Preliminary Risk Model for Environmental Losses of *Campylobacter* from Broiler Litter

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*Prepared for*

New Zealand Food Safety Authority and Ministry for the Environment

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Executive Summary

This report presents background information related to modelling of *Campylobacter* loss into streams from broiler litter applied to land. A stochastic model for simulating the losses is presented. The model takes into account the rates of litter application, concentrations in the applied litter and the effect of litter stacking or treatment, and also the loss of litter from land during runoff events. The litter loss model is embedded in a broader model of catchment *Campylobacter* losses, to put the litter component into perspective. The model uses the @Risk add-in to Microsoft Excel, and is available from NIWA.
1. Introduction

This report describes work conducted on the research programme “Campylobacter in food and the environment: examining the link with public health”. The programme is a collaboration between scientists at the New Zealand Food Safety Authority (NZFSA) and the Ministry for the Environment (MfE), as well as the National Institute for Water and Atmospheric Research (NIWA), the Institute of Environmental Science and Research (ESR) and Massey University. The programme is funded by through NZFSA and MfE under the Foundation for Research and Technology (FRST Cross Departmental Research Pool (CDRP) research portfolio.

The overall objective for this research programme is to unify approaches to risk modelling and management for pathogens that are acquired via both food and environmental pathways. The initial focus is on Campylobacter spp. The programme, which runs from July 2007 – June 2010, is intended to deliver robust intervention strategies that can be adopted by various government departments and regulatory agencies. There are three overall objectives:

1. Improve the existing comparative exposure models.
2. Extend existing ecological/environmental models.
3. Examine the links between human exposure via different pathways and the underlying ecological environmental models by integrating all modelling activities.

This report addresses a component of the research programme associated with determining the risks of loss of Campylobacter from chicken broiler litter to water (the study addresses losses from the litter from broiler farms, rather than losses from manure from laying hen operations). This report reviews information related to Campylobacter loss, describes a conceptual framework for the loss assessment, and also describes a simple risk assessment model developed for this study.
2. **Summary of available information on *Campylobacter* and chicken litter, as it relates to assessment of losses to water**

This section summarises information on *Campylobacter* and chicken litter, as obtained from scientific literature or from individuals with experience of the poultry industry.

2.1 **Animal waste and litter production rates**

In this report, the term ‘animal waste’ is used to represent the urine and faeces produced by the birds; the term ‘litter’ is used as shorthand for ‘used litter’, that is, used bedding material including animal waste. The term ‘fresh litter’ is used to refer to waste when it is removed from the growing shed, before additional storage or treatment.

ASAE (2003, Table 1) give rate of 0.085 kg day$^{-1}$ fresh animal waste production per kg live weight of bird (wet weight, urine and faeces) for broilers. For an average bird weight of 1 kg over the growing period, this would amount to 0.085 kg day$^{-1}$ per bird. Vanderholm (1984) gives a rate of 0.14 kg/day/bird voided waste, with a solids content of 28% based on feed conversion rates at the time and 1.8 kg birds. For higher feed conversion efficiencies (now typically 1.5 kg feed per kg live weight, down from about 2.0 kg in the 1980’s, PIANZ 1999), a smaller mass of waste would be produced (although the birds are now about 2.5 kg, so there might be about 0.09 kg/day/bird fresh animal waste). A representative figure would be 0.1 kg day$^{-1}$ bird$^{-1}$ fresh weight of waste, with a solids content of 28%. For comparison, fresh waste production rates for laying hens are about 0.1 kg day$^{-1}$ bird$^{-1}$ (Dorner et al. 2004, Table 5; Ferguson et al. 2009, Table 8).

The litter from a broiler shed includes bedding material (in New Zealand this is usually wood shavings, Lake et al. 2008). The Ontario Ministry of Agriculture and Food’s Nutrient Management Software, NMAN, gives a litter production rate of about 0.05 kg day$^{-1}$bird$^{-1}$ wet weight for all-in/all-out broilers reaching 2.1 kg and using 0.004 kg bedding per bird per day. The dry matter content is 0.6 kg dry matter per kg wet litter, and the density of the ‘wet’ litter is 320 kg m$^{-3}$ (the litter is quite dry and light). From The Poultry Site$^1$, about 0.55 kg (wet weight) of litter (mixed bedding and animal waste) is produced per kg of bird reared. For a 2.2 kg bird reared over 42 days, the litter production rate is 0.029 kg day$^{-1}$ bird$^{-1}$ wet weight, with 0.75 kg of dry matter per kg of litter solids, and wet density of 0.75 kg L$^{-1}$. This is based on cleaning out the sheds once per year. In New Zealand, litter is usually removed after grow-out (Lake et al. 2008) which may lead to a higher litter production rate, so the Ontario

numbers may be more applicable to New Zealand. A typical litter production figure would be 0.06 kg day\(^{-1}\)bird\(^{-1}\), with a solids content of 60% (kg solids per kg litter).

PIANZ have estimated “that approximately 160,000 to 165,000 tonnes of litter is produced per annum from both the breeders (i.e., grandparent and parent stock) and the broiler birds grown for meat production in New Zealand” (Pers. com., James Fick, PIANZ).

2.2 Shedding of \textit{Campylobacter}

2.2.1 Prevalence in Broiler Flocks

Cox et al. (2002) measured an overall sample prevalence of 62% from faecal samples from 35 broiler flocks in the USA, with farm prevalence ranging from 0 to 100%. There was an overall sample prevalence of 57.1% for droppings from 14 breeder farms, ranging from 12% to 80%. These figures were comparable to the results from other studies.

Dorner et al. (2004) summarised ten studies on prevalence in poultry (8 studies on broiler farms, 2 with layers), and found prevalence in samples from each farm ranging from 3.1% to 100%. They fitted a beta distribution to the data for each study describing the proportion of animals that are affected (the distribution reflects the sampling uncertainty, and would become a very narrow peak for large samples). They also developed a composite weighted multi-peak distribution for the combined studies.

