MODELING ANIMAL WASTE MANAGEMENT PRACTICES: IMPACTS ON BACTERIA LEVELS IN RUNOFF FROM AGRICULTURAL LANDS

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ABSTRACT

Runoff from agricultural lands carrying microorganisms from livestock manure can contaminate the food and water supplies of both animals and humans. Planning and design of animal waste management practices, thus, becomes more important as livestock populations become more concentrated. A computer model is proposed to predict the effects of animal waste management practices on the bacteria concentration of runoff from agricultural lands. The model uses Monte Carlo simulation to combine the deterministic relationships with statistical knowledge concerning rainfall and temperature variation. The model outputs maximum and minimum bacteria concentrations in runoff resulting from a storm assumed to occur immediately after manure is applied to the land. The model can simulate the effects of waste storage, filter strips, and incorporation of manure into the soil. Data and information collected from the Owl Run watershed in Fauquier County, Virginia is used to demonstrate the model's applicability and potential.

Long-term manure storage was found to be the most appropriate practice for reducing bacteria concentrations for the study site. Incorporation of manure was as effective as long-term storage, but is more costly. Buffer strips alone were not sufficient for reducing bacteria concentrations to meet the water quality goal. Since animal waste management practices have only recently been implemented on the watershed, no field data is yet available to validate the model's predictions.

INTRODUCTION

Cows grazing peacefully on rolling pastures please the eyes of human passers-by while they enhance the fertility of the soil upon which they trod. Yet, as livestock operators populate their pastures more densely and establish confinement systems, the 42 L of waste contributed daily by each animal require more conscientious management (Wheatland and Borne, 1970). Improperly managed livestock wastes can lead to fecal contamination of waters receiving agricultural runoff. The danger to humans lies in the possibility of these fecal organisms entering water and food supplies. Groundwater and surface waters may harbor pathogens originating from animal fecal deposits (Patni et al., 1985). Contaminated water may also infect edible shellfish (Elder, 1987). Standards established by the Environmental Protection Agency require that the fecal coliform (FC) count not exceed 200 FC/100 mL, for bathing water and 14 FC/100 mL, for shellfish harvesting water (USEPA, 1976).

Although knowledge concerning the transport and behavior of bacteria in animal waste runoff is far from comprehensive, the knowledge currently available combined with the enhanced capability of computers can greatly facilitate the design of animal waste management practices. Previous modeling efforts have, for the most part, resulted in the development of deterministic relationships that lead to a rough estimate of bacteria concentrations in runoff (Overcash et al., 1983; Springer et al., 1983; Moore et al., 1988). While these deterministic relationships greatly contribute to an understanding of the important factors and processes, a probabilistic modeling approach serves at least three purposes. First, a probabilistic approach acknowledges the uncertainty of the system and derived confidence intervals and probability density functions become more meaningful than single-valued answers. Second, the random driving forces of the system such as rainfall and temperature can easily be incorporated. Third, output in the form of probability distributions is useful for selection of management practices and optimum design of management structures. For example, incorporating manure into the soil might be selected over surface spreading if the probability of exceeding a given water quality standard were smaller for the first practice than for the latter. Building on the results of previous findings, additional efforts should therefore be aimed towards incorporating stochastic modeling techniques and generating results that are applicable to the practical selection and design of animal waste management alternatives.

The overall goal of this study was to develop a model for simulating bacteria loadings in agricultural runoff that will aid in the selection of animal waste management practices. Selected deterministic relationships are coupled with statistical information concerning rainfall and temperature, using Monte Carlo simulation techniques, to predict fecal bacteria concentrations in runoff resulting from single storm events. The model's applicability and potential is demonstrated using data collected from a small watershed located in the Coastal Plain of Virginia.

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BACKGROUND

Pertinent to the development of a bacteria loading model is information concerning the appropriate bacteria species to be modeled, factors and processes which affect bacteria populations, and the effects of animal waste management practices. Although some of the information presented may be too detailed to be included in a model for practical use, such information is useful for understanding the model's underlying assumptions.

BACTERIA SPECIES TO BE MODELED

Although a bacteria model may be ideally used to evaluate disease potential, the model must be based on the characteristics of indicator species, i.e., non-pathogenic species normally present in the intestines of warm-blooded animals for which data have been collected and standards established. Since it is impractical to test a water sample for every known pathogen, most information concerning bacteriological water quality data addresses the concentrations of the indicator groups. The indicator groups most widely recognized are the total coliforms (TC), fecal coliforms (FC), and fecal streptococci (FS) (Thelin and Gifford, 1983). Fecal coliform bacteria are modeled in this study since the EPA recreational standard is based on this indicator group (USEPA, 1976).

FACTORS AND PROCESSES AFFECTING MICROBIAL POPULATIONS

If an accounting approach is to be applied to modeling bacteria, it is useful to understand the factors affecting the quantity of live bacteria originally deposited on the land, the die-off between runoff events, and the quantity of bacteria input to overland flow. The quantity of bacteria deposited on the land is a function of the type and number of livestock as well as whether or not the waste is stored prior to spreading. Once deposited on the land, fecal bacteria populations are subject to drastic environmental changes. Animal waste application method and attraction of bacteria to soil particles, as well as rainfall duration and intensity may determine whether or not bacteria are transported with runoff and eroded soil.

Quantity of bacteria deposited. The microflora and fauna which inhabit the intestines of warm-blooded animals vary in species and number with livestock type. Information concerning the bacteria density of manures from several types of livestock is provided by Geldreich et al. (1964). In addition, animal age, ration, and antibiotic treatment may affect the bacteria population voided, although little work has been done to quantify these effects (Crane et al., 1983).

Cell die-off. Upon defecation, fecal bacteria may experience changes in moisture, nutrient availability, temperature, pH, ultra-violet radiation, exposure to predators, and exposure to toxic compounds. The combined effects of these changes influence the subsequent growth or die-off of the organisms. The effects of time on the die-off rate of microorganisms are frequently modeled using the first-order decay relationship expressed as Chick's Law (Moore et al., 1988):

$$\frac{N_t}{N_o} = e^{-kt} \qquad (1)$$

where

N_t = number of bacteria at time t,
N_o = number of bacteria at time t_o,
k = first-order die-off rate constant,
t = time.

