A Farm-scale *E. coli* model for Gisborne District Council

Richard Muirhead and Graeme Doole (Waikato University/MfE)

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Contents

1. Executive Summary

The nationally-significant swimming sites at Rere Falls and Rere Rockslide on the Wharekopae River in Gisborne do not meet national guidelines for swimming water quality. Previous work by the Gisborne District Council (GDC) had identified that the key source of faecal contamination in the river was from ruminant animals and the catchment land-use is predominantly low intensity sheep & beef farming. GDC approached AgResearch to develop a model of the cost-effectiveness of appropriate mitigation options that could be implemented on farm to address the issue of faecal contamination (as indicated by the presence of *E. coli*) of the river. GDC wanted a model that would be flexible so that it could be applied in other catchments in the region.

There was no information on the effectiveness or associated costs of *E. coli*-focused mitigations for sheep & beef farms. Therefore, this report describes the development of the modelling of the effectiveness and cost-effectiveness of mitigations to reduce *E. coli* losses from sheep & beef farms. While we would like to have a wide range of different mitigation options available to farmers, there was only sufficient data available to make estimations for 4 mitigations: (1) stream fencing, (2) eliminating stream crossing points, (3) changing stock types and (4) land-use change to forestry. The mathematical algorithms used for the calculations were coded into an Excel Spreadsheet that can be used by GDC staff.

The typical data inputs needed can be generated from an interview with the farmer using a questionnaire or can be input directly into the spreadsheet. It is best if the farm has completed a Beef+LambNZ Land and Environment Plan (LEP) prior to using the *E. coli* model. The LEP process can help with setting long term goals and plans for the farm and the mapping will help identify streams, fencing, stream crossings and other information needed as inputs to the *E. coli* model. The outputs are a series of graphs showing the relative effectiveness and cost-effectiveness of the different mitigation options on the farm. Initial mitigation option scenarios can be run using relatively coarse input data or "guesses" that can be later refined as more specific/accurate data becomes available.

2. Background

The Wharekopae catchment in Gisborne contains the nationally-significant swimming sites at Rere Falls and Rere Rockslide. Unfortunately the water quality at these key sites does not meet the swimming standards in the NPS-FW (2014). In response, the Gisborne District Council (GDC) has instigated a catchment project to address this water quality issue. Previous work by GDC had identified that the key source of faecal contamination in the river was from ruminant animals and the catchment land-use is predominantly low intensity sheep & beef farming. Beef+LambNZ has been supporting this work through the development of Land Environment Plans (LEPs) for the farmers in the catchment who are willing to support the project.

Gisborne DC approached AgResearch for information on the most cost-effective mitigation options for sheep and beef farmers to reduce *E. coli* losses from their farms. At that stage there was no readily available information on either the effectiveness of mitigations targeting *E. coli* sources for sheep and beef farms or ways of calculating the cost-effectiveness of these measures. This project was initiated with the aim of collating the best information available on the effectiveness of measures that can reduce *E. coli* discharges to water from sheep and beef farms. Ideally this would cover a wide range of mitigation options but unfortunately there is very little data on *E. coli* losses from sheep and beef farms, or any mitigations for this land use.

One of the challenges for modelling *E. coli* is that large numbers of *E. coli* are generated in runoff from catchments during rainfall events (Nagels et al. 2002; Wilkinson et al. 2011). However, the recreational activity of swimming generally does not occur during rainfall/runoff events as the river flows are higher and dangerous and the colour of the water is typically unattractive. Thus, for this project the focus was on mitigations that would impact on streams during dry weather periods. These are situations where animals may defecate directly into streams. Mitigations like wide riparian buffer strips and detainment bunds would thus not be effective as they intercept rainfall-driven runoff from the land.

A literature review conducted for MPI had identified some data on the effectiveness of fencing cattle out of streams on cattle-only farms, but no data for fencing sheep or fencing cattle only on mixed stock farms (Muirhead, 2016). Thus, any estimates of the effectiveness of stream fencing on sheep & beef farms would require new estimates. Discussions with farmers in the catchment identified 3 important factors related to fencing: (1) fencing in the hill land is more costly and difficult than for flat to rolling land, (2) sheep-proof fencing is more expensive than cattle-proof fencing options, and (3) streams are often the drinking water source for stock on these farms. Therefore, any analysis would need to include these effects. It is accepted that sheep have less direct defecation into streams than cattle and hence the option to remove cattle and farm only sheep was included as an option. Another option for reducing *E. coli* losses from land is the conversion of land use from pastoral agriculture to forestry.

A final consideration for the model was the potential for including the effect of microbial die-off in the catchment. This is the process whereby microbes die as the water flows down a river. So if the aim is to achieve swimming water quality standards at the Rere Falls and Rockslide sites, then the relative effectiveness of mitigations will decrease the further upstream from the swimming sites the mitigations are applied. This is likely to be an important consideration for the cost-effectiveness of environmental subsidies that have a limited budget. What this effect does not take into account is the impact on the locals that swim in the river upstream of the main swimming sites.

The key consideration of this project is an acknowledgement of the costs of applying the mitigations on the farms. Some of these mitigations will have considerable capital cost requirements as well as potential ongoing maintenance costs such as: fencing, water reticulation, bridges or culverts maintenance. Other mitigations such as changing the type of stock, may change the operational costs of the farm. The *E. coli* inputs to the stream from animals may occur most days of a year when animals use the stream as a drinking water supply. In other situations, animals may only be herded through a stream crossing a few times a year for mustering. Thus, to make realistic comparisons of the cost-effectiveness of the different mitigation options, all calculations are annualised.

While the focus of this project is on the Wharekopae catchment, GDC wanted the outputs coded into a spreadsheet so that the model calculations could be used in projects in other catchments. The report describes the development of the model calculations used in the accompanying spreadsheet “Farm scale Ecoli Model for GDC version2.xlsx”. The model is then demonstrated by its application to 3 case-study farms in the catchment.

3. Development of the farm-scale model

3.1 Estimation of the effectiveness of farm-scale *E. coli* mitigations

The farm-scale *E. coli* model is developed for sheep and beef farms and includes 4 different mitigation options: (1) stream fencing, (2) bridging stream crossings, (3) changing animal types on the farm and (4) land-use change to forestry. The following 4 sections describes the science used to estimate the load of *E. coli* deposited into the stream from the 4 measures and hence the amount reduced by applying the respective mitigation options.

3.1.1 Stream Fencing

It is known that cattle and sheep excrete *E. coli* at different rates (Moriarty et al., 2015) and it is anecdotally accepted that cattle have a greater tendency to walk in streams than sheep do. Therefore, any relative assessment of the *E. coli* loads from mixed sheep and beef farms will need to take these factors into account. Furthermore, as there is no published data on either the effectiveness of fencing sheep out of streams, or the proportion of sheep faeces deposited into a stream, unpublished data will be used to estimate the loadings from sheep.

The modelling analyses described below were based on the Monte Carlo approach used in Muirhead et al. (2011). This was adapted by using the sum equation as described in Muirhead and Cave (2014) such that the expected load of *E. coli* deposited into a stream (L) by a single species of animal was calculated by equation (1).

$$L = \sum_{n=1}^{z} \alpha_n C_n W_n M_n \qquad (1)$$

Where α is the proportion of ananimal's faeces deposited directly in the stream, C is the concentration of microbes in the animal's faeces (cfu g^{-1} wet weight), W is the weight of a single defecation event (g wet weight), M is the number of defecation events (# day^{-1}) and Z is the number of animals on the farm. The total load for each farm is the sum of the load from each species. The distributions for α, C, W and M used in the Monte Carlo simulations are shown in Table 1. Each Monte Carlo simulation contained 5000 iterations. The values used for Z were adjusted for relative stock units (s.u.) such that the number of animals of each species on a single farm was the total number of s.u. multiplied by the proportion of s.u. of that species divided by the number of s.u. per animal (Trafford and Trafford, 2011). For this calculation a sheep was equivalent to 1 s.u. and a cow was equivalent to 8 s.u. as the *E. coli* concentrations data used was from dairy cows which would be this number of stock units. However, when the data is applied to a sheep and beef farm a beef animal is assumed to be 6 s.u. recognising that a dairy cow will each more grass than a beef animal. Thus, a farm with a total number of 3600 s.u. with 50% sheep would contain 300 cattle and 1800 sheep.

Table 1. Distributions used for the Monte Carlo simulations run using equation (1) to estimate the relative load of *E. coli* deposited to a stream by sheep or cattle.

Model Input	Cattle	Sheep
α: proportion of faeces deposited directly in a stream	Triangular, Minimum = 1.7%, most likely = 6.1% and Maximum = 10.5%[a]	Exponential, β = 1.1%[b]
C: concentration of *E. coli* in faeces (Log_{10}cfu $g^{-1}ww^{\#}$)	Log Normal, Mean = 4.4 and Std Dev = 1.3[a]	Log Normal, Mean = 6 and Std Dev = 0.8[c]
W: weight of faeces per defecation event (g ww)	Triangular, Minimum = 1500, most likely = 2000 and Maximum = 2700[a]	Triangular, Minimum = 30, most likely = 90 and Maximum = 170[d]
M: number of defecation events (# day^{-1})	Binomial, n=16, p=0.75[a]	Binomial, n=39, p=0.4[d]

\# Wet Weight
a Muirhead et al. (2011)
b Unpublished data collected in the Clean Water, Productive Land MBIE-funded research programme
c Moriarty et al. (2011)
d Haynes& Williams (1993)

The Monte Carlo simulations were run, and the output distributions generated, for a range of stocking rates and stock ratios on a farm. An example of the estimated load of *E. coli* deposited into the stream each day for different ratios of sheep and beef cattle at a stocking rate of 18 s.u. / ha on a 200 ha farm is shown in Figure 1. The results show that the expected load from cattle is in the range of 5 x 10^{11} to 3 x 10^{12} cfu per day and that the load decreases as the proportion of cattle on the farm decreases. The expected load from a sheep-only farm is 2 x 10^{11} to 5 x 10^{11} cfu per day (Figure 1). From each of these individual distributions (as in Figure 1) we calculated the average value as a single point to represent the distribution. These point estimates of the *E. coli* load for a range of stocking rates from 2 to 18 s.u./ha, and different stock ratios are shown in Figure 2. The relationships in this Figure 2 can be used to derive the algorithms for the effectiveness of fencing both sheep and cattle out of the stream i.e. a seven wire or equivalent sheep proof fence.

