A Model for Predicting Bacteria Concentrations in Runoff from Agricultural Lands

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Agricultural Engineering

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October, 1988

Blacksburg, Virginia

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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 best mangement practices (BMPs) thus becomes more important as livestock populations become more concentrated. A computer model is proposed to predict the effects of animal waste BMPs on the bacteria concentration of runoff from agricultural lands. The model uses Monte Carlo simulation to combine the deterministic relationships resulting from previous modeling efforts with statistical knowledge concerning rainfall events and temperature variation. Model output is in the form of monthly maximum and minimum log bacteria concentrations of runoff resulting from a storm assumed to occur immediately after manure is applied to the land. The effects of implementing such BMPs as waste storage, filter strips, and incorporation of manure into the soil can be compared. Data and information collected from the Owl Run watershed in Fauquier County, Virginia is used to demonstrate the model applicability and potential.

Long-term manure storage is determined to be the most appropriate practice for reducing bacteria concentrations for the study site. Incorporation of manure is as effective as long-term storage, but requires additional labor. Buffer strips significantly reduce bacteria concentrations, but not as effectively as long-term storage or incorporation. Additional efforts are needed to investigate the most influential variables and to make the temperature simulation submodel more computationally efficient. Once BMPs have been implemented on the study site, more data should be collected to test the accuracy of the model.

Acknowledgements

I would like to express my gratitude for the advice and insights provided by committee members Dr. Greg Boardman, Dr. Theo Dillaha, III, and Dr. Frank Woeste. A special word of thanks is extended to Dr. Saied Mostaghimi, who served as committee chairman, for his patient reviewing and re-reviewing of the text, as well as for his good advice and constant willingness to help. I thank the Virginia Division of Soil and Water Conservation for partial funding of this project, and particularly, I thank for providing information about the study site and for his helpful suggestions. Gratitude is also expressed to the Virginia Tech Department of Agricultural Engineering for providing a graduate assistantship and to the faculty for taking personal interest in my education.

I also thank , , , , and for their assistance in collecting and analyzing the Owl Run samples. Many thanks are also extended to , , and for untangling many word processing difficulties. I gratefully acknowledge Jim Bollinger for providing programming assistance -- without his contributions, the computer model developed in this study would be sorely handicapped.

Gratitude is expressed to Dr. Robert Hoehn for supplying information concerning cryptosporidiosis. I thank Mr. Jon Utin for inspiring my bovine sympathies which encouraged my interest in this project. I thank Dr. Ken Young of GKY & Associates, Inc. for his role in my technical upbringing, for introducing me to the concept of risk-based design, as well as for his questions about horse manure which started my thinking on the subject of bacteria concentrations in runoff as well as for introducing me to the concept of risk-based design. I thank everyone at GKY for their encouragement and patience.

I thank my parents for putting up with me for so long and for loving me so much. Finally, I acknowledge that no feat, great or small, is possible without the grace of God.

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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 more densely populate their pastures and establish confinement systems, the 42 liters of manure defecated daily by each animal require more conscientious management (Wheatland and Borne, 1970). Improperly managed livestock wastes can lead to problems of eutrophication and fecal contamination of waters receiving agricultural runoff.

The contribution of agricultural activities to the eutrophication of water bodies, such as the Chesapeake Bay and Lake Okeechobee, has received much public attention in recent years, and researchers have devoted much time to modeling the impact of nutrients in agricultural runoff. Comparatively, there has been little focus on the disease hazards of runoff from livestock operations. Although few instances of illness have been traced directly to water contaminated with animal feces, it is hypothesized that such water is responsible for many unreported cases of human and animal diseases (Crane et al., 1983; Robbins, 1979). Microorganisms responsible for approximately 100 human diseases have been found in the feces of animals (Reddy et al., 1981). Some examples are presented in Table 1.

Table 1. Human diseases potentially transmitted by animal feces.

Disease	Responsible Organism	Reference
Anthrax	*Bacillus anthracis*	Moore et al., 1988
Ascariasis	*Ascaris lumbricoides*	Moore et al., 1988
Balantidiasis	*Balantidium coli*	Moore et al., 1988
Coccidiosis	*Eimeria* sp.	Moore et al., 1988
Colibacilosis	*Escherichia coli*	Moore et al., 1988
Cryptosporidiosis	*Cryptosporidium* sp.	Fayer and Ungar, 1986
Hog Cholera	Virus	Diesch, 1970
Leptospirosis	*Leptospira pomona*	Diesch, 1970
Listeriosis	*Listeria monocytogenes*	Moore et al., 1988
Newcastle	Virus	Diesch, 1970
Psittacosis	Virus	Moore et al., 1988
Q Fever	*Coxiella burneti*	Moore et al., 1988
Salmonellosis	*Salmonella* sp.	Diesch, 1970
Sarcocystiasis	*Sarcocystis* sp.	Moore et al., 1988
Tetanus	*Clostridium tetani*	Moore et al., 1988
Tuberculosis	*M. avium* *M. bovis* *M. paratuberculosis*	Moore et al., 1988
Tularemia	*Pasturella tuleransis*	Moore et al., 1988
Toxoplasmosis	*Toxoplasma* sp.	Moore et al., 1988

Overall, the danger to humans lies in the possibility of these fecal organisms entering water and food supplies. Groundwaters and recreation 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 United States Environmental Protection Agency (USEPA) require that fecal coliform (FC) counts not exceed 200 FC/100 mL of sampled water for bathing waters and 14 FC/100 mL for shellfish harvesting waters (USEPA, 1976).

Animals may become infected by drinking from contaminated watering holes or eating contaminated vegetation. Salmonellosis and cryptospridiosis are two diseases spread by fecal contamination (Dazzo, et al. 1973; Fayer and Ungar, 1986). Cryptosporidiosis, caused by species of the protozoan *Cryptosporidium*, is associated with acute diarrhea. Fayer and Ungar (1986) reported $6.2 million as a conservative estimate of the annual loss in the United States due to bovine cryptosporidiosis. *Cryptosporidium* has also been identified in humans: first in patients with acquired immune deficiency syndrome (AIDS) and later in diarrheal samples of otherwise healthy individuals (Rose, 1988).

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 recommendation and design of animal waste best management practices (BMPs). A reliable computer model can aid in the relative comparison of management scenarios or in the optimum design of management structures without performing costly field experimentation.

Previous modeling efforts have, for the most part, resulted in the development of deterministic relationships that lead to the rough estimate of bacteria concentrations in runoff. While these deterministic relationships contribute greatly to understanding of the important factors and processes, a probabilistic modeling approach serves at least three purposes. First, a probabilistic approach acknowledges incomplete understanding of the system (Springer et al., 1983). As knowledge increases, so does awareness of the "roughness" of deterministic estimates, and thus confidence intervals and probability density functions become more meaningful than single-valued answers. The area under a probability density function for a given range of values is equal to the probability that an observation will fall within that range. With a probability density function for bacteria concentration, one could report for example, that the probability of exceeding 200 cells/100 mL of water is 72% rather than naively reporting 200 cells/100 mL as an absolute answer. Second, the random components of such factors as weather and soil conditions can be incorporated. Thus, the results of previous studies concerning the statistical distribution of rainfall or soil particle size can be applied. Third, output in the form of probability distributions is useful for selection of BMPs and optimum design of BMP 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. Applying theory discussed by Young and Walker (1988), a BMP structure, such as a waste storage tank, could be sized so that total annual cost is minimized, i.e., the optimum design capacity could be based on the minimum of the sum of construction costs of the tank and risk (probabilistic) costs associated with exceeding water quality standards. Building on the results of previous findings, additional efforts should therefore aim towards incorporating stochastic modeling techniques and generating results directly applicable to the practical selection and design of animal waste BMPs.

Objectives

The overall goal of this study is to develop a model for simulating bacteria loads in agricultural runoff that will aid in the recommendation and design of animal waste BMPs. Specific objectives will be to:

1) Summarize the published information useful to the development of a bacteria loading model including descriptions of current BMPs, factors and processes governing bacteria

populations, random effects, available hydrologic models, and previous bacteria modeling efforts.

2) Develop and/or select appropriate deterministic relationships and random components for predicting bacteria concentrations in runoff from agricultural lands.

3) Couple the selected deterministic relationships with stochastic modeling techniques to produce ranges of values for fecal bacteria concentrations in runoff resulting from a single storm occurring at various times of the year.

4) Demonstrate the usefulness of the procedure for predicting the effects of implementing animal waste BMPs using data collected from field experimentation.

LITERATURE REVIEW

A wealth of studies has been published concerning the bacteria concentration of runoff from agricultural lands, and yet, usually among the stated or implied conclusions is the recognition that the factors and processes involved are complex, and current attempts to study or mathematically describe them are inadequate. The information presented in this chapter, based on an inexhaustive review of the literature, nevertheless includes some information which, although inadequate, may be too detailed to be included in a model for practical use. However, such information is useful to the understanding of a model's underlying assumptions. Pertinent to the development of a bacteria loading model is information concerning the appropriate bacteria species to be modeled, animal waste best management practices (BMPs) for controlling bacterial pollution, factors and processes which affect bacteria populations, random effects, available models for simulating hydrogeologic processes, and previous approaches to modeling bacteria.

Bacteria Species to be Modeled

Although ultimately a bacteria model may be 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. The presence of such organisms in a water sample indicates fecal contamination and therefore the potential for the presence of disease-causing organisms (Thelin and Gifford, 1983). 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, mainly total coliforms (TC), fecal coliforms (FC), and fecal streptococci (FS) (Thelin and Gifford, 1983). There is some debate, however, as to which group serves as the best indicator of fecal contamination. According to Crane et al. (1983), the most appropriate group depends on the environmental conditions surrounding the sample source as well as the purpose for which the data is being collected.

The total coliforms are those aerobic and facultative anaerobic, Gram negative, non-spore forming rods which ferment lactose with gas production within 48 hours at 35°C (Geldreich et al., 1964). Since bacteria which are not native to human or animal intestines are included in this group, and since TC have been found to reproduce in waters high in nutrients, the concentration of TC in runoff does not provide a good indication of the degree of fecal contamination (Burn and McBean, 1987). The group is more appropriately used in the analysis of treated water in which the presence of any bacteria is undesirable (Crane et al., 1983).

The fecal coliforms are identified by their ability to ferment lactose with gas production in 24 hours at 44.5° C (Geldreich et al., 1964). Although Geldreich (1970) found high positive correlation between FC and fecal contamination, Fujioka and Shizumura (1985) argued that pathogens have been found in waters determined safe based on the recreational water standard of 200 FC/100 mL.

The fecal streptococci are also used as indicators of fecal contamination. *S. bovis* and *S. equinus* serve as indicators of livestock pollution due to the large proportion of these species in the feces of such domesticated animals as cows, horses, and sheep (Geldreich, 1970). However, because these species die off more rapidly than some species of the pathogen *Salmonella* , the *Streptococci* are less useful as indicators of disease potential (Geldreich, 1970).

Animal Waste BMPs

Animal waste BMPs such as manure storage structures, 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 BMPs, it may be inappropriate to base optimum BMP design solely on bacteria reduction. However, information concerning the influence of commonly used BMPs on bacteria concentrations in runoff should be considered in model development aimed at BMP selection and design. A summary of animal waste BMPs is presented in Table 2. Those practices for which some attempt has been made to quantify their effect on bacteria populations in runoff are discussed below.

Table 2. Summary of recommended animal waste BMPs.