The effect of temperature on the die-off rate constant, k, was modeled by Mancini (1978) as:

$$k_T = k_{20}\theta^{T-20} \qquad (2)$$

where

k_T = die-off rate constant at temperature T (1/day),
k_{20} = die-off rate constant at 20° C (1/day),
θ = a regression constant found to equal 1.07 for several microbial species (Mancini, 1978),
T = temperature (° C).

Reddy et al. (1981) and Polprasert et al. (1983) studied the effects of additional environmental factors such as moisture, pH, and sunlight on bacteria population. Moore et al. (1988) compiled an excellent list of die-off rate constants (k) measured under a wide range of conditions.

Bacteria input to overland flow. Factors affecting the transport of bacteria in overland flow include rainfall duration and intensity, method of manure application, fecal deposit age, and adsorption of cells to soil particles. Because manure is less dense than soil, incorporating manure into soil affects the soil's erodibility, and thus the amount of bacteria detached by overland flow (Khaleel et al., 1979a). Mazurak et al. (1975) recognized the fact that low amounts of manure (5-25 Mg/ha) can enhance the condition of the soil by increasing the aggregate size and water holding capacity of the soil. However, at higher application rates, the large contribution of monovalent ions from incorporated manure is believed to be responsible for increasing soil erodibility (Mazurak et al., 1975). In addition, adsorption to soil particles affects the concentration of bacteria in runoff. Cells adsorbed to soil particles may offer resistance to transport by overland flow or may be transported with eroding soil particles instead of infiltrating into the soil. Although the outer surfaces of bacteria cells are normally negatively charged and are thus attracted to positively charged particles in the soil, electrical forces do not appear to be fully responsible for attachment (Daniels, 1980). Bacterial secretion of adhesive substances, clay content, soil cation exchange capacity, organic matter content, pH, temperature, and soil moisture content are cited as factors affecting adsorption of bacteria cells to soil particles (Daniels, 1980; Reddy et al., 1981; Moore et al., 1988).

EFFECTS OF ANIMAL WASTE MANAGEMENT PRACTICES ON MICROBIAL POPULATIONS

Animal waste management practices such as manure storage, vegetated filter strips, and incorporation of wastes into the soil often serve multiple purposes including reducing bacterial contamination of runoff. Because odor control and reduction of nutrients in runoff are also benefits derived from implementing such practices, it may be inappropriate to base optimum management strategy design solely on bacteria reduction. However, information concerning the influence of commonly used management practices on bacteria concentrations in runoff should be considered in model development aimed at BMP selection and design. Animal waste management alternatives for which some attempt has been made to quantify their effect on bacteria populations in runoff (and which are addressed in the model) are now discussed.

The main function of waste storage pits and tanks is to allow manure to be spread under optimum climatic conditions (Moore et al., 1988). With inadequate storage, an operator may be forced to spread waste on frozen soil or during wet periods. Frozen soil may prevent infiltration and encourage bacteria survival due to the low temperature. Spreading manure immediately prior to a rainstorm allows little time for bacteria die-off to occur before transport to receiving waters. In addition, waste storage allows some die-off to take place before spreading (Moore et al., 1988).

Moore et al. (1988) suggested that vegetative filter strips may only be effective in reducing bacteria levels from runoff having more than 100,000 organisms/100 mL. For lower concentrations, the degree of removal is ill-defined due to background bacteria levels, seasonal differences, and variation in soil infiltration rates. To be effective, Moore et al. (1988) recommended that a vegetative filter strip should be at least 3.0 m wide and have a slope between 0 and 15%. Using information from previous research, Moore et al. (1988) developed the following equation to model the effects of vegetative filter strips associated with areas where manure is spread:

$$PR = 11.77 + 4.26\,S \tag{3}$$

where

PR = percent removal of bacteria (not to exceed 75%),

S = filter strip width (ft)/percent slope; (width > 10.0 ft.; 0 < slope < 15%)

MODEL DEVELOPMENT

The development of a model that attempts to incorporate uncertainty in the prediction of the concentration of bacteria in agricultural runoff requires selection of deterministic relationships and identification of variables that can be appropriately treated as random. Because model accuracy and suitability for application must be considered jointly, these steps in the development process are interdependent.

SELECTION OF DETERMINISTIC RELATIONSHIPS

The deterministic relationships required in a bacteria loading model include those which describe runoff, erosion of soil and manure, the number of bacteria cells associated with the soil and manure eroded (cell density), and bacterial die-off. Because some of these relationships vary with land use, it was decided to divide the study area into four classes: 1) areas where manure is surface applied, 2) areas where manure is incorporated into the soil, 3) areas where manure is deposited only by livestock (i.e., pasture), and 4) non-manured areas. The latter category includes those areas which receive fecal contamination only from wild animals. The model does not address pasture areas which receive mechanically applied manure.

Runoff and erosion. It is hypothesized that the bacteria concentration measured in surface runoff is more the result of a recent storm and recent environmental conditions than an accumulated result. Therefore, the event-based modified Universal Soil Loss Equation (MUSLE) was selected, rather than an annual average erosion model, to predict the mass of soil and manure eroded (Williams, 1975):

$$Y = 11.8\,(Qq_p)^{0.56}KLSCP \tag{4}$$

where

Y = sediment yield from a single storm (Mg),

Q = storm runoff volume (m^3),

q_p = peak runoff (m^3/sec),

and K, LS, C, and P are the USLE erodibility, length-slope, cover, and practice factors, respectively, as described by Wischmeier and Smith (1978).

The MUSLE has been widely used and has variables which are familiar to BMP planners. Runoff volume is modeled using the SCS curve number method, and peak runoff rate is modeled using the SCS triangular hydrograph relationships (Schwab et al., 1981). Gully erosion is not modeled since the majority of bacteria cells are contributed by manure and soil eroded from the surface rather than the deeper layers exposed by gullies.