However, some farmers may wish to use a cheaper option of only fencing out the cattle using a single wire electric fence as that is much cheaper to erect. This would leave the sheep still being able to access and defecate into or near the stream. Thus, for each ratio of stock types, the proportion of the total farm load that was from sheep-only was calculated; and this relationship is plotted in Figure 3. Combining the relationships from Figure's 2 and 3 can then be used to estimate the relative effectiveness of fencing only the cattle out of a stream on a mixed stock (sheep and beef) farm.

Furthermore, the direct deposition of animal faeces into a stream will only occur if the animals are in a paddock with an unfenced stream. Therefore, the algorithms need to take into account the proportion of paddocks that have unfenced access to a stream.

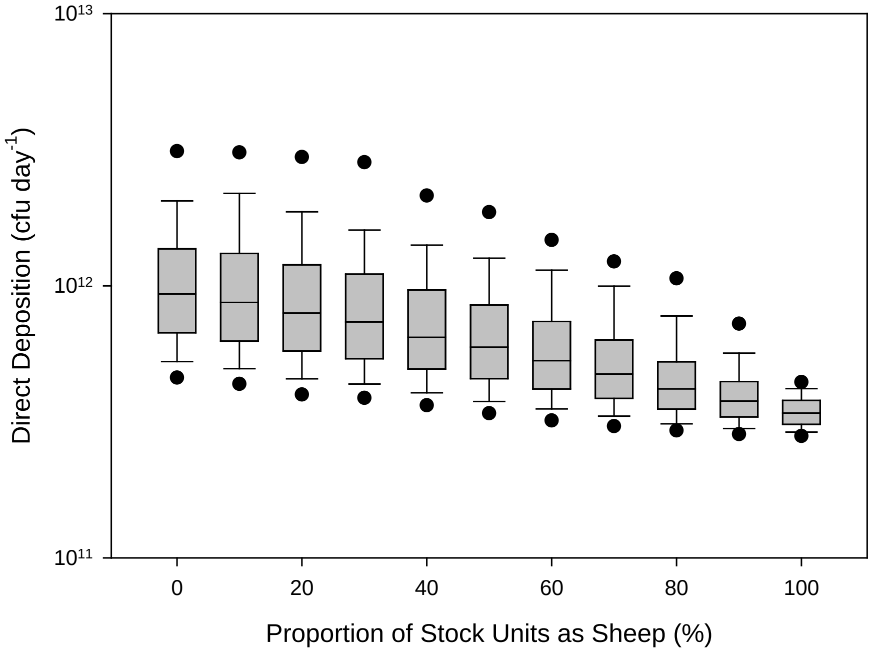

Figure 1. Estimated daily loads of *E. coli* deposited into a stream from a standardised 200 ha farm with 3600 s.u. where the sheep:cattle ratio was varied between 0 and 100%. The results are the outputs from 5000 Monte Carlo simulations. The horizontal line is the median, the boxes span the 25th to 75th percentile values, the whiskers span the 10th to 90th percentile values and the points represent the 5th and 95th percentile values of the distribution.

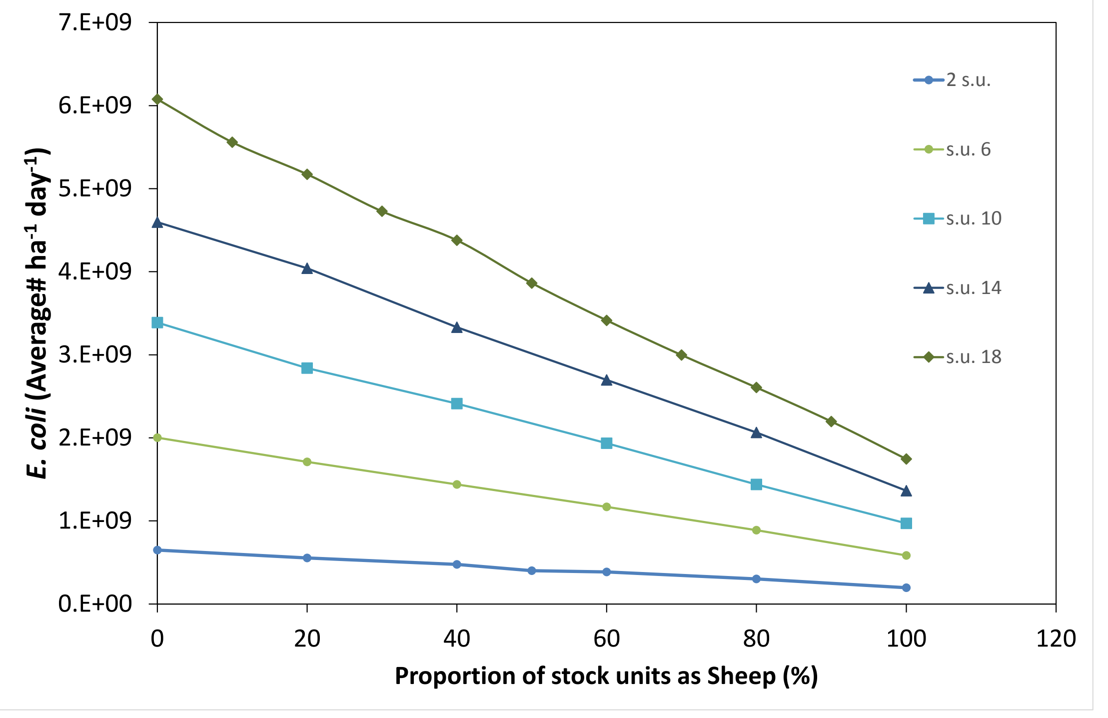

Figure 2. Estimated average daily loads of *E. coli* deposited in a stream from farms with different stocking rates and ratios of sheep to cattle. Note that on the Y axis labels the number “7.E+09” is equivalent to the scientific notation of 7×10^9.

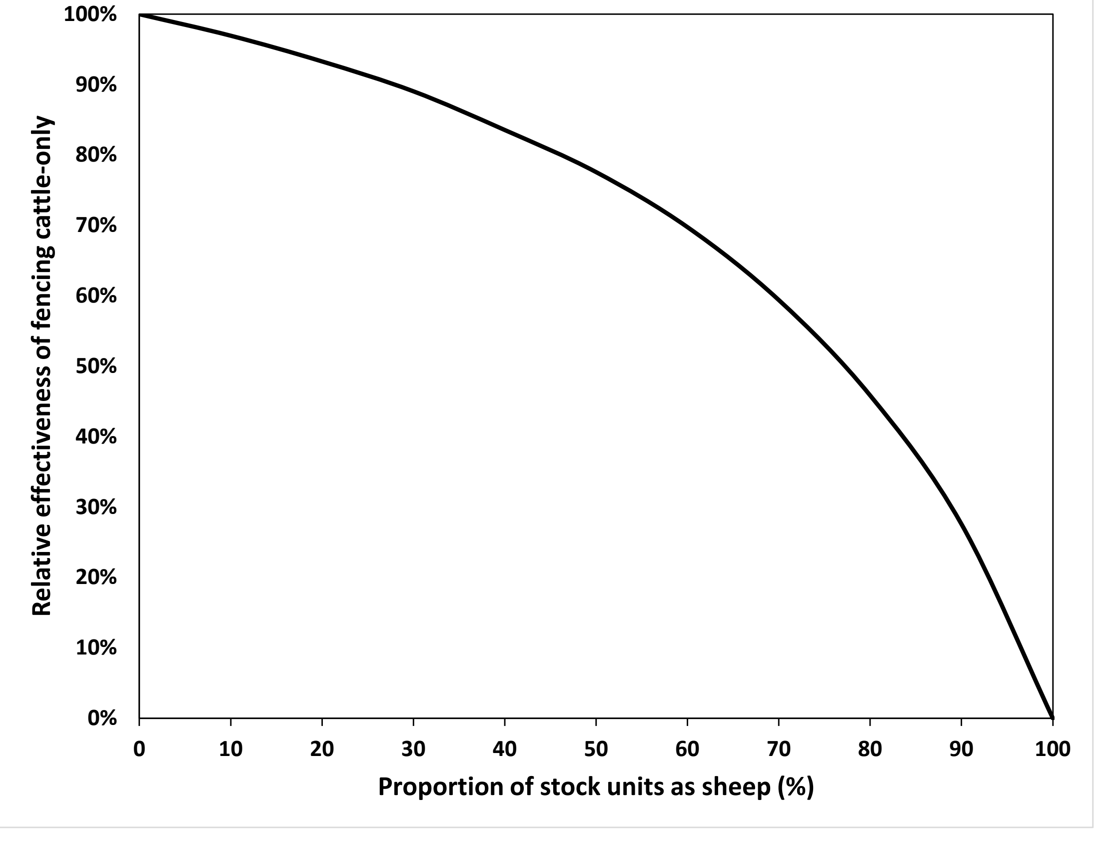

Figure 3. Relationship between the percentage of stock units as sheep and the average effectiveness of fencing cattle-only.