Recommended Practice	Reference
Waste Holding Structures	
- waste storage pits and tanks	Moore et al., 1988
- runoff collection basins	Wheaton and Hale, 1980
- waste stabilization ponds	Porges and Mackenthun, 1963 Bowles et al., 1979 Polprasert et al., 1983
Facility Management	
- maintenance of pasture vegetation	Wheaton and Hale, 1980
- filter strips	Young et al., 1980 Moore et al., 1988
- location of water supply and shade away from streams	Wheaton and Hale, 1980
- diversion of runoff away from facility	Krivak, 1978
Land Application of Wastes	
- spreading on nonfrozen and nonsaturated soil	Wheaton and Hale, 1980 Moore et al., 1988
- incorporation into soil, waste injection	Mazurak et al., 1975 Khaleel et al., 1979a,b Wheaton and Hale, 1980 Moore et al., 1988

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 on frozen soil or during a wet period. Frozen soil prevents infiltration and encourages bacteria survival due to the low temperature. Spreading manure immediately prior to a rainstorm allows little time for bacteria die-off to occur before running off into a receiving water body. In addition, waste storage allows some die-off to take place before spreading (Moore et al., 1988). Fecal coliforms and fecal streptococci in sewage were reduced by approximately one order of magnitude when stored in the dark for 15 days (Burman et al., 1978).

Although waste stabilization ponds are used primarily to reduce the biochemical oxygen demand (BOD) of wastes, they may also be effective in reducing fecal bacteria populations (Polprasert et al., 1983). The high temperatures, exposure to sunlight, high pH, presence of microbial predators, toxins produced by algae, and depletion of nutrients may all contribute to providing an environment hostile to fecal bacteria. Although coliform removals as high as 99% have been reported, remaining populations in pond effluents may still exceed the standards (Porges and Mackenthun, 1963; Polprasert et al., 1983). Bowles et al. (1979) used first-order decay theory to predict the hydraulic retention time required to reduce coliform levels to meet effluent standards without disinfection.

Young et al. (1980) reported an approximate 69% reduction in both total coliforms and fecal coliforms and a 70% reduction in fecal streptococci in experiments using buffer strips to reduce the pollution potential of beef feedlot waste. The authors related TC to buffer strip length using an equation developed by performing a linear regression analysis.

$$TC = 67.34 - 1.90\,L \qquad [1]$$

where TC = total coliforms x 10^{-6} / 100 mL

L = length of buffer strip (m)

The coefficient of determination (r^2) for Equation [1] was reported to be 0.77. The authors concluded that the buffer strip lengths required to reduce bacterial pollution to levels that meet water quality standards were similar to those required to remove the nutrients added by feedlot runoff.

Moore et al. (1988) suggested that buffer strips may only be effective in reducing bacteria from runoff having greater than 100,000 organisms/100 mL. For runoff of lower bacteria 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 buffer strip should be at least 3.0 m wide and have a slope between 0 and 15%. Using information from the literature, Moore et al. (1988) developed the following equation to model the effects of buffer strips associated with areas where manure is spread:

$$PR = 11.77 + 4.26\,S \qquad [2]$$

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

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

Factors and Processes Affecting Microbial Populations

If an accounting approach is applied to modeling bacteria, then it is useful to understand the factors affecting the quantity of live bacteria originally deposited on the land, factors affecting the processes of die-off and adsorption between runoff events, and factors affecting 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 and attraction to soil particles. Rainfall duration and intensity and animal waste application method 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 warmblooded animals vary in species and number with livestock type (Geldreich et al., 1964; Geldreich, 1978). A comparison of the densities of indicator bacteria for several types of livestock is presented in Table 3. 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).

Table 3. Indicator organism densities in manure of various types of livestock (Geldreich, 1978).

Animal	FC count/g fresh manure (10,000s)	FS count/g fresh manure (10,000s)
Cow	23.0	130.0
Chicken	130.0	340.0
Duck	3300.0	5400.0
Horse	1.26	630.0
Pig	330.0	8400.0
Rabbit	0.0020	4.70
Sheep	1600.0	3800.0
Turkey	29.0	280.0

Bacteria populations on the land

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.

Mancini (1978) described three patterns of coliform die-off: The first pattern is a first-order decay. The second pattern includes an initial increase in population followed by the first-order die-off. A third pattern assumes that the die-off rate changes at some point in time. The three patterns are illustrated in Figure 1.

In the model developed by Moore et al. (1988), the environment outside the host body was assumed to be entirely hostile and thus die-off was assumed to follow the first-order decay of pattern 1, frequently expressed as Chick's Law:

$$\frac{N_t}{N_o} = 10^{-kt} \qquad [3]$$

where N_t = number of bacteria at time t

N_o = number of bacteria at time o

k = first-order die-off rate constant

t = time in days

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

$$k_t = k_{20}\,\theta^{t-20} \qquad [4]$$

where k_t = die-off rate constant at temperature t (1/day)

k_{20} = die-off rate constant at 20° C (1/day)

θ = parameter determined to be 1.07 based on unpublished experiments reviewed by Mancini (1978)

t = temperature (°C)

Loehr (1984) found that a θ equal to 1.072 was suitable within the temperature range of 3-35° C. Bacterial activity outside of this range is assumed to be greatly decreased (Loehr, 1984).

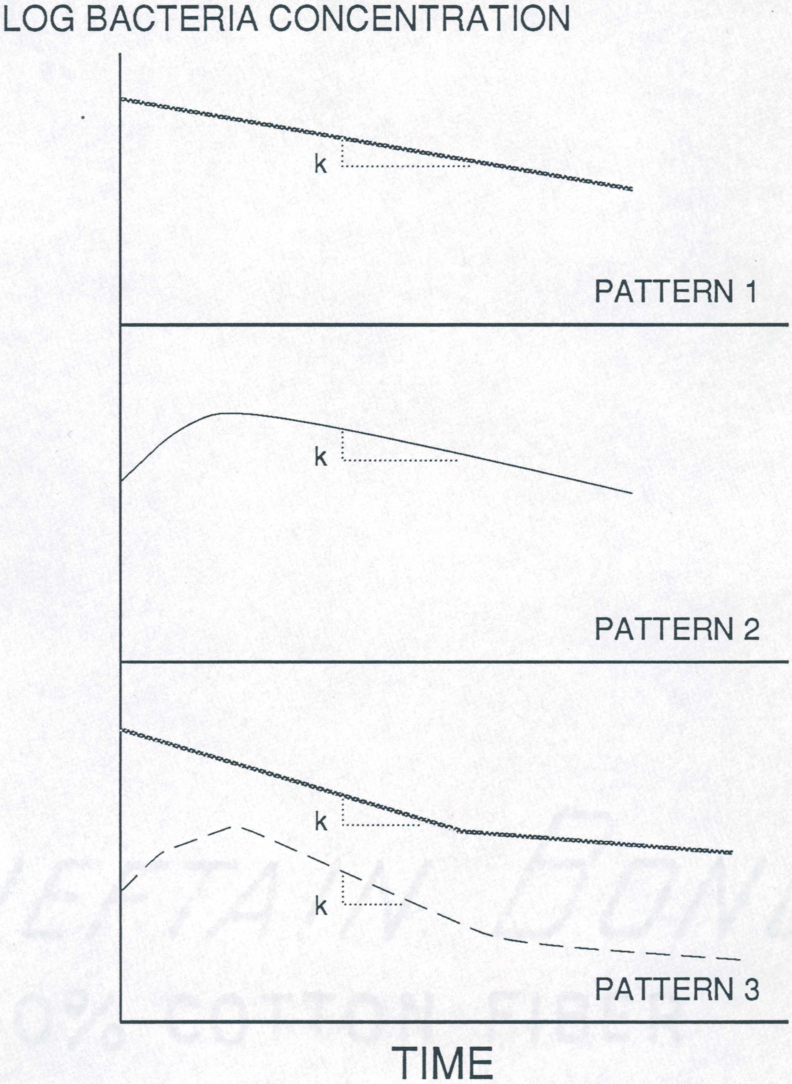


Figure 1. Typical patterns of bacteria die-off (Mancini, 1978).

The combined effects of several environmental factors on the die-off rate constant, k, in Equation [2] can be expressed as (Reddy et al., 1981):

$$k = k_1 F_t F_m F_{pH} F_{ma} \qquad [5]$$

where k_1 = die-off rate constant measured at temperature condition 1 and moisture condition 1 (1/day)

F_t = temperature correction factor = $\theta^{(t_2 - t_1)}$

F_m = soil moisture content factor

= F_{m_2}/F_{m_1}, where F_{m_i} can be empirically expressed as:

F_{m_i} = 1.00 - 0.9 MC for 0 < MC < 0.5 where MC is the measured moisture content.

F_{pH} = soil pH factor

= 1.69 - 0.26 pH for 3.0 < pH < 6.0

= 0.25 for 6.0 < pH < 7.0

= 0.21 pH - 1.22 for 7.0 < pH < 8.0

F_{ma} = method of application factor

= 1.0 for soil incorporated wastes

= 0.5 for surface applied wastes

Similarly, Polprasert et al. (1983) expressed k for die-off in waste stabilization ponds as a function of temperature, algal biomass concentration (a measure of a toxic substance produced by algae), organic loading, and ultra-violet radiation:

$$k = \ln(R) + T\ln(w_1) + C\ln(w_2) + OL\ln(w_3) + U\ln(w_4) \qquad [6]$$

where R, w_1, w_2, w_3, w_4 = regression constants

T = temperature (°C)

C = algal biomass concentration (mg/L)

OL = organic loading (kg COD/ha/d)

U = ultra-violet light index

= 1 + I/100 where I = sunlight intensity ($cal/day/cm^2$)

The authors included an additional constant, λ, to model the effects of differing bacteria species in relation to total coliforms. The *S. bovis-equinus* group generally dies off more rapidly than the fecal coliforms which in turn dies off more rapidly than the *S. faecalis-faecium* group (Burman et al., 1978).

In experiments with surface-applied poultry manure, Crane et al. (1980) noted that fecal coliforms displayed first-order die-off for the first seven days after application with an average k of 0.29/day (using a base of 10 as presented in Equation [3]). After the seventh day, fecal coliforms experienced regrowth until reaching equilibrium after the twelfth day. Fecal streptococci displayed rapid die-off during the first day followed by a brief period of regrowth and then gradual die-off for the remainder of the 30-day experiment. The 30-day average k for fecal streptococci was found to be 0.093/day. Moore et al. (1988) suggested that an initial acclimation period may be responsible for the erratic behavior displayed in similar experiments, and proposed a stepwise application of Chick's Law, i.e. using a separate equation for each period of time governed by a constant k.

In their study of coliform decay in reservoirs, Kay and McDonald (1980) found a distance-decay relationship to be more appropriate than the time-decay relationship of Chick's Law. The distance-decay relationship chosen by Kay and McDonald (1980) is expressed as:

$$C_d = a\,10^{bd} \qquad [7]$$

where C_d = coliform density at a distance **d** from a source

a = a constant

b = distance dependent decay coefficient

d = distance from input

Kay and McDonald (1980) used least squares regression techniques to fit Equation [7] to observed data. Thus, the variables **a** and **b** account for the effects of dilution, sedimentation, and die-off.

Moore et al. (1988) compiled an excellent list of die-off rates measured under a wide range of circumstances. Selected values are presented in Table 4, for which the natural base, e, rather than 10, applies in Equation [3].

Bacteria populations released into runoff

Factors affecting the release of bacteria into overland flow include rainfall duration and intensity, method of manure application, fecal deposit age, and adsorption of cells to soil particles. Springer et al. (1983) studied the effects of rainfall duration and intensity on the release of fecal bacteria. Greater numbers of bacteria were found to be released during storms of greater duration. And while rainfall intensity had little effect for fresh cow manure, 20-day old cowpies had a higher peak FC release at low rainfall intensity than at high intensity. However, despite the results of their experiments, Springer et al. (1983) also argued that high intensity rains may cause more manure, and thus more bacteria, to be eroded and transported with the overland flow. Therefore, more research is needed to understand the effects of intensity on the release of bacteria from fecal deposits.

Although few experiments have been conducted to study the influence of manure application method on the release of bacteria into runoff, more bacteria may be transported with runoff when manure is spread as a solid than as a liquid (Moore et al., 1988). 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 in-

Table 4. Bacterial die-off rate constant, k, for various manure and soil environments (Moore et al., 1988).