Cell density. In order to obtain the number of indicator bacteria cells per 100 mL of runoff water, the mass of soil or manure eroded (as calculated by the MUSLE) must be multiplied by the number of cells per unit mass of soil or manure. For cow manure, the density of fecal coliforms was reported as 2.3x105 cells/g manure (Geldreich, 1978). A value of 400 FC/g soil was selected as an estimate of the cell density of soil uncontaminated by livestock (Faust, 1982). For areas where manure is incorporated into the soil, a weighted average of manure cell density and soil cell density was used to estimate the cell density of the soil/manure mixture:

$$D_i = \frac{m_i D_m + 100\,btD_s}{m_i + 100\,bt} \tag{5}$$

where

D_i = cell density of soil mixed with manure (cells/Mg),

m_i = amount of manure incorporated into the soil (Mg/ha),

D_m = cell density of manure (cells/Mg) (2.3x105 cells/g),

b = density of wet soil at time of incorporation (Mg/m^3),

t = thickness of soil layer into which manure is incorporated (cm),

100 = conversion factor,

D_s = cell density of soil without incorporated manure (cells/Mg) (400 cells/g).

Limited guidance for selecting the USLE soil erodibility factor K for manured areas is provided by Khaleel et al. (1979a, b) and Mazurak et al. (1975). Cover factors were determined on a monthly basis for each of the four classes using the information provided by Wischmeier and Smith (1978). Since manured fields are not directly addressed by

Wischmeier and Smith (1978), the field and crop conditions most closely resembling the conditions at the time of manure spreading or incorporation should be used to estimate the cover factors for manured lands. More information regarding the selection of these parameters is given by Walker (1988).

Cell die-off. The potential number of cells eroded was reduced to account for die-off using equation 1. The base value of bacterial die-off rate constant, k, was selected from data presented in the literature (Moore et al., 1988). The period of die-off is assumed to be the time between defecation and the time at which a runoff event occurs. For this model, the decay period is approximated as the period of time during which wastes are stored before application to the land. The "worst" case is modeled by assuming that a runoff event occurs immediately after waste application. Die-off is not modeled for pasture (areas where manure is deposited by livestock only) and non-manured areas because the supply of bacteria is assumed to have reached a steady state level.

Combined deterministic model. The bacteria yield from each area class is computed as the product of the mass of manure or soil eroded, a cell density factor, and a first-order die-off factor. Thus, combining the MUSLE of equation 4, a cell density factor, Chick's Law (eq. 1) and the temperature correction relationship of equation 2, bacteria yield can be expressed as:

$$B_i = 11.8\left(10 Q_d A F_i q_p\right)^{0.56} K_i \, LS_i \, C_i \, P_i \, D_i \, e^{-k_{20}\theta^{(T-20)} t} \qquad (6)$$

where

B_i = number of bacteria cells eroded from the area class i,

10 = factor to convert mm-ha to m^3,

Q_d = runoff depth (mm),

A = watershed area (ha),

F_i = fraction of the total watershed area in the particular area class,

K_i, LS_i, C_i, P_i = the USLE factors for area class i,

T = temperature of the air or storage environment surrounding the bacteria (° C),

t = die-off period of bacteria cells (days).

Other factors are as previously defined.

Total cell yield from a single storm event is the sum of the yields from each of the four area classes. The total cell yield from the four area classes is then divided by the total runoff volume from the watershed to obtain the bacteria concentration. To avoid implying an unwarranted degree of precision, it is more appropriate to report bacteria concentration in a logarithmic form rather than the linear-scaled concentration. Thus, the deterministic model is expressed as:

$$LBC = \log_{10}\left(\frac{B\,10^{-5}}{Q_d\,A}\right) \qquad (7)$$

where

LBC = the base 10 logarithm of the number of cells yielded per 100 mL of runoff,

$B = \sum_{i=1}^{4} B_i$

B_i = cell yield from individual classes.

RANDOM VARIABLES

A precipitation model developed by Rojiani et al. (1985) is used to model rainfall duration and amount. The model was derived from 28 years of rainfall data collected for Blacksburg, Virginia.

An hourly, dry-bulb temperature, model developed by Kline et al. (1982) was used to simulate hourly ambient air temperature. Because the average temperature for a period of decay can vary widely from year to year, a single average value is insufficient for determining the decay rate. Kline's model was therefore used to provide random temperature variation, and since it was developed using data collected from Blacksburg, Virginia, caution should he exercised in applying it to other locations. If manure is collected and applied to the land on a daily basis, then the temperature of the environment surrounding the fecal bacteria is assumed to closely follow ambient air temperature. However, if the manure is stored in a pit, tank, or lagoon, then the temperature of the waste is assumed to be a weighted average of the ambient air temperatures of the previous 360 hours (15 days), as described by a modified version of a model developed by Smith and Franco (1985):

$$TS_i = \frac{TA_i\,\alpha_i + TA_{i-1}\alpha_{i-1} + \ldots + TA_{i-360}\,\alpha_{i-360}}{\alpha_i + \alpha_{i-1} + \ldots + \alpha_{i-360}} \qquad (8)$$

where

TS_i = temperature of stored manure for hour i,

TA_i = ambient air temperature for hour i,

α = weighting factor = e^{-bt},

b = a constant, estimated to be 0.0083,

t = number of hours preceding hour i.

The model presented by Smith and Franco (1985) used a weighted average of temperatures from the previous year rather than the previous 15 days. The smaller time period is used for this application to shorten the computer run time.

Some degree of spatial variability in the USLE factors K, LS, C, and P is accounted for by considering four area classifications within the watershed. Although the soil erodibility factor, K, has been reported to be log-normally distributed for some soils (Rojiani et al., 1984), insufficient information on the erodibility of manure and manured soils exists to treat K as a random variable in the proposed model. The length-slope, cover, and practice factors are also impractical to model as random variables due to lack of sufficient data.