For calculating the effect of a full sheep-proof fence or cattle-proof fence only the following algorithms can be used.

(a) Algorithm to be used when applying a full sheep-proof fence:

Annual load (cfu $year^{-1}$) = {(SU *336,795,540)+(SU * %Sheep *-2,333,407)} * %Access * area * 365 (2)

Where SU is stock units per ha, %Sheep is the percentage of stock units on the farm/block that are sheep, %Access is the proportion of paddocks on the farm/block where animals have direct access to a stream and area is the area of the block (ha). The factor of 365 converts the loads per day into an annual load.

(b) Algorithm to be used when applying a cattle-only fence:

Annual load (cfu $year^{-1}$) = {(SU *336,795,540)+(SU * %Sheep *-2,333,407)} * %Access * area * {(1.0496*(1-(2.718^(-2.77*(1-%Sheep)))))+((1-%Sheep)*0.016)} * 365 (3)

Therefore, for a sheep and beef farm both the effectiveness and the cost of fencing will be different for a sheep-proof versus a cattle-proof fence.

3.1.2 Stream crossings

Stream crossings occur on farm laneways where animals are moved as a large mob. In this situation we are estimating the amount of faecal material deposited directly into the stream as the mob of animals cross the stream. The effective mitigation options are building a bridge or culvert across the stream. Both options will have the same effectiveness in terms of preventing the direct deposition of animal faeces into the water and the same mitigation will work for both sheep and cattle. The difference between a bridge and culvert is the cost and method of installation. Typically a culvert will be much cheaper but the actual option chosen by a farmer will take into account other uses of the crossing, such as for vehicles, and other landscape features at the specific site.

There is only one published study on the rate of defecation events from a mob of animals being herded through a stream in NZ. This identified that approximately 10% of dairy cows defecated directly into the stream (Davies-Colley et al., 2004). Hence this model is based on the calculation of approximately 10% of the animals making a faecal deposit into the stream. There are no estimates of the deposition rate for sheep so we will have to assume the same 10% rate as for cattle, recognising that this may overestimate the actual defecation rate from sheep during a stream crossing event. However, in this model the sheep calculation will have different sizes for the faecal deposit and *E. coli* concentration in the sheep faeces (Table 1). As with the stream defecation calculations, these calculations are initially run using the Monte Carlo simulation method; a summary statistic from the Monte Carlo distributions is then used in the farm-scale spread-sheet model. The Monte Carlo simulations of the number of *E. coli* deposited by a mob of animals crossing a stream is given by equation 4:

$$\text{Crossing (cfu crossing}^{-1}\text{)} = \sum_{n=1}^{Z} \alpha_n C_n W_n \qquad (4)$$

Where α is the proportion of an animal's faeces deposited directly in the stream (Muirhead et al. 2011), C is the concentration of microbes in the animal's faeces (cfu g^{-1} wet weight – Table 1), W is the weight of a single defecation event (g wet weight – Table 1) and Z is the number of animals in the mob.

The Monte Carlo simulations were run, and the output distributions generated, for a range of sizes of mobs of sheep and cattle (Figure 4). The results show that the expected load from a mob of 50 cattle is in the range from 2 x 10^9 to 9 x 10^{10} cfu per crossing. The expected load from a mob of 50 sheep ranged from 1 x 10^9 to 9 x 10^9 cfu per crossing (Figure 4). From each of these individual distributions (as in Figure 4) we calculated the average value as a single point to represent the distribution; these point estimates for a range of mob sizes are shown in Figure 5. The relationships in Figure 5 can be used to derive the algorithms for estimating the amount of *E. coli* deposited into a stream from a mob of sheep or cattle crossing a stream. Note that even with using the "cattle defection rate into a stream" for the sheep calculations, the sheep loads are approximately 10 time less than for cattle due to the relative sizes of the individual faecal deposits (Figure 5).

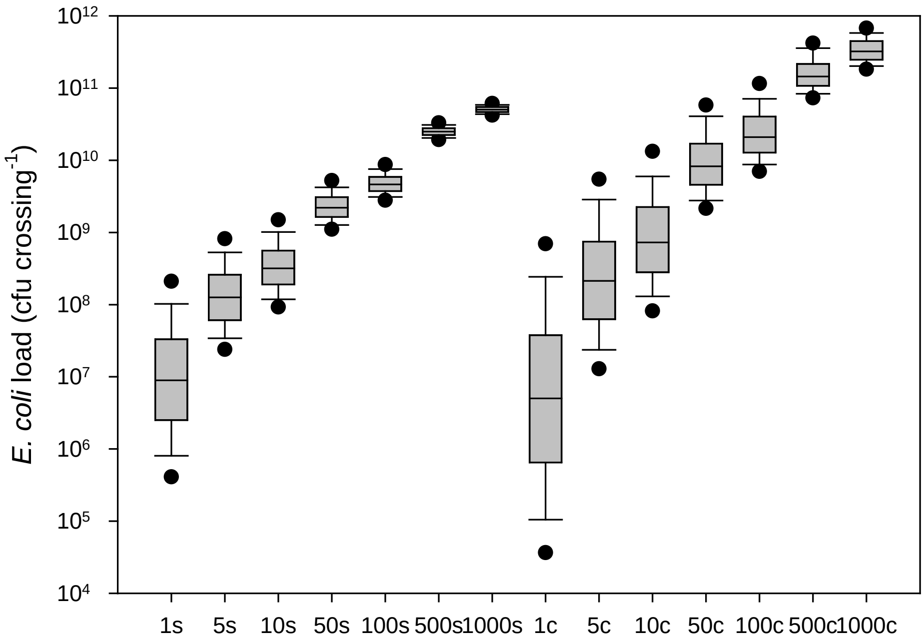

Figure 4. Estimated loads of *E. coli* deposited into a stream from mobs of sheep or cattle crossing a stream. On the X axis the label number refers to the number of animals in the mob and the letter refers to sheep or cattle. The results are the outputs from 5000 Monte Carlo simulations. The horizontal line is the median, the boxes span the 25th to 75th percentile values, the whiskers span the 10th to 90th percentile values and the points represent the 5th and 95th percentile values of the distribution.

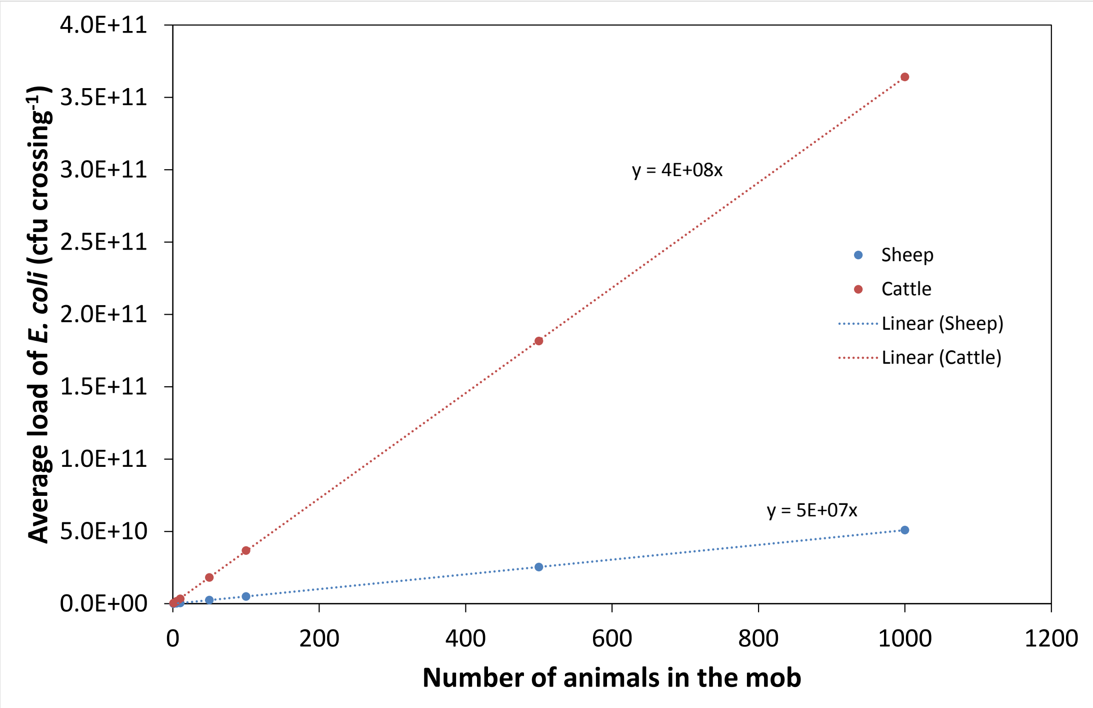

Figure 5: The average loads of *E. coli* deposited into a stream from mobs of sheep or cattle crossing a stream. Loads are derived from the average values shown in Figure 4.

Thus the annual load of *E. coli* from stream crossings (*SC*) in a farm block is given by equation 5:

$$SC \text{ (cfu year}^{-1}) = [(4 \times 10^8 * N_c * F_c) + (5 \times 10^7 * N_s * F_s)] * C \quad (5)$$

Where N_c in the typical number of cattle in a mob, F_c is the typical number of times per year that cattle are moved through the stream crossing, N_s is the typical number of sheep in a mob, F_s is the typical number of times per year that sheep are moved through the stream crossing and *C* is the number of stream crossings in the block. This load represents the amount of *E. coli* mitigated by installing a bridge or culvert across the stream crossing.