Environment	Organism	Season or Temperature	Die-off Rate, k (day^{-1})
Dairy manure pile	TC	Oct. - Feb.	0.051
	FC		0.066
Stored dairy manure slurry	*S. dublin*	late winter	0.107 - 0.428
	S. typhimurium		0.106 - 0.246
	S. aureus		0.153
	E. coli		0.102 - 0.287
	Br. abortus		0.410 - 1.090
Beef manure lagoon (aerobic)	FC	25° C	0.829 - 1.760
	FS	25° C	1.110 - 2.180
	FC	7° C	0.557
	FS	7° C	0.143
Poultry manure applied to bare clay soil and allowed to dry	FC	25° C	0.257 - 0.342
	FS		0.093
Swine manure applied to field plots	FC (surface applied manure)	7 - 15° C	0.286
	FC (subsurface applied manure)		0.306
Grass field plots inoculated with pure cultures	*E. coli* (exposed to sun)	Spring	0.371
		Summer	0.667
		Fall	0.439
		Winter	0.223
	E. coli (shade)	Spring	0.575
		Summer	0.303
		Fall	0.172
		Winter	0.227
	S. faecalis (exposed to sun)	Spring	0.178
		Summer	0.882
		Fall	0.347
		Winter	0.117
	S. faecalis (shade)	Spring	-----
		Summer	0.426
		Fall	0.187
		Winter	0.115

creasing soil erodibility (Mazurak et al., 1975). Mazurak et al. (1975) incorporated manure into a 10 cm layer of soil at application rates of 90, 200, and 415 Mg/ha/yr and described the effect on soil detachment with the following regression equation:

$$Y = 1.12\,X^2 + (46.4 + 0.084\,Z)\,X \qquad [8]$$

where Y = detachment rate of soil (mg/cm^2/h)

X = rainfall intensity (cm/h)

Z = manure applied (Mg/ha/yr)

However, if the manure is plowed into the soil with a moldboard plow such that the manure becomes buried under a layer of soil instead of incorporated with the soil, then little manure and accompanying bacteria will be transported with runoff (Khaleel et al., 1979a).

Thelin and Gifford (1983) listed fecal deposit age as a factor affecting the number of bacteria released during a rainfall event. Depending on the climate, a cowpie can remain on the soil surface for up to a year and a half. Because the material protects FC and other species from sunlight, a fecal deposit can be a long term source of bacteria, although the number of bacteria released generally decreases over time (Thelin and Gifford, 1983; Springer et al., 1983).

In addition, adsorption to soil particles affects the concentration of bacteria in runoff. Adsorption is used in this study to mean the processes by which bacteria cells become closely associated with soil particles. Cells adsorbed to soil particles may offer resistance to transport by overland flow or may be transported with eroding soil particles instead of infiltrating through 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 is one of several additional components (Daniels, 1980). According to Reddy et al. (1981), once bacteria cells are in the soil, they tend to adhere to clay particles rather than remain free in the soil water. Clay content, soil cation exchange capacity, organic matter content, soil surface area, pH, temperature, time of contact, 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).

Reddy et al. (1981) used a simplified Freundlich isotherm to describe soil retention of bacteria cells:

$$M_r = K_r M_s \qquad [9]$$

where M_r = number of cells retained / g of soil

K_r = retention coefficient (mL/g)

M_s = number of cells present in soil solution (number of cells / mL soil solution)

Measurement of K_r is complicated by the die-off and regrowth of bacteria; consequently, few published values for K_r are available (Reddy et al., 1981). Table 5 provides a limited selection of K_r values. Insufficient information exists to determine whether the wide range of values in Table 5 is due to measurement procedure, inherent differences between indicator bacteria and viral species, soil properties, or a combination of these factors. Thus, if a Freundlich isotherm is used to model soil retention, these values serve as suggested starting values at which to begin the calibration procedure.

Table 5. Retention coefficients for various soil types.

Soil Type	Organism	K_r (mL/g)	Reference
River sediment	TC	863	Reddy et al., 1981
River sediment	FC	1909	Reddy et al., 1981
River sediment	FS	261	Reddy et al., 1981
Aastad	virus (bacteriophage ϕX-174)	72.5	Burge and Enkiri, 1978
Kranzburg	virus (bacteriophage ϕX-174)	161	Burge and Enkiri, 1978
Palouse	virus (bacteriophage ϕX-174)	45.7	Burge and Enkiri, 1978
Parshall	virus (bacteriophage ϕX-174)	4.61	Burge and Enkiri, 1978

Random Effects

The difference in measured bacteria counts is, in part, due to the random components associated with changes in weather, soil properties, and enumeration technique, as well as unknown processes. Random variation of rainfall and soil properties will contribute to sample variation in time and space. Random error linked with the enumeration technique will contribute to variation among replicates. It is hypothesized that the combined random effects are significant to the extent that it is appropriate to incorporate uncertainty in a model for simulating bacteria loads.

Random variation of rainfall

The amount of runoff, and hence the amount of bacteria transported, is dependent on the amount of precipitation, the duration of the precipitation event, and the time between events. Precipitation amount and duration are usually considered to be correlated. Using ten years of data from Ahoskie, North Carolina, Mills (1980) applied a bivariate model with a two-parameter Weibull distribution to describe rainfall duration and lognormal distributions to describe rainfall amount for each of five duration classes. Rojiani et al. (1984) analyzed 28 years of data from Blacksburg, Virginia and found rainfall duration to follow a gamma distribution in winter and a lognormal distribution in summer. Rainfall amount was described with lognormal distributions for both winter and summer. Time between storms was described using gamma distributions. Shape and scale parameters did not significantly differ with season for either rainfall amount or time between storms.

Random variation of soil properties

Antecedent moisture condition (AMC) of the soil is closely related to time between rainfall events. If the soil is already saturated at the time of a storm, runoff will occur more readily than if dry conditions have persisted for several days. Mills (1980) determined the frequency of occurrence of each of the three AMC classes, defined by the Soil Conservation Service (USSCS, 1972) as presented in Table 6, for the Ahoskie, North Carolina data. The moisture condition before observed storms was found to be class I for 79% of the storms, class II for 12% of the storms, and class III for 9% of the storms.

Table 6. SCS Antecedent Moisture Condition Classes (USSCS, 1972).

Condition	Description	Five-day antecedent rainfall (mm)	
		Dormant season	Growing Season
I	Optimum soil condition (inbetween lower plastic limit and wilting point)	< 13	< 36
II	Average value for annual floods	13 - 28	36 - 53
III	Heavy rainfall or light rainfall and low temperatures within five days prior to given storm	> 28	> 53

Data collected from rainfall simulator experiments on plots of sandy loam and silt-silt loam soils were used by Rojiani et al. (1984) to determine distributions for soil erodibility. Lognormal distributions were found to be appropriate for both soils.

Random variation of temperature

Temperature of the environment affects the bacteria die-off rate as well as the antecedent moisture condition of the soil. Using nine years of hourly dry-bulb temperature data for Blacksburg, Virginia, Kline et al. (1982) developed a computer model to simulate both the periodic and stochastic variations for hourly temperature. A Fourier series was used to model the yearly, 24-hour, 12-hour, and 8-hour variations. The remaining variation in hourly temperature was then described using a normal distribution.

Random error associated with enumeration techniques

Two enumeration techniques for indicator bacteria are prescribed by Standard Methods (APHA, 1985). The most probable number (MPN) technique makes use of the fact that fecal coliform bacteria produce gas when they ferment lactose. Test tubes containing lactose broth and a small tube for trapping gas are inoculated with decimal dilutions of the sample. If a decimal dilution contains sufficient fecal coliforms at the time of inoculation, incubation will cause gas to form in the small trapping tube, interpretted as a "positive" test result. The dilutions that produce positive results allow the examiner to statistically determine the MPN of fecal bacteria along with confidence intervals. Additional tests can be done to confirm the identity as fecal bacteria (APHA, 1985). According to Rippey et al. (1987), the MPN technique has an estimated precision of ±300%.

The membrane filter (MF) technique provides a more direct count than the MPN method (APHA, 1985). Decimal dilutions are vacuum filtered through 0.45 μm pore membrane filters. Any cells present are caught on the filter surface, and when incubated on selective media, form visible colonies which can be counted (APHA, 1985). It is generally assumed that counts from replicates of the same sample follow a normal distribution (Haas and Heller, 1986). However, Haas and Heller (1986) concluded from their studies that often a lognormal distribution is more appropriate. Studies assuming the normal distribution may underestimate the likelihood of large values from the upper tail of the distribution and thus underestimate the risk to public health.

Hydrologic Models

Because rainfall is the primary driving force behind the detachment and transportation of bacteria and associated particles from the fecal deposit or the manured field to a body of water, a bacteria loading model is heavily dependent on its hydrology and erosion components. Thus, employing relationships from established, widely used agricultural hydrologic models takes advantage of previous research and lends credibility to the proposed bacteria model.

Mathematical models are typically grouped into such categories as empirical or theoretical; deterministic or probabilistic; and event-based or continuous. An empirical model is based on observed data (e.g. a regression analysis), whereas a theoretical model is based on both physical laws and experimental observations (Woolhiser and Brakensiek, 1982). Caution should be used when applying empirical models or empirical components of models to circumstances outside of those in which the experimental observations were made.

Deterministic models are those for which the variables are assumed to be without random variation (Woolhiser and Brakensiek, 1982). Although generally more complicated than deterministic models, probabilistic models attempt to quantify the uncertainty (accompanying all models) associated with the output based on assumed distributions of input variables. Probabilistic models are of particular value in the study of extreme, rather than average, events.

Event-based models simulate the response of the study area to a single runoff event. The response described by an event-based model usually occurs within a time frame of minutes, hours, or a few days. Thus, short-term processes are modeled with great detail while long-term processes are usually ignored. In comparison, a continuous model simulates response for a series of events and generally includes processes applicable to periods of time on the order of months or years (Larson et al., 1982).

Mathematical runoff models

Perhaps the most widely used model for predicting storm runoff from agricultural watersheds is the SCS curve number method (USSCS, 1973):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad [10]$$

where Q = runoff (mm)

P = precipitation (mm)

S = retention parameter

= 25,400/N - 254 where N is the curve number based on soil type, land use, hydrologic soil condition, and AMC.

Equation [10] is an empirical, deterministic, event-based runoff model resulting from the study of several years of rainfall and runoff records from agricultural watersheds in the United States (Schwab et al., 1981). Several widely used sediment yield models employ the SCS runoff model including AGNPS (Young et al., 1986), CREAMS (Knisel, 1980), EPIC (Williams et al., 1982), and SWRRB (Williams et al., 1985).

Some other mathematical runoff models are based on conservation of mass and momentum equations. ANSWERS combines Manning's stage-discharge equation with the conservation of mass equation to model runoff volume (Beasley and Huggins, 1981):

$$I - Q = \frac{dS}{dt} \qquad [11]$$

where I = inflow rate (m^3/s)

Q = outflow rate (m^3/s)

S = volume of water stored (m^3)

t = time (s)

Peak runoff rate is modeled by the SCS using triangular hydrograph relationships (Schwab et al., 1981):

$$q_p = \frac{0.0021\, Q\, A}{T_p} \qquad [12]$$

where q_p = peak runoff rate (m^3/s)

Q = runoff depth (mm)

A = watershed area (ha)

T_p = time to peak (h)

= $0.5D + 0.6T_c$ where D is the duration in hours of excess rainfall and T_c is the time of concentration in hours for the watershed.

