Modelling farm dairy effluent (FDE) discharges in Northland

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Contents

1. Executive Summary ... 1

2. Background ... 4

3. Methods ... 4

3.1 Model structure ... 5

3.2 Up-stream *E. coli* concentrations and flow rates ... 6

3.3 Landscape features of soil type and rainfall ... 7

3.4 Modelling three FDE management systems ... 8

3.4.1 2-Pond system ... 8

3.4.2 FDE irrigation systems ... 8

3.5 Outputs of the Model ... 10

4. Results and Discussion ... 10

4.1 Modelled losses from excess FDE volume ... 10

4.2 Calibration of the outputs ... 13

4.3 Scenario outputs for sensitivity testing of the model ... 15

4.4 Scenario analysis and implications for swimming water quality metrics ... 23

4.5 General Discussion ... 24

5. Conclusions ... 26

6. Acknowledgements ... 27

7. References ... 28

1. Executive Summary

DairyNZ has commissioned this modelling exercise to define the potential impacts of farm dairy effluent (FDE) discharges upon stream faecal indicator concentrations for a hypothetical farm system and receiving environment. Scenario details were developed to approximate a typical Northland dairy farm load discharged at one location to a single receiving stream. The results of the scenario modelling are intended to offer a first-order approximation of the impact of a FDE discharge on stream *E. coli* concentrations, to assess impacts on state of water quality for human health.

The report is structured as follows. The methods section describes the structure of the model and the Northland-specific data used in the simulations. In the results section we:

a) initially describe the modelling assumptions used to estimate the daily volumes and *E. coli* concentrations from the FDE irrigation management practices,

b) provide some calibration of the model outputs against measured data from Northland 2-pond discharge effects on stream *E. coli* concentrations,

c) run a series of simulations to see how sensitive the outputs are to the different factors in the model,

d) conduct a series of simulations to estimate the effects of different FDE management approaches on *E. coli* concentration for a distance 2 km down-stream from the point of discharge.

The modelling equations and approach are based predominantly on that described in Muirhead et al. (2011) and Muirhead et al. (2010), modified to better reflect the situations in Northland. The model uses Monte Carlo simulations to take into account the expected or natural variability in the input values and generates a distribution of expected stream *E. coli* concentrations. Thus the outputs include a range from best case to worst case outcomes, generating a distribution of likely stream *E. coli* concentrations for each of the different FDE scenarios.

To estimate the effect of the FDE management scenarios on the downstream human health state, four different up-stream or background *E. coli* concentration distributions, were used. For the calibration tests, modelled effects were varied to approximate actual, measured FDE impacts from stream monitoring data collected by Northland Regional Council (NRC). For other simulations, up-stream *E. coli* concentrations were set to swimmable attribute states of either A (blue), B (green) or C (yellow) in the 2017 Clean Water Government revisions to the National Policy Statement for Freshwater Management.

The calibration model outputs of stream *E. coli* concentrations at the point of discharge were similar to the NRC measured observations, at a stream flowrate of 10 L s^{-1}. But at high stream flow rates the model underestimated measured observations. This indicates that the model generated a reasonable representation of the real situation generated by 2-pond FDE discharges to Northland streams at low stream flow rates.

The FDE scenario modelling demonstrated marked impacts of 2-pond FDE discharges on stream *E. coli* concentrations for >12 km downstream, whereas outputs from the irrigation scenarios (without storage) extended for <5 km. Even at an exceptionally high stream flow rate of 300 L s^{-1}, there is still a noticeable impact from the 2-pond FDE scenario compared to no observable effect from the FDE irrigation scenarios (without storage), on the distribution of immediate *E. coli* concentrations. This was largely the consequence of considerable proportions of FDE loads not reaching the stream under irrigation scenarios. Sensitivity analysis demonstrated greater storage enabled greater retention of FDE on-farm, preventing its loss to stream, with 90 days storage associated with zero FDE loss to stream for 95% of the time.

In summary, the model demonstrated stream *E. coli* concentrations were:

- most sensitive to the stream flow rates, FDE management (2-pond vs irrigation) and FDE storage in irrigation scenarios,
- moderately sensitive to farm size and FDE irrigation connectivity (risk of FDE reaching the stream),
- least sensitive to climate, soil type and FDE irrigation rate (mm h^{-1}).

Findings from scenario testing of effects 2-km down-stream, on a background of A to C bands under the swimming water quality metrics in the Clean Waters 2017 revision to the NOF attributes are shown in Table 1. In these scenarios the FDE irrigation systems included 90 days storage, but under a high level of connectivity to the stream, across combinations of two common soil types, high and low rainfall conditions, and high and low rate irrigation systems. In all three NOF bandings (A to C) the downstream impact of a 2-pond direct discharge to water is an un-swimmable grade (E). In contrast, for all FDE irrigation scenarios across wide-ranging environmental conditions but with 90 days storage, the downstream water quality would still achieve a swimmable grade of A or B.

Table 1. Water quality swimability grading 2 km downstream from the farm when the water up-stream from the farm is a swimmable (A, B or C) grade.

Management	**Up-stream WQ grade**		
	A	B	C
	Downstream WQ grade		
2-pond FDE discharge	E	E	E
High Rainfall, Ultic Soil, High Rate FDE Irrigation	A	A	B
High Rainfall, Ultic Soil, Low Rate FDE Irrigation	A	A	B
High Rainfall, Brown Soil, High Rate FDE Irrigation	A	A	B
High Rainfall, Brown Soil, Low Rate FDE Irrigation	A	A	B
Low Rainfall, Ultic Soil, High Rate FDE Irrigation	A	A	B
Low Rainfall, Ultic Soil, Low Rate FDE Irrigation	A	A	B
Low Rainfall, Brown Soil, High Rate FDE Irrigation	A	A	B
Low Rainfall, Brown Soil, Low Rate FDE Irrigation	A	A	B

The adoption of FDE irrigation systems utilising a deferred irrigation strategy would reduce *E. coli* discharges from dairy farms in the Northland Region. While sensitivity analysis indicated a maximum of 90 days storage would deliver greatest benefit for stream *E.coli* concentrations from FDE irrigation scenarios, the actual storage volume required on farms will vary in line with particular farm setup and conditions. This can be readily calculated using the dairy effluent storage calculator developed by Massey University and DairyNZ.

Further work on understanding and modelling of catchment scale *E. coli* concentrations and loads would be required to determine the impact of adopting FDE irrigation across dairy farms throughout actual Northland river networks. Our model calibration highlighted potentially important factors affecting microbial die-off in streams that are as yet poorly understood by current modelling approaches, a finding also acknowledged in the international literature.

2. Background

The process of milking cows generates a liquid waste stream from washing the milking shed that is usually referred to as farm dairy effluent (FDE; can also include stand-off pad and/or feed-pad associated animal waste). In the dairy industry the management of this FDE has improved to reduce the impact of this waste stream on water quality metrics, principally organic matter, nutrients and faecal indicators. Most regions in NZ have adopted FDE land-application irrigation systems as the preferred management approach for risks to water quality. However, Northland Regional Council (NRC) still permits FDE discharges directly to water from 2-pond systems and also hybrid systems where they irrigate to land under dry weather conditions but allow direct discharge to water during “high” flows. This approach is at odds with wider-Industry and regional authority developed good management practice (GMP) of FDE risks to water quality in New Zealand.

DairyNZ has commissioned this modelling exercise to approximate potential impacts of FDE discharges on stream faecal indicator (*E. coli*) concentrations for a hypothetical farm system and receiving stream. Scenario details were developed to approximate a typical Northland dairy farm FDE load discharged at one location to a single receiving stream. The results of the scenario modelling are intended to offer a first-order approximation of the impact of FDE management on stream *E. coli* concentrations and from this, water quality for human health state. Findings are of value to determine dairy farming performance on current and proposed faecal indicator objectives in the Northland regional water and soil plan as well as national objectives for 90% of streams and rivers to achieve a swimmable state by 2040. Note that further research is needed to extrapolate from this first-order approximation of current or altered FDE management impacts on stream faecal indicator concentrations across actual river networks in Northland; the report is intended to determine relative change to stream *E. coli* concentrations for a single farm under broadly representative farm and environmental conditions for Northland.

This report is structured as follows. The methods section describes the structure of the model and the Northland-specific data used in the simulations. In the results section we:

a) Initially describe the modelling assumptions used to the estimate the daily volumes and *E. coli* concentrations for the FDE irrigation management practices.

b) Provide some calibration of the model outputs against measured data from Northland 2-pond discharge effects on stream *E. coli* concentrations.

c) Run a series of simulations to see how sensitive the outputs are to the different factors in the model.

d) Conduct a series of simulations to estimate the effects of differing FDE management approaches on *E. coli* concentrations for a distance 2 km downstream of the farm.