Wallace et al. (1997) found seasonal variation in concentrations in the caeca of chickens from a single processing plant, ranging from an unusually low value of 30% in autumn and an overall median (median of monthly values) of 90%.

In relation to the modelling of litter, the shed prevalence is likely to be of most relevance (rather than the individual or sample prevalence), because the litter is likely to be somewhat mixed or homogenised. There is still variability between farms, as shown in the summary of Dorner et al. (2004) and the study of Cox et al. (2002), and there is also likely to be variability over time. The overall loading in litter should take the variability in concentrations and the variability in prevalence into account.

2.2.2 Concentrations in poultry faeces and caeca contents

Cox et al. (2002) measured a log-mean \textit{Campylobacter} concentration of \(10^{5.1}\) gfw\(^{-1}\) for faecal droppings from 35 broiler farms in the USA. The variability was not given, so the arithmetic mean cannot be determined.

Nauta (2006) reported on unpublished measurements from 176 positive samples (taken from caeca of birds before hanging) from 36 broiler flocks. Both within and
between-farm variability was assessed. The geometric mean farm concentration followed a log-normal distribution with a geometric-mean of $10^6$ g$^{-1}$, and log$_{10}$-sd of 1.52 (between-farm variability). Within a farm, the concentrations also varied in a log-normal fashion, with a log$_{10}$-sd of 0.73. The arithmetic mean value within a farm would then be $10^{0.6}$ times the farm geometric mean. There is additional variability between farms; the combined log$_{10}$-sd is 1.68, giving an overall sample arithmetic mean of $10^{9.2}$ g$^{-1}$ (a high number, consider that $10^9$ or $10^{10}$ g$^{-1}$ approaches pure bacteria, pers. comm., Rob Lake, ESR).

El-Shibiny et al. (2005) measured $10^{4.5}$ to $10^{9.7}$ cfu g$^{-1}$ in caecum contents for an organic farm, and $10^{6.7}$ to $10^{9.2}$ cfu g$^{-1}$ for a free-range farm geometric means of samples taken at a certain age; the range is related to different ages of animals. The lowest concentration of $10^{5.5}$ g$^{-1}$ was an outlier in the distribution (the next lowest age had a concentration of about $10^{7.5}$ g$^{-1}$). There was additional variation between animals for a given sampling age (log-10 s.d. of about 1). Overall, the geometric mean concentration would be about $10^{7}$ g$^{-1}$ with a log$_{10}$-sd of about 1.5. If this is averaged over the ages of the animals in a shed (representing accumulation of faecal material), the arithmetic mean concentration for infected animals would be about $10^{9.5}$ g$^{-1}$.

Wallace et al. (1995, 1997) measured a mean concentration of $2.9 \times 10^{11}$ MPN g$^{-1}$ in caeca (swabs of dissected intestines) from a single plant with highest concentrations in early summer. The median was more like $10^{7.3}$ g$^{-1}$ (read from a plot). Stern et al. (1995) measured a geometric mean concentration of $10^{5.44}$ MPN g$^{-1}$ in caeca from 10 broiler farms.

Overall, these studies suggest a geometric mean concentration of about $10^5$ g$^{-1}$, but with considerable shed-to-shed variability (log$_{10}$-sd of about 1.5) and within-shed log$_{10}$-sd of about 0.7, which inflate the arithmetic mean well above the geometric mean, to about $10^{9.5}$ g$^{-1}$.

### 2.3 Concentration of *Campylobacter* in fresh litter

Rothrock et al. (2008) measured a mean concentration of *C. jejuni* of $6.3 \times 10^7$ cells g$^{-1}$ by quantitative real time PCR from extracted DNA in fresh litter from one site (s.d of $1.7 \times 10^7$ cells g$^{-1}$).

Kelley et al. (1995) measured *C. jejuni* in litter using MPN methods, initial concentrations and maximum concentrations (after 25 days) in a broiler house where the litter was kept in conditions similar to normal litter. The concentration reached a geometric mean of $7.2 \times 10^3$ g$^{-1}$, with a log-10 sd of 3.6 for poultry waste on fresh shavings. The arithmetic mean based on these numbers would be massive if the concentrations followed a log-normal distribution. Kelley et al. (1994) reported
concentrations in fresh litter: the geometric mean concentration was $10^{3.12 \pm 3.26}$ for one house and $10^{3.53 \pm 3.66}$ for another house.

Hutchison et al. (2004) measured a prevalence of 19.4 % in fresh poultry litter (67 wastes) in the UK. In the positive samples, the geometric mean concentration was $2.6 \times 10^2$ cfu g$^{-1}$. Arithmetic means were 11 to 16 times larger than the geometric means (log10-sd of 0.95 for fresh wastes).

The concentrations from PCR are much larger than the other two concentrations, and will include non-viable and non-culturable DNA, and may also be biased high due to the characteristics of the method (pers. comm. Rebecca Stott, NIWA).

2.4 Decay in litter and storage

Geometric concentrations in fresh litter are much lower than in faeces (by about 3 orders of magnitude, see the previous sections) suggesting considerable decay in the litter before removal from the shed. The implied decay rate can be estimated. If there is a first order decay rate of $k$ and excreta are added a constant rate, then the overall decay factor over 40 days would be $(1-e^{-40k})/(40k)$. So a decay factor of $10^3$ suggests a $k$ value of about 20 per day. This is supported by Cox et al. (2001) who found that only 15% of pine shaving samples inoculated with $10^5$ cells of *Campylobacter* tested positive after 30 minutes, suggesting rapid die-off on pine shavings, but there was some uncertainty about recovery efficiency from dried samples.

