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COLLABORATIVE EXPERT JUDGEMENT ANALYSIS OF UNCERTAINTY ASSOCIATED WITH CATCHMENT-SCALE NITROGEN LOAD MODELLING WITH OVERSEER®

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Summary

The widespread view that use of OVERSEER®-derived N loss estimates to set catchment-scale nutrient limits is an inappropriate use of this tool needs to be addressed to maximise stakeholder acceptance of these limits. Accounting for uncertainty is the best way to deal with this issue. Uncertainty quantification also allows decision-makers to consider the likelihood that a proposed management approach will be successful and understand the probability that model projections of future water quality will eventuate. Pure numerical analysis of OVERSEER® uncertainty for the range of soil and land use types within a catchment would be extremely time-consuming, with some authors concluding that quantifying all sources of uncertainty involved in the N leaching value produced by OVERSEER® is impossible. In the absence of conclusive measured data, which may never be attainable at affordable cost and in due time given the complexity of environmental systems, expert opinion is often the only source of evidence. This paper shows how a formal expert judgement elicitation framework was used to approximately quantify uncertainty around catchment-scale modelled N loss rates. Although application of the study outputs to the nutrient limit decision-making process is ongoing at the time of writing, findings from initial analysis suggest that understanding uncertainty is likely to be extremely valuable.

Background

The National Policy Statement for Freshwater Management 2014 (NPSFM) directs regional councils, in consultation with their communities, to set objectives for the state of fresh water bodies in their regions and to set limits on resource use to meet these objectives (MfE, 2017). The Canterbury Water Management Strategy provides a collaborative framework to achieve sustainable management of the Canterbury Region’s water resources. Setting catchment-specific nitrogen leaching limits through a local Zone Committee to meet the NPSFM requirements is a key part of this process.

The Waimakariri Zone is one of ten management zones within the Canterbury region. Nitrate concentrations are elevated in groundwater and surface water courses in the Waimakariri Zone, with median annual concentrations in one of these watercourses (Silverstream, a tributary of the Kaiapoi River) exceeding the NPSFM National Bottom Line of 6.9 mg/L nitrate-N in recent years. The Waimakariri Water Zone Committee is currently exploring options to achieve environmental, economic and community priority outcomes through a range of non-statutory and statutory measures within the zone. Controls on nitrogen leaching rates from land within stream catchments is one option for reducing stream nitrate concentrations. OVERSEER®-based estimates of current nitrogen (N) leaching rates and the reduction that would be required to reduce nitrate to below the target concentration (e.g. <6.9 mg/L in all years) are required to determine nitrogen loss targets and to assess the associated economic impacts.

Arbuckle (2015) notes that OVERSEER® has historically been used as a nutrient use advice tool, to help farmers make improvements to farm management practices and the use of inputs like fertiliser. Through its continual development through industry and science, it has become a trusted farm decision support tool. Many regional government groups now rely on OVERSEER® to estimate nitrogen losses from the soil profile, to underpin nitrogen emission limit setting. Experienced regional council staff have communicated their unease about the use of the OVERSEER® model beyond its purpose as a farm decision support tool, however.

Industry practitioners (e.g. Edmeades, 2015) and the farming community have also voiced concerns over OVERSEER's® fitness for purpose for setting nutrient limits in regional council plans.

Modelled N loss uncertainty analysis

Understanding modelled N loss uncertainty is important in two regards. Firstly, the widespread view that use of OVERSEER®-derived N loss estimates to set catchment-scale nutrient limits is an inappropriate use of this tool needs to be addressed to maximise stakeholder acceptance of these limits. Accounting for uncertainty is the best way to address this issue. Uncertainty quantification also allows decision-makers to:

- Understand the probabilities associated with model predictions of future nitrate concentrations;
- Weigh these likelihoods against potential economic impacts; and
- Consider the likelihood that a proposed management approach will be successful.

Watkins and Selbie (2015) note that while the importance of the various sources of uncertainty in models can be recognised, quantifying and accounting for them is particularly challenging, especially for a model describing complex farm systems like OVERSEER®. The authors reference a widely-cited report by Ledgard and Waller (2001), which estimated uncertainty of 25-30% for model predictions for N. They note, however, that this estimate did not include errors associated with measurements or uncertainty from data inputs, thus providing only part of the uncertainty picture. Since 2001 there have been several changes to the model; uncertainty estimates for the newer versions will be different. Although an updated uncertainty analysis could usefully be undertaken, quantifying all sources of uncertainty involved in the N leaching value produced by OVERSEER® is extremely difficult.