3. Methods

The modelling equations and approach are based predominantly on that described in Muirhead et al. (2011) and Muirhead et al. (2010) but modified to better reflect the situations in Northland. These modifications are discussed below.

3.1 Model structure

The model is structured as a daily time step process so the load of *E. coli* estimated for the FDE management practice is diluted into the daily volume of water flowing in the river or stream (Figure 1). There is an up-stream concentration of *E. coli* already in the river or stream. The concentration at the point of discharge is the average concentration of the combined load of *E. coli* and volume of water from the river and FDE discharge assuming perfect mixing. From the point of discharge the *E. coli* concentration decreases using a first-order decay coefficient to account for die-off and assumes no additional inputs to the stream (Muirhead et al. 2011).

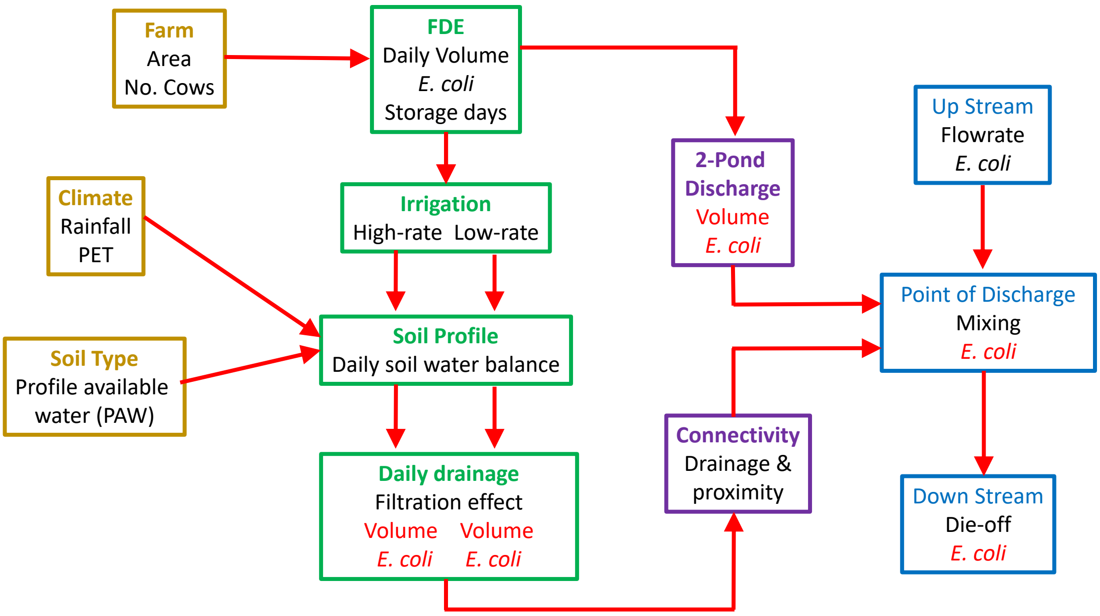

Figure 1. Structure of the Monte Carlo simulation model used for estimating the impacts of FDE discharge on in-stream water quality metrics. The brown boxes represent the farm and landscape-specific information used to drive the models. The green boxes represent the FDE management practices. The purple boxes represent the losses of FDE to the stream network. The blue boxes represent the in-stream processes that are modelled. The coloured text in the boxes describe the processes or managements that are represented in the model. The black text describes the specific factors that are varied in the different model simulations. The red text describes specific outputs of the model. Note – PET is potential evapotranspiration rate.

The model uses Monte Carlo simulations to take into account the expected or natural variability in the input values and generates a distribution of the expected results. Thus the outputs can be seen as a range from best-case to worst-case outcomes for the different input scenarios.

There are three different components in each model situation: (a) the up-stream *E. coli* concentration and flow in the river water, (b) the landscape features of specific soil types and rainfall and (c) the type of FDE management system used. **Note** the 2-pond effluent management system is assumed to discharge directly to the river so does not use the landscape components of the model.

The base farm inputs used in the modelling were a 136 ha farm milking 315 cows, derived from an expert workshop held by DairyNZ in May 2017, to represent the average farm setup for Northland. The farm was seasonal milking with no FDE generated during the winter period. A large farm of 400 ha milking 920 cows was also modelled to test the effect of a large volume of FDE on stream impacts, this scenario was also derived at the expert workshop.

3.2 Up-stream *E. coli* concentrations and flow rates

Four different up-stream *E. coli* concentration distributions were used. For the calibration tests comparing the modelled outputs to measured data from NRC the up-stream concentration was based on the FDE impact-assessment monitoring data which was calculated as a log-normal distribution with mean and standard deviation values of 2.6 and 0.8 Log_{10} *E. coli* 100 mL^{-1}, respectively (n = 350; 2010-2012; faecal coliform up-stream measurements). All other simulations were conducted assuming that the up-stream concentrations achieved the swimmable attribute states of either A (blue), B (green) or C (yellow) in the 2017 Clean Water Government revisions to the National Policy Statement for Freshwater Management. These attribute states relate to a generalised risk of infection to primacy contact users of <1, <2 and <3% for attribute states of A, B and C, respectively. The *E. coli* concentration distribution for attribute state C was calculated as a log-normal distribution with mean and standard deviation values of 2.1 and 0.6 Log_{10} *E. coli* 100mL^{-1}, respectively, and are based on the data in Table 2. For attribute states A and B, the mean remained at 2.1 but the standard deviation was adjusted to 0.37 and 0.54 Log_{10} *E. coli* 100 mL^{-1}, respectively (data not shown). **Note** that to achieve an attribute state the *E. coli* concentration data must meet all 4 of the metrics in Table 2 – otherwise, the lowest graded metric determines the overall grade. Also **note** that the measured data from Northland have a higher mean and standard deviation than any of the distributions used for the swimmable water quality metrics (i.e. would currently be classified as unacceptable for swimming).

Table 2. Data showing the relationship between the numeric attributes for minimum swimmable guidelines and the comparable metrics for the modelled up-stream *E. coli* concentrations based on a log-normal distribution with a mean and standard deviation of 2.1 and 0.6 Log_{10} *E. coli* 100mL^{-1}, respectively.

Minimum swimmable water quality attributes – C grade		Modelled up-stream *E. coli* concentration distribution	
Numeric Attribute State Metrics	**Equivalent concentration (log_{10} *E. coli* 100mL^{-1})**	**Percentile of the modelled distribution**	**Modelled concentration (log_{10} *E. coli* 100mL^{-1})**
Median concentration <130 cfu 100mL^{-1}	2.1	50%	2.1
≤34 % exceedances over 260 cfu 100mL^{-1}	2.4	65%	2.3
≤20 % exceedances over 540 cfu 100mL^{-1}	2.7	80%	2.6
95th percentile of ≤1200 cfu 100mL^{-1}	3.1	95%	3.1

The other important up-stream factor in the model is the up-stream flow rates. This determines the volume of water each day that the FDE is diluted into that determines the downstream concentrations. After analysis of river flow rates in Northland and the expert workshop with DairyNZ, flow rates of 10, 300 and 10,000 L s^{-1} were selected to represent the flow rates in small tributary type streams, medium streams and large rivers, respectively.

3.3 Landscape features of soil type and rainfall

To model the FDE irrigation systems (see section 3.4) a soil water balance was calculated, which required input information for soil types, rainfall and potential evapotranspiration (PET). There is considerable variability in rainfall patterns and in soil characteristics across Northland. For this analysis, we chose two sets of soil type and rainfall characteristics, to represent best-case and worst-case situations on Northland dairy farms.

The rainfall and PET data was provided by David Horne from Massey University and is the same data that he has used in the dairy effluent storage calculator (DESC). From the 20 available rainfall data sites, we selected data from the highest and least rainfall locations. These were the Kerikeri and Arapohue sites, with average annual rainfall, of 1820 and 1143 mm, respectively.

The key soil characteristic that is used in calculating a soil water balance is the "profile available water" (PAW) or water holding capacity of the soil. Mapping analysis of the locations of dairy farms in Northland was conducted by DairyNZ as part on an ongoing inventory project to characterise the national distribution of environmental conditions on dairying and dairy support land, which identified that the majority of Northland dairy farms were located on Brown (BA) and Ultic soil types (UE). From the Smap, national soils database, we selected the Mangonui Hills soil to represent the Brown soil type, which had a PAW of 63 mm, and the Puketitoi soil to represent the Ultic soil type, which had a PAW of 145 mm. These two soil types represent the range of likely PAW values for most soils in Northland that are used for dairy farming.

3.4 Modelling three FDE management systems

There were 3 different FDE systems modelled: (1) a 2-Pond direct discharge to the stream; then two different types of irrigation systems, (2) a high-rate travelling irrigator; and (3) a low-rate system (e.g. K-line pods). The two irrigation system scenarios included different amounts of storage for operating a deferred irrigation strategy (Houlbrooke et al. 2004).