3.1.3 Changing the type of stock

As sheep defecate less *E. coli* into a stream than cattle, and in situations where it is unpractical to fence off a stream (even a cattle-only fence), then an option may be to consider farming sheep only. Farming sheep only has other practical and economic issues that will be discussed in Section 3.2.4. We can use the information in Figure 2 to estimate the relative *E. coli* loads deposited into a stream from the existing farm with mixed stock and a new farm with the same stocking rate but 100% Sheep. The calculation is shown by equation 6:

$$X = A - B \quad (6)$$

Where *X* is the reduction in load of *E. coli* deposited in the stream from replacing cattle with sheep, *A* is the existing load calculated using Equation 2 and the current stock numbers, and *B* is the load calculated using Equation 2 but assuming 100% sheep. In theory, this mitigation could be applied to paddocks that were difficult to fence and cattle could be grazed only in paddocks where streams could be fenced. However, it is not known how practical this option would be on an operating farm and it would be difficult to model. Therefore, in our farm-scale model this option is evaluated assuming the whole farm is converted to sheep.

3.1.4 Land-use change to forestry

Forestry land will contain a number of other wild animals and birds that will deposit *E. coli* into the streams flowing through the forests. However, there is very little understanding about these *E. coli* impacts at low or base-flow conditions. Therefore, we cannot calculate the effect of this mitigation with the methods used above. The SPARROW *E. coli* model contains estimates of the relative load of *E. coli* discharged per year from pastoral and forested land-use (Elliott et al., 2016).

We can, therefore, use these values from the SPARROW model to estimate the relative reduction in annual *E. coli* discharges from this land-use change using equation 7:

$$Y = (P * A_1) - [(F * A_2) + (P * (A_1 - A_2)] \quad (7)$$

Where Y is the annual mitigation effect (cfu year^{-1}), P is the load from pastoral land-use (8.8 x 10^{11}cfu ha^{-1} year^{-1} from Elliott et al., 2016), F is the load from forestry land-use (5.2 x 10^{9} cfu ha^{-1} year^{-1} from Elliott et al., 2016), A1 is the existing area of the farm and A2 is the area of the farm that is converted to forestry land-use (ha).

3.2 Estimation of the economic effects of the 4 mitigation options

3.2.1 Calculating cost-effectiveness

The cost-effectiveness (cfu reduced \$$^{-1}$ spent) is calculated as the effectiveness (cfu year^{-1}) divided by the cost (\$ year^{-1}). This requires the estimation of all *E. coli* mitigation effects and costs on a yearly basis. For the stream fencing and stream crossing mitigations in the following sections, costs are estimated as a capital cost of installing the mitigation. These capital costs are then converted to an annual cost using the PMVT function in excel. The PMVT function uses input parameters of interest rate (%) and term (years) and calculates the annual cost of repaying the capital cost over the term of the "loan".

3.2.2 Stream fencing

The cost of fencing in hill country can be quite variable due to a number of factors. These include: steepness and difficulty of the terrain, type of fencing (temporary vs permanent and number of wires and/or electrification) and whether the farmer builds the fence themselves or employs a contractor. To allow for the flexibility of inputs for these effects, the model leaves it open for the input of values from the cost of fencing per km of stream length. Furthermore, the farm can be split into 2 separate blocks to allow for different fencing costs on different classes of land (i.e. a flat block in the valley bottom and a steeper block on the hills). The separate (and cheaper) costs of fencing cattle and the more expensive sheep fencing costs are both entered into the model and calculated using equation 8:

$$H = F \times L \times 2 \quad (8)$$

Where *H* is the capital cost (\$), *F* is the cost of fencing (\$ km^{-1}), *L* is length of stream requiring fencing and the factor of 2 allows for fencing both sides of a stream. The length of the stream for fencing should be estimated from the farm LEP and estimates of the costs of fencing can be found in Anon (2017).

The other cost associated with fencing streams is that an alternative drinking water source may be required for stock. In the model we have kept the water reticulation and fencing costs separate for 2 reasons. Firstly, the farm block may already have a water reticulation system and hence this is not an additional cost to installing stream fencing. Secondly, in a recent study on the cost-benefit of water reticulation systems in hill country farms it was identified that this may actually result in a positive benefit to the farm (Journeaux and van Rennan, 2016) and hence should not be seen as a “cost” of fencing. So for flexibility we have left these “costs” as separate inputs in the model so that the individual farmer can decide if the water reticulation is a direct cost of fencing the stream, or if they will use that opportunity to enhance the productivity of the farm and hence pay for the water reticulation from elsewhere in the business. The cost of installing water reticulation is entered into the model as a single capital cost. This cost can be derived from farmer knowledge, a quote from a contractor or estimated from the details provided in Journeaux and van Rennan (2016).

3.2.3 Stream crossings

The costs of installing a bridge or culvert for a stream crossing will vary for a number of reasons such as the size of the stream and landscape features, such as being located in a small gully. The choice of using a bridge or culvert will not affect the effectiveness of the mitigation for reducing *E. coli* losses to the stream, but will be determined by the relative costs, the ease of installation and the use of the crossing for other activities like access for farm machinery. Typically, a culvert will be cheaper than a bridge but other factors could be the farmer’s ability to build the infrastructure themselves or the need for a contractor to do so. Therefore, we have kept the inputs open to input suitable farm-specific values and assumed that farms will install either all culverts or all bridges on all crossings in the block. Obviously, if it makes more sense to install a mixture of bridges and culverts then the outcome will be intermediary between the 2 modelled outcomes. The calculations of cost are therefore based on the cost of installing individual infrastructure at a crossing points multiplied by the number of crossings needed in the block.

3.2.4 Changing stock types

The sheep:cattle ratio is an important component of farm strategy - helping to match pasture growth with animal demand - on sheep and beef farms in New Zealand (Parker et al., 1997). This is particularly relevant to extensive hill-country farms, where beef cattle play a vital role in managing pasture quality, provide diverse income streams, and reduce labour inputs per stock unit (Rattray et al., 1987; Lambert et al., 2000). The benefits for pasture quality are most evident when beef cattle do not compete with sheep for quality pasture; indeed, on most hill-country farms, they can complement other stock classes by consuming lower-quality feed or having their intake limited at key times of the year (Morris and Smeaton, 2009).

Conceptually, an economic model should consider an explicit relationship between profit and sheep:cattle ratio. However, there is evidence to suggest this relationship should not be included in the economic evaluation performed for the Wharekopae catchment. The key reasons for this are:

1. The profitability associated with altering the sheep:cattle ratio on hill-country farms depends greatly on the relative prices received for sheep and beef products and thus can vary broadly across time. Indeed, this recently motivated research investigating the profitability of changing the sheep:cattle ratio on Waikato farms to reflect changes in relative prices (Olubode, 2015).

2. The profitability of changing the sheep:cattle ratio depends greatly on the management ability of the farmer. Various studies indicate the profitability of altering the sheep:cattle ratio (e.g. Olubode et al., 2014; Perring Ag, 2014). However, the change in financial returns associated with this activity depends entirely on the capacity of a farmer to successfully adapt their system to the new configuration.

3. Empirical evidence indicates that there is no relationship between farm profit and sheep:cattle ratio. Beef and Lamb NZ possess an in-depth repository of information pertaining to profit and sheep:cattle ratio on Gisborne and Hawkes Bay sheep and beef farms. An analysis of this data for 2010–2015 shows that there is no statistically-significant relationship between farm profit and sheep:cattle ratio on these farms (data not shown). Moreover, this outcome is observed across intensive

finishing, hill country, and hard hill-country farms. These results highlight that profit is driven more by other factors of sheep and beef farm management, chiefly number of lambs born, lamb growth rate, and ewe condition at weaning.

4. Mixed sheep and beef systems possess a number of inherent feedback relationships that help to offset significant changes in profit occurring as sheep:cattle ratio changes. For example, a reduced number of beef cattle will increase returns from the sheep operation if a constant stocking rate is maintained, but also lead to reduced pasture quality, higher labour inputs, and reduced buffering to price variation.

5. The peripheral benefits of running beef cattle (e.g. pasture quality, labour, hedging risk) are difficult to quantify, particularly given temporal and spatial variation in pasture production. For this reason, they are seldom considered in economic evaluations of changing sheep:cattle ratios (e.g. Olubodeet al., 2014; Perrin Ag, 2014).

For these reasons, in this economic analysis of the Wharekopae catchment, base farm profit is assumed not to change as a result of altering sheep:cattle ratios. The constant relationship is assumed to be most relevant for sheep:cattle ratios between 20:80 and 80:20, given the multiple complementarities that exist between these different enterprises on-farm. Nevertheless, it is assumed in the following that changing from a mixed system to one that consists solely of sheep incurs no change in profit. Key drivers for this assumption are the fact that the loss of benefits accruing to the cattle herd (e.g. improved pasture quality, labour, hedging risk) are likely offset by the costs imposed by the:

- High maintenance requirements of beef animals.
- Low growth rates of pasture during winter/summer that reduces the amount of feed available for these animals.
- Limited pasture quality on hill country that reduces the digestibility of available feed.
- Intense competition by beef cattle for winter feed as lambing approaches.
- Impact of beef cattle on soil compaction that depresses pasture growth.
- Sustained non-productive periods for beef cows (Morris and Smeaton, 2009).