Rojiani et al. (1984) applied Equation [12] in their Monte Carlo simulation of sediment yield. EPIC and SWRRB use an equation similar in form to that of Equation [12] except that time of concentration instead of time to peak appears in the denominator (Bingner, 1988). CREAMS and AGNPS model peak runoff rate using an equation developed by Smith and Williams (1980):

$$q_p = 200\, A^{0.7}\, S_c^{0.159}\, Q^{0.917\, A^{0.0166}}\, LW^{-0.187} \qquad [13]$$

where q_p = peak runoff rate (cfs)

A = drainage area (mi^2)

S_c = channel slope (ft/mi)

Q = runoff volume (in)

LW = length-width ratio of the watershed

Equation [13] resulted from data collected from 304 storms on watersheds ranging in size from 0.275 to 24 mi^2. The variable exponent is used so that the model can be applied to areas of smaller size than those from which the equation was developed (Smith and Williams, 1980).

Mathematical erosion models

AGNPS, CREAMS, EPIC, and SWRRB all use some form of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978) as presented in Equation [14]:

$$A = R\ K\ LS\ C\ P \qquad [14]$$

where
- A = annual soil loss per unit area (ton/[ac yr])
- R = annual erosivity (hundreds of ft-tonf in/[ac hr yr])
- K = soil erodibility factor (ton ac hr/[hundreds of ac ft-tonf in])
- LS = length-slope factor $(ft/ft)^m$ where m is an exponent varying from 0.2 to 0.5
- C = cover management factor (dimensionless)
- P = conservation practice factor (dimensionless)

The USLE is an empirical, deterministic model that predicts average annual soil loss. The model has since been modified to predict sediment yield on an event basis (Williams, 1975):

$$Y = 11.8\,(Q q_p)^{0.56}\ K\ LS\ C\ P \qquad [15]$$

where
- Y = sediment yield from a single storm (Mg)
- Q = storm runoff volume (m^3)
- q_p = peak runoff rate (m^3/sec)
- K, LS, C, P = USLE factors

Equation [14] was developed using data collected from small watersheds in Texas and Nebraska for clay and silt loam soils and was found to account for approximately 92% of the variability in sediment yield (Williams, 1975). Although ANSWERS does not use the USLE or the modified USLE (MUSLE) directly, it relates soil detachment rate to rainfall intensity and to the USLE factors K and C (Bingner, 1988; Beasley and Huggins, 1981).

Researchers for the USDA Water Erosion Prediction Project (WEPP) modeled interrill and rill erosion separately (Lane et al., 1987). As in ANSWERS, interrill erosion is related to the square of the rainfall intensity and to a soil erodibility factor and cover factor. Rill erosion (detachment of soil particles by concentrated flow) is related to the detachment capacity of the flow and the shear stress necessary for detachment to occur. Although still in the developmental stages, WEPP incorporates erosion mechanics theory, and is thus intended to be an improvement upon the empirically-based USLE.

Techniques for Coupling Stochastic and Deterministic Models

The generation of system moments approach, Monte Carlo simulation, and a recursive technique that uses probability generating functions are three methods that have been used to include random components in hydrologic and water quality models (Mills, 1980). Prior to applying any of the techniques, one must identify the variables in the deterministic model which should appropriately be considered as random. To generate system moments, the model, expressed as a function of random variables, is expanded using a Taylor series (Hahn and Shapiro, 1967). The first moment (system mean) is derived by retaining only second and lower order terms in the expansion, the second moment (system variance) is derived by retaining third and lower order terms in the expansion, and so forth. Such an approach has been used to determine means and variances of annual sediment yield and dissolved and sorbed phosphorus (Mills, 1980). The major limitations of this approach are the mathematical complexity of applying the method to some models, and that only the moments, not the actual form, of the output distribution are determined (Hahn and Shapiro, 1967; Mills, 1980).

Monte Carlo simulation is performed by evaluating the deterministic model for several sets of random input values (Mills, 1980). A random number generator is used to select a value from the known distribution of each random input variable. Evaluation of the function for a set of random inputs produces a random output value. By performing a large number of trials, a histogram can be constructed for the random outputs and a probability density function approximated. Monte Carlo simulation was used to approximate the probability density function of soil loss over the liftime of a surface mining operation (Rojiani et al., 1984). The authors chose the MUSLE as the deterministic model, using rainfall amount, storm duration, and soil erodibility as random inputs (Rojiani et al., 1984). Disadvantages of using Monte Carlo simulation include the computational expense of performing large numbers of trials and the fact that the tails of the output distribution are often poorly defined (Mills, 1980). The former becomes less significant as computer speeds increase.

Mills (1980) developed a recursive technique that uses probability generating functions to couple stochastic and deterministic models. The technique is useful for determining the probability density function of an output that is the cumulative result of a random number of stochastic events. Mills (1980) demonstrated this technique by determining the probability distribution of annual runoff from the Ahoskie watershed in North Carolina, using rainfall amount as the stochastic input variable and antecedent moisture condition as the stochastic state variable. The SCS method for computing storm runoff (Equation [10]) served as the deterministic model. He extended the example by determining the distribution for annual sediment yield using the MUSLE of Equation [15] as the deterministic model. Although the method is computationally efficient in comparison to

Monte Carlo simulation, it becomes mathematically cumbersome to apply for complex deterministic models.

Previous Approaches to Bacteria Modeling

Three models are presented in this section: the Animal Waste Version of the Agricultural Runoff Model (ARM) II (Overcash et al., 1983), the Utah State model (Springer et al., 1983), and MWASTE (Moore et al., 1988). The models are new enough that their application by parties other than the model developers themselves has not been reported. It is not known if the animal waste portion of ARM II has yet been coded, however it predicts numbers of bacteria transported separately by runoff and sediment from agricultural lands. The Utah State model accounts for uncertainty by including Gaussian white noise terms, but does not consider the distributions of individual input variables. MWASTE is perhaps the most suited of the three for practical application to BMP planning, but is a purely deterministic model.

Animal waste version of ARM II

The animal waste version of the ARM II, diagrammed in Figure 2, approaches the modeling of bacteria with the use of partition coefficients to separate water transported bacteria from sediment transported bacteria (Overcash et al., 1983).

Watershed hydrology is modeled using a modification of the Stanford Watershed Model and the Hydrocomp Simulation Program (Overcash et al., 1983). The partition coefficients and die-off rates were estimated from the literature for the simulation study conducted by Overcash et al. (1983). The die-off rate was assumed to be the same for both adsorbed bacteria and bacteria in solution.

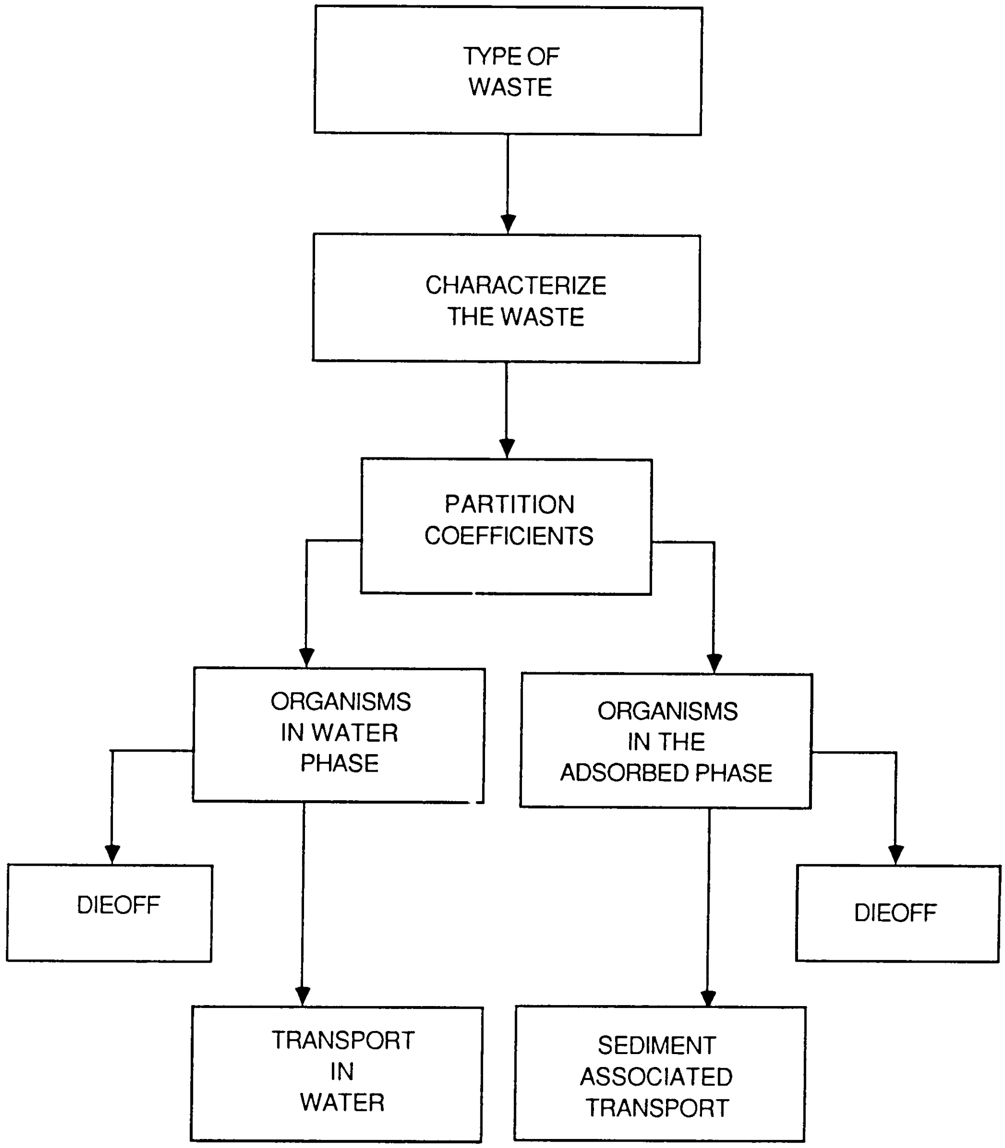


Figure 2. Flow chart for the animal waste version of ARM II (Overcash et al., 1983).

The effects of animal waste management practice implementation cannot be directly modeled and output is in the form of FC counts per hectare, with no confidence intervals suggested.

Utah State Model

Springer et al. (1983) conducted experiments at the Utah State University Ecology Center Compound in North Logan, Utah to study the release of fecal coliforms from cow manure. The experiments involved determining the concentration of fecal coliforms in runoff collected from simulated rainfall events on "standard" cowpies (manure, collected from cattle fed on controlled diets, mixed, and remolded in standard sized cake pans). Both smooth concrete and a clay soil were used as runoff surfaces. A preliminary model was then developed and the predicted and observed results were compared. A schematic of the model developed by Springer et al. (1983) is presented in Figure 3.