3.4.1 2-Pond system

The load of *E. coli* discharged from the 2-Pond FDE system was calculated from the volume of FDE produced per day and the concentration of *E. coli* in the effluent using the values from Muirhead et al. (2011). A search for more specific FDE volumes from Northland was conducted but did not identify any more credible data. The volumes of FDE produced are based on L/cow/day so can be easily changed for different sizes of farms. As the 2-pond systems discharge directly to streams, 100% of the daily load was used as the input for the steam model (Figure 1).

3.4.2 FDE irrigation systems

FDE irrigation systems in Northland typically irrigate from the outlet of an existing 2-pond system. Therefore, the FDE irrigation systems were modelled using the same daily load of *E. coli* as discharged from the 2-pond systems. However, only a proportion of the daily FDE load will actually reach the stream from these irrigation systems. There are 3 different factors that need to be modelled to understand the proportion of irrigated FDE that is lost to a stream and these are: (1) the volume of FDE that is greater than the soils water holding capacity (soil water balance: Figure 1), (2) even if the soils are saturated then only a proportion of the FDE will actually start to flow away from the irrigation site (drainage: Figure 1) and (3) of the FDE that starts moving, only a proportion of that FDE will actually travel all the way to the stream (connectivity; Figure 1). Some of the FDE will be absorbed into soil during the transport process. These 3 factors are modelled as individual steps.

3.4.2.1 Calculating the excess FDE volume (soil water balance)

If the soils are dry enough then all of the FDE irrigated will be absorbed into the soil. Thus the excess FDE volume will only occur when the irrigation occurs on soils already at or wetter than field capacity or if the volume of FDE applied resulted in field capacity being breached, this varies considerably from day to day. This volume will be affected by rainfall and evaporation from the soil, the soil water holding capacity and if FDE is irrigated on that day or not.

To conduct Monte Carlo simulations requires an input distribution of the probability of FDE irrigation exceeding soil field capacity on a daily basis. To generate this distribution we modelled the FDE irrigation system over a 30 year period (10,950 data points) which should account for long-term expected conditions of rainfall and evaporation across Northland dairy farms.

Firstly, a daily soil water balance was generated for each combination of rainfall and the two soil types. If there was no deferred irrigation pond storage capacity available then, during the milking season, the load of FDE was applied by the irrigation system (either high- or low-rate) and any excess FDE volume calculated for that day. Note - the high- and low-rate irrigation systems applied a similar depth of FDE each day (Muirhead et al., 2010). If there was deferred irrigation pond storage available then this was used, following the rules described in Muirhead et al. (2010). For each scenario the daily data from the 30 years was summarised as a cumulative probability distribution of excess FDE volumes applied to land. This cumulative probability distribution was then used in Monte Carlo simulations to estimate the stream effects of that load being received by the hypothetical stream.

3.4.2.2 Estimating the proportion of *E. coli* lost from the irrigation site (drainage)

Monaghan et al. (2010) showed that even under wet soil conditions that exceeded field capacity, less than 100% of the applied FDE actually discharged from the irrigation site. This effect is likely due to spatial variability of water holding capacity in the soils and was different for the high- and low-rate irrigation systems. In line with the findings of Monaghan et al. (2010), in this analysis we used a proportion of 81 and 40% to represent the volume of excess FDE that started moving from the irrigation site for the high- and low-rate irrigation systems, respectively.

3.4.2.3 Estimating the proportion of *E. coli* that reaches the stream (connectivity)

There is no published data on the proportion of FDE that would reach a stream, once flow over or through wet soils (exceeding field capacity) occurs. This component was therefore, estimated using AgResearch Scientists expert opinion. This effect is sometimes referred to as “connectivity” between the source of the contaminant loss and the stream where the effect occurs. The factors used in this estimate and type of landscape features that these could represent are summarised in Table 3. These specific factors were included in the Monte Carlo simulations to represent three scenarios of high, medium and low connectivity. The scenarios enable the effects of differing FDE managements on Northland dairy farms to be established across a gradient of risk for runoff of FDE to water.

Table 3. Level of connectivity between the irrigation site and the stream based on different landscape features.

Proportion of FDE that reaches the stream	Likely landscape features that would result in this level of connectivity
0.5 (high connectivity)	(a) FDE irrigation to poorly drained soil types with close proximity to the stream (<100m) or (b) FDE irrigated to soils with artificial drainage systems.
0.1 (medium connectivity)	(c) FDE irrigation to poorly drained soil types >100m from the stream or (d) FDE irrigation to well-drained soil types with close proximity to the stream (<100m).
0.01 (low connectivity)	(e) FDE irrigation to well-drained soil types >100m from the stream.

3.5 Outputs of the Model

The output of the model is the concentration of *E. coli* at the point of discharge to the stream and also at a number of points downstream, including a factor accounting for die-off. As this is a Monte Carlo simulation model the outputs are a distribution of concentrations estimated from all of the input distributions (e.g., across the gradient of PAW, FDE excess and FDE connectivity generated by scenarios). Thus, output represents a range of likely *E. coli* concentrations stream to cover the spectrum of extremes in processes governing FDE loss from dairy ponds or irrigators. The downstream concentrations are modelled on first order die-off rates which did not change in any of the scenarios (i.e., stream relative attenuation patterns are identical, downstream of the varying inputs). Therefore, for many of the scenario comparisons only the data from the point of impact are presented.

4. Results and Discussion

4.1 Modelled losses from excess FDE volume

One of the critical steps in the estimation of losses from FDE irrigation is the step of calculating the volume of FDE that is applied in excess of soil moisture deficit or the ability to infiltrate into it (see section 3.4.2.1). Our scenarios utilised Northland-specific data on soils (PAW), rainfall and PET to ensure that the results are regionally relevant to underlying risk factors on dairy farms.

The cumulative probability distributions of the proportions of FDE lost to water, across the two major dairying soil types in Northland, are shown in Figures 2 & 3. All cumulative probability curves intercept the Y axis at greater than 0.6 which indicates that FDE losses to runoff from irrigation equate to 0% for at least 60% of the time. This is due to no irrigation during the non-milking season and the many days during each year that the soils can absorb all of the irrigated FDE. The coloured lines on each individual graph show the large effect that storage days have and hence the importance of implementing a deferred irrigation strategy for reducing the risk of FDE excess generating runoff. For instance, having 90 days storage is sufficient to prevent any irrigation losses for 95% of the time regardless of the soil type, rainfall or irrigation system (i.e., equating to zero FDE ponding or runoff for approximately an extra third of the year, compared to no storage).

In Figures 2 and 3, comparing the top and bottom row of graphs shows that there is little difference or effect on FDE runoff generation, between the high- and low-rate irrigators. This is due the irrigators applying similar total amounts of FDE per day which the PAW can generally accommodate (Muirhead et al., 2010). In each Figure, comparing the left and right columns shows that the losses of FDE via runoff are greater for the high rainfall scenario, as expected given fewer days with adequate SWD. Also note that Figures 2 and 3 show FDE losses from the Brown soil type are greater under equivalent application volume, than the Ultic soil type, due to the Ultic soil type being able to absorb larger volumes of rain and FDE.

Other points to note about this modelling analysis is that the main effect of the soils is their different "profile available water" (PAW) which was modelled as 63 mm for the Brown soil type and 145 mm for the Ultic soil type. Other soils types in these soil series will have differing PAW values. The effect of the different drainage characteristics of these two soil types is captured in the connectivity factors shown in Table 3. In all FDE irrigation situations a low rate application system will have a lower risk of generating excess FDE volume but this effect is not captured using a daily time step model.