This assumption may easily be altered, however, if information is available that can attest to the relationship between sheep:cattle ratio and farm profit. Hence the model has included the option of inputting an estimate of the percent reduction in farm profitability associated with running sheep-only on the property. The farmer can include their own data on profitability per hectare and estimated % reduction in profit. The default settings in the model are 0% reduction in profit and $187 ha^{-1} profitability (see section 3.2.5). While this "zero cost" is a practical outcome for the cost analysis, this creates a challenge for the cost-effectiveness calculations in the model as this numerically calculates the cost-effectiveness as infinity. Therefore, for the cost-effectiveness analysis, when a zero cost is entered, we have assumed a value of 500 Million cfu $^{-1}, which is higher than all the other mitigation options but still allows the output to be plotted on the same graphs. When a percentage reduction is input, the actual cost-effectiveness value is calculated.

3.2.5 Land-use change to forestry

Transition of land from sheep-and-beef farming to plantation forest is a potential strategy to reduce faecal microbe losses on East Coast hill country. Analysis of the available data on the relative profitability of these 2 land-uses indicates that forestry is more profitable. But there are large areas of land in pastoral land-use which indicates there are other factors, besides profitability, influencing decisions around land-use. This section attempts to quantify the costs associated with this land-use change. The identification of how farm profit is affected by the area of plantation forest that is established is difficult, due to barriers to uptake that exist for forest establishment. The primary objective of this section is to outline one method of measuring how to determine pastoral and forestry income on East Coast hill farms, explicitly considering such barriers to adoption.

Beef + Lamb NZ (B+LNZ) provide detailed farm budgets for representative East Coast North Island farms, based on their annual sheep&beef farm surveys. These representative farms are defined over hill-country, hard hill-country, and intensive-finishing farms. A representative sheep&beef farm is generated for the Wharekopae catchment from this data, assuming that half of the farm is hill country and half of the farm is hard hill country. Average data from the last five years is used to determine the revenue, variable costs, fixed costs, and interest costs of this farm as $617, $334, $130, and $82 ha^{-1}, respectively. This yields a level of farm profit before tax of $187 ha^{-1}. The assumed size of the farm is 715 ha and the level of equity is 70%, based on B+LNZ data. The level of equity is important because it impacts the size of the interest costs, contained in the farm budget.

The level of profit determined for a hectare of forest land in the catchment is assumed to be $380. This estimate is drawn from work performed by Phil Journeaux in the East Coast region. It is the annual equivalent payment earned for one hectare of a commercial *Pinus radiata* forest. An annual equivalent payment denotes the net present value of an investment, as a series of equal cash flows earned across the duration of the investment. This approach is necessary here because a plantation forest does not provide an annual profit stream; rather, the earning of revenues is concentrated at the harvest of the stand after 28–30 years.

The profit estimates of plantation forest versus sheep-and-beef farming presented thus far pose an interesting problem in the context of the modelling analysis. It is more profitable to plant forestry ($380 ha^{-1}) than maintain current sheep&beef operations ($187 ha^{-1}), according to these estimates. Thus, model output could be biased towards a movement towards forestry in the catchment, especially because this land use should also greatly reduce faecal-microbe loss to waterways, relative to grazed pasture.

This logic is inconsistent with reality, however. The majority of sheep&beef farmers can be assumed to be rational economic actors, who will seek to optimise their returns subject to their resource constraints (Hazell and Norton, 1986; Elliott and Wakelin, 2016). If it was more profitable to plant extensive forests on their sheep&beef farms, then landholders would likely have done this already. Indeed, the superior profit estimate provided for plantation forest, relative to sheep-and-beef husbandry, does not consider important barriers to uptake for this enterprise.

Barriers to the adoption of agricultural enterprises are reviewed at length by Pannell et al. (2006). The barriers listed in this review are used to determine constraints facing the extensive use of plantation forestry on sheep-and-beef farms. Key constraints are identified as:

1. There are limited benefits of the forest plantation compared with other enterprises on the farm. For example, plantation forests are seldom used as shelter or feed sources to support grazing animals.

2. There is high uncertainty around the returns that farmers will receive for pine products at harvest, in around thirty-years time. This increases the uncertainty around the financial reward accruing to plantation forest.
3. High up-front and maintenance costs are required for forest plantations, but most of the revenue is received at harvest that occurs around thirty years after planting. This is a significant impediment to landholders that require ongoing income to service debt and fund personal expenditures.
4. A lack of existing forest area reduces annual returns, because a profitable and sustainable harvest rotation cannot be practiced.
5. There is uncertainty around environmental policy in the region, such that pine forests on steep hill country may not be able to be harvested in the future due to high soil-erosion risk.
6. There is a risk that plantation forests can suffer damage from extreme weather and pests/disease.
7. Maintenance of significant forest areas on sheep&beef farms may conflict with existing values and beliefs of landholders.
8. Maintenance of significant forest areas on sheep&beef farms may conflict with the existing skills of landholders, most of whom possess more experience in the management of pastoral, rather than silvicultural, systems.
9. Broad uptake of forestry within the catchment will greatly impact community vitality and the amount of agricultural production from this region (TLG, 2016).
10. There is a strong inertia in established management plans given a strong drive to repeat learned actions, even in the presence of new opportunities or constraints (Gonzalez and Dutt, 2011).
11. Not all areas of a farm are generally suited to the establishment, maintenance, and harvest of plantation forests; for example, because of soil and slope constraints.

These factors highlight the complexity of adoption, especially for forestry systems that take many years to yield an economic return. It also highlights the many attributes that impact the suitability of a new practice for a given farming system.

It is difficult to capture these constraints to adoption within a quantitative model; nevertheless, they are important to incorporate. The following method is proposed as an accessible and intuitive approach. It is based on the use of a calibration function that manipulates the profitability of a farm enterprise to depict barriers to uptake not represented in a quantitative model. This approach is used here to improve the realism in the way that the profitability of plantation forest is represented. The conceptual foundations of this approach are drawn from positive mathematical programming (PMP) (Howitt, 1995). For example, in the original application of PMP described in the literature, Howitt (1995) utilised a mathematical function to describe how crop yield per ha falls as greater areas of crop are planted, due to reduced land suitability.

The calibration function utilised here represents a fall in the profitability of plantation forestry, as more area on a farm is allocated to this enterprise. The key motivation for this formulation is that landholders need to service their fixed costs from their pastoral enterprise; otherwise, the business will be unable to remain viable. In contrast, the lack of an annual return to the forest enterprise precludes its ability to service fixed costs. (Fixed costs include: insurance, levies, rates, drawings, interest, and rent.)

A farm model is generated for the representative sheep&beef farm described above. Whole-farm budgeting is then used to identify annual pastoral returns for the farm for different proportions of the farm being allocated to plantation forest. This data is used to determine the proportion of fixed-costs that are covered by the pastoral enterprise versus the proportion of the farm planted to forest, for 56 different land allocations between sheep&beef and forest enterprises on the representative farm. Values below 0.01 (1%) of fixed costs are set equal to 0.01 (1%) in this output, to prevent forest profits becoming negative when the pastoral enterprise becomes too small to service fixed costs. This is very useful from a computational perspective while introducing little bias, given that these outcomes are already greatly penalised (being 99% lower than their baseline level).

A calibration function is then estimated from this data using the Curve Fitting Toolbox in MATLAB 2016. This calibration function relates the proportion of fixed costs serviced by the pastoral enterprise (the dependent variable) to the proportion of the farm planted to forestry (the explanatory variable). This relationship is used to scale the profitability of forest as forest area increases. This is based on the intuition that the pastoral enterprise maintains a principal role in servicing the fixed costs of the farm; therefore, as its area decreases through forest establishment, its relative importance grows.

The calibration function is shown in Figure 6, together with the data points and 95% confidence intervals. The function has a negative slope, representing that forest profit falls from its baseline value as greater areas of the farm are planted to this enterprise, in line with the barriers to uptake listed above.

The profitability of forest is determined through equation 9:

$$C = T \cdot P \cdot F \cdot \left[1.131 \cdot \mathrm{e}^{-13.69 \cdot P} \right] \quad (9)$$

Where:
C = Profitability of the plantation-forest enterprise for the farm ($).
T = Total size of farm (ha).
P = Proportion of farm planted to plantation forest (0–1).
F = Baseline profitability of forest (F = $380 ha^{-1}).
e = The exponential function (e.g. that defined in Excel when using the EXP() function).

The term in square brackets in eq. 9 is the calibration function determined using the Curve Fitting Toolbox in MATLAB 2016. It has an excellent fit to the simulated data, with a sum of squared errors of 0.006, an R-square measure of 0.9978, and a Residual Mean Square Error of 0.0108.

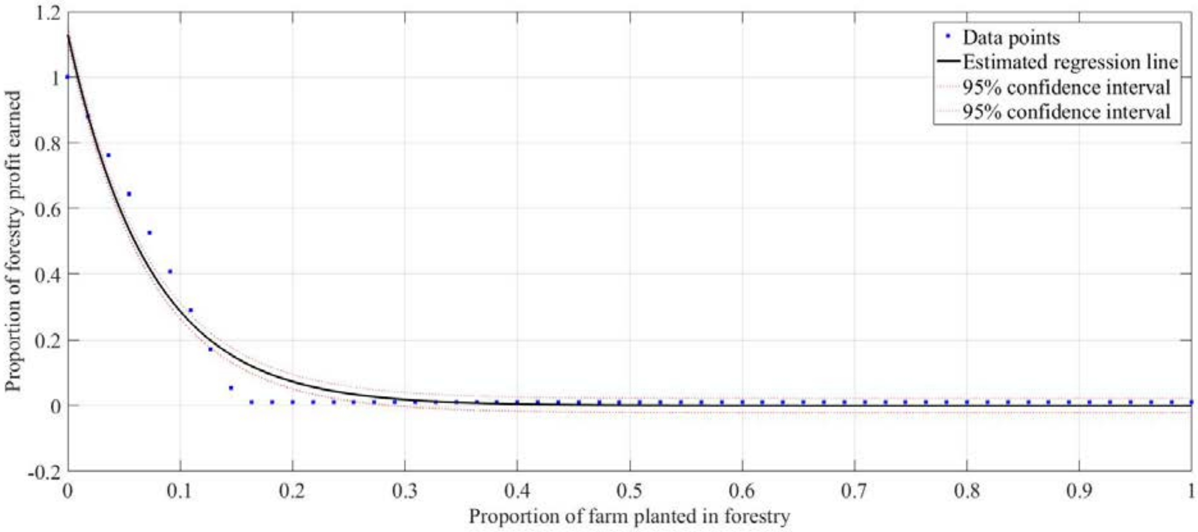

Figure 6. Shape of the calibration function used to dampen the profit of plantation forest as a greater proportion of an East Coast sheep & beef farm is planted to this enterprise.