MODEL DESCRIPTION

The model COLI predicts the log bacteria concentration of runoff resulting from a single storm occurring immediately after land application of wastes. The simulation is performed on a bimonthly basis so that seasonal variation may be observed. A simplified diagram of the model is presented in figure 1a. Model COLI is composed of three major nested loops: a scenario loop to compare the effects of different practices; a date loop to model seasonal variation; and a trial loop to determine a range of outputs for a particular date. An options file"read" outside the outermost (scenario) loop specifies the number of scenarios to be modeled, the number of random output deviates to be generated per date modeled, and the date for which histogram points are to be generated.

Within the outermost loop, shown in figure 1b, the input data file for a particular scenario is "read". The input data file contains information concerning the watershed, manure, bacteria, soil, and waste management practices. Typical variations among scenarios include changes in manure application rate, manure storage time, the use of buffer strips, and the proportion of area where manure is incorporated into the soil.

The second loop, shown in figure 1c, is used to increment the Julian hour and to generate random pairs of rainfall duration and amount. Simulation is performed on a monthly basis for one year to allow the observation of seasonal variations. Deviates for rainfall duration are generated from the gamma distribution for winter months using the uniform random number generator DRAND given by Law and Kelton (1982). Deviates for summer storm duration are generated from a log-normal distribution by transforming normal deviates generated using the Box and Muller method (Law and Kelton, 1982). Rainfall amounts are then calculated using regression equations developed by Rojiani et al. (1985). Rainfall intensity is calculated by dividing rainfall amount by storm duration. To avoid simulating extremely rare events, the calculated intensity is compared to the intensity corresponding to the storm return period of interest. If an intensity exceeds that of the desired return period, then that pair of duration and amount is discarded and a new pair selected.

Once the random inputs have been generated, each set is entered into the deterministic submodel, contained within the innermost loop, shown in figure 1d. For each set, the antecedent moisture condition (AMC) is determined based on the time since the last storm and the previous rainfall amount. Runoff volume and peak flow rate are then calculated for the random storm. The modified MUSLE (equation 6) is then used to estimate potential bacteria yield for each of the four area classes. Adjustments are made if buffer strips are used on the areas where manure is spread or incorporated using equation 3. Die-off is modeled on an hourly basis for the period of manure storage specified in the input data file. Subroutine KLINE is called to calculate the hourly temperatures during the period of decay. If the period of decay is greater than one day, the manure is assumed to be stored in a pit, tank, or lagoon and the temperature is modeled according to equation 8 by means of subroutine STORAGE which uses KLINE to model air temperature.

The resulting bacteria yields from the four area classes are added together and divided by the runoff volume. A counter is incremented if the bacteria concentration exceeds the EPA recreational water quality standard of 200 FC/100 mL (USEPA, 1976). The bacteria concentration is stored in an array, and the loop is repeated for the desired number of trials. Detailed information on model development and description is presented in Walker (1988).

MODEL APPLICATION

The Owl Run watershed located in Fauquier County, Virginia, is currently being monitored to determine the effects of animal waste BMPs on water quality in the Chesapeake Bay. The 1153 ha watershed is approximately 90% agricultural. Five major dairy operations are located in the watershed which must manage the wastes from a total of about 1250 head of cattle (Payne, 1988). The watershed is characterized by shallow silt loam soils, overlying Triassic shale. A portion of the Owl Run watershed was selected for demonstrating the proposed model's potential (subwatershed D). The 324-ha subwatershed contains a high concentration of dairy cattle (358 head). The outlet of this subwatershed is located at station QOD (figure 2).

Rainfall duration and amount and temperature were modeled using the procedures outlined by Rojiani et al. (1984, 1985) and Kline et al. (1982). Although these parameters vary with geographic location, the three years of meteorological data collected from Owl Run watershed is presently insufficient to adequately describe the statistical distribution of these parameters. Rainfall duration is thus modeled using a gamma distribution for winter months and a log-normal distribution for summer months based on 28 years of data from Blacksburg, Virginia. Rainfall intensity is calculated and then compared to 25-year return period intensities for Culpeper, Virginia (approximately 40 km from the Owl Run watershed) (Shanholtz and Lillard, 1973). If a rainfall intensity calculated from a generated pair of duration and amount exceeds the 25-year intensity, then a new duration and amount are selected by the model. Hourly temperature is modeled using KLINE.

A list of input data required by COLI for the Owl Run subwatershed D is given in Table 1. Required inputs include parameters describing the watershed, manure quantity, bacteria quantity and die-off, soil properties, and waste management practices. The subwatershed area and land use fractions for the four area classes were calculated using the information collected from the watershed (VDSWC, 1986) and from personal communication with SCS representatives (Payne, 1988). The SCS curve numbers were estimated using values provided by the USSCS (1972). Hydraulic length and land slope used in computing runoff volume and peak runoff rate were estimated using a USGS 1:24,000 topographic map of the watershed.

The USLE erodibility factor for spread manure was reported as 0.0066kg h/(Nm^2) by Khaleel et al. (1979b). The erodibility factor for the non-manured soil, was estimated to be 0.0553 kg h/(N m^2) based on the dominant soil types in the watershed. Length-slope factors for the four area classes were calculated using the topographic map of the watershed (Wischmeier and Smith, 1978). Cover factors for the USLE were determined on a monthly basis for each of the four area classes using the procedures outlined by Wischmeier and Smith (1978) and crop stage information for the site (Payne, 1988). For areas where manure is spread, surface conditions at the time of spreading were assumed to resemble those of fallow land for all months since manure is not spread on growing crops. The cover factor was also considered to be constant