Krueger et al. (2012) note that there are an increasing number of models for environmental assessment and management that formally incorporate and rely on expert opinion sourced from a diverse range of experience and stakeholders. Development and application of these models is also increasingly set within the context of participatory, analytic-deliberative and adaptive approaches to managing complex environmental problems. In the absence of conclusive measured data, which may never be attainable at affordable cost and in due time given the complexity of environmental systems, expert opinion is often the only source of evidence (see Vrana et al., 2012). The authors observe that it is particularly when timescales are short and policy demands urgent, that expert opinion can bridge incomplete process understanding to operationalise academic research (see Rowan et al., 2012).

Given the above difficulties associated with a comprehensive quantitative uncertainty analysis of OVERSEER®, and the programme limitations of the Waimakariri project (the first phase of the uncertainty analysis needed to be completed within six weeks), an expert judgement uncertainty analysis approach was adopted.

Method

The Sheffield Elicitation Framework (SHELF, see Oakley and O'Hagan, 2016) for expert judgment was used to guide this project. The practical steps undertaken during the elicitation process (see O'Hagan, 2012) were as follows:

1. Select and engage expert panel. The selection process objectives were to recruit experts with good knowledge of the OVERSEER® software, soil science, farming practice and local conditions. Industry, research and regional council representation was sought, with time constraints being a factor in panel member availability.
2. Orientation and training. Options for the elicitation were discussed, such as whether uncertainty should be considered in terms of absolute nitrogen leaching rates or percentage deviation from the modelled leaching rate. The concept of personal probability was introduced: the outcome of the elicitation should be their own assessment of uncertainty based on their expert knowledge. The experts were given a training exercise to undertake, to cement the concept of personal probability and to familiarise them with the elicitation method.
3. Problem definition and elaboration (see explanation below).
4. Compile evidence dossier, circulate amongst panel and incorporate additional expert knowledge: a literature review of previous OVERSEER® modelling, uncertainty and sensitivity analysis studies, soil property information, irrigation efficiency assessments and climate modelling was undertaken, the results of which were summarised in an evidence dossier. Summary information on soil, topography, land use and climate data from the Waimakariri Zone was also included. Experts were invited to contribute additional information and knowledge to the evidence dossier (see discussion below).
5. A one-day initial elicitation workshop was convened on 10/10/2017 to discuss the information contained within the evidence dossier, finalise the elaboration, discuss quantity dependencies and start the uncertainty elicitation. The experts completed their personal probability analysis for each constituent quantity (see below) outside of the workshop.
6. Feedback and revision: a final workshop was held on 13/11/17 to review the personal probability analysis results and agree on how these should be combined into a set of group consensus probability distributions.

Problem definition and elaboration

Previous studies (e.g. Shepherd et al., 2013) discuss model uncertainty in terms of model inputs, model structure, model parameters and model implementation. The expert panel for this study agreed that elicitation of uncertainty around catchment-scale N leaching via direct elicitation would be challenging and error-prone due to soil and land use variability within the catchment, and difficulties in lumping model structural error with input error. The alternative to direct elicitation of a quantity of interest is to express the quantity in terms of other quantities, to elicit probability distributions for those constituent quantities (by direct elicitation) and then to derive the implied probability distribution for the quantity of interest (O'Hagan, 2012). The expert panel chose to break the nitrate leaching uncertainty analysis down into five soil class and land use groups and into five modelling uncertainty variables (Figure 1).

The OVERSEER® model evaluates N losses under the assumption that Good Management Practice (GMP) is undertaken in accordance with the Industry-agreed Good Management Practices relating to water quality (MGM Governance Group, 2015).

Evaluation of the benefits of land users moving from current management practice (CMP) to GMP was an important component of the study, since a key question for nitrate management in the Waimakariri zone is whether implementation of GMP is likely to be sufficient to achieve nitrate targets in surface water and groundwater. An additional constituent quantity was included to address the uncertainty associated with assumptions made to translate modelled GMP N loss rates into CMP rates.