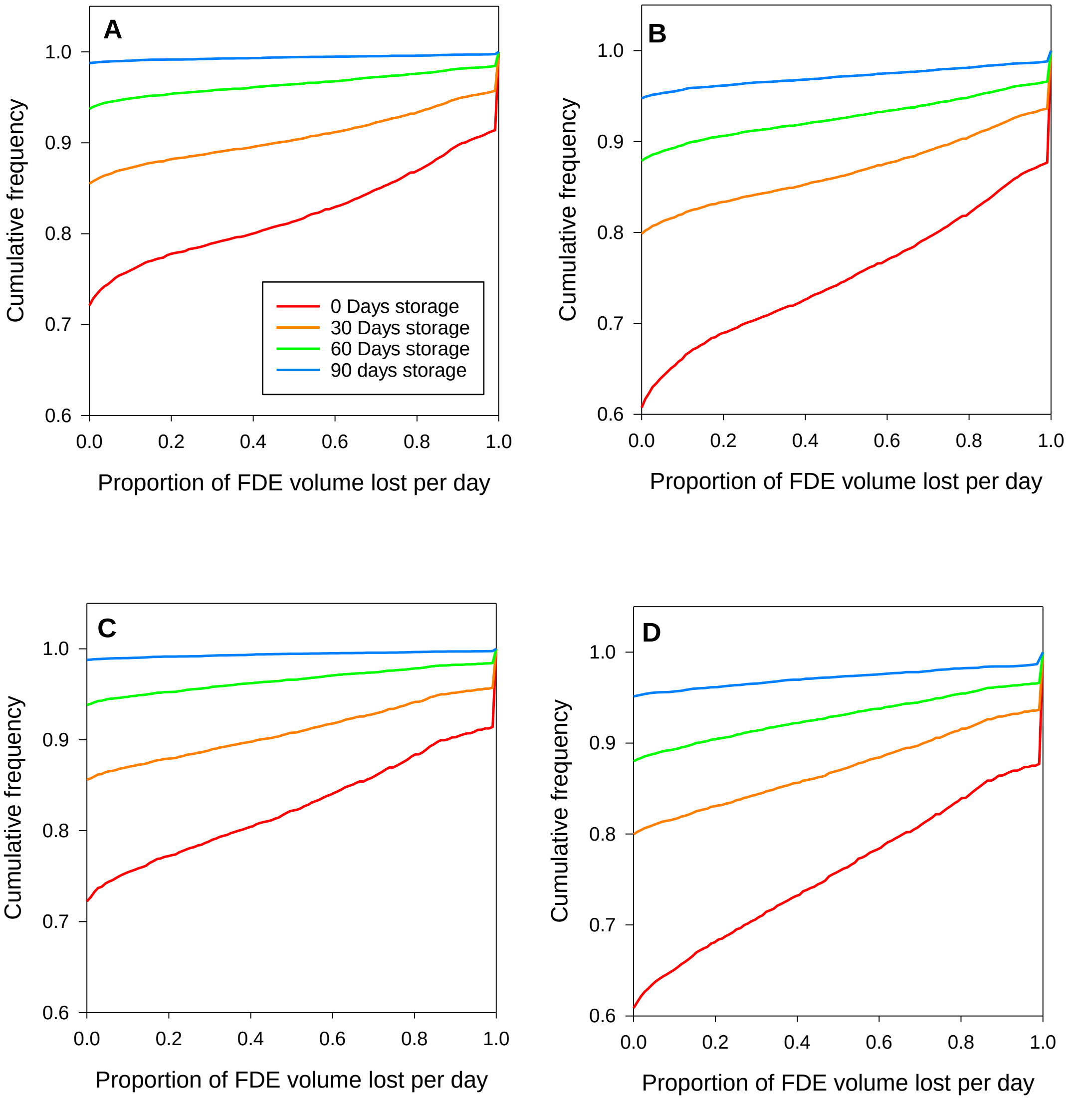

Figure 2. Cumulative probability distributions for the proportion of the FDE volume that is lost per day from irrigating onto the **Brown soil type** for scenarios with different irrigators, rainfalls and availabilities of pond storage. Graph A is the low rainfall and high-rate irrigator, Graph B is the high rainfall and high-rate irrigator, Graph C is the low rainfall and low-rate irrigator and Graph D is the high rainfall and low-rate irrigator. The different coloured lines represent the different number of days of FDE storage available for implementing a deferred irrigation strategy.

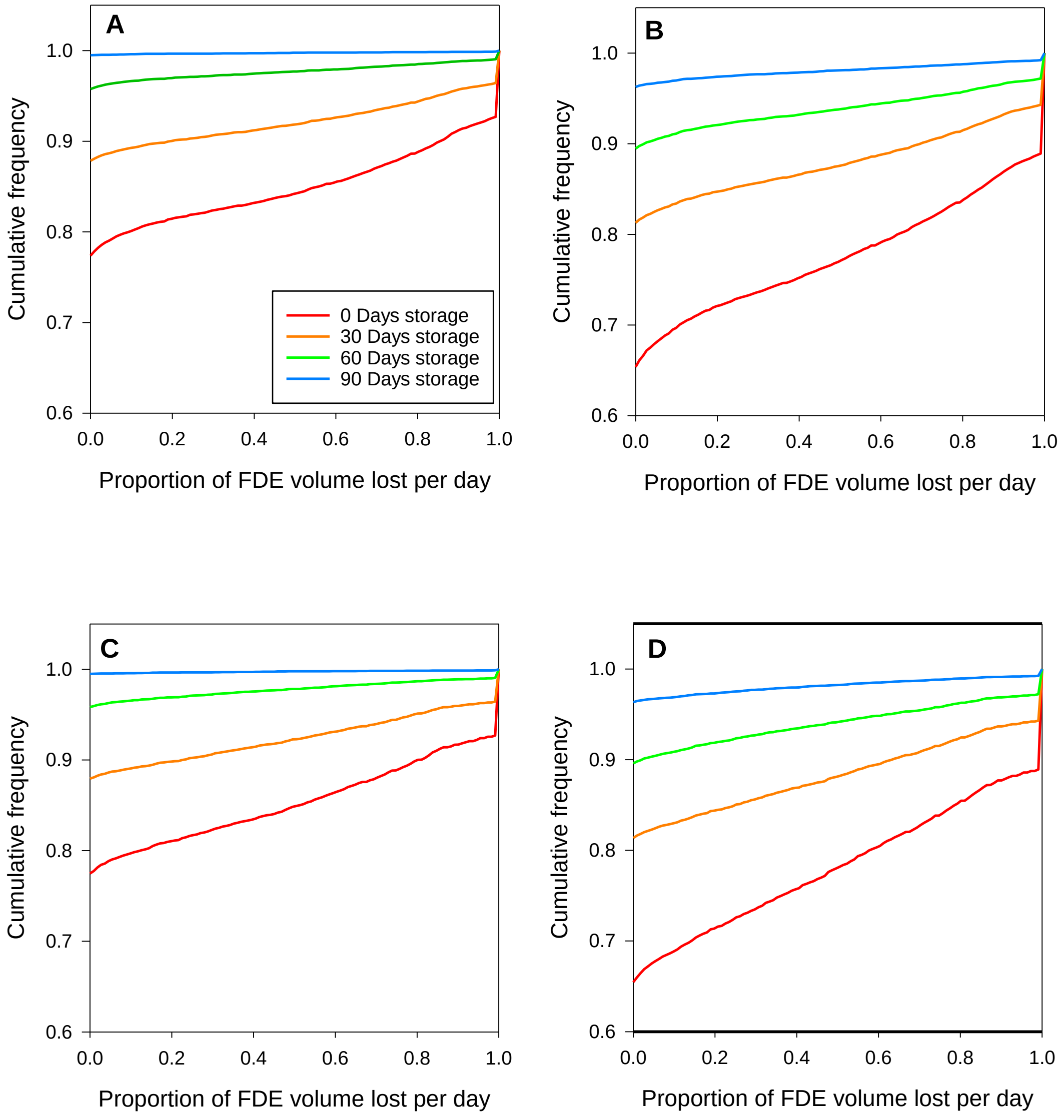

Figure 3. Cumulative probability distributions for the proportion of the FDE volume that is lost per day from irrigating onto the **Ultic soil type** for scenarios with different irrigators, rainfalls and availabilities of pond storage. Graph A is the low rainfall and high-rate irrigator, Graph B is the high rainfall and high-rate irrigator, Graph C is the low rainfall and low-rate irrigator and Graph D is the high rainfall and low-rate irrigator. The different coloured lines represent the different number of days of FDE storage available for implementing a deferred irrigation strategy.

4.2 Calibration of the outputs

From time to time, as a part of the resource consents, NRC collect stream samples from up-stream, at the mixing point and downstream from the discharge point of a 2-pond FDE system. However, as the farm size and flow rates in-stream are not recorded during sampling, and the distance of the downstream sample is unspecified, we cannot use this data to provide a truly quantitative and definitive calibration of our modelling. Instead, we can use monitored data for FDE 2-pond discharges in Northland, to determine if outputs from our Monte Carlo simulations are in a similar range to those observed on Northland dairy farms.

Figure 4 shows the stream *E. coli* concentrations from 350 monitored samples of 2-pond FDE discharges to Northland streams, which have then been modelled at three different stream flow rates for the base model farm. In this and all subsequent figures the distributions of stream *E. coli* concentrations are presented as boxplots where the horizontal line is the median, the boxes span the 25th to 75th percentiles, the whiskers span the 10th to 90th percentiles, and the extreme points represent the 5th and 95th percentile values. Note also the use of the Log-scale on the Y axis.

For the calibration analysis the up-stream concentrations were set to match the measured NRC data, so are the same in all graphs (Figure 4). Model outputs of stream *E. coli* concentrations at the point of discharge (0 km) were highly similar to measured observations, for the 10 L s^{-1} stream flow rate but underestimated concentrations at the higher stream flow rates (Figure 4). This indicates that the model is generating useful data that is a reasonable representation of the real situation generated by FDE discharges to Northland streams.