Processing of litter by placing it in ‘deep stacks’ or piles (typically 2 m deep and covered for 3 weeks or more) in which high temperatures are reached (45°C or more) reduces concentrations markedly. Jeffrey (2001) found a rapid decline of *Campylobacter* numbers in stacked litter, apparently due to rapid temperature increase in the piles. *Campylobacter* became undetectable after 2 hours (estimated 2-3 log reduction), implying a decay rate of 24 day$^{-1}$ or more. Hutchison et al. (2005a) measured a decay rate of 0.91 day$^{-1}$ in laying chicken bedding inoculated with *Campylobacter* and stored in heaps. Nicholson et al. (2005) measured decay for litter inoculated with *Campylobacter* and stored in 10 m$^3$ piles, which generally reached temperatures of 55°C. The concentrations were measured by enrichment methods which allowed for the recovery of sub-lethally injured organisms. The *Campylobacter* survived for up to 4 days in the piles, amounting to a decay rate in the order of 1 log-10 unit per day, or $k$ of 2.3 day$^{-1}$. Kelley et al. (1994) measured the decay of *C. jejuni* in broiler litter stored in 1.3 m high bins from two farms. The temperature peaked at 43°C after 5 days, and the reduction was typically 3 log-10 units in 8 weeks (by MPN methods), although this amounts to a relatively small decay rate of 0.12 day$^{-1}$.

Such large reductions with storage are not universal. Hutchison et al. (2005b) measured a prevalence of 7.7 % in stored poultry litter (26 wastes) in the UK.
compared with 19.4 % for fresh litter (67 wastes). In the positive samples, the geometric mean concentration was $5.9 \times 10^2$ cfu g$^{-1}$ for stored wastes, which was comparable to the value of $2.6 \times 10^2$ cfu g$^{-1}$ for fresh wastes. This suggests little decay (apart from the reduction in prevalence). However, the stored and fresh wastes were not necessarily from the same source (not a pairwise comparison), and there could be a range of different storage methods. Rothrock et al. (2008) measured a mean concentration of $6.3 \times 10^7$ cells g$^{-1}$ by quantitative PCR in fresh litter (s.d of $1.7 \times 10^7$ cells g$^{-1}$), which only reduced to $1.2 \times 10^7$ cells g$^{-1}$ after 4 weeks under incubation at 25 $^\circ$C but reduced to $<10^4$ after 8 weeks. The decay rate for incubated untreated litter was minimal over the first 4 weeks, but was substantial over the next 4 weeks. For alum-treated litter (10% by weight) the concentration reduced from $9.3 \times 10^7$ cells g$^{-1}$ to $<10^4$ after 4 weeks.

Controlled heat treatment is likely to reduce concentrations to undetectable levels. Jeffrey at al. (1998) found no Campylobacter on heat treated poultry litter used for feeding dairy cattle in California (104 samples from 13 dairy farms).

In summary, it appears that there are substantial reductions (about 3 logs) from excreta to fresh litter. Deep pile storage reaching a high temperature (such as 45 degrees) will likely reduce concentrations by at least 3 logs. Casual storage (such as in shallow bins or piles) will result in variable treatment efficiency, because the temperature may not reach a high-enough value to kill the bacteria. In addition, turning of piles is likely to improve the treatment, due to more uniform exposure of the litter to high temperature.

2.5 Litter disposal and application

ESR conducted an “on-farm survey” of broiler farms in 2006-7 (Lake et al. 2008). Of the 158 broiler farms, 60 were visited and the average number of birds on these farms was 94,000. From the report:

All farms in the survey used wood shavings for litter. All but one farm reported that litter was removed from the farm after grow-out, with 53/60 farms reporting removal by a commercial company. For 6/60 farms the farmers reported removing the litter themselves. 20/60 farms reported the litter was spread on other nearby farms.

David Marks, one of the veterinarians involved in the survey, with long experience with Tegel and now as an independent consultant, reports that most poultry litter is used as fertiliser of some description, or for mushroom production. Commercial operators prefer litter dry as it is easier to spread. Little if any controlled composting is performed; the only effect would be incidental during storage. David agreed that most spreading of litter would occur close to the poultry farms producing it.
It is of interest that litter is fed to cattle rarely if ever in New Zealand, in contrast to practices in the USA (Jeffrey et al. 1998).

Poultry Industry Association of New Zealand (PIANZ) were contacted in this study regarding treatment of poultry litter, who provided the following information (email from James Fick, PIANZ, 8/10/2010):

We estimate that approximately 160,000 to 165,000 tonnes of litter is produced per annum from both the breeders (i.e., grandparent and parent stock) and the broiler birds grown for meat production in New Zealand.

The breakdown in how this is used is as follows:

92% spread on pasture, i.e., dairy farms, maize farms, mushroom farms.
5% fertiliser - either put into a fertilizer product (commercially sold or used farm general farming purposes).
3% compost - once composted, this is also spread onto pasture or used for general farming purposes.

When the used poultry litter is spread on pasture there is typically a downtime of 14-21 days (as previously mentioned). This used litter is generally collected and put to pasture as soon as it can be (this is also barring poor weather conditions).

Used litter which is composted is generally composted for a minimum of 21 days (and in rare occasions, up to 49 days) before it is further utilised.

The form of storage (if any) before application was not stated, but it is likely that any storage is informal rather than under specific conditions (such as controlled deep pile storage), except in cases where the litter is composted.

Grazing of pasture with litter applied is a potential exposure pathway for cows. However, the withholding period before grazing (14-21 days) will allow for substantial reductions in concentrations likely to be at least 2 orders of magnitude (see later sections on decay). Also, the loadings from manure are less than typically from the cows themselves (see approximate calculations later). Hence increases in environmental loading from cows infected from litter does not seem to be a prominent source of loading to freshwater environment. Possibly application to pasture could lead to re-contamination of broiler sheds (via flies, for example), and that exposure pathway has not been assessed in this report.

