Modelling of *Escherichia coli* Density on Land and Concentration in Surface Runoff

T. Y. Ling¹, R. L. Bengtson², C. M. Drapcho³, E. C. Achberger⁴, G. J. Sabbagh⁵ & J. Jackson²

¹Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

²Department of Biological and Agricultural Engineering, Louisiana State University, Baton Rouge, LA 70803, U.S.A.

³Department of Agricultural and Biological Engineering, Clemson University, South Carolina, SC 29634, U.S.A.

⁴Department of Biological Sciences, Louisiana State University, Baton Rouge, LA 70803, U.S.A.

⁵Bayer, Kansas City, U.S.A.

ABSTRACT

Integrated farming of crop and animal enables resources from animal waste to be utilised. However, bacterial pollution is a concern. In this study, a bacterial model, ECOLI, was developed to simulate *Escherichia coli* density daily on land and its concentration in surface runoff. Loss of *E. coli* was assumed to occur through decay, runoff, sediment and percolation. *E. coli* decay was assumed to follow the first order decay affected by soil pH, soil temperature and soil moisture. In testing the model, the ECOLI model was interfaced with the GLEAMS-SWT hydrologic and erosion model. Calibration and evaluation was performed with field-scale data from Franklinton, Louisiana. Fresh cow manure was applied on grassed plots and runoff was collected and analysed. Predicted *E. coli* concentrations versus observed *E. coli* concentrations in surface runoff gave a regression line with coefficient of determination of 0.993, intercept of 0.011 and a slope of 0.995 indicating good agreement of model predicted concentrations with observed concentrations. The ECOLI model can be used to study the effects of various animal waste application practices such as waste loading rate, timing of application and frequency of application. More research needs to be conducted to incorporate databases so as to expand the capabilities of this model.

Keywords: Modeling, *E. coli*, runoff, die-off, decay, pollutant

INTRODUCTION

Animal waste is known to contain nutrients for plants (Fontenot and Ross 1980). However, animal waste applied on land is subjected to hydrologic and other forces that can result in microbial pollution (Pell 1997; Hooda *et al.* 2000).
Models are useful in decision making. Reddy et al. (1981) proposed a conceptual model that was incorporated in ARMII (Overcash et al. 1983). Springer et al. (1983) used a continuity equation to describe fecal coliform movement. The model was partially tested for runoff on a concrete surface. Moore et al. (1989) modified relationships proposed by Reddy et al (1981) in estimating decay and proposed estimation bacteria movement during a rainfall event. Walker et al. (1990) proposed a combination of deterministic and statistical models to predict bacterial loss from the field and bacterial loss was assumed to be sediment bound. However, bacterial loss may not be adequately accounted for by binding to sediment as a vegetative filter strip was found to be able to remove sediment but not fecal coliform (Chaubey et al. 1994). Different models have been proposed but none are available to farm managers. Therefore, the objective of this study was to develop a model capable of continuously simulating E. coli density in the soil and concentration in surface runoff from agricultural land where animal manure is applied.

THEORETICAL BACKGROUND

The survival of E. coli determines its availability for transport. The first order decay model is most commonly used to describe the decay of bacteria (Crane and Moore 1986; Matthess et al. 1988):

\[ D_t = D_0 e^{-kt} \] (1)

where \( D_t \) and \( D_0 \) are the density of E. coli at time \( t \) and \( t = 0 \), respectively (cell/cm\(^2\)), \( t \) is time (d), and \( k \) is the decay coefficient or decay rate (d\(^{-1}\)). Key environmental factors that affect decay are soil temperature, pH and moisture (Reddy et al. 1981; Crane and Moore 1986).

Temperature Factor

According to Reddy et al. (1981), the effect of temperature can be represented by a simplified Arrhenius equation as follows:

\[ k_T = k_{20} f_T \] (2)

\[ f_T = \theta^{T-20} \] (3)

where \( k_T \) and \( k_{20} \) are the decay rates at temperature \( T^\circ C \) and \( 20^\circ C \), respectively, \( f_T \) is the decay coefficient at any temperature relative to the decay coefficient at \( 20^\circ C \), and \( \theta \) is the temperature correction factor. For E. coli, \( \theta \) ranged from 1.02 to 1.17 with a mean of 1.07±0.05 (Reddy et al. 1981).

pH Factor

Studies of E. coli decay at different pH show that E. coli survive best in a pH ranging from 5.5 to 7.5 (Mcfeters and Stuart 1972). Based on this data, decay rates at different pH relative to decay rate at pH 7 (\( f_{ph} \)) was obtained and by regression:
\[ f_{ph} = 0.0377h^2 - 0.5173h + 1.8019 \]  \( (4) \)

where \( h \) is the pH of the soil and \( f_{ph} \) is the decay coefficient at any pH relative to the decay coefficient at pH 7 \( (R^2=0.98, \ 4 \leq pH \leq 10) \).