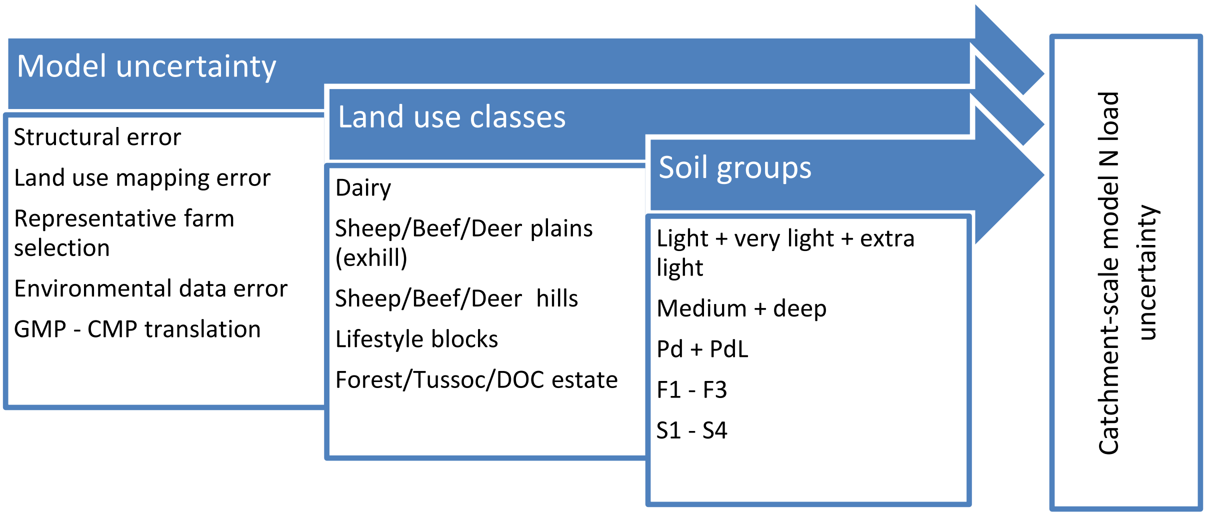

Figure 1 Elaboration of modelled N load uncertainty

Evidence dossier

Oakley and O'Hagan, (2016) advise that compilation and review of an evidence dossier is a fundamental part of the elicitation process to:

- Ensure that the final elicited distribution is firmly based on all available evidence;
- Make sure all experts are making their judgements on the same body of evidence; and
- Address the availability heuristic, a source of judgement bias identified in psychological research, whereby people make judgements based only on the evidence that they can quickly recall, and so they ignore less memorable evidence. If they later bring more data to mind, it may be selectively accessed to support opinions based originally on the readily available evidence.

Initial elicitation

Experts were asked to use the MATCH Uncertainty Elicitation Tool (Morris et al., 2014) to define their personal probability distributions around the modelled N loss rate for each soil and land use group and for each of the constituent quantities. The area of land covered by some soil and land use combinations was negligible (e.g. dairy farming on F1-F3 soils); this reduced the total number of constituent quantities to 32. The Roulette method was adopted since this provided a relatively quick, visual method for definition of a probability distribution (see Figure 2).