Equation 9 can be used to determine the profitability earned from plantation forest when a certain proportion of the farm is planted with forest. The function also seeks to capture the other general barriers to uptake listed above to determine the profitability earned from plantation forest when a certain proportion of the farm is planted with forest. Table 2 presents examples for cases involving proportions of 0.05 (5%) and 0.2 (20%) of the farm planted to forest. In line with Figure 6, this data shows how total forest profit falls with increased forest area, to represent the degree to which the pasture enterprise is less able to service fixed costs in any year. While explicitly depicting this relationship, the broad decrease in forest profit characterised by the calibration function also seeks to capture the other general barriers to uptake listed above.

Table 2: Profitability of plantation forest when planted on differing proportions of the farm, computed using equation 9.

Description	Symbol	Proportion of 0.05 (5%)	Proportion of 0.2 (20%)
Total farm size	*T*	715 ha	715 ha
Proportion of forest	*P*	0.05	0.2
Baseline forest profit	*F*	$380	$380
Calibration function	$1.131 \cdot e^{-13.69 \cdot P}$	0.57	0.07
Total forest profit	*C*	7,749	3,976

Meanwhile, the profitability of the pastoral enterprise is simply computed through:

$$D = T \cdot (1 - P) \cdot G \qquad (10)$$

Where:

T = Total size of farm (ha).

P = Proportion of farm planted to plantation forest (0–1).

G = Baseline profitability of the sheep-and-beef enterprise (*G* = $187 ha^{-1}).

Point estimates of the profitability of plantation forest on sheep&beef farms are difficult to utilise in economic assessments of mitigation activities. The magnitude of returns are typically favourable, especially once compared to sheep&beef profits. However, the timing of cashflows impairs the capacity for farm businesses to maintain viability when large proportions of their land are allocated to this activity. Moreover, significant expansion of plantation forest can reduce community vitality and agricultural production within hill-country catchments. These factors highlight the importance of deriving pragmatic means to considering the broad economic value of increasing plantation forest on extensive pastoral farms in the East Coast region. The methodology described in this document is a step in this direction.

3.2.6 Distance upstream

One other factor that was agreed to be investigated is the effect of distance upstream on the effectiveness of a mitigation. It is well known that microbes will die-off as they travel downstream. Therefore, mitigation options applied immediately upstream of the point of interest in a river will have greater impact on the *E. coli* concentrations than mitigations applied further upstream. Having an understanding of this distance effect would be valuable. The SPARROW *E. coli* model expresses this effect as a decay coefficient as described in equation 11 (Elliot et al., 2016).

$$k\ (\mathrm{km}^{-1}) = 0.048Q^{-0.77} \qquad (11)$$

Where k is the decay coefficient when using $\mathrm{Log_e}$ and Q is the stream discharge in $m^3\ s^{-1}$. Therefore we can rearrange equation (11) to calculate the % reduction in *E. coli* based on the distance upstream and the flowrate in the river using equation 12:

$$\text{Reduction (\%)} = e^{(d(-0.048\ Q^{-0.77}))} \qquad (12)$$

Where d is the distance upstream (km) and Q is the stream discharge ($m^3\ s^{-1}$). Using equation 12 on the main stem of the Wharekopae river, assuming that the river flow rate is 250 L s^{-1}, then the *E. coli* die-off over a distance of 5 km upstream will be 50%. This implies that a mitigation applied 5 km upstream of the Rere rockslide will be 50% less effective than a mitigation applied directly above the Rere rockslide. Using equation 12 on a small farm tributary flowing at 10 L s^{-1}, then a 50% reduction will occur over a distance of only 400 m. This analysis is very interesting for the implications on the cost-effectiveness of mitigations but there are 2 factors that are thought to be important reasons not to code this information into the current farm-scale model.

Firstly, the equation as used in the SPARROW model has been calibrated at the "large river scale" (Elliott et al., 2016), certainly much larger than the small tributary size of only 10 L s^{-1}. Therefore, this analysis is extrapolating the data beyond the data range used for calibration and hence we cannot be entirely confident in the results. More research and data of *E. coli* attenuation rates in these small streams would be needed before we could have confidence in the results.

Secondly, in discussions with the farmers in the catchment it is clear that they swim in the Warekopae River on their own farms. Therefore, a key point of these mitigations is that improving the water quality at the Rere Rockslide is important but should not be the entire focus of the mitigations in the catchment. The water quality along the whole river should be improved as the community recreate in the whole length of the river.

But a simple message from this analysis would be that, at either the farm- or catchment-scale, you will get better cost-effectiveness for your mitigation options if you start fencing (or applying other mitigation options) from the bottom of your farm first and then work your way upstream.

4. Results and Discussion

This sections describes the results of applying the model to 3 case-study farms. All case-study farms had B+LNZ Land and Environment Plans (LEPs) written which helps with identifying some of the inputs required for the model. The model input data in the tables was provided by GDC after interviewing the farmers and filling in a questionnaire.

4.1 Mitford's Farm

The data provided for modelling the Mitford's farm is shown in Table 3.

Table 3. Input data as provided by GDC for Mitford's farm.

Description	Total Farm	Rolling	Hill (other)
Area	800 ha	200ha	400ha(200 trees)
Sheep numbers	3000	*Autumn grazing only*	*7.5SU/ha*
Cattle numbers	500	*2.5 head/ha*	*Autumn grazing only*
Stocking polices?		*Cell grazing/Bulls. No sheep until Autumn*	*no cattle except Autumn. Ewes rotation except lambing*
Length of stream on property (estimate)		1.2km	Main stream 2.3km
% paddocks with stream access		*40% with stream access*	*90% with stream access*
Estimated cost to fence one side of a stream		$5,000 / km for cattle only fence. $ 16,000/ km for sheep and cattle fence	$5,000 / km for cattle only fence. $ 16,000/ km for sheep and cattle fence
Proportion of paddocks with off-stream stock drinking water?		*100% off stream*	*52 paddocks, 22 with stream as only stock drinking water source*
Cost to provide off-stream reticulated stock drinking water		All done	$100,000 + pumps to higher country
Number of Stream crossings		*2 fords*	*9 fords and 3 culverts*
Frequency of crossing use		*Mob of 50 cattle 5 times per year, mob of 800 sheep 5 times a year…*	*Mob of 100 cattle 5 times per year, mob of 1500 sheep 12 times a year…*
Costs to install bridge or culverts		$50,000 per bridge, $20,000 per culvert	$50,000 per bridge, $20,000 per culvert

The data from the Mitford's farm covers all inputs needed to run the model, with the results shown in Figure 7. The most effective mitigation option is fencing off the streams in Block B, the hill block. Fencing both sheep and cattle is always more effective than cattle-only, but the cheaper cattle-only fences are more cost-effective. If a reticulated water supply is included in the costs, this reduces the cost-effectiveness of fencing this block. The second most effective mitigation is replacing cattle with sheep; this is also the most cost-effective option. Land-use change to forestry was modelled as converting an additional 200 ha (1/3 of the current S&B operation) to forestry. The fourth most cost-effective mitigation option is fencing the streams on Block A, the rolling land block. Stream fencing on Block A is less effective than on Block B, as Block A is a smaller size and more of the stream is already fenced. However, as only a short length of stream requires fencing, then fencing off the streams in this block is more cost-effective. For Block A there is existing stock drinking water reticulation so there is no additional cost required; the model therefore, calculates the same effectiveness and cost-effectiveness data for this block (note the overlay of the light blue dots in Figure 7). The least effective and cost-effective mitigations are addressing the stream crossings. Block B has more stream crossings that are used more frequently, so the results indicate that bridges or culverts will be more effective and cost-effective on this block relative to Block A (Figure 7).