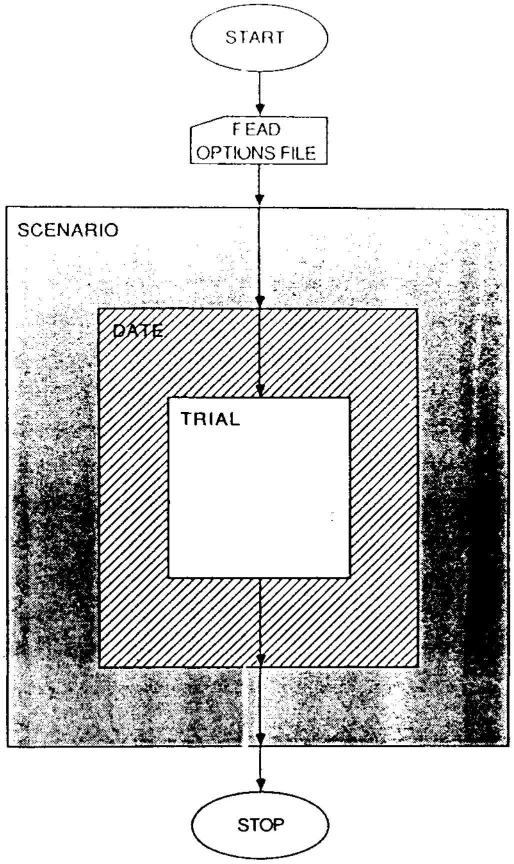

Figure 1a–Diagram of model COLI.

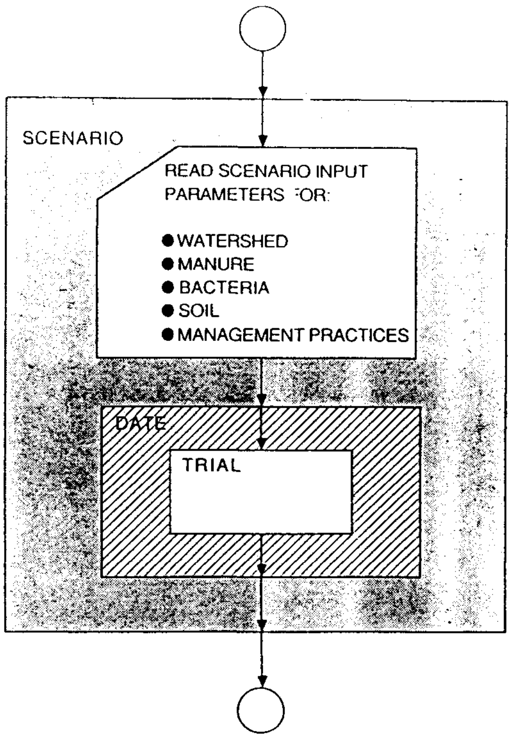

Figure 1b–Scenario loop of model COLI.

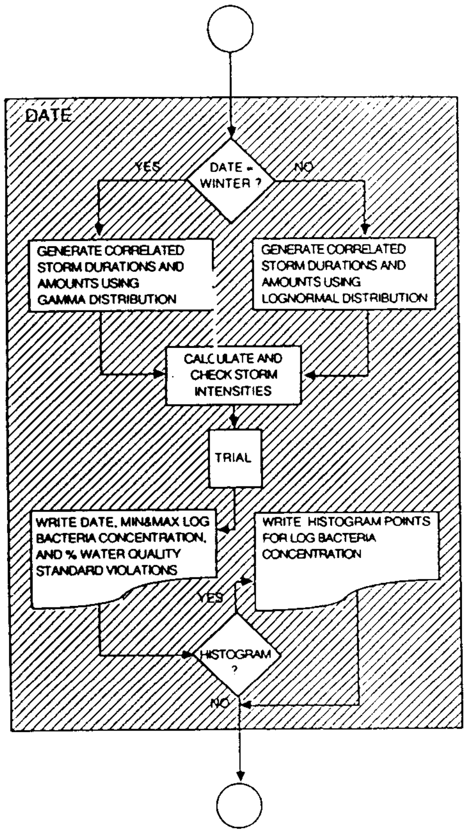

Figure 1c–Date loop of model COLI.

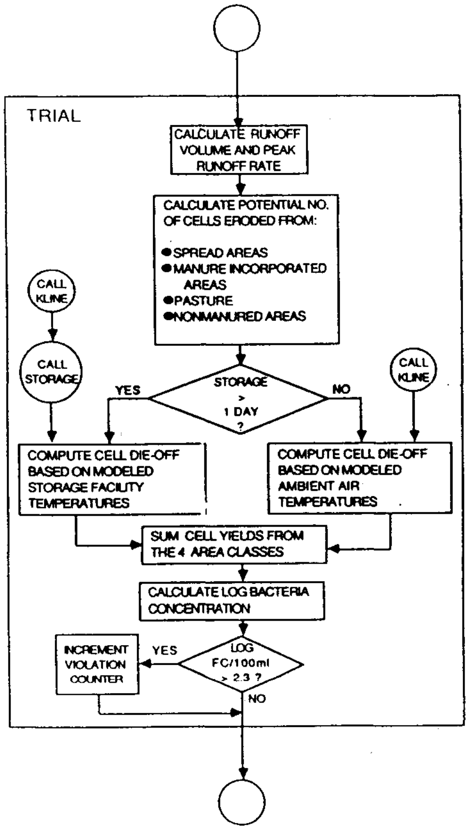

Figure 1d–Trial loop of model COLI.

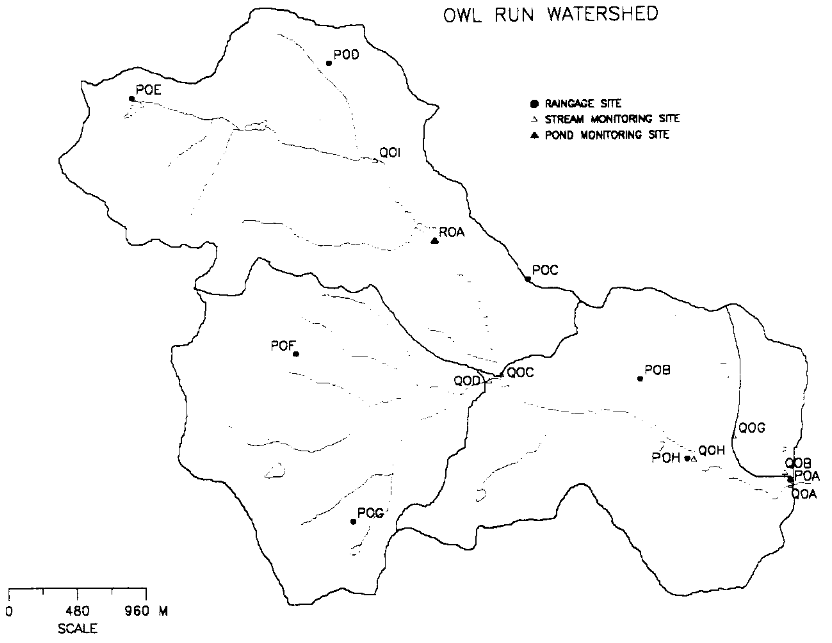

Figure 2–Sampling sites on the Owl Run watershed.