**Moisture Factor**

Boyd *et al.* (1969) reported that decay rate of *E. coli* increases as moisture content drops from 50 to 10% for two types of fine sandy loam soil, by regression:

\[ f_{sw} = 2.9 s_w^{-0.2} \]  \( (5) \)

where \( s_w \) is the soil water content (% saturation) and \( f_{sw} \) is the decay coefficient at any moisture content relative to the decay coefficient at saturation \( (R^2=0.99, \ 16\% < s_w \ 100\%) \).

**Adjusted Decay Coefficient**

The adjusted decay coefficient proposed by Reddy *et al.* (1981) was modified to account for the effect of temperature, pH, and soil moisture on decay rate of *E. coli* in the soil:

\[ k = k_b f_T f_{ph} f_{sw} \]  \( (6) \)

where \( k \) is the adjusted decay coefficient \( (d^{-1}) \), \( k_b \) is the base decay coefficient \( (d^{-1}) \) at 20°C, moisture content of saturation, and pH 7.

**Retention and Movement**

*E. coli* can occur freely in the liquid phase of the soil-water system or adsorbed to soil particles especially the clay fraction (Marshall 1971; Ling *et al.* 2002). Schillinger and Gannon (1985) reported that more than 50% of fecal coliforms were not settled or filtered showing a large proportion in suspended phase. Therefore, in the ECOLI model, *E. coli* is assumed to move suspended in runoff as well as attached to sediment. According to Matthess *et al.* (1988), microorganisms are subjected to reversible adsorption and desorption processes which approximately follow the model of the Freundlich’s isotherm. In dilute concentration, the equilibrium between the concentration of the suspended and adsorbed *E. coli* is governed by:

\[ C_s = k_d C_w \]  \( (7) \)

where \( C_s \) is the concentration of *E. coli* on solid phase and \( C_w \) is the concentration in liquid phase and \( k_d \) is the partition coefficient. A quantitative relationship between bacterial concentration in percolated water and distance moved and soil properties were not found in literature. For high clay soils, Weaver *et al.* (1978) reported 99-100% retention in the first centimeter of the soil column. However, for sandy soils, retention in the first centimeter was reported to be 55%.
MODEL FORMULATION

At the end of day $i$, by the principle of conservation of mass:

$$D_i = D_{i-1} - D_d + D_a - D_r$$  \hspace{1cm} (8)

where $D_{i-1}$ is the $E. \ coli$ density at the end of the previous day, $D_d$ is the decay loss, $D_r$ is the loss in rain water and $D_a$ is the addition through manure application on day $i$, all in cells/cm$^2$. On days when waste is applied, $E. \ coli$ loading rate can be expressed as:

$$D_a = 10^{-8} (W_m C_m)$$  \hspace{1cm} (9)

where $D_a$ is the $E. \ coli$ from waste application (cells/cm$^2$), $W_m$ is the weight of manure applied (kg/ha), $C_m$ is $E. \ coli$ concentration in manure (cells/kg) and $10^{-8}$ is the conversion factor.

In the ECOLI model, decay loss of $E. \ coli$ is estimated by Equation 1. The decay coefficient (Equation 6) is adjusted and computed daily based on daily average soil surface temperature and moisture content of the surface layer. However, pH of the soil is fixed for a particular soil. Rain available density is:

$$D_{av} = D_{i-1} + D_{add} - D_{decay}$$  \hspace{1cm} (10)

where $D_{av}$ is the $E. \ coli$ density available and $D_{add}$ is the density added due to the application of waste. After the rain, $E. \ coli$ density left is the density at the end of ith day:

$$D_i = D_{av} - D_r$$  \hspace{1cm} (11)

$$D_r = D_{ro} + D_s + D_p$$  \hspace{1cm} (12)

where $D_i$ is the $E. \ coli$ density at the end of day $i$, $D_{ro}$ is the $E. \ coli$ density loss in runoff on day $i$, $D_s$ is the $E. \ coli$ density loss in sediment on day $i$, $D_p$ is the $E. \ coli$ density loss in percolation on day $i$, and $D_{av}$ is the available density (cells/cm$^2$).