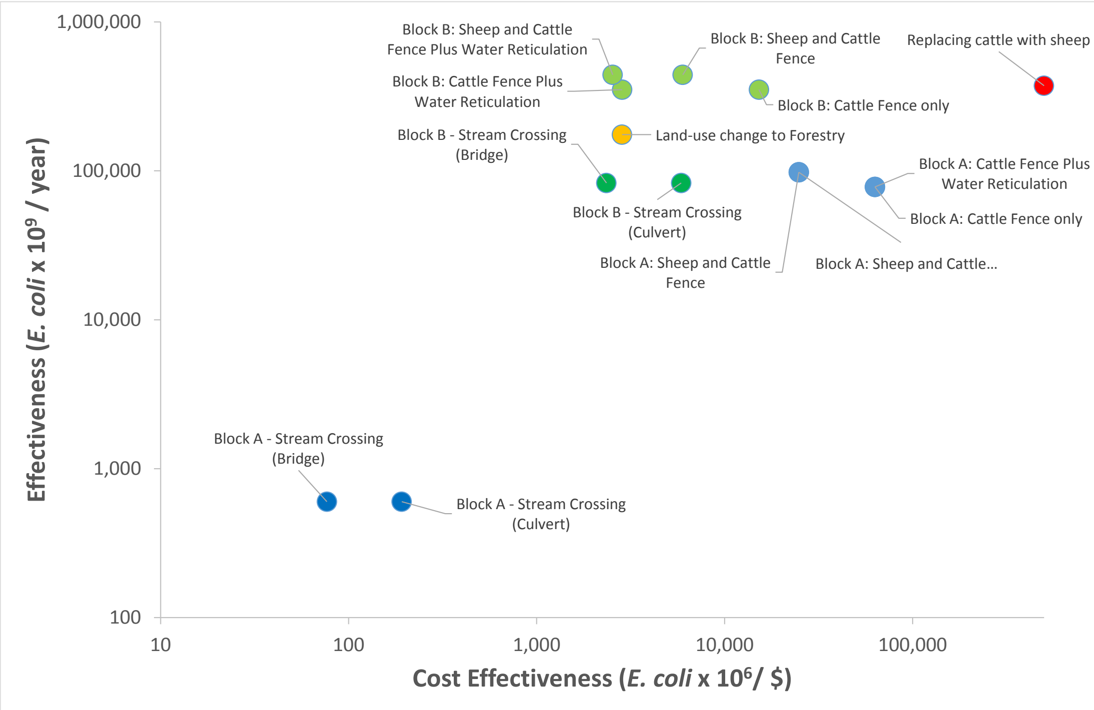

Figure 7. Relationships between effectiveness and cost-effectiveness for the mitigation options on the Mitford farm.

4.2 Mokonui Station

Mokonui station is owned by Mark and Sam Gemmell. The data provided for the *E. coli* model are shown in Table 4.

Table 4. Input data as provided by GDC for Mokonui station.

Description Mokonui Station, Rere	Total Farm	Flats	Hill (other)
Area	760ha	25ha	735ha
Sheep numbers	3600	9.5su/ha	9.5su/ha
Cattle numbers	618	9.5su/ha	9.5su/ha
Stocking polices?	Breeding and finishing	Some summer crop on flats above	Integrate sheep and cattle grazing.
Length of stream on property (estimate)	3km	1km above flats	2km
% paddocks with stream access	River now virtually fenced off	None	10%
Estimated cost to fence one side of a stream	Up to $15/m	$ 8/m for cattle only fence. $ 15/m for sheep and cattle fence	$ 8/m for cattle only fence. $ 15/m for sheep and cattle fence
Proportion of paddocks with off-stream stock drinking water?	50%	Currently dam water with a few creeks	70 paddocks with 50% dam and 50% creeks
Cost to provide off-stream reticulated stock drinking water	$70,000 - $100,000	$70,000 - $100,000 to reticulate the flats	Will be part of the cost to reticulate to flats
Number of Stream crossings	Two on Wharekopae River	2 bridges for sheep and 2 fords for cattle	
Frequency of crossing use	30-40 times per year through fords	Mobs of up to 50 cattle at a time going through fords	
Costs to install bridge or culverts	Unknown at present	$ per bridge, $ per culvert	$ per bridge, $ per culvert

The data provided in Table 4 is relatively comprehensive but lacks some specific details, particularly for stock crossings. Firstly, no estimates of the cost of bridging or culverts has been provided so I have filled this in the model assuming $20,000 per culvert and $50,000 per bridge, based on the costs provided by Mitford Farm. Secondly, animal numbers for using these stream crossings have only been provided for cattle and not sheep; but I assume that sheep will still need to be herded through the crossings as well. I have used only the cattle numbers provided in the model, using an average of 35 crossing events per year and made no estimate of the potential sheep loading.

Other issues are the ambiguity in the responses relating to stream fencing and stock drinking water. For the fencing questions the survey states that in the hill block 90% of the streams have been fenced off, but in the stock drinking water question the response is that in 50% of the paddocks the stock drink out of a “creek”. Given the definition of a “stream” should be any flowing water on the farm, then the true level of fencing might actually be only 50%. However, I have entered the “90% fenced off” value in the model.

The results of the model are summarized in Figure 8. For the land-use change to forestry mitigation I have assumed that 200 ha of the farm is converted to forestry which is the most effective mitigation for reducing *E. coli* loads to the stream. The mitigation of replacing the cattle on the farm with sheep is the most cost-effective due to the fact that the model assumes this can occur at no cost. There are 4 data points for the cost-effectiveness of measures for Block B, the hill block, showing the most effective option is fencing both sheep and cattle, but fencing only the cattle is more cost-effective. The effectiveness remains the same but the cost-effectiveness reduces if you include the cost of having to reticulate water to the paddocks as well as the fencing costs. There are no estimates of fencing for Block A (the flats) as the streams in this block are already fully fenced. The least effective mitigation option is the stream crossings. Note that the effectiveness of bridges or culverts is the same but the cost-effectiveness changes due to the greater cost of building a bridge.

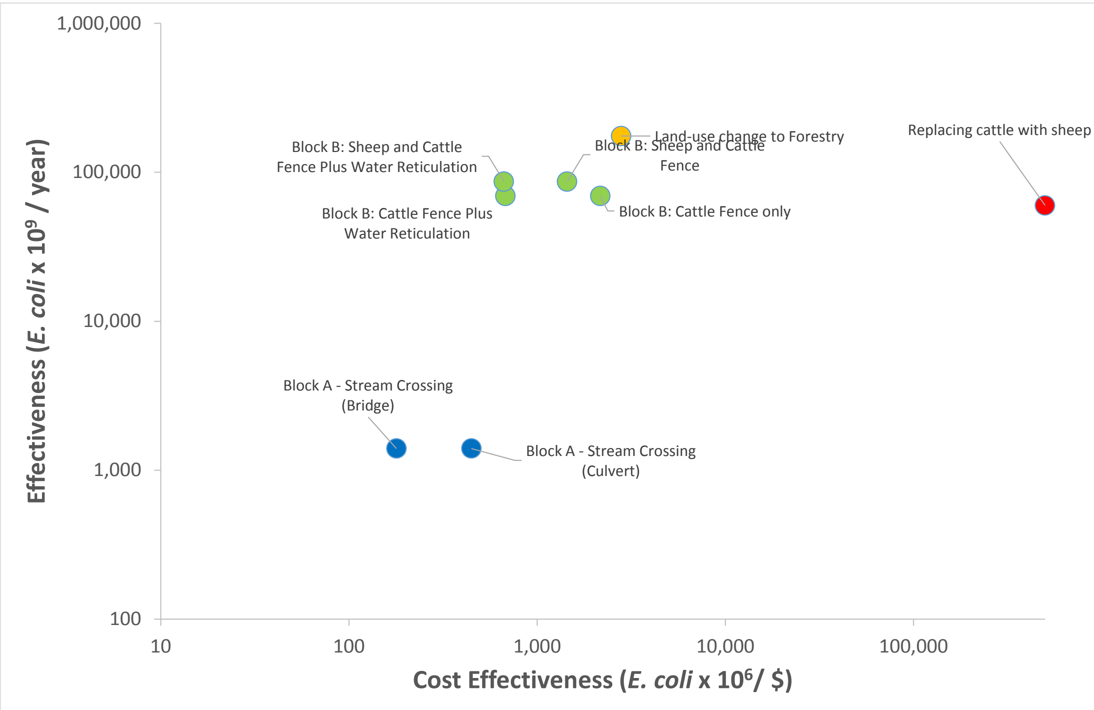

Figure 8. Combined effectiveness and cost-effectiveness of the mitigation options for Mokonui station.

4.3 Worsnop's Farm

The data provided for modelling Worsnop's farm is shown in Table 5.

Table 5. Input data as provided by GDC for Worsnop's farm.

Description	**Farm total**	**Flats**	**Hill**
Sheep no's	2500	250	2250
Cattle no's	200	0	200
Stocking policies	Breeding and finishing Lambs, finishing cattle.	Lambs finished on flats.	Ewes, lambs and all cattle grazed (on rotation mostly) on hill areas.
Length of stream	2km of river, 3 km of streams	2 km of river	3 km of streams (but both sides need fencing so 6km)
Proportion of stream fenced	550 meters	550 meters	0
Estimated fencing costs	$15/m to fully stock proof, $9-10/m for cattle only. Materials included.	1450 meters $20,000 estimate	6km $80-90,000 estimate
Proportion of paddocks with off stream stock water	20 out of 30	3 of 5	18 out of 25
Cost to provide off stream water	$10,000 per dam	$20,000 Plus ongoing maintenance	$70,000 Plus ongoing maintenance
Number of stream crossings	Stock cross small streams (they are very small on summer) in 12 paddocks	2	9
Frequency of use	Stock would cross at will when held in these paddocks	Sheep are in these paddocks maybe seven days out of thirty.	Sheep and cattle can be set stocked or rotated through these paddocks. How often they cross depends on lots of factors, and so is hard to quantify.
Cost of culverts	$2000 each	$4000	$18000

For Worsnop's farm there was no data provided on the area of the total farm or specific blocks on the farm. However, they did provide data on the numbers of animals grazing the 2 blocks. So if we assume a whole farm stocking rate of 9 s.u./ha then the total farm area will be 410 ha with the flats block of 28 ha and the hill block of 382 ha. Due to the larger land area, the fencing of streams in Block B, the hill block, are the most effective mitigations. Replacing cattle with sheep is the most cost-effective mitigation (Figure 9). As water reticulation would be needed on both blocks, the inclusion of the costs of this reduces the relative cost-effectiveness of this mitigation on both blocks.