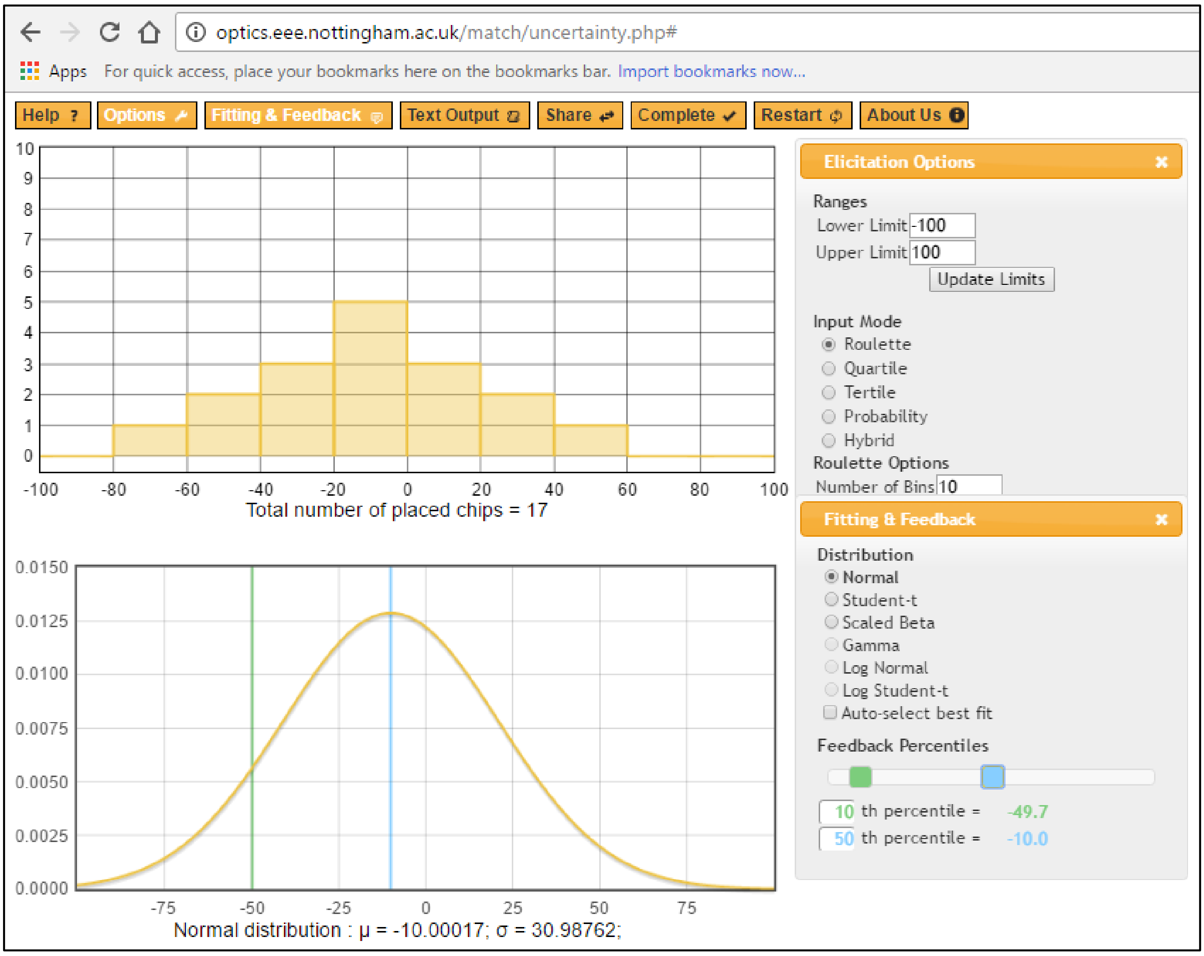

Figure 2 **Roulette web-based elicitation tool**

Quantity dependencies

Determination of whether the constituent quantities defined through the elaboration process should be treated as independent or dependent quantities is necessary for statistically valid uncertainty analysis. A set of quantities are independent if learning additional information about one of them would not affect an expert's judgements about the others. However, as Oakley and O'Hagan, 2016 note, independence is itself a subjective judgement. For instance, two quantities X and Y may be independent for one expert but not for another. If X and Y are not judged to be independent, distributions for X and Y can still be elicited separately, but these marginal distributions are now not a complete description of the experts' knowledge about X and Y. In this instance it is necessary to also elicit how knowledge of one quantity would affect judgements about the other.

All experts agreed during the initial elicitation workshop that at least some of the soil class and land use group constituent quantities should be treated as dependent. A correlation matrix was used to elicit dependencies, with the matrix values processed using the Spearman rank-order method. The model uncertainty components were assumed to be summative such that:

- Total uncertainty for modelled CMP N loss = Structural error+ Land use mapping error + Representative farm selection error + Environmental data error + GMP/CMP translation error; and
- Total uncertainty for modelled GMP N loss = Structural error+ Land use mapping error + Representative farm selection error + Environmental data error

Feedback and revision

The personal probability constituent quantities for model uncertainty (left hand box in Figure 1) were summed to generate a combined probability density function (PDF) for each soil and land use group and for each expert prior to the final workshop. A weighted average Group PDF was also generated, with each expert initially assigned a weighting factor of 1. The experts were then shown plots of their summed personal PDFs and the Group PDF for each soil/land use group; individual experts were then asked to explain the reasoning behind their uncertainty estimates, particularly where significant divergences of opinion were apparent from the plots (see Figure 3). Some of the views discussed amongst the experts are summarised below.

Dairy on light soils

- Modelled losses are likely to increase with improved understanding of water holding capacity in light stony soils.
- The variability in field conditions is impossible to manage in modelling. Non-uniform conditions and consequences of on-farm management are much more significant on soils with low PAW. It is also hard to manage deficit irrigation on light soils.
- Issues around default pasture quality values were cited, noting that the regional shapefile dataset is ten years old. Modellers need to change the default value in order to replicate actual pasture growth and consumption. This leads to a higher modelled N intake and discharge, and cancels out some of the positive bias in the modelling results.

Dairy in medium + deep soils

- Modelled N leaching rates for Medium soils is likely to be more reliable than light soils, and in particular for dairy farms, since the model has been tested and optimised using data that more closely matches the Medium soil dairy farms. The error margins around the dairy medium soils group should therefore be smaller than all other groups.

PD soils

- Estimates of nutrient losses from land with mole drains (a common feature of poorly drained soils) are not thought to be reliable. The model is likely to underestimate N losses because bypass flow via soil drains is not well represented, and there is little information available as to the location and effectiveness of mole drains. On the other hand, the ME (metabolisable energy) value of pasture is likely to be underestimated, with more energy in feed than OVERSEER® assumes. This probably cancels out some of the positive bias in the model results.