The pesticide model, CREAMS, (Leonard and Wauchope 1980) was adapted to determine the concentration of $E. \ coli$ in runoff. $E. \ coli$ concentrations is given by:

$$C_{av} = D_{av}/m_s$$  \hspace{1cm} (13)

where $C_{av}$ is the overall soil concentration of $E. \ coli$ in the surface layer before rainfall event (cells/g), $D_{av}$ is the available density of $E. \ coli$ (cells/cm$^2$) and $m_s$ is the soil mass of the surface layer (g/cm$^2$) given by:

$$m_s = r_b d$$  \hspace{1cm} (14)

where $r_b$ is the bulk density of surface layer (g/cm$^3$), and $d$ is the depth of surface mixing layer (cm). Considering an unit volume of runoff, the total number of $E. \ coli$ cells transferred to runoff water is:

$$N = a C_{av}$$  \hspace{1cm} (15)
where \( N \) is the number of cells released per unit volume of runoff (cells/mL). \( C_{av} \) is the overall soil concentration of \( E. coli \) in the surface layer before a rainfall event (cells/g), and \( a \) is the release coefficient which reflects the amount of soil and/or manure involved in the release of \( E. coli \) per unit volume of runoff (g/mL). Assuming the suspended cells establish equilibrium with water and sediment:

\[
N = C_w V + C_s a
\]  
(16)

where \( V \) is the volume of water per unit volume of runoff, \( C_w \) and \( C_s \) are concentrations in water (cells/mL) and on soil (cells/g), respectively. Assuming that the volume of solid is negligible compared to the volume of water, \( V \), and that \( E. coli \) adsorption is described by linear adsorption isotherm, solving the last two equations, the concentration of suspended \( E. coli \) in water:

\[
C_w = \frac{\alpha C_{av}}{1 + \alpha k_d}
\]  
(17)

and the concentration of \( E. coli \) on solid phase or sediment:

\[
C_s = \frac{\alpha k_d C_{av}}{1 + \alpha k_d}
\]  
(18)

where \( k_d \) can be determined experimentally for a particular soil according to the method of Ling et al. (2002). A relationship between distribution coefficient and clay content of the soil (Ling et al. 2002) was also used in the model as an option:

\[
k_d = \exp (3.9 \ln C_y - 11.3)
\]  
(19)

where \( C_y \) is the clay content of the soil (%). This relation has a coefficient of determination of 0.67 and it is valid for clay content of 10 – 54 %.

The runoff loss of \( E. coli \) is given by:

\[
D_{ro} = C_w Q
\]  
(20)

where \( D_{ro} \) is the runoff \( E. coli \) loss (cells/cm²), \( C_w \) is the average storm runoff concentration of suspended \( E. coli \) (cells/mL), and \( Q \) is runoff amount (cm). \( E. coli \) lost below the surface layer was estimated from experimental data (Weaver et al. 1978). By regression, the concentration of \( E. coli \) exiting the surface layer:

\[
C/C_w = \exp [0.0021 (C_y)^2 - 0.242 C_y + 1.6]
\]  
(21)

where \( C \) is the concentration of \( E. coli \) exiting the surface layer (cells/mL), \( C_w \) is the concentration of suspended \( E. coli \) in water (cells/mL), and \( C_y \) is clay content of the soil (%). The loss of \( E. coli \) in percolation is:

\[
D_p = C P
\]  
(22)
where \( C \) is the concentration of \( E. coli \) leaving the top cm surface layer (cells/mL), \( P \) is the amount of percolating water moving beyond the surface layer (cm) and \( D \) is the \( E. coli \) loss in percolation (cells/cm²).

The loss of \( E. coli \) attached to sediment is:

\[
D_s = C_s E S_s
\]

where \( D_s \) is the \( E. coli \) loss in sediment (cells/cm²), \( C_s \) is the sediment \( E. coli \) concentration (cells/g), \( E \) is the enrichment ratio of specific surface area, and \( S_s \) is the sediment yield (g/cm²). The overall concentration of \( E. coli \) in runoff with sediment is:

\[
C_{rs} = D_s/Q + C_w
\]

where \( C_{rs} \) is the overall concentration of \( E. coli \) in runoff containing eroded sediment (cells/cm³), \( D_s \) is the total \( E. coli \) loss in sediment (cells/cm²), \( Q \) is total storm runoff (cm), and \( C_w \) is the \( E. coli \) concentration in runoff water (cells/mL). The ECOLI model was compiled and run in a PC using MS PowerStation 4.0. Analysis results show that the ECOLI model is sensitive to the base decay coefficient and temperature, moderately sensitive to the release coefficient, \( \alpha \), and \( E. coli \) density in the manure.