for areas where manure was incorporated, with the assumption that conditions immediately after incorporation resembled those of a seedbed crop stage. USLE conservation practice factors for all four area classes were assumed to be 1.0 since there is no indication that any erosion control practices are currently being employed on the watershed.

Bacteria yield from pasture areas is dependent on the number of livestock on the pasture, the number of days the animals are on the pasture, the number or defecations per animal per day, the area of an average fecal deposit, and a non-uniformity coefficient. A steady-state level of bacteria is assumed to be equal to the amount of bacteria deposited in a year since it has been reported that bacteria can remain viable in a pasture up to a year (Springer, et al., 1983). Thus, the number of days the animals are on pasture is expressed in terms of days per year. The values selected for these parameters are listed in Table 1. The non-uniformity coefficient is a measure of the spatial nonuniformity of fecal deposits in a pasture and is used in calculating the fraction of pasture area covered with manure (Khaleel et al., 1979b).

The number of cells per unit mass of fresh cow manure and soil was estimated to be 2.3x105 and 400 FC/g, respectively, as discussed earlier. For stored manure, the base die-off rate constant was estimated to be 0.3/day (Moore et al., 1988). The fraction of soil mass consisting of particles small enough to be suspended in water was estimated to be 0.40, based on a particle size analysis conducted on samples collected from a non-manured field in the study area. If a scenario in which manure is incorporated into the soil is to be modeled, then the density of the soil and the depth of incorporation must be determined. Soil density was measured using samples collected from the watershed.

Parameters related to waste management practices include the amount of manure spread on the land or incorporated into the soil, the time the manure is stored before spreading or incorporating, and the width of buffer strips associated with fields where manure is spread or incorporated. The values chosen for these inputs are listed in Table 1. For the study site, due to lack of storage facilities, approximately 2.2 Mg/ha of manure is spread daily (Payne, 1988). Thus, manure storage time is assumed to be 24 hours. Since no manure presently is incorporated into the soil, the values for the incorporated mass and storage time will not affect the output.

RESULTS AND DISCUSSION

Model COLI was used to simulate various scenarios for the subwatershed D of Owl Run. A "base" scenario was chosen that represents conditions for the Owl Run subwatershed prior to the implementation of any animal waste management practices. The other scenarios are used to demonstrate the impacts of animal waste management practices on bacteria levels in runoff.

The simulated results of employing no animal waste management practice on the subwatershed are presented in figure 3. The bars in the upper plot represent the range of results of applying animal waste to the land on a particular date assuming a runoff event occurs immediately after application. Each bar represents the range of log fecal coliform concentrations of runoff determined from 100 simulation trials. The horizontal line inside each bar marks the location of the average value of the 100 trials. The horizontal line across the plot represents the recreational water quality standard of 200 FC/100 mL (USEPA, 1976) and serves as a suggested goal for use in evaluating various management practices.

As shown in figure 3a, average log fecal coliform concentrations lie above the suggested water quality goal for all 12 simulated dates. Because cells were allowed to die off for only a short period of time (24 hours), only a slight depression in average log concentration can be seen

TABLE 1. Input parameters for COLI

Parameter	Input Value*			
WATERSHED PARAMETERS				
Area of watershed			324 ha	
Fraction of area spread with manure	(1) 0.43	(2) 0.43	(3) 0.43	(4) 0
Fraction of area where manure is incorporated	(1) 0	(2) 0	(3) 0	(4) 0.43
Fraction of area in pasture			0.21	
Fraction of non-manured area			0.36	
SCS CN for areas spread with manure:			81	
SCS CN for areas where manure is incorporated			81	
SCS CN for pasture			86	
SCS CN for non-manured areas			75	
Hydraulic length (m)			2160	
Average land slope (%)			3	
Average time between storms (hours)			57.6	
USLE erodibility factor for manure (SI)			0.0066	
USLE erodibility factor for soil (SI)			0.0553	
USLE length-slope factor			2.8	
USLE practice factor			1.0	
USLE cover factors by month and area type				
	Manure	Incorporated	Pasture	Non-manured
January	0.3600	0.6000	0.0921	0.0403
February	0.3600	0.6000	0.1591	0.0403
March	0.3600	0.6000	0.0827	0.0403
April	0.3600	0.6000	0.0609	0.0109
May	0.3600	0.6000	0.0423	0.0109
June	0.3600	0.6000	0.0423	0.0109
July	0.3600	0.6000	0.0609	0.0109
August	0.3600	0.6000	0.0640	0.0403
September	0.3600	0.6000	0.0423	0.0403
October	0.3600	0.6000	0.0609	0.0403
November	0.3600	0.6000	0.0640	0.0403
December	0.3600	0.6000	0.0827	0.0403
MANURE PARAMETERS				
Animal days on pasture			34905	
Number of defecations/day/animal			12	
Area of a fecal deposit (m^2)			0.093	
Nonuniformity constant			2.0	
BACTERIA PARAMETERS				
Bacteria in fresh manure (cells/g)			230,000	
Bacteria in soil (cells/g)			400	
Die-off rate at 20°C			0.3	
Temperature correction factor			1.07	
SOIL PROPERTIES				
Mass fraction of suspended soil particles			0.4	
Soil density (Mg/m^3)			1.6	
Depth of manure incorportion (cm)			10.0	
WASTE MANAGEMENT PRACTICES				
Mass of manure spread per spread event (Mg/ha)	(1) 2.2	(2) 2.2	(3) 2.2	(4) 0
Mass of manure incroporated into the soil (Mg/ha)	(1) 0	(2) 0	(3) 0	(4) 2.2
Spread manure storage time (hours)	(1) 24	(2) 24	(3) 4320	(4) 0
Incorporated manure storage time (hours)	(1) 0	(2) 0	(3) 0	(4) 24
Buffer strip width for areas spread with manure (feet)	(1) 0	(2) 100	(3) 0	(4) 0
Buffer strip width for manure incorporated areas (feet)	(1) 0	(2) 0	(3) 0	(4) 0