Runoff was estimated using the Green and Ampt infiltration equation for a clay soil surface condition. Kinematic wave equations were used to model overland flow. The slope-roughness factor and the channel shape factor of the kinematic wave equations were then used to relate time of travel (of the bacteria to the slope outlet) to the distance traveled. Three cases arose concerning the relationship of time, t, with time of travel, t*, time at which equilibrium flow conditions are established, t_e, and time at which rainfall stops, t_r:

Case 1: $t^* \leq t \leq t_e$ or $t^* \leq t \leq t_r$

Case 2: $t_e \leq t \leq t_r$

Case 3: $t_e \leq t^* \leq t \leq t_r$

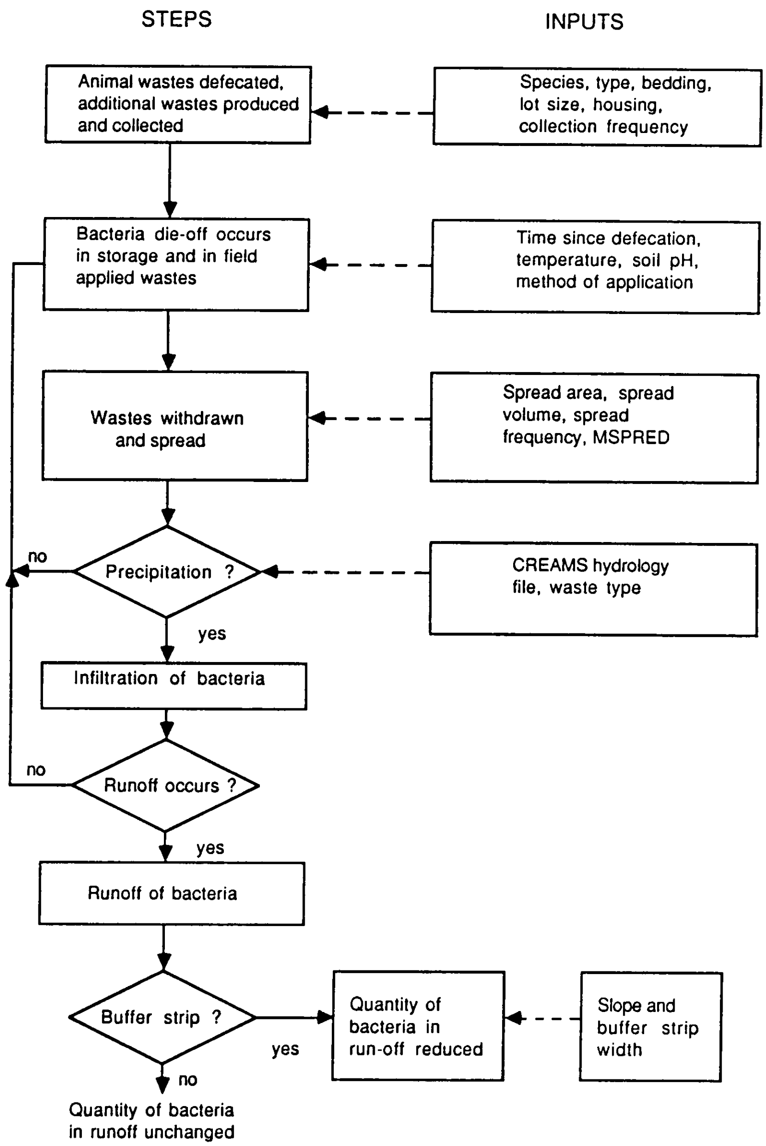


Figure 3. Flow chart for the Utah State bacteria model (Springer et al., 1983).

Case 1 was considered to be most important since overland flow rarely reaches equilibrium for natural storms. These three cases each resulted in a different solution to the mean and variance of a probability distribution function of the fecal coliform concentration (Springer et al., 1983).

Bacteria movement was modeled using the continuity equation. The value of the input term (the number of coliforms input to the overland flow) was determined to be 6.0 x 10^6 MPN/100 mL from experiments conducted by Springer et al. (1983). Retention of the bacteria by soil particles was based on the linear form of a Freundlich isotherm as presented by Reddy et al. (1981) in Equation [9]. Springer et al. (1983), based on their review of pertinent literature, suggested the values of 1909.0 mL/g for soil retention (K_r) and 0.67/day for bacteria die-off (k). Gaussian white noise terms (normally distributed error) were added to the continuity equation to account for random error due to variation in surface roughness, imprecise bacteria counting techniques, and incomplete understanding of the system (Springer et al., 1983). The solution of this equation resulted in the definition of an initial probability density function for fecal coliform concentration.

Whether this initial distribution was assumed to be normal or a Dirac delta function, the resulting distribution for FC concentration at the bottom of the test plot slope was determined to be normal, with mean and variance computed for the appropriate case 1, 2, or 3. Management decisions can thus be based on probabilities that the FC concentration in runoff will exceed a set standard. In instances where the probability distribution function cannot be mathematically derived, the management decisions are based on the computed mean and variance alone. The authors found that the predicted values did not fit the observed data well, with predicted values approaching steady state more quickly than the observed data. Inadequate estimation of the roughness and retention factors was suggested as a possible source of error.

One limitation of the model is that it only considers the rising limb of the hydrograph, i.e., the removal of bacteria from the land strictly by overland flow is not modeled (Springer et al., 1983). In addition, the model is not tailored to evaluating BMPs. One strength of the model is its probability distribution approach. Predictions which indicate confidence intervals, rather than single values, are more meaningful due to fluctuating bacteria populations and imprecise enumeration techniques.

MWASTE

MWASTE, developed by Moore et al. (1988), estimates the concentration of FC and FS in runoff as affected by type of livestock, livestock confinement system, waste storage practice, waste spreading practice, rainfall amount, and presence of buffer strips. The interconnection of these factors is illustrated in the flow chart shown in Figure 4.

The wastes considered by MWASTE include both those output directly by the animals as well as additional wastes such as bedding, washwater, and lot runoff. The user can input known values of bedding volume or use default values based on species of livestock. The volume of washwater is specified by the user and lot runoff is a function of lot area, precipitation, and a surface factor. The additional wastes contribute to the total stored waste volume (if a waste storage system exists) and thus affect the frequency of waste spreading on fields. Once the animal type, number, and confinement system are specified, MWASTE determines the total number of FC and FS before die-off based on fixed values of volume of fresh manure generated per animal and fixed values of bacteria counts per volume of manure.

MWASTE assumes that the waste is spread on a user-specified area (either by mechanical means or by pastured animals). A manure spreading schedule can be input to a separate file with the aid of program MSPRED. If such a file is not created, MWASTE will prompt the user for a spreading frequency and duration.

Bacteria die-off is governed by the first-order decay equation expressed by Chick's Law in Equation [3]. The die-off rate constant, k, is assumed to be 0.3 for stored waste based on an average

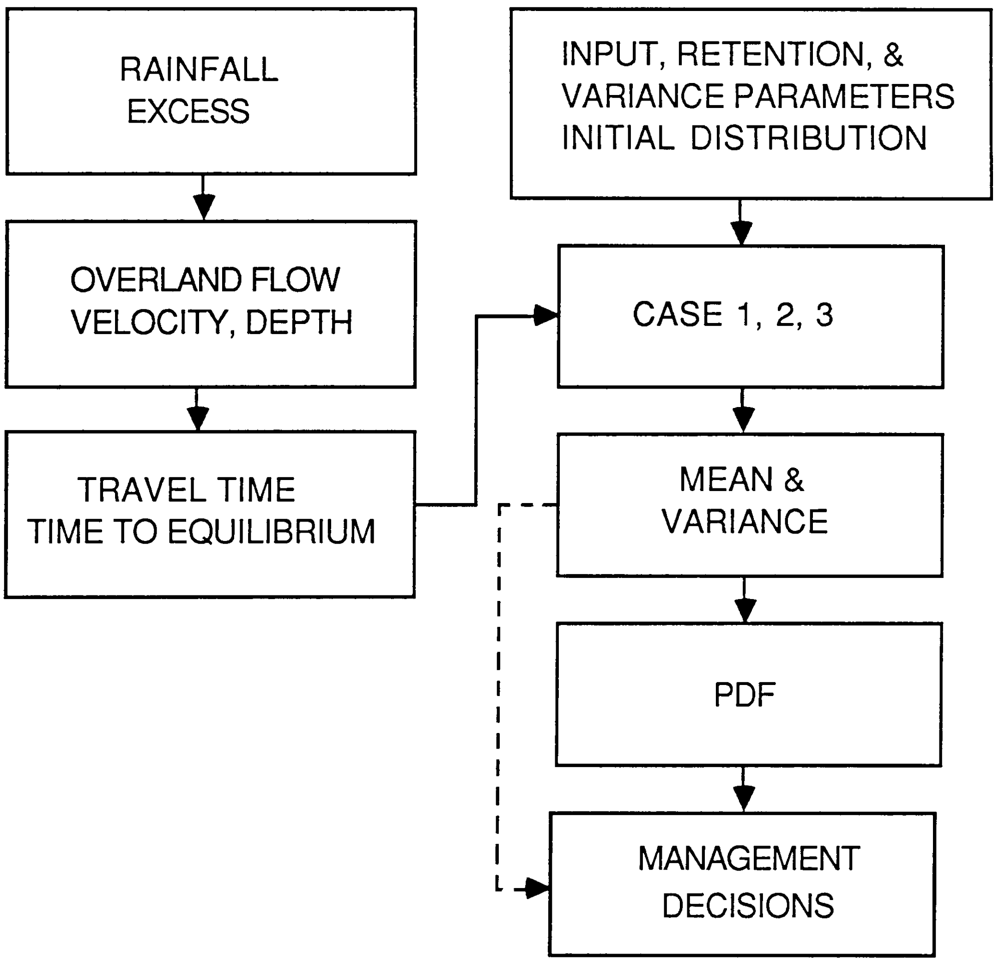


Figure 4. Flow chart for MWASTE (Moore et al., 1988).

of values Moore et al. (1988) noted from the literature. For spread waste, k is calculated in a manner similar to Equation [5]:

$$k = k_1 \; F_t \; F_{ma} \; F_{pH} \qquad [16]$$

where k_1 = base die-off rate constant (0.50)

F_t = temperature correction factor (1.0675^{t-20})

F_{ma} = method of application factor (0.50 for surface application)

F_{pH} = soil pH factor;

= 1.69 - 0.26pH, $3 \leq pH < 6$

= 0.25, $6 \leq pH < 7$

= 0.21pH - 1.22, $7 \leq pH < 8$

As indicated in Figure 4, CREAMS (Knisel, 1980) can be used to calculate the runoff for the system. If a CREAMS hydrologic pass file is not used, MWASTE will obtain hydrologic information interactively.

Once a rainfall event occurs, Equation [17] is used to calculate F, the number of bacteria remaining on the soil:

$$F = FO\,(1 - p)^r \qquad [17]$$

where FO = number of original bacteria remaining on soil

r = runoff or infiltration water depth (in)

p = percent reduction factor of infiltration or runoff as given in Table 7.

Table 7. Percent reduction factors, p, for infiltration and runoff (Moore et al., 1988).

Waste Type	Spreading	Infiltration p	Runoff p
solid	----	0.05	0.40
liquid	day 1	0.20	1.00
liquid	> day 1	0.05	0.40

The effects of buffer strips are modeled using Equation [2].

One strength of MWASTE is its attempt to account for the effects of factors such as animal type and confinement system. In addition, it is compatible with the reputable model CREAMS. A major weakness is the output of bacteria quantities as single values instead of as confidence intervals. Also, MWASTE could be improved by including other BMPs in addition to buffer strips.

Summary

A review of the literature has revealed that bacteria populations of runoff contaminated by animal wastes are affected by many, often complex, factors and processes. Type of livestock, waste application method, die-off, adsorption, severity of the rainfall event, and enumeration technique can all influence the concentration of cells measured in water bodies receiving runoff from agricultural lands. In acknowledging an incomplete understanding of these factors and processes, it is also acknowledged that purely deterministic methods for quantifying bacterial populations are inadequate. Continued efforts are therefore needed to combine the deterministic relationships developed by previous researchers with knowledge of the stochastic behavior of the input variables.

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, identification of variables that can be appropriately treated as random, and selection of a stochastic coupling technique. Because model accuracy and suitability for application must be considered jointly, these three steps in the development process are interdependent. Although one deterministic relationship may be more accurate than another, some may include variables for which it is difficult to describe their statistical distributions. Also, the more complex the deterministic relationship, and the more variables identified as random, the more impractical it becomes to apply some stochastic coupling techniques.

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, and the die-off of the cells. Because some of these relationships vary with land use, it was decided to divide the study area into four classes: a) areas where manure is spread, b) areas where manure is spread and incorporated into the soil, c) areas where manure is deposited only by livestock (i.e. pasture), and d) non-manured areas. The latter category includes those areas which receive fecal contamination only from wild animals.