**MODEL EVALUATION**

The model was calibrated and evaluated by using field scale data located in Franklinton, Louisiana, with Tangi Silt Loam soil, 3-8% slope (USDA-NRCS, 1997). Climatic data was provided by AgriClimatic Information System, Louisiana State University. Two manure applications were carried out whereby

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Input parameter values and sources in the evaluation of the ECOLI model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Release coefficient, ( \alpha ) (g/cm³)</td>
<td>0.22</td>
</tr>
<tr>
<td>Depth of interaction layer (cm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Distribution coefficient (mL/g)</td>
<td>0.33</td>
</tr>
<tr>
<td>Manure concentration of ( E. coli )</td>
<td>1.35x10⁹</td>
</tr>
<tr>
<td>Waste addition rate (kg/ha)</td>
<td>510</td>
</tr>
<tr>
<td>Initial density of ( E. coli ) on land (cfu/ha)</td>
<td></td>
</tr>
<tr>
<td>Base decay rate of ( E. coli ) (d⁻¹)</td>
<td>0.083</td>
</tr>
<tr>
<td>Temperature correction factor</td>
<td>1.07</td>
</tr>
<tr>
<td>Soil pH</td>
<td>6.3</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>14</td>
</tr>
<tr>
<td>Saturated moisture content</td>
<td>0.41</td>
</tr>
<tr>
<td>Initial soil water content</td>
<td>0.36</td>
</tr>
<tr>
<td>SWT</td>
<td></td>
</tr>
<tr>
<td>Bulk density of surface soil (g/cm³)</td>
<td>1.59</td>
</tr>
</tbody>
</table>
Modelling of *Escherichia coli* Density on Land and Concentration in Surface Runoff

![Graph showing observed and calibrated E. coli concentrations in surface runoff versus time after the first manure application.](image)

**Fig. 1:** Observed and calibrated *E. coli* concentrations in surface runoff versus time after the first manure application

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean observed <em>E. coli</em> concentration (cfu/100mL)</th>
<th>Mean predicted <em>E. coli</em> concentration (cfu/100mL)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26/7/97</td>
<td>209,430</td>
<td>212,030</td>
<td>+1.2</td>
</tr>
<tr>
<td>2/8/97</td>
<td>15,409</td>
<td>14,930</td>
<td>-3.1</td>
</tr>
<tr>
<td>3/8/97</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fresh cow manure was surface applied on previously ungrazed, established Bermuda grass pasture. Three plots, 2.1m x 2.4m each were evenly spread with manure. Three control plots were not applied with manure. A rainfall simulator produced rain 3 to 4 times over a period of 37 days after each manure application. Surface runoff was collected and *E. coli* analysed according to the spread plate method on EMB agar (Clesceri *et al.* 1998).

In this simulation, the GLEAMS-SWT model (Reyes *et al.* 1993) was modified to generate the necessary hydrologic and erosion variables for input into the ECOLI model. Inputs of the ECOLI model and their sources are given in Table 1.

Parameters were varied until the model predicted *E. coli* concentrations in runoff were comparable to the observed concentrations. It was found that a release coefficient of 0.22, surface mixing layer of 0.5 cm thick, and base decay rate of 0.083 d⁻¹ produced the best fit.

### RESULTS AND DISCUSSION

The calibrated concentrations were compared to the observed concentrations for the four simulated rains after the first manure application (*Fig. 1*). The calibrated decay value was within the range of 0.84 to 0.033 d⁻¹ as reported in literature (Reddy *et al.* 1981; Crane and Moore 1986; Bogosian *et al.* 1996; Wang *et al.* 1996; Sjogren 1994). Release coefficient was comparable with that of pesticide, 0.05 to 0.2 (Leonard and Wauchope 1980). The thickness of the surface
interaction layer for *E. coli* has not been established. It was only reported that fecal coliforms were found predominantly on the surface centimeter of pasture (Faust 1982).

For the second manure application used for model evaluation, in all the three simulated rains, the difference between runoff *E. coli* concentrations of the predicted values from the mean observed value were small, 0-3.1% (Table 2).

The first runoff *E. coli* concentration predicted was slightly higher than the observed concentration and the second runoff *E. coli* concentration was 3.1% less than the mean observed value, but within the range of the observed concentrations. Comparisons between predicted and observed concentrations of *E. coli* in logarithmic transformation with duration after application are shown in Fig. 2. Good agreement of the predicted values with observed values was observed (Fig. 3). It is shown that the coefficient of determination is 0.993 which is very close to the value 1 of perfect fit. In addition, the slope of 0.995 and the intercept of 0.011 are close to perfect fit of one and zero, respectively.
CONCLUSIONS
A model, ECOLI, was developed, capable of simulating daily E. coli densities on land and concentrations in surface runoff from land applied with animal waste. Evaluation of the model’s predicted runoff concentrations with observed concentrations indicated good agreement. The ECOLI model can be used to study the effects of various animal waste application practices on surface runoff quality such as waste loading rate, timing of application, and frequency of application according to the type of soil. More research needs to be conducted to expand the capabilities of the model, incorporate appropriate databases and to establish the thickness of interaction layer of runoff with E. coli during runoff.

REFERENCES