Lifestyle blocks

- Some lifestyle block land is irrigated, with feed brought onto site and fertiliser applied. This means that intensive land use can occur on these blocks.
- Some lifestyle block land is leased to farmers, hence stocking rates can be similar to dryland farm rates.
- Conversely, orchards and gardens are likely to have low N loss rates.
- The mean modelled N loss rates for lifestyle blocks in the Waimakariri zone is ~5 kg/ha/year, which is consistent with low intensity land use. However, if 80% of lifestyle blocks are low intensity and the remaining 20% are high intensity (e.g. leaching 12 kg/ha/year, a typical model leaching rate for dryland on the Waimakariri plains), the mean loss rate would be 6.4 kg/ha/year, some 30% higher than the assumed value. This provides an indication of the potential for significant negative bias in the assumed value for lifestyle blocks

Sheep/Beef/Deer

- Soils and climate data are limited for hill country, which introduces more error.
- Conversely the absence of irrigation on this land reduces error associated with irrigation efficiency uncertainty.
- There is no validation data for OVERSEER® hill country modelling.

Forest/Tussock/DOC estate

- The assumed N loss rate for these land types appears high. A previous comparison of modelled loss rates for the Ashley River/Rakahuri catchment at the Ashley Gorge monitoring site showed that modelled rates were much higher than measured rates, even after accounting for reasonably in-stream uptake by periphyton and macrophytes and time lags between land use change and nitrogen transport through groundwater. The N loss estimates for this land in the Waimakariri Zone are therefore uncertain and may be positively biased.

GMP – CMP translation

- The likelihood of a 5% positive bias in the assumed GMP/CMP translation was raised.
- Alister Metherell's Canterbury Land and Water Regional Plan: Plan Change 5 hearing evidence was discussed, which shows that a 95th percentile certainty positive bias of 20% could be appropriate.

Model structural error

- It was noted that use of mean annual synthetic daily time series climate data is likely to introduce error: modelling long-term transient time series data would yield different results. The magnitude of this error is currently unknown but could be quantified through a modelling study.
- The impact of flush-through events was discussed, whereby nitrogen accumulates in the soil profile and vadose zone during prolonged dry periods and is subsequently discharged to groundwater when the dry period ends. This matter needs to be considered when applying modelled N loss rates for surface and groundwater quality simulation.

The discussion of individual views was extremely productive: experts were receptive to knowledge held by their fellow experts, and were willing to change their views where a compelling line of reasoning was presented. This collaborative mentality resulted in group agreement to adjust the weighting factor for individual expert PDFs such that the Group PDF was weighted towards areas of individual expertise for each constituent quantity. For instance, if an expert presented a well-supported view on why the modelling is likely to have underestimated N loss for Dairy on Light soils, other experts who had not included a positive bias in their PDF agreed to reduce the weighting factor for their PDFs for that quantity.

Experts were then presented with the Group PDF 5th, 50th and 95th percentile uncertainty factors for each soil and land use group. They were asked to think carefully about whether they really were 90% confident that the true N leaching rate fell between their 5th and 95th percentile values, and whether positive or negative biases, as defined by a non-zero Group PDF median value, were appropriate. Some further adjustments were made to the Group PDFs following these deliberations.

Results

Individual and Group PDFs and CDFs (cumulative density functions) plotted in Figure 3a and Figure 3b show where the pre-feedback and revision individual expert PDFs were reasonably well aligned (e.g. Sheep/Beef/Deer for all three soil classes) and where significant differences were apparent (e.g. Forest/Tussock/DOC estate).