Runoff and erosion

Equation [15], the modified Universal Soil Loss Equation (MUSLE), was selected to model the mass of soil and manure eroded during a single runoff event. Although the MUSLE was developed using data from western United States watersheds, Rojiani et al. (1984) applied the model to surface mined regions and Mills (1980) applied the model to a North Carolina watershed. Due to lack of better information, Equation [15] is assumed to be generally applicable within the United States and adequate for the proposed bacteria model. It is hypothesized that the bacteria concentration measured in a water sample is more the result of a recent storm and recent environmental conditions than an accumulated result. Although cattle walking through a stream may resuspend bacteria cells accumulated in the sediment, insufficient information exists to account for this phenomenon in the proposed model (Sherer et al., 1988). Thus, the MUSLE was selected over the USLE because it was considered to be more reasonable to attempt to model the effects of a single storm rather than accumulated annual effects. The MUSLE has been widely used, is credible, and has variables which are familiar to BMP planners. The variables Q and q_p, runoff volume and peak runoff rate, respectively, in the MUSLE were modeled using the SCS relationships presented in Equations [10] and [12]. The SCS runoff volume equation is used by reputable models such as CREAMS, SWRRB, EPIC, and AGNPS. Many erosion models include a channel slope factor when computing peak runoff rate, such as presented in Equation [13]. However, for the model developed in this study, Equation [12] seems adequate since the model is concerned mainly with the overland flow. 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.

Variation among the four area types is accounted for in the selection of the SCS curve numbers and USLE factors. Guidance for curve number and USLE factor selection for the pasture and non-manured areas can be found in documents published by the SCS and USDA, such as USSCS (1972) and Wischmeier and Smith (1978). The literature reviewed provided no guidance for selecting curve numbers for the areas where manure is spread or areas where manure is incorporated, and thus best engineering judgement must be applied. As noted in the literature review, 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). For areas where manure is incorporated into the soil, the detachment rate, modeled by Mazurak et al. (1975) in Equation [8], was assumed to be proportional to the soil erodibility factor **K**:

$$\frac{K_0}{K_Z} = \frac{Y_0}{Y_Z} = D \qquad [18]$$

where K_0 = soil erodibility factor for soil with no manure incorporated

K_Z = soil erodibility factor for soil into which **Z** Mg of manure/ha/yr is incorporated

Y_0 = detachment rate as computed from Equation [8] assuming no manure incorporated into the soil

Y_Z = detachment rate as computed from Equation [8] assuming **Z** Mg of manure/ha/yr incorporated into the soil

D = a constant equal to less than 1.0 since added manure tends to increase soil detachment at high manure application rates (Mazurak et al., 1975).

Thus, the **K** factor for soil with incorporated manure can be determined after computing **D**:

$$K_Z = \frac{K_0}{D} \qquad [19]$$

The length-slope factor for each area class can be determined with the aid of a topographic map of the study site. Cover factors are 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 are used to estimate the cover factors for manured lands. Conservation practice factors are determined using the guidance provided by Wischmeier and Smith (1978) unless buffer strips are the practice employed. The effects of buffer strips are modeled using Equation [2], developed by Moore et al. (1988). The selection of these values is demonstrated in the MODEL APPLICATION section.

Number of cells associated with eroded soil and manure

In order to obtain the number of indicator bacteria cells per 100 mL of runoff water sampled, 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. As noted in the literature review, cell density of manure is dependent on bacteria species, type of livestock, and many unquantified factors. Cell density of soil contaminated by animals other than livestock appears to be no less variable. For this study, the fecal coliform bacteria were selected for modeling since it is this group upon which USEPA standards (for untreated water) are based (USEPA, 1976). The information presented in Table 3 is used to select a cell density for eroded manure. For cow manure, the density of fecal coliforms is reported as 2.3×10^5 cells/g manure or 2.3×10^{11} cells/Mg manure (Geldreich, 1978). A value of 400 FC/g soil was selected as an estimate of the cell density of soil uncontaminated by livestock manure based on data presented by Faust (1982). A weighted average of manure cell density and soil cell density was used to estimate the cell density of soil mixed with manure, as presented in Equation [20].

$$CD_I = \frac{M_I\, CD_M + 100\, B\, T\, CD_S}{M_I + 100\, B\, T} \qquad [20]$$

where CD_I = cell density of soil mixed with manure (cells/Mg)

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

CD_M = cell density of manure (cells/Mg)

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

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

100 = factor to convert Mg cm/m^3 to Mg/ha

CD_S = cell density of soil without incorporated manure (cells/Mg)

A runoff water sample may contain suspended material, but will generally not contain large particles that are deposited on the bottom of the channel. Thus, even if bacteria are adsorbed to the surfaces of large soil particles, they will not be available for enumeration in the water sample. Therefore, the mass of soil eroded was multiplied by the fraction of soil composed of particles small enough to be suspended in water, i.e. the particles having diameters less than or equal to 0.010 mm, or the combined clay and silt fraction (Foster et al., 1980). This product was then multiplied by the estimated number of cells per unit mass of soil, as shown in Equation [21]:

$$P_{soil} = E \; S \; CD_S \qquad [21]$$

where P_{soil} = number of cells potentially available from eroded soil

E = mass of eroded soil as calculated by the MUSLE (Mg)

S = fraction of soil mass composed of clay and silt particles

CD_S = cell density of the soil (cells/Mg)

The potential number of cells eroded is reduced to account for die-off according to Chick's Law, presented in Equation [3], using the natural base, e, rather than a base of 10. Because it would be difficult to measure the distances of all the manure sources on a watershed from the sampling location, the distance-decay relationship of Equation [7] was not used. The base die-off rate, k, is selected from Table 4 or from more detailed tabulations presented in the literature, such as by Moore et al. (1988). The base die-off rate constant is then corrected for temperatures other than

20° C using a factor θ of 1.07 (Mancini, 1978). Loehr (1984) suggested that a θ of 1.07 is appropriate within the temperature range of 3-35°. Below 3° C, as water approaches the freezing point, the die-off rate is assumed to be zero. For the model of this study, a temperature correction factor of 1.07 is assumed adequate for all temperatures above 3° C, even though above 35° C, the die-off rate may, in reality, be close to infinity for some organisms. 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 the 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 considered to be insignificant for pasture (areas where manure is deposited by livestock only) and non-manured areas because the supply of bacteria is assumed to be constantly replenished. If livestock are not kept on pastures during the winter months, then bacteria yields from these areas will be overestimated if die-off is not modeled. This overestimation is considered acceptable since the error is on the side of conservatism and since die-off occurs at a slow rate during cool weather.

Combined deterministic model

The bacteria yield from each area class (areas with spread manure, areas with incorporated manure, pasture areas, and non-manured areas) 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 [15], a cell density factor CD, Chick's Law of Equation [3] (using the natural base, e), and the temperature correction relationship of Equation [3], bacteria yield can be expressed as:

$$Y_i = 11.8\,(10\ Q\ A\ q_p)^{0.56}\ K_i\ LS_i\ C_i\ P_i\ F_i\ CD_i\ e^{-k_{20}\,\theta^{(T-20)}\,t} \qquad [22]$$

where Y_i = number of bacteria cells eroded from the area class **i**

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

Q	=	runoff (mm)
A	=	area of the watershed (ha)
q_p	=	peak runoff rate (m^3/s)
K_i, LS_i, C_i, P_i	=	the USLE factors for area class i
F_i	=	fraction of the total watershed area in the particular area class
CD_i	=	cell density of the soil or manure (cells/Mg)
k_{20}	=	base die-off rate at 20° C (day^{-1})
θ	=	temperature correction factor
T	=	temperature of the air or storage environment surrounding the bacteria (°C)
t	=	die-off period of bacteria cells (days)

Total cell yield from a single storm event is the sum of the yields from each of the four area classes.

$$Y = Y_{spread} + Y_{incorp} + Y_{pasture} + Y_{soil} \quad [23]$$

where

Y	=	total cells eroded during a single storm
Y_{spread}	=	number of bacteria cells eroded from areas where manure is spread
Y_{incorp}	=	number of bacteria cells eroded from areas where manure is incorporated into the soil
$Y_{pasture}$	=	number of bacteria cells eroded from pasture areas
Y_{soil}	=	number of bacteria cells eroded from areas where the soil is not contaminated with manure from livestock

In calculating the cell yields from manure spread and pasture areas, some adjustment must be made to Equation [22] to account for the fact that not all the area specified as spread or pasture is covered with manure. Typically, a manure wagon, such as pictured in Figure 5, is driven up and down a field such that the waste is applied in strips, as shown in Figure 6. To estimate the fraction of spread area receiving wastes, the linear relationship shown in Figure 7 was developed based on the mass of wet manure required to cover one hectare to a depth of 6.35×10^{-3} m (0.25 in). If a manure density of 9933 Mg/(ha m) (62 lb/ft^3) is assumed, then this mass is approximately 63 Mg (Midwest Plan Service, 1975). Mathematically, the relationship between the fraction of area covered with manure and the manure application rate is expressed:

$$FM = \frac{M}{63.0} \qquad (\text{for } M \leq 63.0) \qquad [24]$$

where FM = fraction of spread area covered with manure

M = amount of manure spread (Mg/ha of designated spread area)

When the manure loading exceeds 63.0 Mg/ha, **FM** is assumed to be 1.0, i.e., the entire area is assumed to be covered with manure. In reality, **FM** may also depend on field conditions and field proximity to the manure collection site.

The fraction of pasture area covered with cowpies is estimated using a relationship presented by Khaleel et al. (1979b):

$$FP = 1.0 - \left(1.0 + \frac{R\ D\ A_{pie}}{10000\ F_{pasture}\ A_w\ N} \right)^{-N} \qquad [25]$$

where FP = fraction of pasture area covered with manure

N = nonuniformity constant estimated to be 2.0 by Khaleel et al. (1979b)

R = rate of animal defecation estimated to be

Figure 5. Manure wagon used by a Fauquier County, Virginia dairy operation.

Figure 6. Field in Fauquier County, Virginia spread with manure.

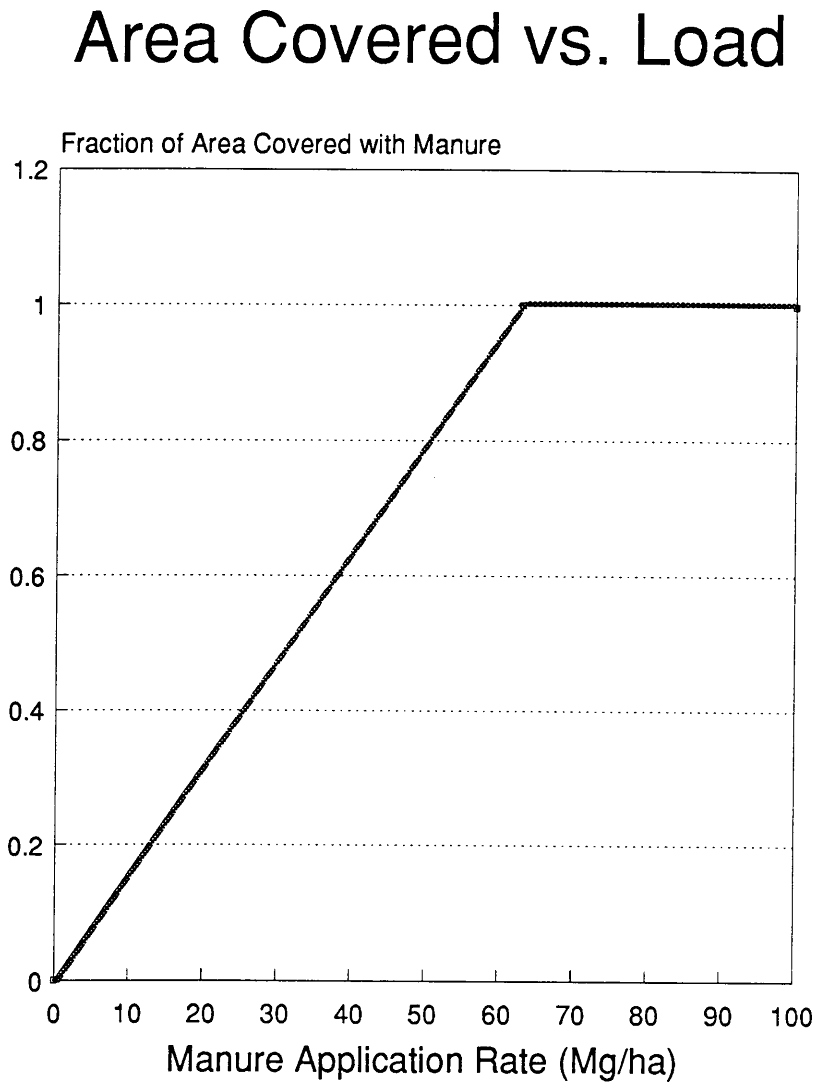


Figure 7. Relationship between area covered with manure and manure loading rate.