Controlled composting is a routine component of mushroom compost preparation. It is standard practice to heat compost to kill harmful organisms and then condition it under controlled conditions above 45°C. It is possible that the occasional detection of Campylobacter in retail mushrooms (Doyle and Schoeni 1986; Whyte et al. 2004) is

2 http://www.mushroomgrowers.org.nz/mushroom-growing-process.php
attributable to insufficiently treated chicken litter used as a component of mushroom growing media, although Doyle and Schoeni (1986) argue that this is unlikely.

While disposal of waste from the laying industry animals was not included in the scope of this model, the Egg Producers Federation of New Zealand (EPFNZ) did provide some information to PIANZ on this question (email from James Fick, PIANZ, 9/11/2010). An assessment of the waste streams was prepared based on approximate calculations, and the use of the waste was also assessed. A summary of waste produced was provided (Table 1).

<table>
<thead>
<tr>
<th>Source</th>
<th>Dried manure (tonnes)</th>
<th>Used litter (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cage layers</td>
<td>14,500</td>
<td>0</td>
</tr>
<tr>
<td>Barn layers</td>
<td>1,500</td>
<td></td>
</tr>
<tr>
<td>Free range layers</td>
<td>4,500</td>
<td></td>
</tr>
<tr>
<td><strong>Total layers</strong></td>
<td><strong>6,000</strong></td>
<td></td>
</tr>
<tr>
<td>Pullets</td>
<td>4,100</td>
<td></td>
</tr>
<tr>
<td><strong>Total from all sources</strong></td>
<td><strong>14,500</strong></td>
<td><strong>10,100</strong></td>
</tr>
<tr>
<td><strong>Total manure plus litter</strong></td>
<td><strong>24,600</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1:** Waste produced by layer industry (provided by PIANZ and EPFNZ). Here the term refers to animal waste without bedding material.

They also note that:

*In terms of what is done with the manure, it is usually applied to pasture (i.e., dairy farms, maize farms, mushrooms farms) once it leaves the production farm. When the used litter from barn and free range production systems is removed from the barns, it is generally composted already. It is then used as a composted product (sold for general farming purposes or it can be applied to pasture). If the used litter requires more composting time, it is generally handled like meat chicken litter, where used litter which is composted is generally composted for a minimum of 21 days (and in rare occasions, up to 49 days) before it is further utilised and eventually put to pasture.*

and:

*Caged-egg production systems generally dry down manure before it is collected and taken off-site (where, it is typically collected every 1-3 weeks and then is taken off-site).*
The production of litter from the layer industry (10,100 t/year) is small compared with the amount from broilers and breeders (160,000 t/year), and waste is applied in a similar way to that from broilers. The concentration in litter from barn and organic operations is apparently composted, which is likely to reduce the concentrations considerably. The concentration in waste from pullets is not known, but it would be reasonable to assume concentrations similar to broiler litter.

We were unable to obtain information on the concentration of *Campylobacter* in ‘dried-down’ manure from cage operations.

Magic Poultry Compost provide well-composted manure from laying hens³, and their target market is home users. As noted in the previous section, thorough composting is likely to reduce concentrations in manure markedly, which is appropriate considering that there is potential for exposure risks directly related to human consumption.

### 2.6 Application rates to land

Poulfert⁴ recommend application of their product at a rate of 2.5 – 5 tonnes per ha for pasture. Their website states that Poulfert has a sand/sawdust like consistency, and is dry to touch. When applied at 2.5 t/ha, Poulfert provides 70 kg ha⁻¹ N and 32.5 kg ha⁻¹ P.

In New Zealand, there are generally no restrictions on the use of poultry litter, except that litter should not be applied in hot dry days in Canterbury in order to avoid odour problems. The New Zealand Fertiliser Code of Practice excludes litter from its coverage.

In the Midwest of the USA, application of litter is limited on the basis of P content. P is often added to chicken feed to strengthen bones, resulting in a high P content in the waste. This is reflected in the fairly high P to N ratio in the Poulfert analysis (2.3N to 1.6P).

As noted in the on-farm survey (Lake et al. 2008), most of the litter is applied on farms in the same region as the poultry houses, which is reasonable considering the high fertiliser value and to minimise transport costs.

The order-of-magnitude land loading from chicken litter applied as fertiliser can be compared with the loading from an intensive dairy grazing episode. For application of 5 t ha⁻¹ and a concentration of 10⁸ g⁻¹, there would be 5×10⁹ ha⁻¹ applied. For grazing of 15 cows ha⁻¹ for 5 days and a shedding rate of 10⁹ cow⁻¹ day⁻¹, there would be 5×10¹¹ organisms applied per grazing rotation (which might be repeated 12 times per

² [http://www.poulfert.co.nz/products.htm](http://www.poulfert.co.nz/products.htm)
year). Therefore, it would seem that application of the litter would provide land loadings about 2 orders of magnitude lower than would be applied during a grazing rotation. The concentrations in the litter are quite uncertain.

2.7 Decay on land and washoff from land

After application, there may be some time before there is sufficient rain for mobilisation of litter, during which time the concentrations in the litter and the erodibility of the litter may reduce.

Nicholson et al. (2005) measured the decay of Campylobacter which were inoculated on broiler litter which was then applied to the land. The Campylobacter numbers were measured in sampled soil cores. The Campylobacter survived for up to 4 days when incorporated in a sandy arable soil, and up to 16 days when applied to the surface of clay loam grassland soil. The decay on the grassland soils was approximately 0.5 day\(^{-1}\), with a soil temperature of about 16°C. This decay rate is consistent with Campylobacter decay rates in soil. For example, Ross and Donnison (2006) measured a decay rate of about 0.4 day\(^{-1}\) for C. jejuni applied to four different soil types in New Zealand at 10°C. The decay rates are likely to be less in winter than in summer, due to the well-established influence of temperature on decay rates for Campylobacter. With a decay rate of 0.5 day\(^{-1}\), and 10 days between runoff events, there will be a 160-fold reduction in concentrations, highlighting the significant role of decay after application to land. This decay is also relevant to withholding periods for stock grazing after fertiliser application. This decay is likely to be temperature-dependant, based on the experiments in water (e.g., Thomas et al. 1999), and the decay rate will typically increase by a factor of 2 going from winter to summer (5°C to 15°C).