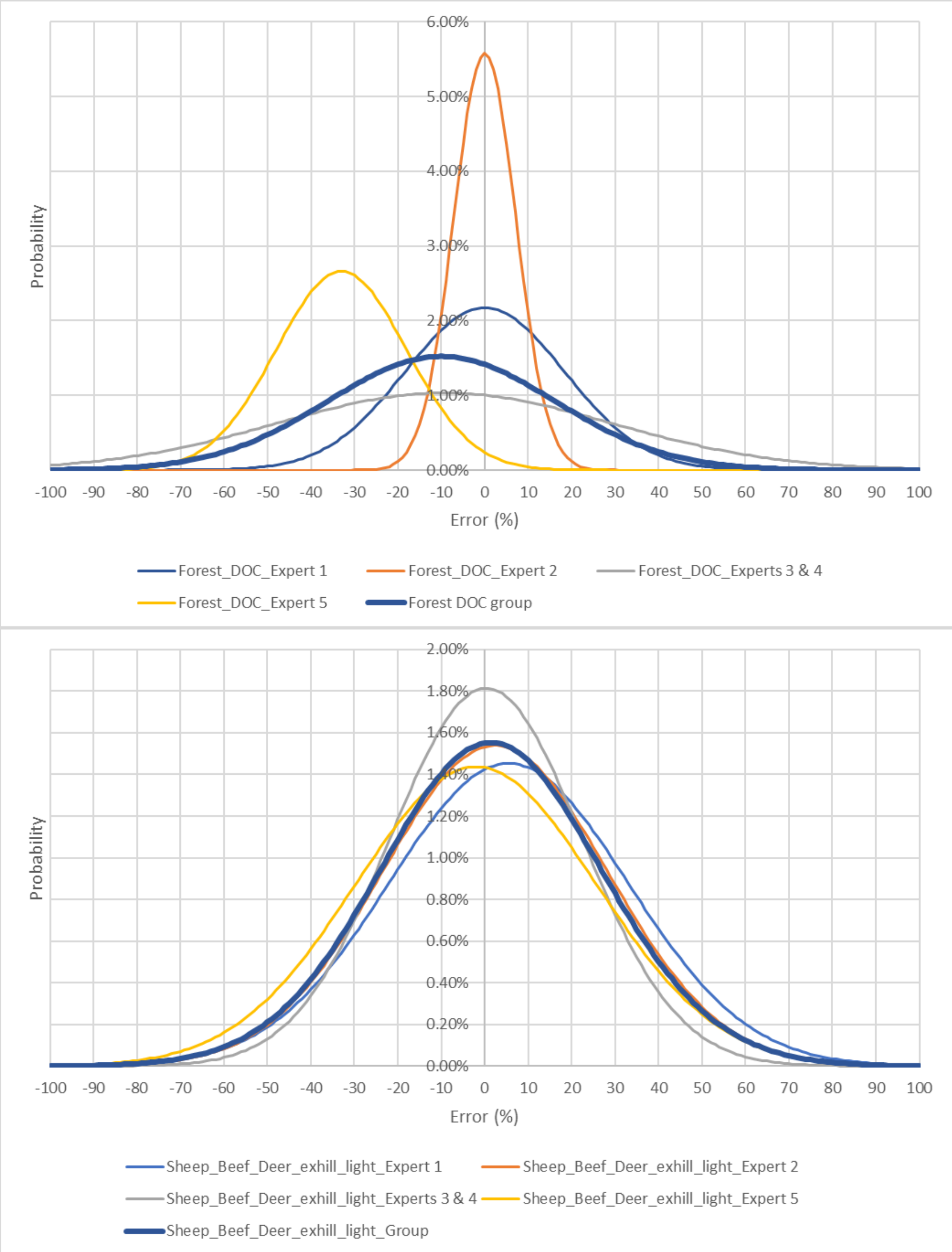

Figure 3a Individual and Group PDFs for Forest/Tussoc/DOC estate and Sheep/Beef/Deer ex-hill Light soils

Summary statistics for the Group CDFs (Table 2) show modest positive bias in the median values for Dairy farms on Light and PD soils and Sheep/Beef/Deer farms on F and S class soils – i.e. the experts considered that model results are likely to under-predict N losses from this land slightly. The experts considered that true N loss from Forest/DOC/Tussock is likely to be 11% less than the modelled value. 90 % confidence intervals ranged from -34 to 32% (Dairy on Medium soils) to -50 to 60% (Sheep/Beef/Deer hill on S class soils).

Table 1 Summary N loss uncertainty statistics for soil/land use groups

Class	5th	Median	95th
Dairy/Light	-32%	5%	49%
Dairy/Medium	-34%	0%	32%
Dairy/PD	-35%	6%	62%
Forest/DOC/Tussock	-54%	-11%	32%
Lifestyle	-46%	0%	40%
Sheep/Beef/Deer ex-hill/F	-34%	7%	48%
Sheep/Beef/Deer ex-hill/Light	-42%	1%	43%
Sheep/Beef/Deer hill/S	-50%	4%	61%

The constituent quantity correlation matrix (Table 2) shows a strong correlation between N loss uncertainty for Dairy farms on all main soil types in the zone and a modest correlation between Dairy farms and Sheep/Beef/Deer farms on the plains (i.e. ex-hill). Dairy farms and Lifestyle blocks were considered to be weakly correlated, and N loss estimates for Forest/Tussock/DOC estate were assumed to be independent of all other soil/land use groups. It should be noted that, due to time constraints, the correlation matrix was subjected to less expert group scrutiny than the constituent quantity PDFs during the feedback and revision workshop. The correlation matrix is therefore less robust than the Group modelled N loss uncertainty PDFs.