12.0 defecations per day per animal by Khaleel et al. (1979b)

D = number of animal days pasture is used by livestock

A_{pie} = area of a typical cowpie (m^2)

estimated to be 0.093 by Khaleel et al. (1979b)

10000 = factor to convert ha to m^2

$F_{pasture}$ = fraction of watershed area designated as pasture

A_w = area of watershed (ha)

Material eroding from the fraction of area covered with manure is assumed to have a cell density equal to that of manure, while material eroding from the remaining fraction is assumed to have a cell density equal to that of soil. Thus, for spread and pasture areas, additional terms must be added to Equation [22]:

$$Y_{adj_j} = Y_j \; [\; FC_j \; CD_M \; + \; (1 - FC_j) \; CD_S \; S \;] \qquad [26]$$

where Y_{adj_j} = the adjusted number of eroded cells from the area class (spread or pasture)

Y_j = the number of cells eroded from the area class (spread or pasture) as determined from Equation [22]

FC_j = fraction of area covered with manure for the area class (FM for spread areas or FP for pasture areas)

CD_M = cell density for manure (cells/Mg)

CD_S = cell density for soil (cells/Mg)

S = fraction of soil mass composed of clay and silt particles

The total cell yield from the four area classes is divided by the runoff volume to obtain the bacteria concentration.

$$BC = \frac{Y \; 10^{-5}}{Q \; A} \qquad [27]$$

where BC = number of bacteria cells per 100 mL of runoff

Y = total cells eroded during a single storm

10^{-5} = factor to convert mm-ha to 100 mL

Q = runoff (mm)

A = area of the watershed (ha)

Because BC may imply an unwarranted degree of precision, it may be more reasonable to report the base 10 logarithm of the bacteria concentration. Thus, the deterministic model is expressed as:

$$LBC = \log_{10}\left(\frac{Y\ 10^{-5}}{Q\ A}\right) \qquad [24]$$

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

Selection of Random and Single-Valued Variables

The USLE factors, rainfall duration and amount, time between storms, the SCS curve number, temperature, and cell die-off rate can all be considered to vary either spatially or in time. Whether or not such variability is incorporated into a model depends on the amount of information available concerning each variable and the magnitude of influence the variability has on the final output.

The USLE factors

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 Rojiani et al. (1984) found the soil erodibility factor, **K**, to be lognormally distributed for the soils tested, insufficient information on the erodibility of manure and heavily manured soils exists to treat K as a random variable in the model of this study. The length-slope, cover, and practice factors are also impractical to model as random variables due to lack of data.

Rainfall duration and amount

The results of the study conducted by Rojiani et al. (1985) were used to model rainfall duration and amount. When rainfall duration and amount were treated as correlated random variables in the proposed model, rather than single-valued variables, the order of magnitude of the log-scaled output was maintained, but the first significant digit was affected. Duration values are generated from the distribution (gamma or lognormal) appropriate to the season and correlated amounts are then calculated according to the regression relationships developed by Rojiani et al. (1985):

$$P_w = 25.4\, e^{-1.95 + 0.118\, D_w} \qquad [29]$$

where P_w = rainfall amount for a winter storm (mm)

25.4 = factor to convert inches to millimeters

D_w = winter rainfall duration (hrs) generated from a gamma distribution with a shape parameter of 2.031 and a scale parameter of 0.340. Winter is defined as the period between October 1 and March 31.

and

$$P_s = 25.4\, e^{-1.57 + 0.100\, D_s} \qquad [30]$$

where P_s = rainfall amount for a summer storm (mm)

25.4 = factor to convert inches to millimeters

D_s = summer rainfall duration (hrs) generated from a lognormal distribution with a shape parameter of 0.761 and a scale parameter of 0.922. Summer is defined as the period between April 1 and September 30.

Time between storms and SCS curve numbers

Time between storms affects the five-day antecedent moisture condition, which in turn, affects the SCS curve number selected for computing runoff volume. If a storm occurs more than 120 hours (5 days) after the previous storm, then AMC I curve numbers are used by the model. When time between storms was modeled by selecting deviates from a gamma distribution, as suggested by Rojiani et al. (1984), the resulting log-scaled output was very similar to that when the computed, arithmetic average of the generated deviates was used. As further discussed in the MODEL SENSITIVITY ANALYSIS section, this similarity is due to the model's lack of sensitivity to the AMC class used. Although Rojiani et al. (1984) conducted their study using 28 years of rainfall data for Blacksburg, Virginia, it is assumed that the results are generally applicable to Virginia and surrounding states. Thus, time between storms is modeled as a constant, using the computed average of 57.6 hours, rather than as a random variable. Some spatial variability of the curve number is acknowledged by computing a weighted average of the selected curve numbers for each of the four area classes (Schwab et al., 1981).

Temperature and cell die-off rate

The period of die-off for bacteria cells in manure is the time between defecation and the time at which the cells are enumerated in a water sample. For the proposed model, the decay period is estimated as the time between manure collection and manure application to the land, or the manure storage time. Thus, the worst case, the situation in which a rainfall event occurs immediately after manure application, is simulated. Because temperature can vary over the decay period, the die-off rate can also change over the course of the decay period. 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 mass as a whole 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):

$$TS_i = \frac{TA_i \alpha_i + TA_{i-1} \alpha_{i-1} + \dots + TA_{i-360} \alpha_{i-360}}{\alpha_i + \alpha_{i-1} + \dots + \alpha_{i-360}} \qquad [31]$$

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 (Smith and Franco, 1985)

t = number of hours preceding hour **i**

The model presented by Smith and Franco (1985) used a weighted average of air 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. This modification is justified by the fact that the weighting factor, α, is only 0.05 for the 360th hour.

Subroutine KLINE, developed by Kline et al. (1982), was used to model hourly ambient air temperature. The results of using an average temperature and a single decay rate for the period of decay varied only in the third significant digit from the results of computing a new decay rate for each simulated hourly temperature. However, when KLINE was used to generate hourly temperatures for the arbitrarily selected decay period of the first five days of May, the computed average temperature varied from 3.23° C to 22.79° C. Such variation in temperature resulted in a change in log FC concentration from 5.56 to 4.33. Thus, 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 is therefore used to provide random temperature variation. Because KLINE was developed using data collected from Blacksburg, Virginia, caution should be exercized in applying it to other locations.

Insufficient information exists to describe the die-off rate constant, **k**, with a statistical distribution. For the proposed model, a base die-off rate constant is selected from Table 4 or from the literature. The base die-off rate constant is then adjusted for temperature on an hourly basis using Equation [3]. Since the die-off values presented in the literature were determined by conducting experiments under specific (but not always thoroughly described) conditions, it was not thought appropriate to further adjust **k** for other environmental factors, such as pH and soil moisture, using Equation [5].

Coupling the Deterministic and Stochastic Models

Of the three coupling techniques discussed in the literature review, Monte Carlo simulation seems to be the most appropriate for modeling bacteria concentrations of runoff. The method of generating system moments was judged to be too cumbersome for the deterministic relationships selected and the number of random variables. Mills' (1980) recursive technique was not selected since it was developed to obtain distributions for outputs that represent the cumulative effect of stochastic inputs rather than the result of a single stochastic event.

For the model COLI, the desired number of sets of storm durations and amounts are generated from the distributions described by Rojiani et al. (1984, 1985) and the regression relationships of Equations [29] and [30]. Bacteria yield is then calculated using Equation [22] for each set of random inputs. Thus, the model produces a range of bacteria concentration values rather than a single output value. The range of values produced is more realistic than single-valued output because the effects of random variation of rainfall and temperature are considered. The resulting output is also more meaningful because the probability that the bacteria concentration of runoff will exceed a given value can be estimated from the distribution of the output values generated.

Description of Model COLI

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. The model is useful for evaluating the relative impacts of various BMPs on bacteria concentrations in runoff.

A simplified diagram of the model is presented in Figure 8. Model COLI is composed of three major loops nested within each other: 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 loop specifies the number of scenarios to be modeled, the number of random output deviates to be generated per date modeled, the date for which histogram points are to be generated, and the temperature submodel to be used. An example options file is shown in Appendix C.

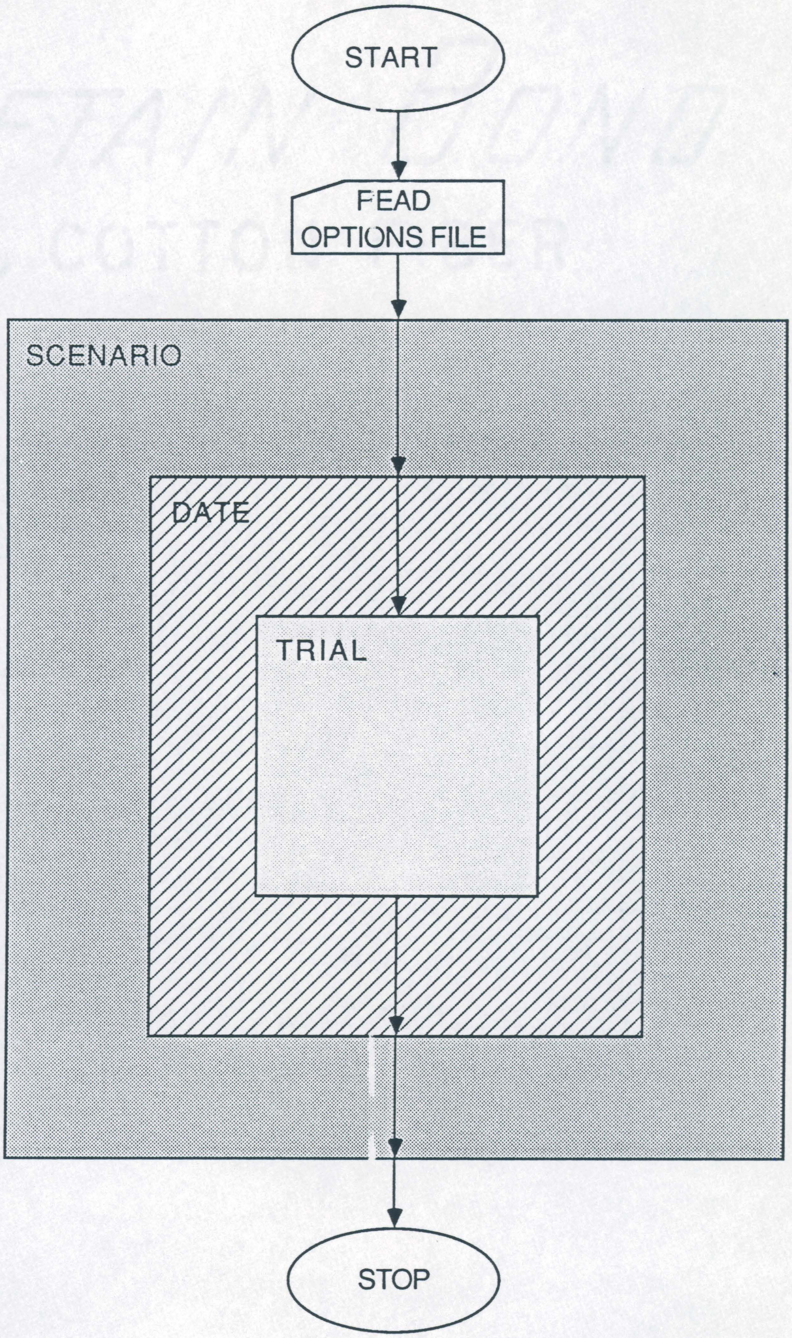


Figure 8. Diagram of model COLI.