Brooks et al. (2009) measured the loss of various microbes including Campylobacter in runoff from poultry litter (5 t/ha or 18 t/ha) applied to 1.46 m long by 0.187 m wide PVC troughs filled with silt loam soil, with Bermuda grass in a greenhouse. Artificial rain was applied at 27 mm/hr for 30 minutes, at 1 to 26 days from the litter application. Campylobacter were detectable in the raw litter but not in the applied litter, which was stored for 10 days of storage at 10°C. Campylobacter were not detected in the runoff, whereas other pathogenic microbes were. The litter was applied at up to 1800 g m\(^{-2}\) over a plot area of 0.27 m\(^2\) and had an initial Staphylococci concentration of approximately 10\(^{9.5}\) /g, thus the initial application amounted to 491 g of litter and 10\(^{12.2}\) microbes. There were approximately 10\(^{10.5}\) Staphylococci washed off in the first day, which amounts to 2% of the applied Staphylococci. For Enterococci there were 10\(^{7}\) washed off and 10\(^{6}\) per g applied (10\(^{8.7}\) applied in total), giving a washoff efficiency of 2%. For C. perfringens there were 10\(^{8.5}\) washed off and 10\(^{6}\) per g applied, giving a washoff efficiency of 0.6%.
Edwards et al. (1994) used a rainfall simulator to generate loss of fresh broiler litter (with rice husks and wood shavings used for bedding) applied to the surface of fescue pasture on silt loam in 6 m long runoff plots at 5% slope in Arkansas under various litter application rates (up to 23 t/ha), rainfall intensities, and times from application. The litter solids loss ranged from 0.06 to 0.11% of the applied litter for a rainfall intensity of 50 mm/hr, and from 0.25 to 0.30% for a rainfall intensity of 100 mm/hr (rainfall was applied until there was 0.5 hr of runoff). At the lower application rate, the percentages losses of litter are an order of magnitude smaller than percentage losses of microbes from Brooks et al. (2009). This could be due to preferential enrichment of microbes in the solids transported from the plot, or mobilisation of microbes unattached to solids.

Based on these experiments, Edwards et al. (1994) also assessed the erodibility of chicken litter in the Modified Universal Soil Loss Equation (MUSLE):

\[ Y = 9.05(Qq_p)^{0.56}KLSCP \]

where \( Y \) is the sediment load (t/ha), \( Q \) is the runoff volume (m\(^3\)), \( q_p \) is the peak run-off rate (m\(^3\)/s), \( K \) is the soil erodibility (t hr ha\(^{-1}\) N\(^{-1}\)), \( L \) is the slope-length factor from the revised universal soil loss equation (RUSLE) (dimensionless), \( S \) is the slope factor from the RUSLE, \( C \) is the cropping factor from the RUSLE, and \( P \) is the practice factor from the RUSLE. Note that the \( K \) value in the units above is 1.29 times the \( K \) value in conventional imperial units.

For a litter application rate of 5 t/ha, the erodibility was about 1.4 t hr ha\(^{-1}\) N\(^{-1}\), which was about 10 times larger than the erodibility of the underlying soil. The large erodibility relates to the low density and small particle size of the litter particles. Erodibility increased linearly with solids application rate but was not influenced by rainfall intensity. The erodibility decreased with successive rainfall events, to the point where the sediment yield matched the background yield of the base soil after two rainfall events. The erodibility was not influenced by the time until first rainfall application (up to 14 days), presumably because the litter did not wet up and decay or become incorporated into the soil.

Soupir et al. (2006) measured the loss of bacterial indicators (\( E. \) coli, faecal coliforms, \( Enterococcus \)) from stacked turkey litter applied at 2.8 t/ha to fescue-clover pasture in 18m long plots of 5.5 % slope and with silt loam soil. Artificial rain was applied with a rainfall simulator at 44.5 mm/hr, initially for 3 hours on dry soil and then for 1 hour on wet soil (producing 3.8 and 9.2 mm of runoff respectively). The load of indicator bacteria was elevated by about 3 \( \log_{10} \) units above the control. For \( E. \) coli the concentration in the litter was \( 3 \times 10^3 \) g\(^{-1}\), and the flow-weighted concentration in the second event was \( 1.6 \times 10^4 \) /100ml (with similar concentrations for the other
indicators). The application was $8.4 \times 10^9 \text{ ha}^{-1}$ and the runoff was $92 \text{ m}^3 \text{ ha}^{-1}$, giving a loss of $1.5 \times 10^{10} \text{ ha}^{-1}$ and suggesting that all the applied microbes were washed off. This result seems unlikely, considering that little of the solids were washed off, and so it should be given little weight.

Fergusson et al. (2007a) use a washoff fraction of 0.5% for poultry in their model, at an extreme of very large runoff. This value is comparable to the highest values from the experiments of Edwards et al. (1994). The value was derived from experiments with bovine faeces under simulated rainfall events, for *E. coli*, *Cryptosporidium*, and a bacteriophage on slopes of 18 degrees (Fergusson et al. 2007b), but also seems to have been adjusted downward for poultry. The fraction of microbes decreased with ‘effective rainfall’ runoff in their model, according to a multiplicative term of the form $1 - \exp(- (U/U_o)^2)$, where $U$ is the effective rainfall for the event and $U_o$ is a scale runoff depth (with a default value of 50 mm). The effective rainfall is the total runoff, including a baseflow component. So, for 5 mm of runoff the fraction lost will be only 1.6% of the fraction lost at 50 mm runoff. Also, there is an implied depletion effect, so that for large runoff, there is little sensitivity to runoff. This seems to be an assumed functional form without supporting data, and the form contrasts with the essentially linear dependence in the MUSLE, although it is somewhat consistent with the form in HSPF (Edwards et al. 1994), which has an exponential term with a depletion effect for large runoff. Soupir et al. (2006) did not note a depletion effect during runoff events for microbial indicators from turkey litter.

