Very low										Low									
Direct discharge	Present					Absent					Present					Absent				
Slope %	V Low	Low	Medium	High	V High	V Low	Low	Medium	High	V High	V Low	Low	Medium	High	V High	V Low	Low	Medium	High	V High
Very High	1	1	1	1	1	0.6	0.7	0.8	0.9	1	1	1	1	1	1	0	0	0	0	0
High	0	0	0	0	0	0.4	0.3	0.2	0.1	0	0	0	0	0	0	0.6	0.7	0.8	0.9	1
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.3	0.2	0.1	0
Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A1. Model specification continued

ST connectedness	Very_high		Probabilities are conditional on Leachfield removal and Leachfield connectedness. Where Leachfield removal is ‘Very_low’ or ‘High’, Leachfield connectedness remains unaltered. For ‘Low’ and ‘Medium’ removal rates, probability of Leachfield connectedness is reduced by 30% and 70%, respectively.
	High		
	Medium		
	Low		
	Very_low		

Leachfield removal	Very low					Low					Medium					High				
Leachfield connectedness	V High	High	Medium	Low	V Low	V High	High	Medium	Low	V Low	V High	High	Medium	Low	V Low	V High	High	Medium	Low	V Low
Very High	1	0	0	0	0	0.7	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0
High	0	1	0	0	0	0.3	0.7	0	0	0	0.7	0.3	0	0	0	1	0	0	0	0
Medium	0	0	1	0	0	0	0.3	0.7	0	0	0	0.7	0.3	0	0	0	1	0	0	0
Low	0	0	0	1	0	0	0	0.3	0.7	0	0	0	0.7	0.3	0	0	0	1	0	0
Very Low	0	0	0	0	1	0	0	0	0.3	1	0	0	0	0.7	1	0	0	0	1	1

Calculated variables			
ST load in SRP [kg ha^{-1} yr^{-1}]	None	0 - 1E-05	Specified as the product of ST density [No ha^{-1}] * ST concentration [mg L^{-1}] * 150 [L] average daily water consumption per person * 365 days in a year * average No of persons per household 2.17/1E+06.
	Very_low	1e-05-0.6	
	Low	0.6_2	Discretisation is based on interpolation to represent plausible probabilities for combination of the same risk class (e.g. high+high=high, low+low=low).
	Medium	2_6.5	
	High	6.5_17	
	Very_high	>17	
Realised ST load [kg ha^{-1} yr^{-1}]	None	0-1e-05	Calculated as the product of ST load and delivery factors related to ST connectedness based on expert elicitation.
	Very_low	1e-05-0.6	
	Low	0.6-1.8	The delivery factors for five states of ST connectedness were specified as Beta distribution on scale 0-1 based on 3-point expert elicitation for a ‘typical’ ST in each connectivity class as outlined in Chapter 3.2.3 above.
	Medium	1.8-5.5	
	High	5.5_15	
	Very_high	>15	Discretisation was based on interpolation to represent plausible probabilities for combination of extreme risk classes (e.g. high+high=high, low+low=low)

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