Table 2 Constituent quantity correlation matrix

	Dairy Light	Dairy Medium/ deep	Dairy PD	Sheep/Beef/ Deer (ex-hill) Light	Sheep/Beef /Deer (ex-hill) F	Sheep/Be ef/Deer (hill) S	Lifestyle
Dairy Light	1	0.9	0.85	0.4	0.4	0.15	0.05
Dairy - Medium/ deep		1	0.85	0.4	0.4	0.15	0.05
Dairy PD			1	0.4	0.6	0.15	0.05
Sheep/Beef /Deer (ex-hill) Light				1	0.7	0.6	0.4
Sheep/Beef /Deer (ex-hill) F					1	0.6	0.4

	Dairy Light	Dairy Medium/ deep	Dairy PD	Sheep/Beef/ Deer (ex-hill) Light	Sheep/Beef /Deer (ex-hill) F	Sheep/Beef/Deer (hill) S	Lifestyle
Sheep/Beef /Deer (hill) S						1	0.24
Lifestyle							1

Application of uncertainty analysis outputs

N load modelling method

The modelling method summary in Figure 4 (which all experts were familiar with prior to the elicitation process) explains how a nitrogen loss estimate layer was generated for the study area. A summary of the process undertaken to generate this layer, upon which the uncertainty analysis was based, is provided below. Further details are presented in Lilburne et al. (2017).

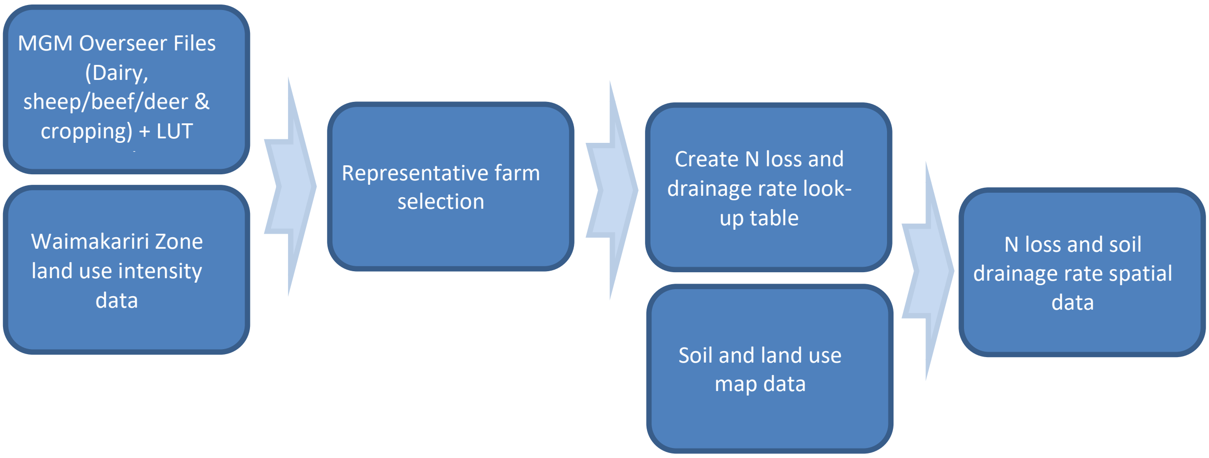

Figure 4 Spatial nitrogen leaching modelling

The lookup table of N loss rates for the Waimakariri area was derived using a combination of values from the MGM (Robson et al. 2015). An earlier database (known as the Look Up Table Patch; LUT; Lilburne et al. 2013) was used to obtain estimates for farm types not covered by MGM (horticulture, forestry, pigs). The MGM values are based on version 6.2.2 of the Overseer Nutrient Budget model.

Three spatial datasets were generated: N losses (kg/ha) under Good Management Practice (GMP), N losses under current management practice (CMP) and drainage (mm of water) below the root zone under GMP. For the CMP N loss data a set of coefficients were developed to back-translate N losses under GMP to CMP, with a single coefficient used for each broad land use class (cropping, dairy, dairy support, sheep & beef). These factors were derived by estimating the average effect of MGM GMP proxies using a sample of local and regional OVERSEER® nutrient budgets. Masked areas (including urban and non-agricultural land) and rural areas with unknown land use are assigned default values of 2 and 21 kg/ha respectively. Dairy loss rates were not available for all climate zones and soils, so the N loss rates for the nearest equivalent climate zone/soil were used (Lilburne et al., 2017).