* A single value indicates that the value was used in all four scenarios. Otherwise, numbers in parentheses indicate the scenario for which the value was used:
- (1) Base scenario
- (2) Buffer strip scenario
- (3) Storage scenario
- (4) Incorporation scenario

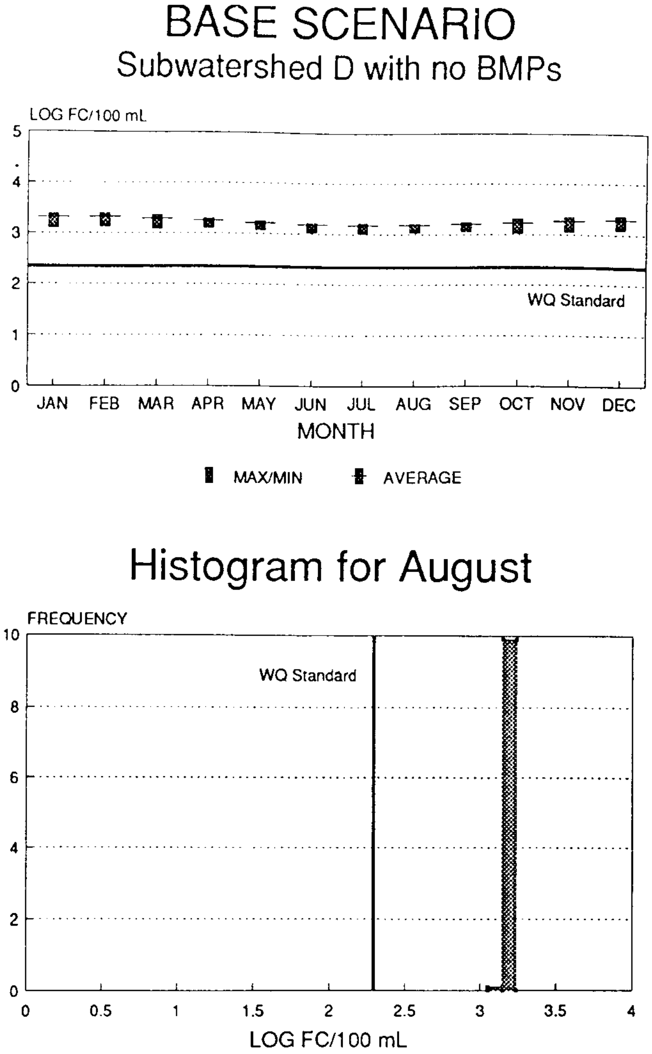

Figure 3–Simulated results for the Owl Run subwatershed assuming no animal waste management practices are employed.

as temperatures become warmer. The short die-off period also causes the average values to fall near the top of the range of values determined for each date. This is due to the fact that die-off is governed by both temperature and storage time in the model. For short periods of time, the amount of die-off that occurs will be approximately the same for low and medium temperatures. Less frequently occurring high temperatures result in less frequently occurring low bacteria concentrations at the lower limit of the range bars. The frequency of occurrence of the values represented by a single range bar can be seen more clearly in the histogram of figure 3b for the month of August. For the 100 trials conducted, all trials yielded FC concentrations in excess of the recommended standard. Such histograms are generated by COLI to aid in estimating the probability of exceeding a design goal, such as the recreational water quality standard of 200 FC/100 mL.

Vegetative filter strips reduce bacteria concentrations in runoff by trapping sediment and associated cells. Comparison of the base scenario represented in figure 3 with the results presented in figure 4a, illustrates the effect of using 30 m buffer strips in all areas where manure is spread. For the 30 m filter strip length and 3% slope, equation 3 predicted a 75% maximum bacterial reduction. Increasing the filter strip length did not result in any additional reduction in stream bacteria concentrations. In general, the vegetative filter strips alone were not adequate to meet the recreational water quality standard of 200 FC/100 ml, as shown in figure 4a.

Die-off of bacteria is dependent on storage time and temperature. COLI models the reduction of bacteria cells over a specified storage time. The results of storing manure for a six-month period before its application is shown in figure 4b. Currently, plans are underway to install concrete manure storage tasks for providing several months of storage at the Owl Run watershed. For this scenario, the temperature of the stored manure was modeled using a weighted average of air temperature as simulated by KLINE. In figure 4b, the seasonal variation of bacteria concentration ranges is more pronounced than for other management practices discussed. Bacteria concentrations for all months were below the recommended water quality standard.

The simulated results of incorporating manure are shown in figure 4c. The manure application rate and storage period were assumed to be 2.2 Mg/ha and 24 hours, respectively. It was assumed that the applied manure was thoroughly mixed with the soil to a depth of 10 cm. The results indicate that nearly all bacteria concentrations fall below the suggested goal and imply that incorporation is an effective BMP for the conditions described. However, incorporating one day's worth of waste (2.2 Mg/ha) is not a practical means of waste disposal. It is more common to incorporate several month's worth of waste. Thus, a scenario was investigated in which 400 Mg of manure per hectare, stored over a period of six months, was incorporated into the soil. The results (not shown) were not noticeably different from those of figure 4c (Walker, 1988).