Measured downstream *E. coli* concentrations show a greater amount of variability than the measured point of discharge *E. coli* concentrations (Figure 4). This is highly unusual as the FDE load would be expected to become diluted, ensuring less variable concentrations downstream relative to the point of discharge. Hence, the modelled outputs showed a smaller but consistent reduction of stream *E. coli* concentration including the 95th percentile. This data indicates there are potentially important factors affecting microbial die-off in streams that we are unable to reflect in our current modelling approaches which is a phenomenon also acknowledged in the international literature (Oliver et al., 2016). Nevertheless, this analysis shows that at the point of impact in a hypothetical stream the model is able to generate *E. coli* concentrations similar to that measured in what are likely to be small rural Northland streams (≤10 L s^{-1}).

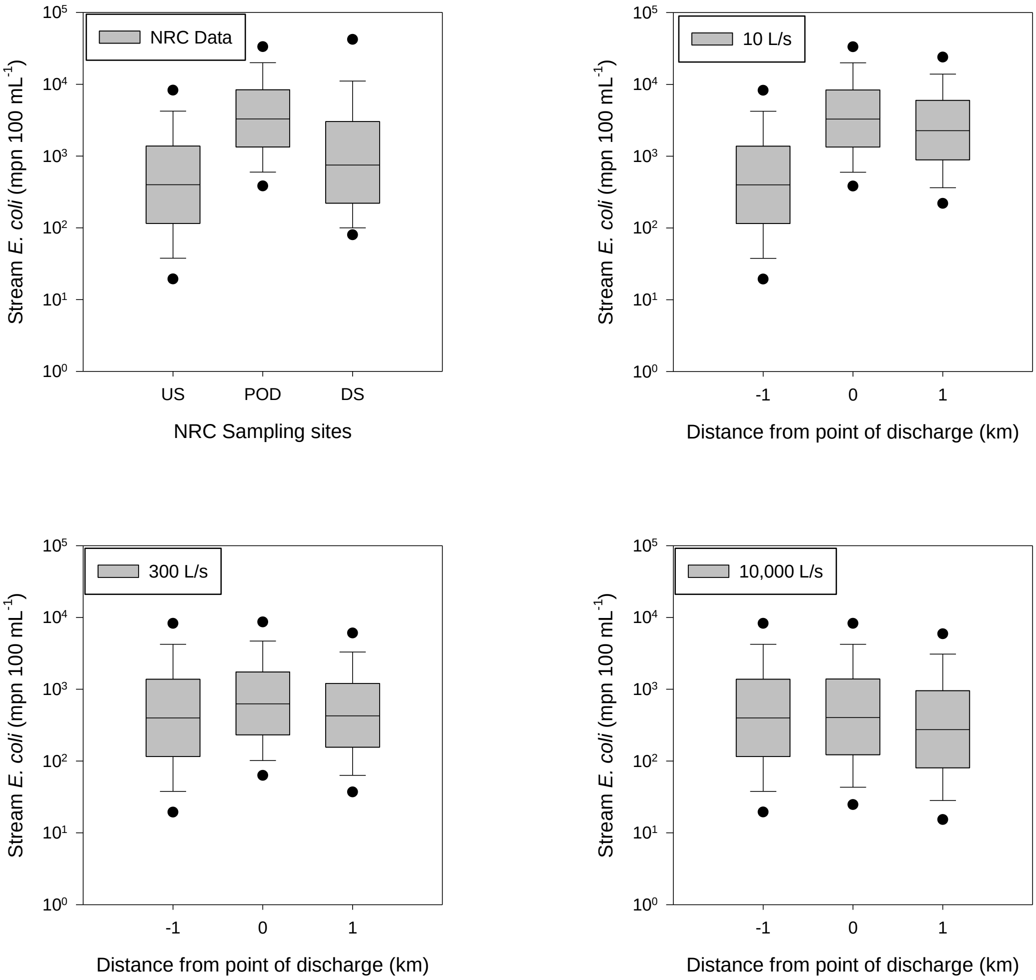

Figure 4. Stream *E. coli* concentrations from 2-pond FDE discharges as measured by NRC and modelled at 3 different stream flow rates. In the NRC data graph US, POD and DS refer to up-stream, point of discharge and downstream sampling sites.

4.3 Scenario outputs for sensitivity testing of the model

To conduct sensitivity testing the model is set up with most factors designed to generate a high load of *E. coli* to the stream and then one (or two) individual factors are varied to determine the size of response in the model outputs. Thus references to best and worst case scenarios in this section are referring only to those one or two factors being varied in that specific scenario. For all sensitivity testing the up-stream concentrations were set to NOF *E. coli* attribute state C (Table 2).

Outputs for the three FDE management scenarios demonstrated that the 2-pond discharge causes much higher stream *E. coli* concentrations and a greater absolute spread in distribution than the alternate FDE irrigation options (Figure 5). The 2-pond FDE discharge increased *E. coli* concentrations by more than an order of magnitude above the acceptable swimming water quality standards.

Figure 5 demonstrates the effects of worst- (Figure 5B) and best-case (Figure 5C) soil and rainfall conditions on stream *E. coli* concentrations likely under the two irrigation scenarios. These are likely to be typical of Northland dairying but notably, in the absence of any FDE storage. For all three FDE management scenarios downstream *E. coli* concentrations show a steady decrease but are accompanied by increased variability (Figure 5). The increase in variability is caused by the wide input distribution of stream die-off rates used in the Monte Carlo simulations (Muirhead et al., 2011) such that high *E. coli* concentrations could occur on cloudy days and lower concentrations on very sunny days.

Notably, these specific model simulations indicate that the impacts of the 2-pond FDE discharge extends for >12 km downstream, whereas both irrigation scenarios (without storage) altered % distributions of *E. coli* for no more than 5 km downstream, including the 95th percentile values (Figure 5). Presentation of further results comparing different scenarios will present only the outputs from the point of discharge.