For the land-use change to forestry scenario we have assumed 100 ha (~1/4 of the farm) is planted in trees. This mitigation option is less effective but more cost-effective than fencing Block B. In the questionnaire there is no detail provided on the sizes of mobs or frequency of use of stream crossings; no data are therefore plotted for this mitigation option (Table 5, Figure 9).

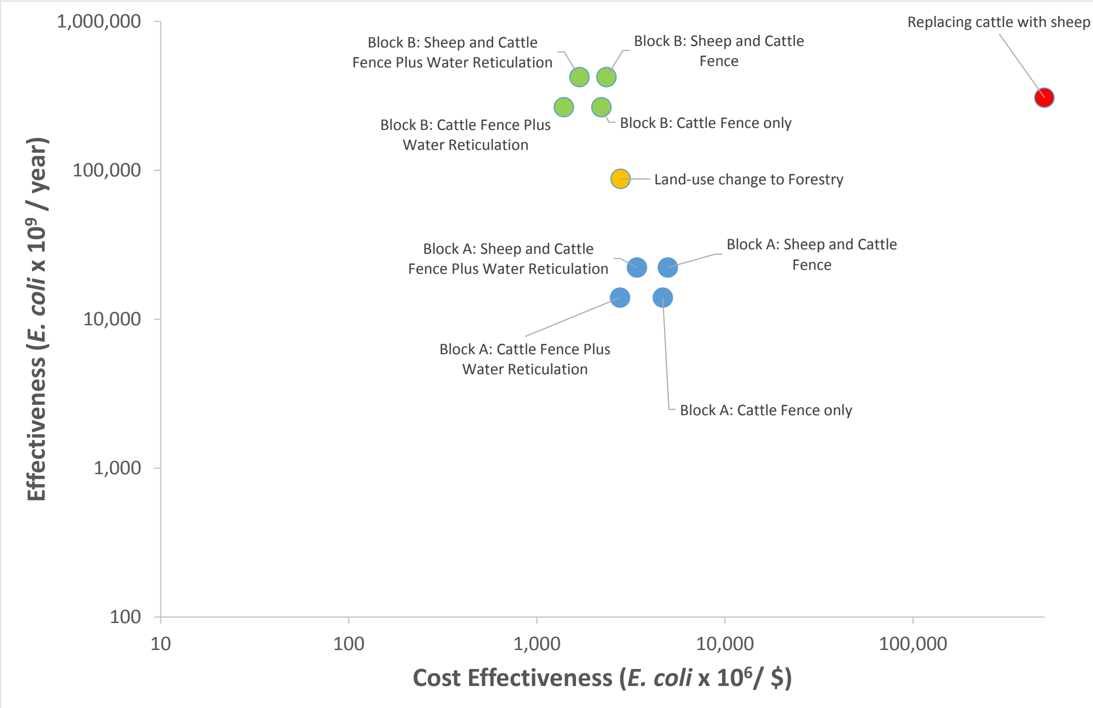

Figure 9. Combined effectiveness and cost-effectiveness of the mitigation options for the Worsnop farm.

4.4 Interpretation of the Graphs

The 2 key outputs of the analysis are the effectiveness and cost-effectiveness of the mitigation options. The effectiveness is as an indication of the amount of impact the mitigation will have on reducing *E. coli* inputs to the streams under base-flow conditions in the Wharekopae catchment. In Figures 7-9 the most effective mitigation options are shown in the top of the graph. The second output is cost-effectiveness which is the “bang for buck” for the mitigation option; this is plotted on the X axes. Ideally you would select the mitigation options that are both the most effective and cost-effective; these are the data points in the top right hand corner of Figures 7-9. If you were to prioritise the implementation of the mitigations for impact on the river, you would follow the sequence of (1) top right, (2) top left, (3) bottom right and (4) bottom left.

The other important feature of the graphs is that on both axes data is plotted on a Log_{10} scale. This means that you need a large difference in the numbers before the data points will shift substantially on the graphs. For example, on Mitford farm, for the fencing options on Block B, the sheep and cattle fence is 1.3 times more effective than the cattle-only fence, but the cattle-only fence is 2.5 times more cost-effective (light blue dots on Figure 7). Likewise, there is greater than a 10 times difference in the effectiveness and cost-effectiveness of the stream crossing mitigations on blocks A and B (Figure 7). What this means is that if your input estimates, such as the cost of fencing or frequency of stream crossing use, is out by a factor of 2, then this will not have a big impact on the *relative* effectiveness or cost-effectiveness of the different mitigation options.

4.5 General Discussion

The application of the farm-scale *E. coli* model to these 3 case study farms generates some general patterns in the relative effectiveness and cost-effectiveness of the modelled mitigation options. The relative effectiveness of the stream fencing options for the 2 blocks is driven by the relative size of the farm blocks. The farms in the Wharekopae catchment typically have a large hill country block and only a small flat or rolling block of land and therefore, stream fencing on the larger block will always be the most effective. Within a farm block, the cattle-only fencing option is always less effective, but more cost-effective, than a sheep proof fence. The cost-effectiveness of the stream fencing mitigation is reduced when a reticulated stock drinking water is needed. However, the reticulated water system may have other benefits for the farm so the costs could be offset by increased production (Journeaux and van Reeneen, 2016). The stream fencing option for the smaller flat land blocks is often more cost-effective than the hill blocks which is likely due to the relatively shorter length of stream in the flat land. As you trace a stream into the headwaters, in the hills the dendritic stream network will spread, resulting in a greater “drainage density” of stream length per ha. As a result the sheep-proof fences on the flat land bocks are more cost-effective than cattle-only fencing on the hill blocks.

The mitigation of replacing cattle with sheep is always modelled as the most cost-effective option as we have assumed that this change can be made with no cost over the long term. Sensitivity analysis of the models showed that for Mitford Farm, Mokonui Station and Worsnop Farm you would have to reduce farm profitability by 5, 15 and 70%, respectively, before the cost-effectiveness of this mitigation was equivalent to the next most cost-effective mitigation. This result for Worsnop's Farm is likely due to the high cost of fencing 6 km of stream on the hill block. These results indicate the potential benefit of this mitigation option if it can be practically implemented on farm. The effectiveness of this mitigation option will always be less than the stream fencing options at the farm-scale, but is similar to the cattle-only fencing option. An option may be to apply this mitigation only to paddocks where it is not practical to fence off the stream and only run cattle in fenced paddocks. Due to the complexity of this scenario, we have not modelled this option but its effectiveness would be similar to a cattle-only fence option, but with less cost.

The mitigation option of land-use change to forestry is typically less effective than the stream fencing options. The forestry option appears more effective on Mokonui Station (Figure 8) but the modelling has assumed that the streams in the hill block are already 90% fenced off. This has resulted in the relative lowering of the effectiveness of further stream fencing on this farm, relative to the other case-study farms. The key pattern is that increasing the area of farm planted in trees increases the effectiveness, but decreases the cost-effectiveness, of this mitigation option.

The stream crossing mitigations are typically less effective and less cost-effective than the other mitigation options. This is due to the infrequency of animal deposition into the stream when large mobs of animals are being moved relative to animal access to the stream during grazing. Typically the effectiveness of mitigating the crossings is greater on the hill blocks relative to the flat blocks. This is likely the result of two separate effects: (1) due to the stream networks, there are likely to be more stream crossing points used in the hill blocks, and (2) on the flat land where stream crossing are more frequently used, they have most likely already been bridged to provide easier and safer access for animals and farm vehicles. The cost-effectiveness of these options is dependent on the estimated costs of installing bridges or culverts. As noted earlier, there is some caution needed around the use of the "cattle defecation rates during stream crossings" for the sheep calculations. However, the stream crossing mitigation options is typically the least effective and least cost-effective mitigation so this assumption in the calculations should only have a minor effect on the farm-scale decision making. Also note – many regions are developing specific rules around the requirements for installation of mitigations for stream crossings based on the frequency of use. Farmers are recommended to check their local rules regarding the need to install bridges and culverts and whether a resource consent is needed for the construction.

The development and application of this farm-scale *E. coli* mitigation model to the case-study farms has generated some typical patterns of mitigation effectiveness in the Wharekopae catchment. However, these patterns may change in other areas/landscapes if there are substantial changes in the relative costs of mitigation options and/or farm/forestry profitability.

One of the challenges illustrated by the case-study farm analysis is getting the required input values needed to operate the model. These can be the costs for fencing, bridges, water reticulation, and frequency of stream crossing use, or the profitability for the farm or potential forestry land-uses. However, a "best guess" value can be used in the first instance to generate some results for all mitigation options. The farmer may then decide on which mitigation option best suits their future plans and then invest the time and effort in getting more accurate information to revise the model. The model can also be run using different future scenarios assuming different values for costs/profit etc.

5. Summary and conclusions

This report describes the science used to develop a farm-scale *E. coli* mitigation model. This is in the Excel Spreadsheet "Farm scale Ecoli Model for GDC version2.xlsx" that accompanies this report.

A workshop will be held at Gisborne District Council to train some of their staff in the use of the model. Following this training GDC staff will be able to use the model to help farmers in the Wharekopae catchment to prioritise planning and implementation of appropriate mitigations to improve the microbial water quality of the Wharekopae River at the Rere Falls and Rockslide swimming sites.

Initial consultations with farmers may act as a scoping study to explore mitigation options using relatively coarse input data or "guesses". The model can be re-run at follow-up meetings as more accurate data is available to support the decision making process.

We note and stress that this model can be used for estimating the relative effectiveness and cost-effectiveness of *E. coli* mitigations for reducing impacts under base-flow conditions in a stream. The model does not consider the impacts from storm-driven runoff events and hence does not calculate total loads of *E. coli* from farms.

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7. References

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