For the subwatershed studied, long-term storage appears to be the most appropriate management practice for meeting the suggested water quality goal. Incorporation of a practical amount of manure implies that manure is collected and stored over a long period of time. Comparison of the results from the incorporation scenario of figure 4c with those of the long-term storage scenario of figure 4b reveals little difference. Thus, incorporation is not recommended for reducing bacteria concentrations because of the additional labor expense and because there is no significant advantage over long-term storage alone. Nevertheless, incorporation may be advantageous in terms of nutrient management or odor control. Vegetative filter strips are the least expensive of the strategies examined, however,they do not lower the bacteria concentrations sufficiently to meet the suggested water quality standard.

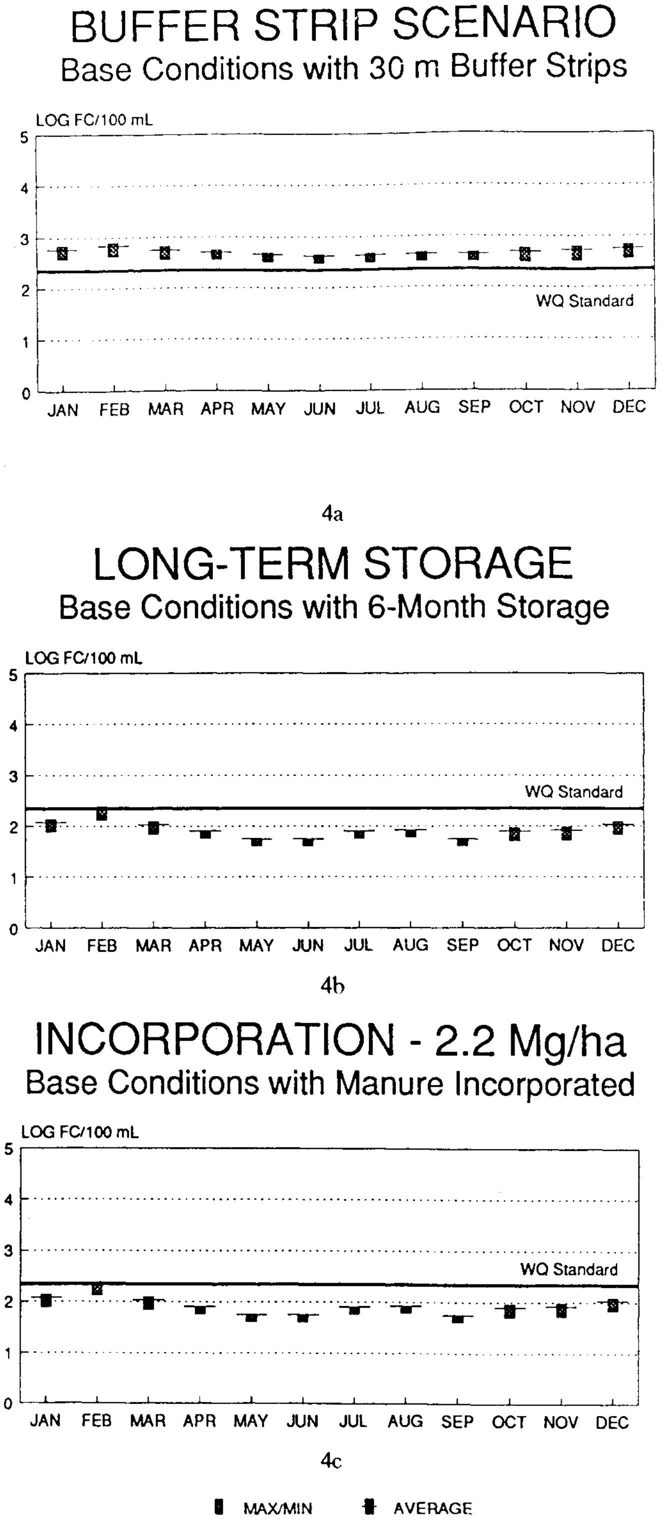

Figure 4–Simulated effects of various management practices on bacteria levels from subwatershed D.

SUMMARY AND CONCLUSIONS

Model COLI was developed for predicting the concentration of bacteria in agricultural runoff. The main purpose of the model is to aid in the evaluation of animal waste management alternatives for reducing the amount of bacteria transported by runoff from animal waste-applied areas. COLI is a probabilistic model which uses Monte Carlo simulation to combine deterministic relationships with stochastic storm duration, rainfall amount, and temperature data. The deterministic relationships used include the SCS curve number method for predicting storm runoff, the MUSLE for estimating the mass of soil and manure eroded by runoff from a single storm, and Chick's Law for describing bacteria die-off. The "worst" case scenario is modeled by assuming that a storm occurs immediately after land application of manure.

In developing COLI, the following assumptions were made:

1. Bacteria populations in runoff are the result of recent environmental conditions and can be simulated by modeling the effects of a single storm.

2. The decay rate constant is affected only by changes in temperature. The effects of pH, moisture conditions, exposure to sunlight, and other environmental factors are insignificant.
3. Die-off is significant only for bacteria in manure mechanically applied to the land. The population of bacteria on pasture and nonmanured lands is assumed to have reached a steady-state level.
4. Infiltration of bacteria beneath the layers of soil and manure subject to erosion is not significant.

The proposed model was applied to a small watershed in Fauquier County, Virginia. The model output for a scenario which assumed no animal waste management practices in use was compared to output from scenarios in which management practices were employed. It was determined that long-term storage of wastes is an effective practice for reducing the bacteria concentration in runoff to the recreational water quality standard of 200 FC/100 mL. Incorporation of manure provides no additional advantage over long-term storage in terms of reducing the bacteria concentration of runoff, but may provide advantages in terms of nutrient management and odor control. For the watershed studied, filter strips were not sufficient for reducing bacteria concentrations to meet the water quality goal.

Finally, it should be noted that the scenarios explored in this article serve only to demonstrate COLI's potential. Because animal waste BMP implementations on the Owl Run watershed has only recently begun, no data is available to verify the model's predictions. The model should be used with caution until it has been field tested.

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