By way of comparison, the experiments of Muirhead et al. (2006) with *E. coli* from cow pats suggest that the concentration in runoff (per L) is typically 3 times the concentration in cow pats (per dry g). For 50 mm of runoff (50 L m$^{-2}$) and a cow pat dry mass of 2000 g m$^{-2}$ (based on 20 mm thickness and a dry density of 10%) there will be 2.5% loss of microbes from the cow pats. In this context, a loss of 1% from litter does not seem unreasonable.

There is very little information to assess the delivery ratio of *Campylobacter* from plot scale to hillslope scale, nor the effectiveness of riparian filter strips. As noted in the experiments by Edwards et al. (1994), the bedding material is not mobilised from plots. The remaining particles have a low density and are fine, so settling of these solids is unlikely. Infiltration may occur in filter strips where stock are excluded, however, it is difficult to spread flow across such areas, and riparian areas may also be water-logged. Considering these factors and the high uncertainty in sources, we consider that in most cases there will be little removal in filter strips, and it is not warranted to include this factor in a model.
2.8 Leaching and subsurface transport

There is little information on the leaching of Campylobacter from chicken litter and the associated impacts on groundwater quality, yet this is a concern of water quality managers in some parts of the Manawatu (Nigel French, pers. comm.). Cook (2007) reported on preliminary results from a laboratory study of leaching through a core with litter on the surface, but the results are too sketchy to interpret.

Some information is available on leaching and survival in soils influenced by dairy grazing in New Zealand. Donnison and Ross (2009) measured the Campylobacter leached through 10 cm-deep cores of Topehaehae gley soil and Keroene sandy loam at Toenepi by simulated rain events of 12.5 or 25 mm/hr, for various times after application of simulated dairy effluent containing spiked Campylobacter. Approximately 60% of the applied Campylobacter were leached by application of 25 mm, 21% for 12.5 mm of rain on the gley soil 1 day after effluent application. For the sandy silt, and this percentage decreased to 9% for 12.5 mm of rain. After time resting, there was a much smaller proportion of leaching (of the remaining microbes), for example, 5% for the gley soil with 25 mm of rain after 7 days, and 0.7% after 28 days, suggesting immobilisation over time.

Close et al. (2010) found that there was very little leaching of Campylobacter through 1.5 m of a lysimeter in stony Lismore silt loam (with underlying gravel) on a dairy farm with up to 80 mm of irrigation applied by a travelling irrigator. For 80 mm of irrigation (representing typical irrigation of 50 mm plus rainfall of 30 mm) on lysimeter plots with fresh cow pats there was some leaching, but concentrations were less than 4 MPN/100ml. There was often leaching of E. coli under these conditions, consistent with the lower decay rates for E. coli compared with Campylobacter as measured in decay experiments. Also, there was no impact of a centre pivot irrigator on C. jejuni presence in groundwater collected from a depth of approximately 10 m upstream and downstream of a dairy farm. In contrast, Close et al. (2008) found Campylobacter in 16% of samples in shallow groundwater under areas with border-dyke irrigation, with nearly all the concentrations less than 0.1 MPN/100ml.

Pang (2009) summarised literature on microbial attenuation in soils. The attenuation varied with soil type, reflecting the degree of soil structure. First-order distance-based microbial removal rates are typically 10 log_{10}/m for allophone and pumice soil, generally in the order of a few log_{10}/m for most soils, with better removal for sandy loam than for silt loam, and down to 0.1 log_{10}/m for clayey soils and clay loam. The attenuation rates are smaller for larger irrigation rates. The microbial removal rates estimated for vadose zone media are generally in the order of $10^{-1}$ log_{10}/m for clay and silt, sand, sand-gravels, coarse gravels, and fractured chalk and granite. Microbial removal rates are in the order of $10^{0}$ log_{10}/m for pumice sand and clay till, and also
occasionally for sand. Attenuation rates in groundwater were given for various aquifer types and flow rates. The data did not include *Campylobacter* but highlights the differences between soils, and attenuation for *Campylobacter* can be expected to be comparable or greater than the values above, due to the similar physical characteristics but larger decay rates compared with other bacteria.

These attenuation data could be of some use for modelling the attenuation of *Campylobacter* in soils and groundwater. However, the relation between the concentrations in litter and the concentrations in water washed off litter by rain is unknown. As an indicative number, the experiments of Muirhead et al. (2006) with *E. coli* washed from cow pats suggest that the concentration in runoff (per 100 mL) is typically 0.3 times the concentration in cow pats (per dry g).

Experiments with mole-tile Palic soils at Massey dairy farms (MAF, 2007) demonstrated that there can be high concentrations of *Campylobacter* in drain water (up to 10^3/100ml), especially for rainfall shortly after rainfall.

A key data gap limits our ability to predict the leaching of *Campylobacter*. Specifically, we have no information on the washoff from the litter into the soil, and without this information (or even an approach to estimate it), we cannot predict the effect on groundwater from a mass balance perspective. Moreover, the attenuation rates mentioned above might not apply to microbes from litter, because the microbes could be associated with fairly coarse particles. In addition, modelling the dilution between the litter area and drinking water supplies would be difficult. Therefore, we have not attempted a model for groundwater quality effects associated with chicken litter.