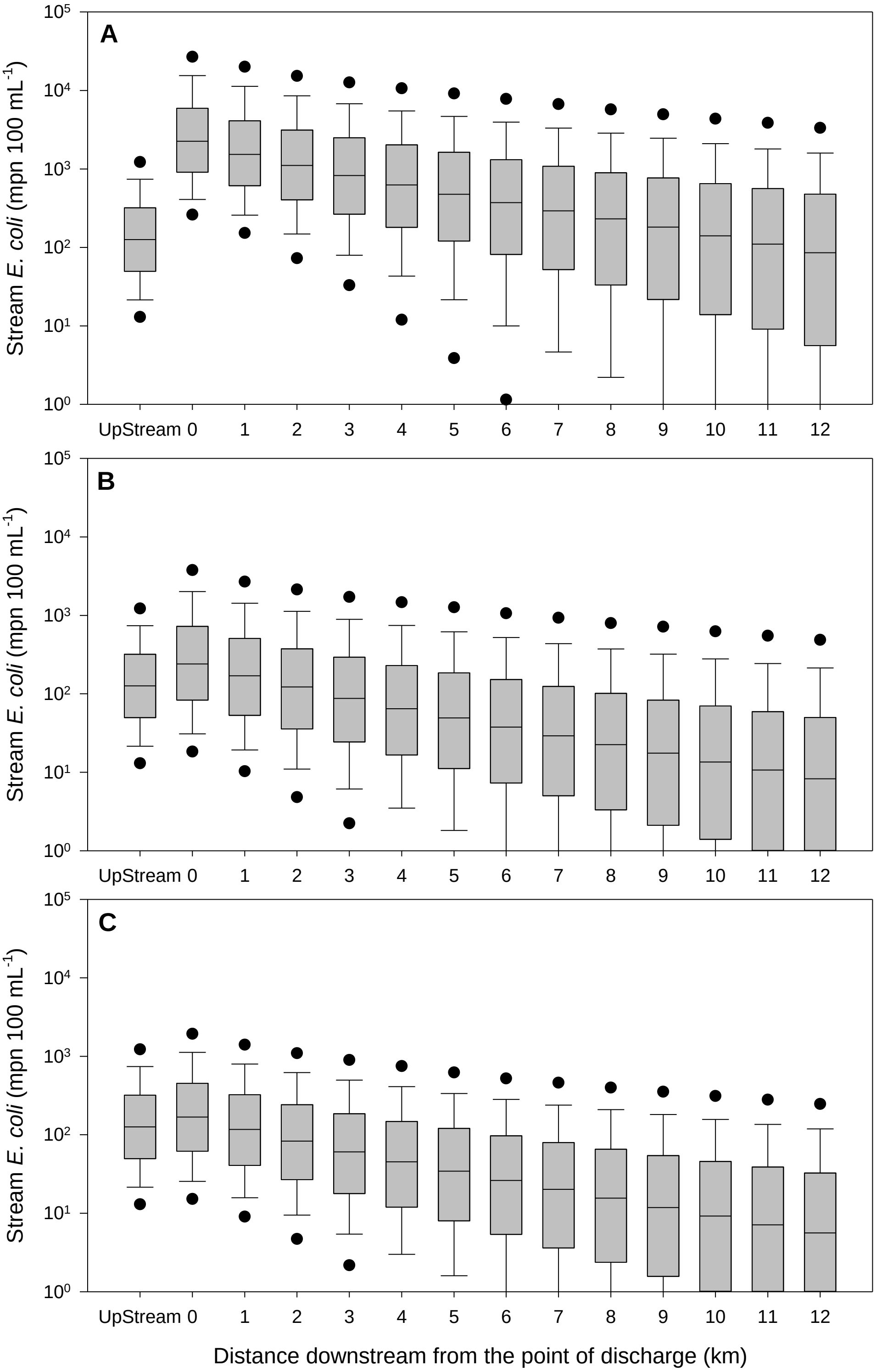

Figure 5. Stream *E. coli* concentrations modelled for three scenarios of (A) 2-pond discharge, (B) FDE irrigation by a high-rate irrigator with no storage onto the Brown soil type under the high rainfall conditions with high connectivity to the stream, and (C) FDE irrigation by a low-rate irrigator with no storage onto the Ultic soil type under the low rainfall conditions with high connectivity to the stream. Distributions calculated for discharge into a stream flowing at 10 L s^{-1}.

Figure 6 demonstrates the effect of stream flow on the consequent *E. coli* concentrations stream for the various FDE management scenarios. Peak *E. coli* concentrations are considerably less as stream flow rate increases due to marked dilution of FDE input (Figure 6). However, even at a stream flow rate of 300 L s^{-1} there is still a noticeable impact from the 2-pond FDE discharge despite no observable effect from the FDE irrigation system (without storage) on the distribution of immediate *E. coli* concentrations at the point of discharge.

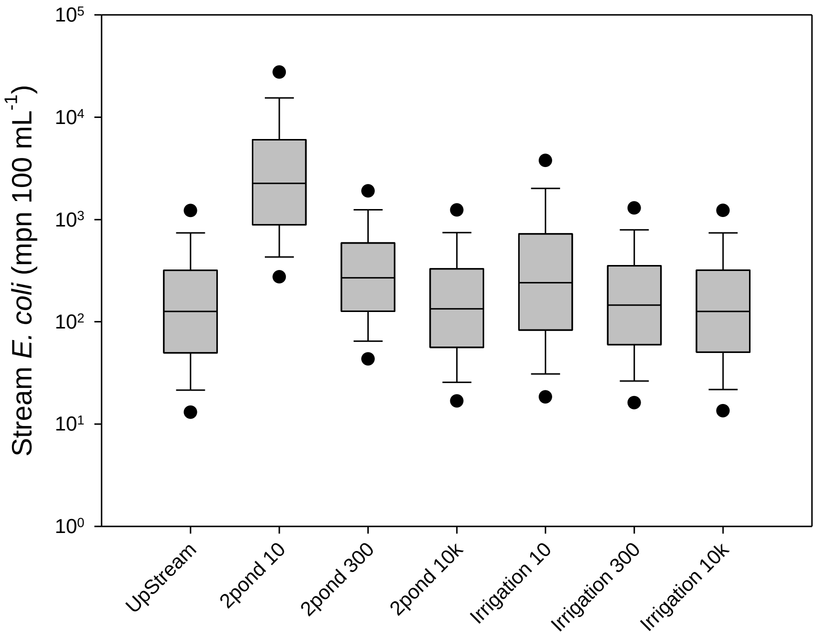

Figure 6. Stream *E. coli* concentrations up-stream and at the point of discharge for 2 FDE management systems at 3 different stream flow rates. In the X axis labels: 2pond refers to the 2-pond management system; Irrigation refers to the worst case FDE irrigation system of high-rate irrigation with no storage irrigating to the Brown soil type under the high rainfall condition with high connectivity to the stream. The 10, 300 and 10K labels refer to stream flow rates of 10, 300 and 10,000 L s^{-1}, respectively.

Soil type and rainfall conditions had very much less effect than flow rate on stream *E. coli* distributions across the FDE scenarios (Figure 7). In line with earlier findings in Section 4.1 that the volume of FDE generated as runoff is considerably reduced by storage and deferred irrigation (zero for 95% of time with ~90 days storage), FDE storage and application of a deferred irrigation strategy had a strong effect on stream *E. coli* concentrations, under the worst case FDE irrigation scenario (Figure 8A) and a smaller but notable effect under the best case FDE irrigation scenario (Figure 8B). The effect of stream connectivity also had a strong effect even using the worst case FDE irrigation scenario of no storage and challenging soils and rainfall conditions; higher connectivity resulting in greater stream effect from FDE irrigation (Figure 9).

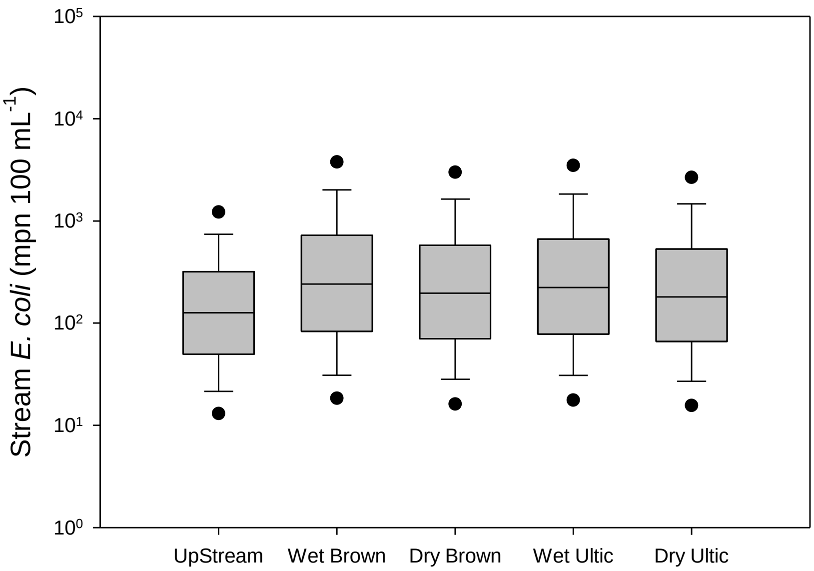

Figure 7. Impact of the different soil types and rainfall conditions on modelled *E. coli* concentrations in the stream. The modelled FDE scenarios all used a high-rate irrigator with no storage, assumed high connectivity to the stream and a stream flowrate of 10 L s^{-1}. On the X axis labels, Wet and Dry refer to the high and low rainfall conditions, respectively, and Brown and Ultic refer to the soil type modelled.

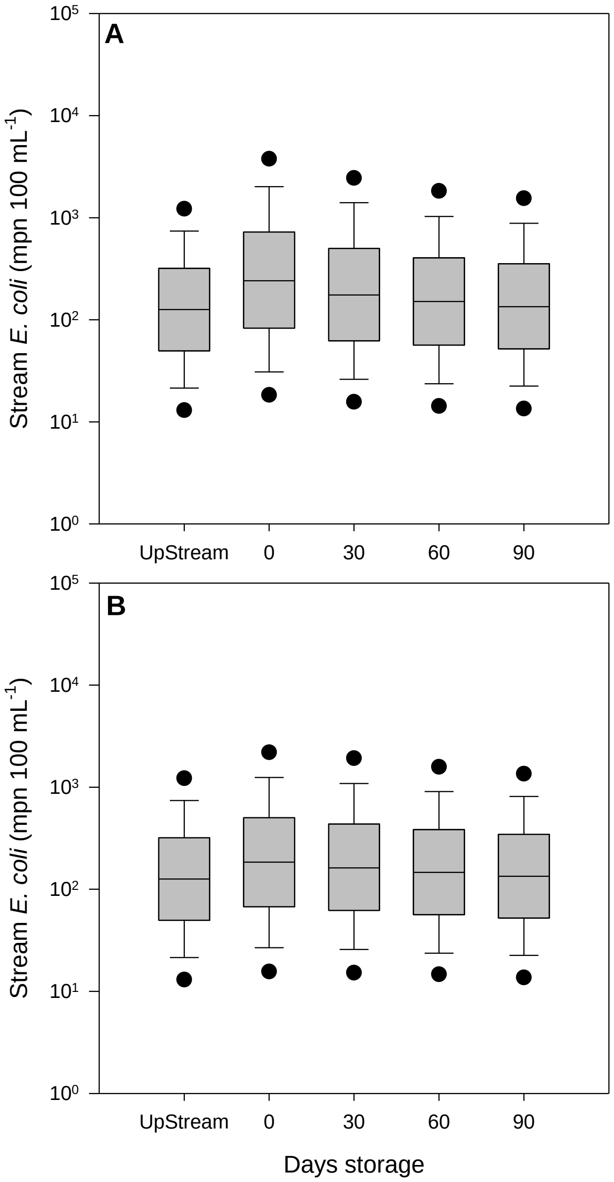

Figure 8. Impact of days of FDE storage for implementing a deferred irrigation strategy for 2 different FDE irrigation scenarios discharging into a stream flowing at 10 L s^{-1}. Scenario (A) was the worst-case, with a high-rate irrigator applying FDE onto the Brown soil type with high rainfall and high connectivity. Scenario (B) was a low-rate irrigator applying FDE onto the Ultic soil type under low rainfall conditions, but still with high connectivity to the stream.