Application of uncertainty analysis results

Nitrate limits are likely to be implemented in the Waimakariri zone through spatially defined management areas. Because these management areas will encompass a range of soil/land use groups, it was necessary to translate soil/land use Group PDFs into management area PDFs. These were, in effect, spatially weighted means of the soil/land use group PDFs which accounted for constituent quantity correlations (Table 2). The method used to generate these management area N loss uncertainty PDFs was is summarised below.

1. Assign uncertainty PDFs to each soil/land use/climate class polygon in modelled N loss layer
2. Run Monte Carlo simulation for each of the eight soil/land use groups using the Group PDFs to generate 10,000 random samples of possible nitrate leaching values
3. Use the mc2d package in R (Poulilot and Delignette-Muller, 2010) and expert-elicited correlations between nitrate leaching values for soil/land use groups to perform a spearman rank correlation on the samples for each group. This orders data such that errors between elicited constituent quantity correlations and rank-ordered Monte Carlo dataset correlations are minimised. The result is 10,000 iterations of eight correlated nitrate leaching values, one corresponding to each soil/land use group
4. Create shapefiles of nitrate management areas within Waimakariri Zone and index soil/land use/climate class polygons to management area shapefiles
5. Write and run Python script to generate specific N loss uncertainty PDFs for each management area.

Examples of the outputs of this data processing for three of the proposed nitrogen management areas (Table 3) give 90% confidence range modelled N loss uncertainties ranging from -38% to + 42% and -27% to +33%. These uncertainty factors have been translated into N load estimates for various uncertainty percentiles in the lower part of the table.

Although application of these outputs to the nutrient limit decision-making process is ongoing at the time of writing, findings from initial analysis suggest that understanding uncertainty is likely to be extremely valuable. In management area No. 2, for instance, the modelled N loss rates (780 t/year prior to adjustment for bias) are much higher than can be accounted for from current measured nitrate data. This suggests that nitrate concentrations are expected to increase over time, as N losses associated with more recent land use intensification move slowly through the groundwater system and start to arrive in the surface water body (nitrate attenuation in groundwater is likely to be negligible in this area). Without uncertainty analysis, the difference between modelled and measured values might be attributed to model error. However, the 5th percentile model-based nitrate load for management area No. 2 (539 t/year) still represents a significant increase relative to current measured data. This implies that experts are 95% confident that nitrate concentrations in the management area are likely to increase significantly in the future. Better-informed decisions on appropriate nitrate limits can be made based on this understanding.

Table 3 Example of N loss uncertainties for nitrate management areas

Percentiles	5th	25th	50th	75th	95th
Management area No.	Uncertainty				
1	-38%	-15%	2%	19%	42%
2	-28%	-10%	3%	17%	35%
3	-27%	-10%	3%	16%	33%
	N loss (tonnes/year)				
1	399	542	654	764	910
2	539	691	804	914	1,072
3	18	22	25	28	32

The uncertainty analysis method presented in this paper could be readily applied to any area in which N loss rates have been modelled to provide relatively quick, low cost approximate estimates of modelled N loss uncertainty. The approach could be adapted to encompass a range of scales from individual farm to large catchment.

Conclusions

Uncertainty associated with OVERSEER®-based catchment and sub-catchment scale N loss modelling was approximately quantified using an expert judgement elicitation process. Elicitation results show modest positive bias in the median N loss values for Dairy farms on Light and PD soils and Sheep/Beef/Deer farms on F and S class soils – i.e. the experts considered that model results are likely to under-predict N losses from this land slightly. The experts considered that true N loss from Forest/DOC/Tussock is likely to be 11% less than the modelled value. 90% confidence intervals ranged from -34 to +32% (Dairy on Medium soils) to -50 to +60% (Sheep/Beef/Deer hill on S class soils) relative to the modelled values.

The Roulette elicitation method provided a relatively quick pathway for generation of personal probabilities. Previous experience of the authors has indicated that use of the Quartile method, with strict adherence to SHELF, can provide more robust results. Consideration should be given to the range of possible elicitation methods for any future application of this approach to N loss uncertainty analysis.

Elicitation of the correlation matrix was undertaken within a very short timeframe and with limited feedback and revision by the expert panel. This should be addressed by a more thorough review of constituent quantity dependencies in the future.

A larger data set of GMP versus CMP Overseer files should be reviewed in the future to provide a more rigorous assessment of the uncertainty associated with translation of modelled GMP N loss rates to CMP rates.

Comparison on measurement-based N loads with model data for one catchment provided useful insights into the likely model error magnitude. The robustness of the uncertainty elicitation process could potentially be improved significantly by including more such comparisons. Undertaking the uncertainty analysis process for a larger area, in which more sites with measurement data are available, would make this possible.

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