As noted above however (in the section on land loadings), it seems that loadings from litter are likely to be less than from routine dairy grazing. The various studies discussed above suggest that for most soil types where there are aquifers, there is little effect of dairying on *Campylobacter* concentrations in groundwater supplies; it follows that there would be low risk from litter application. While dairying can affect groundwater quality when there is border-dyke irrigation, it is unlikely that litter would be applied in that situation. Also, dairying can affect subsurface water quality if there are poorly-drained soils, but it is unlikely that *Campylobacter* from litter would pose a threat, because groundwater in such areas would not be used for drinking water, or the bores would be tapping deeper confined sources. This provides further some reassurance that excluding a groundwater component from the litter model is not missing a large risk.
2.9 Numbers for production of broilers in New Zealand

According to the Statistics New Zealand Agricultural Production Census/Survey, the population of poultry in New Zealand (as at 30 June 2007) was 18.8 million chicken broilers, 3.0 million laying hens, and 2.1 other poultry. The typical broiler growing period is 6-7 weeks, (typically 42 days), or 5.5 flocks produced per year. PIANZ reports that 80.1 million broilers were produced in 2008.\(^5\)

3. **Risk model**

A risk model was developed in the Monte Carlo simulation software @Risk (Palisade Corporation, Ithaca, USA), which is an add-in to Microsoft Excel. The decision to use @Risk was based on the ease of prototyping in Excel, easy uptake and manipulation by model users, and the use of this software in other components of the overall *Campylobacter* modelling programme. Also, it was considered desirable to formulate the chicken litter model in a manner that would be compatible with modelling of other microbial sources such as grazing animals, to enable inter-comparisons between risks from different sources.

3.1 **Broad conceptual diagram**

A conceptual model of the pathways and interventions associated with broiler litter is shown in Figure 1. This includes a wide range of pathways and points at which interventions can be achieved. It is not necessary to model all these pathways (for example, the chicken litter component of mushroom compost is heat-treated and might be considered to be a less important pathway of exposure to humans).

3.2 **Simplified conceptual diagram**

In this simple model of key pathways associated with surface water quality and drinking water (Figure 2), there is no spatial component. Rather, we consider a single representative area of interest. In addition, parts of this model were incorporated into a simplified catchment model, which is described in the Elliott and Harper (2010).
Figure 1: Broad conceptual diagram of the model. The fate of waste from laying hens and breeders has not been assessed in this model.
Figure 2: Simplified conceptual diagram. A groundwater component has not been implemented.
3.3 Description of model components

The model uses a mean concentration of *Campylobacter* in fresh litter under baseline conditions, representing a typical broiler operation. This represents a concentration averaged over the birds in the flock/house, and is sampled from a distribution with a given mean and variability. Typically the mean concentration would be $10^3$ g$^{-1}$, but with a wide uncertainty (log-10 standard deviation of 1). It was decided to use the concentration in fresh litter rather than the concentration in faeces, because there is a large and variable reduction from faeces to litter.

The baseline concentration can be reduced to take account of measures which decrease the prevalence or concentration, such as might be achieved with improved biosecurity, cleanout, or prevalence in chicks from breeder houses. This factor is supplied by the model user, and is multiplied by the baseline to give a fresh litter concentration.

The fresh litter concentration is then reduced to account for storage and treatment. The treatment is specified as a log-10 reduction. For well-managed stacking, there would typically be a 4 log-10 unit reduction. It is assumed that has a triangular distribution to account for uncertainty and variability in the treatment efficiency (with a range of 3-5 for well-managed storage). For litter with casual storage, the reduction might range from 0 to 1 logs. After the reduction, the concentration in the applied litter is $C_a$ (number g$^{-1}$).

The application rate to land ($R$) will typically be 2.5 to 5 tonnes/ha. The values are assumed to take a uniform distribution with a user-defined range.

It is assumed that the litter is applied to any particular paddock once per year, for those areas where litter is applied. A user-specified fraction of the land in the modelled area will have litter applied. The total area of litter application associated with a particular broiler farm could be estimated by the user based on the number of birds in the broiler farm (at any one time, that is, the standing population) and a litter production of 0.06 kg day$^{-1}$ bird$^{-1}$. For an application of 5 t ha$^{-1}$ once per year, each bird in the standing population requires 44 m$^2$ disposal area.

The decay of *Campylobacter* on land can reasonably be modelled with a first order decay coefficient, which will be in the order of 0.5 day$^{-1}$, which is likely to be smaller in winter and larger in summer (by a factor of about 2). The erodibility of the litter also decreases over time, due to washing into the roots, incorporation into soil, or compaction or decay. From the experiments of Edwards et al. (1994), the erodibility decreased by a factor of 2 each 7 days once the litter was wetted up, giving a first-order rate of 0.1 day$^{-1}$. This process can be combined with the microbial decay to give a combined decay coefficient, $k_p$, which will be dominated by the microbial decay.
In any catchment there may, in principle, be a number of litter application areas, each of which have litter applied once per year, but with the timing of application differing between the application areas.

In an extreme case, all of the areas for litter application will have the litter applied simultaneously, as might apply if we are studying a single paddock. We assume that on any given day, the age of the litter will be drawn randomly from a uniform distribution (going up to year). If the total area over which litter is applied during a year is $A_i$, then the number of microbes available for loss will be:

$$M = A_i RC_a \sum_{i=0,Y} e^{-k\gamma (\alpha+i)}$$  \hspace{1cm} (2)

where $Y$ is the length of a year and $\alpha$ is a random value from the range $[0,1]$. The decay rate needs to be greater than zero to avoid infinite build-up of microbes.