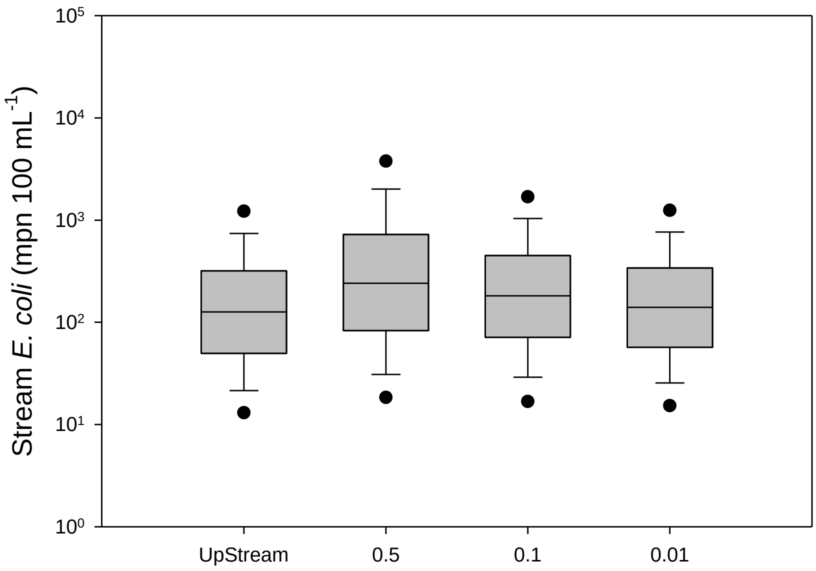

Figure 9. The effect of connectivity between the FDE irrigation site and the stream on *E. coli* concentrations for the worst-case scenario of a high-rate irrigator with no storage, irrigated onto the Brown soil type under high rainfall conditions (the stream flowing at 10 L s^{-1}).

Increasing the farm size to 400 ha, from earlier being constrained to the typical Northland dairy farm size of 135 Ha, increased the number of cows and total volume of FDE generated each day. With other factors affecting FDE runoff, connectivity or discharge to stream remaining equivalent, increasing the size of the dairy farm increased the modelled *E. coli* concentrations in the stream (Figure 10) by a proportionate amount relative to the typical farm size (Figure 6). However, this proportionate effect is most marked at lower flow when dilution effects are minor, including at the 10 L s^{-1} stream flow rate earlier recognised to be most likely that of streams receiving FDE discharge in Northland. Hence, changes to FDE management are likely to result in greater effect for larger farms and/or smaller streams.

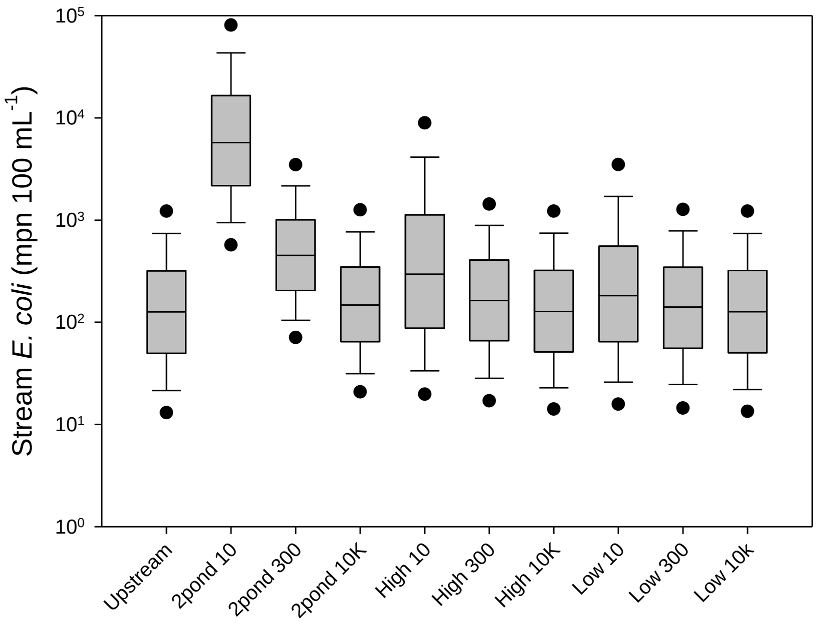

Figure 10. The effects of a larger farm size on stream *E. coli* concentrations for 3 different FDE management scenarios and 3 different stream flow rates. For X axis labels: 2pond refers to the 2-pond FDE management system; High refers to a FDE management system using a high-rate irrigator with no storage applying onto a Brown soil under high rainfall conditions with high connectivity to the stream; Low refers to a FDE management system of a low-rate irrigator with no storage applying onto an Ultic soil under low rainfall conditions with high connectivity to the stream; the numbers 10, 300 and 10K refer to stream flow rates of 10, 300 and 10,000 L s^{-1}, respectively.

Earlier modelling analyses use different combinations of model inputs to illustrate the impact of different components and inputs in the model on stream *E. coli* concentrations. Figure 11 shows the combined effect of the extremes in soil and climate factors assuming 90 days of storage and different levels of connectivity to the stream. Deferred irrigation requires storage which, as Section 4.1 demonstrated, has a substantial effect on the proportion of the farm FDE load lost in runoff. Deferred irrigation is incorporated into the DairyNZ/Massey University Dairy Effluent Storage Calculator, a widely utilised GMP tool for farmers that has been adopted throughout New Zealand to manage for risks of FDE degrading water quality. Figure 11 demonstrates there can be next to no immediate or downstream impact on the human health water quality metrics, when 90 days storage is coupled to land application of FDE across Northland's two dominant soil type and rainfall conditions.

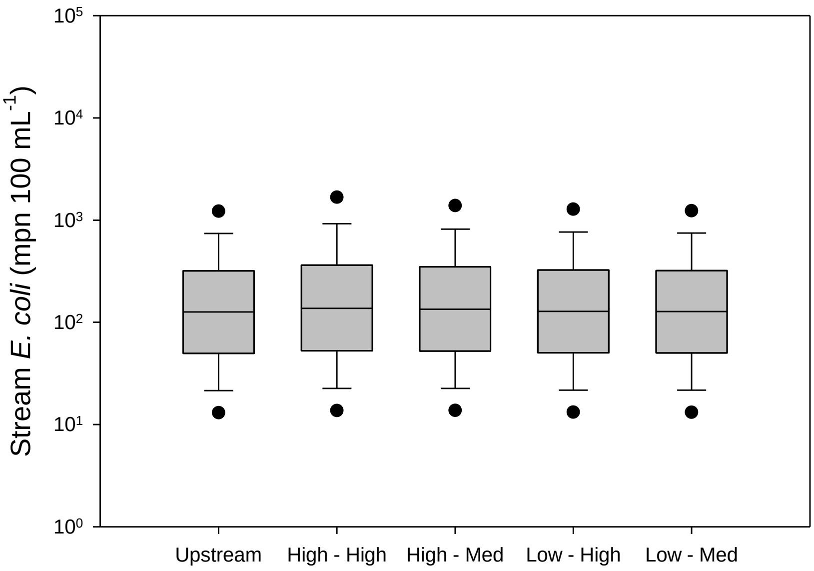

Figure 11. Effect of FDE management on stream *E. coli* concentrations at the point of discharge from GMP approaches as promoted in other regions of NZ. Each scenario is based on irrigation of FDE to land utilising 90 days storage under a deferred irrigation strategy. For X axis the labels: High – High refers to a high-rate irrigation system apply onto the Brown soil under high rainfall conditions with high connectivity to the stream; High – Med refers to a high-rate irrigation system applying onto the Brown soil under high rainfall conditions with medium connectivity to the stream; Low – High refers to a low-rate irrigation system applying onto the Ultic soil under low rainfall conditions with high connectivity to the stream; and Low – Med refers to a low-rate irrigation system applying onto the Ultic soil type under low rainfall conditions with medium connectivity to the stream.

In summary, the model outputs were most sensitive to stream flow rate, 2-pond discharge and the introduction of FDE storage to the irrigation system. The model outputs were moderately sensitive to farm size and assumed connectivity. Model outputs were least sensitive to climate, soil type and FDE irrigation rate.

4.4 Scenario analysis and implications for swimming water quality metrics

In this analysis we wanted to estimate the impact of a single farm discharge on the four swimming water quality (*E. coli*) metrics in the Clean Waters 2017 revision to the NPS-FM. For all scenarios we assume recreation is not practiced within 2 km of the point of

FDE discharge, and that no further *E. coli* inputs to the stream occur from neighbouring farms within 2 km of the point of FDE discharge, or other faecal sources (i.e., inputs from livestock access, sediment reservoirs, wild birds or wastewater treatment plants are not accounted for). These assumptions may not hold in reality, but permit the differences in effects solely due to changes to FDE management to be identified for the three bands of up-stream water quality for human health, across the four *E. coli* metrics.

In this analysis the up-stream distribution of *E. coli* concentrations in the model were set from A to C (swimmable) grade under the NOF, whilst changes were then determined for locations 2 km downstream and assigned to the appropriate NOF grade. In these scenarios the FDE irrigation systems were set to GMP settings of 90 days storage but assumed a high level of connectivity to the stream (i.e., well managed but high risk environments). The FDE irrigation scenarios were run on both dominant soil orders and high and low rainfall conditions as used earlier to describe typical Northland conditions. Scenarios and interpretations of the swimming water quality grades are presented in Table 1 in the Executive Summary.

For all three NOF A-C grade scenarios, the downstream impact of a 2-pond direct discharge to water is the lowest reportable and unswimmable grade (E), with *E. coli* concentrations failing all 4 NOF metrics. In contrast, for all FDE irrigation scenarios (good practice at high connectivity risk for both soil and rainfall types), downstream water quality for human health would be swimmable (e.g., NOF grade A to B for *E. coli*; Table 1). Furthermore, under the various irrigation scenarios the downstream NOF grades for *E. coli* improve (e.g., are a grade higher than the up-stream grades under up-stream B and C scenarios). This is the consequence of (i) dilution and die-off of the irrigated FDE that does reach the hypothetical stream, and (ii) lack of other downstream *E. coli* inputs. It needs to be noted that these irrigation scenarios cover the range of expected soil and climate types across Northland and also assume high connectivity to the stream; expected results would be for even greater improvement under low or moderate connectivity. This NOF scenario modelling illustrates the effectiveness of the appropriate FDE storage and deferred irrigation strategy for dominant Northland soil and rainfall conditions, whether at low or high risk of connectivity (e.g., Houlbrooke et al., 2004).

4.5 General Discussion

Monte Carlo simulation modelling of 2-pond discharges and low-rate and high-rate land application of FDE for a typical Northland dairy farm setup, across dominant Northland soil types and climatic conditions, has revealed that FDE discharge of 2-pond systems having notable degradational effects on stream water quality for human health (*E. coli*).

Effects of 2-pond discharges are marked and observed for median values and across the distribution of consequent stream *E. coli* concentrations, especially 95th percentile values. Effects of 2-pond discharges likely extend across those distributions of *E. coli* concentrations for more than 12 km downstream, resulting in a high likelihood of cumulative effects in Northland river networks.

In contrast, both low and high-rate scenarios of FDE irrigation to land are estimated to markedly increase stream *E. coli* concentrations, for both maxima and percentile distributions. For instance, under a worst-case FDE irrigation scenarios (e.g., high connectivity, no storage, high rainfall, high application rate), stream effects were negligible within 5km of the farm, and could be reduced considerably through deferred irrigation (i.e., 90 days FDE storage enabled <5% of days where FDE could be lost via runoff, of which only a fraction would be lost to receiving waters depending on the assumed degree of connectivity). Notably, these findings whilst relevant to typical conditions across Northland dairy farms, are in agreement with earlier equivalent scenario modelling of dairy farm effects in other regions (Muirhead et al., 2010).

In light of the National Policy Statement on Freshwater Management and explicit national objectives for stream *E. coli* concentrations to support primary contact recreation nationwide, all bar two regional authorities (including NRC) have adopted land treatment of FDE as a more appropriate, lower impact management system for reducing the risks presented by FDE on water quality. Whilst soil type and climate impact how readily irrigation can be managed to avoid excess application (inducing runoff of FDE), this analysis shows that both can be readily accommodated across Northland's typical conditions for dairying systems (see Figure 11 and Table 1). For both the Brown and Ultic soils that dominate Northland dairying, and across the wide range of rainfall conditions experienced in Northland over the past 30 years, ensuring ~90-days storage of FDE will have a considerable effect on reducing stream *E. coli* concentrations downstream of dairy farms. **Note**: any calculation of appropriate FDE storage volumes should be based on the DairyNZ/Massey University dairy effluent storage calculator to accommodate differences in local soil, climate and farm system attributes. Deferred irrigation with ~90 days storage, coupled to low or high-rate irrigation, resulted in no more than 5% of days when FDE is applied to saturated soils with the risk of runoff. Scenario findings indicate that the use of a deferred irrigation strategy, will have a substantial impact on stream *E. coli* concentrations (i.e., decreasing stream median and 95th percentile values by at least an order of magnitude within 2 km of the point of discharge).

Scenario findings also indicate that FDE 2-pond discharges are likely occurring to streams discharging at <10 L s^{-1}, the equivalent of low-order small systems or larger systems at low-flow. Equally, stream flow has a marked impact on any scenario outcomes due to dilution. However, the effect of stream flow in this analysis needs to be interpreted with caution. Under high stream flow rates the FDE discharged does not have a large effect on concentrations due to dilution effects – but this will still increase the total load of *E. coli* being discharged from the stream network, risking human or cultural health conditions in receiving lakes or estuaries.

The adoption of FDE irrigation systems coupled to an appropriate deferred irrigation strategy, would considerably reduce the loads of *E. coli* discharged from dairy farms in the Northland region. Sensitivity analysis suggested that 90 days storage was optimal for a typical Northland dairy farm, for the two dominant soil and rainfall classes. However, the actual optimal FDE storage volume will vary but can be readily calculated using the DairyNZ/Massey University dairy effluent storage calculator.

Our modelling approach has focused on the impacts of a single FDE discharge from a typical Northland farm to a hypothetical stream across a range of flows and background *E. coli* concentrations. As shown in Figure 4, *E. coli* concentrations observed in Northland streams are likely to be unacceptable under the NOF, with our modelling suggesting that cumulative impacts from 2-pond FDE discharges are a likely contributing factor (i.e., that minimum distances between 2-pond discharges would need to be >12 km to prevent cumulative impacts on stream *E. coli* concentrations). There are other factors that will also affect the full impact of FDE discharges at the catchment scale. One of the key gaps is our understanding of microbial die-off rates as well as the spatial distribution of FDE and other faecal matter inputs (Oliver et al., 2016). Further work on understanding and modelling catchment scale *E. coli* concentrations and loads would be needed to determine the impact of adopting deferred land irrigation of FDE within particular Northland river networks. It is, however, clear that such an approach would have marked impacts on stream water quality for human health where *E. coli* loads are dominated by 2-pond FDE inputs.

5. Conclusions

The Monte-Carlo permutation modelling of FDE impacts on stream *E. coli* concentrations undertaken in this study clearly demonstrates that marked improvement in median and upper percentile concentrations would occur downstream of Northland dairy farms if FDE management shifted from 2-pond direct discharges, to land irrigation, especially when coupled with deferred irrigation. Modelling results showed that optimal deferred storage is expected to be ~90 days for typical soil and climatic conditions on

Northland dairying farms. These results are consistent with the DairyNZ/Massey University dairy effluent storage calculator estimations. Modelling also showed that switching to deferred land irrigation of FDE resulted in increases of two or more NOF bands from those currently expected in Northland streams receiving 2-pond discharges (E grade for human health 2 km downstream at <10 L s^{-1}). Results suggest that deferred land irrigation of FDE is therefore likely to be an important mechanism for helping to attain national swimmable standards by 2040 across typical Northland dairy farm catchments. We recommend that actual volumes of FDE storage required to achieve good practice standard are calculated using the DairyNZ/Massey University dairy effluent storage calculator to accommodate for farm-scale differences in farm setup and soil, climatic and irrigation system attributes.

Further analysis is needed to determine regional costs and timeframes needed to reasonably achieve such a shift in FDE management across Northland dairy farms. Additionally, further spatially explicit modelling is required to extrapolate the cumulative effects on receiving environments across Northland following a switch to deferred land irrigation. We suggest any such modelling is coupled to economic modelling of farm-systems.

6. Acknowledgements

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