The summation in Equation (2) is to account for microbes available from previous years. In the case of negligible contributions from previous years (as would be expected), only the first term in the equation would be necessary. It is assumed that the litter could be applied at any time of the year; the alternative would be to apply the litter on a given date, which would be unrealistic as litter is produced continuously throughout the year. If the litter component of Campylobacter losses only were being considered, then we would focus on simulating the period after litter application. However, it is of more interest to compare losses from litter with losses from other sources such as grazed animals, in which case it is appropriate to examine losses throughout the year, and only a small number of instances of recent litter application would be encountered. We could not devise a system to combine these two perspectives within the @Risk model, so we chose to include the other sources, with the understanding that to build up suitable statistics of the losses from litter, a large number of years of simulation may be required.

If litter is applied to $N$ sub-areas, each of area $A_i/N$, and the timing of litter application is spaced out in regular intervals throughout the year (cycling through the sub-areas once per year) then the mass on any random day will be

$$M = \sum_{i=0,Y} \frac{A_i}{N} RC_a e^{-k\gamma (\alpha+i)} = \frac{A_i}{N} RC_a \sum_{i=0,Y} e^{-k\gamma (\alpha+i)}$$  \hspace{1cm} (3)

where $Y$ is the length of a year. This reduces to Equation (2) when $N = 1$.

In the limit of a large number of application areas,

$$M = \int_{0}^{\infty} \frac{A_i}{Y} RC_a e^{-k\gamma d(\alpha Y)} d(\alpha Y) = \frac{A_i RC_a}{Yk_p}$$  \hspace{1cm} (4)
For the washoff into water, it is assumed that the loss associated with a rainfall event ($M_s$) varies with the number of microbes ($M$), the runoff ($D$) and slope according to:

$$M_s = \beta MS \frac{D}{D_0}$$

(5)

where $\beta$ is the fraction lost (typically 0.002) under a reference runoff depth $D_0$ (taken as 20 mm) and a reference slope of 5.1 degrees, or 9%, and $S$ is the USLE slope factor:

$$S = 65.41 \sin^2 \theta + 4.65 \sin \theta + 0.065$$

(6)

where $\theta$ is the slope in degrees. This results in a strong slope dependence for large slopes.

### 3.4 Model implementation

The model is implemented within @Risk. The litter component is embedded into a broader catchment model that considers the range of land-uses and stock types within a catchment. The model simulates a number of days of rainfall and runoff, drawing rainfall values from a time-series of rainfall (normalised to the mean annual rainfall). The model accounts for soil moisture, which is relevant to generation of runoff and percolation. The source parameters associated with animal defecation can vary seasonally, and include variability associated with natural variability and uncertainty.

The poultry litter component differs from the treatment of other animals:

- The user specifies the concentration in fresh litter, rather than the concentration in faeces. This is because the link between concentrations in broiler faeces and concentrations in litter are uncertain.

- The method of calculating wash-off is different: the method for poultry is based on the proportion of litter washed off, whereas the method for other animals is based on the concentration in water generated from faecal matter, or on direct deposition to streams.

- The application of litter occurs only once per year for a particular piece of land.

- The area of litter application coincides with one of the other main land-uses, such as pasture. The litter application area is specified as a fraction of the total area.

- Litter application does not contribute to baseflow concentrations.
The following inputs are required from the user:

**Table 2:** Parameters required for the litter component of the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical values or data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of sub area with chicken litter applied</td>
<td>fraction of sub-area</td>
<td>From knowledge of litter application the area</td>
</tr>
<tr>
<td>Litter areal application rate</td>
<td>t ha(^{-1})</td>
<td>2.5 to 5</td>
</tr>
<tr>
<td>Baseline mean concentration in fresh litter</td>
<td>Number gfw(^{-1})</td>
<td>1.00E+03. See main text for references</td>
</tr>
<tr>
<td>log-10 sd of fresh litter concentrations</td>
<td>dimensionless</td>
<td>1.0. See main text for references</td>
</tr>
<tr>
<td>Reduction factor by stacking</td>
<td>factor</td>
<td>0.01. See main text.</td>
</tr>
<tr>
<td>Litter decay rate in summer</td>
<td>day(^{-1})</td>
<td>0.5. See main text.</td>
</tr>
<tr>
<td>Litter decay rate in winter</td>
<td>day(^{-1})</td>
<td>0.25. See main text.</td>
</tr>
<tr>
<td>Cycled or simultaneous</td>
<td>option</td>
<td>Depends on the use/application of the model</td>
</tr>
<tr>
<td>Litter fraction washed off for 20 mm runoff</td>
<td>fraction</td>
<td>0.005. See main text.</td>
</tr>
<tr>
<td>Slope</td>
<td>degrees</td>
<td>Topography maps or knowledge of the area</td>
</tr>
</tbody>
</table>
4. Key information gaps

Some key information gaps were identified in this study:

- There is little information on the concentrations of *Campylobacter* in fresh litter (when it is removed from the shed) and none in New Zealand. There is also no information on concentrations in applied litter after withholding under typical conditions in New Zealand. Clearly, this is of key importance for the model. While there is more information on the concentration in fresh excreta, there is very large uncertainty about reductions between excretion and fresh litter, hence building a model starting with concentrations in excreta does not resolve the problem of estimating concentrations in fresh litter.

- We have not information on the concentration in manure from laying hens, before application to land.

- The effectiveness of litter storage for removal of *Campylobacter* in typical New Zealand storage conditions is uncertain.

- The effects of drying and ultraviolet (sunlight) on survival of *Campylobacter* once litter is spread on pasture.

- The rates at which microbes are washed off litter and into the ground are unknown. This makes it very difficult to estimate the loadings to groundwater sources. Moreover, the form of the microbes washed from litter, as it affects attenuation by soil, is unknown.

5. Acknowledgment

We would like to thank Rob Lake and Andrew Ball from ESR for providing useful information and data, and for reviewing a draft of the report. We also wish to thank PIANZ and EPFNZ for providing information on the amount of litter and waste produced and the methods of using these.
6. References

American Society of Agricultural Engineers (2003). Manure production and characteristics. ASAE Standards D384.1 FEB03. ASAS, St Joseph, Michigan, USA.