The steps performed within the outermost loop are presented in Figure 9. Within this loop, 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. Up to four scenarios can be modeled. 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 10, is used to increment the Julian hour and to generate random pairs of rainfall duration and amount. Simulation is performed on a monthly basis (at 720 hour intervals) for one year. An increment of 720 hours allows seasonal variation to be observed. Deviates for rainfall duration are generated from the gamma distribution for winter months using the uniform random number generator DRAND described by Law and Kelton (1982) and methods described in Haan (1977). Deviates for summer storm duration are generated from a lognormal distribution by transforming normal deviates generated using the Box and Muller method (Law and Kelton, 1982). Rainfall amounts are then calculated using Equations [28] and [29]. Rainfall intensity is calculated by dividing rainfall amount by storm duration. To avoid simulating irrelevantly rare events, the intensity is compared to that of the storm return period of interest. If an intensity that exceeds that of the desired return period, then that pair of duration and amount is discarded and a new pair selected. A new pair is also selected if the duration is less than 0.0005 hours or greater than 144 hours since insignificant runoff would be associated with such durations (Rojiani et al., 1984).

Once the random inputs have been generated, each set is entered into the deterministic submodel, contained within the innermost loop, shown in Figure 11. For each set, the AMC is determined based on the time since the last storm (modeled as a constant) and a random, previous rainfall amount. Runoff volume and peak flow rate are then calculated for the random storm. The MUSLE is 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 the relationship developed by Moore et al. (1988) as presented in Equation [2]. Die-off is modeled on

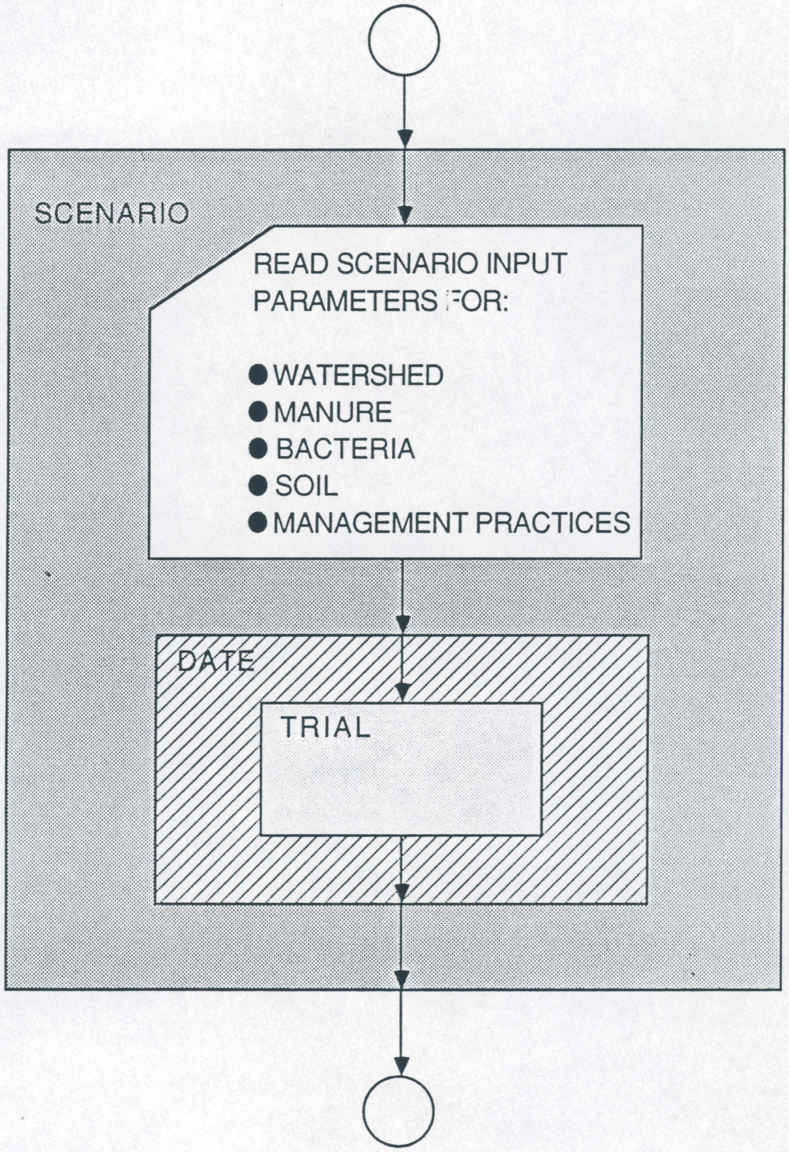


Figure 9. Diagram of outermost loop of model COLI.

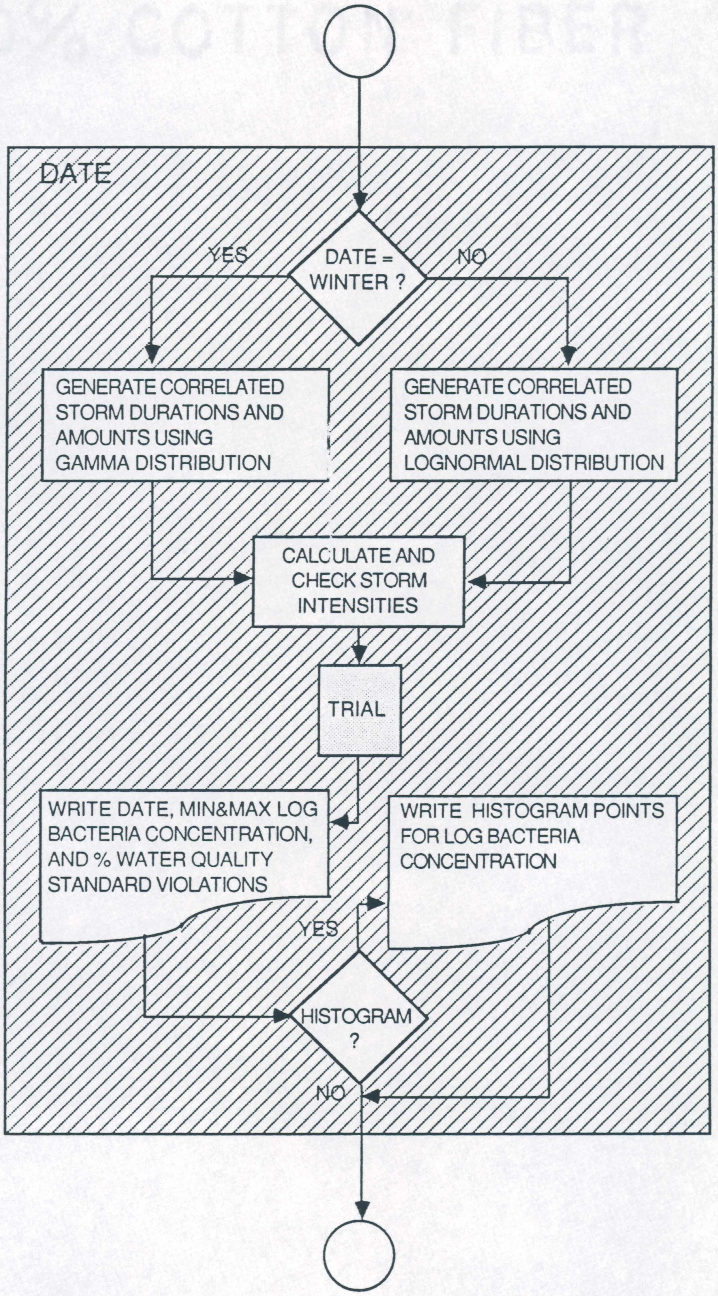


Figure 10. Diagram of second loop of model COLI.

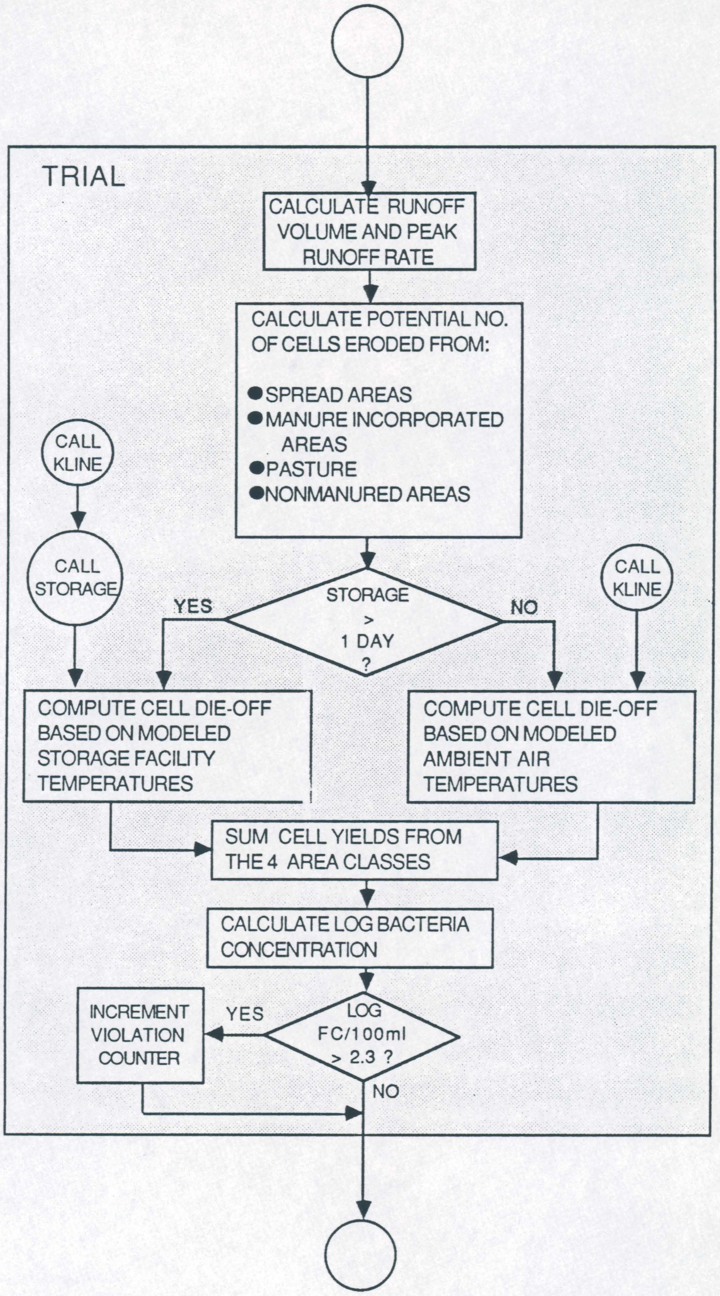


Figure 11. Diagram of innermost loop of model COLI.

an hourly basis for the period of manure storage specified in the input data file. Subroutine KLINE (Kline, 1982) 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 [31] by means of subroutine STORAGE which uses KLINE to model air temperature. Since calling subroutine STORAGE can result in a very long computer run time, the user can choose to model stored waste temperature as ambient air temperature (modeled by KLINE) by setting the flag **LSTOR** equal to 0 in the options file read outside the first loop. Although the seasonal trend will be preserved, the results will tend to be lower (less conservative) than those determined with the use of subroutine STORAGE. If the user is interested only in the relative effects of various BMPs, both KLINE and STORAGE can be bypassed and temperature will be modeled using monthly averages supplied by the user. To select this option, the flag **LAVG** is set equal to 0 and the DATA statements of subroutine AVERAGE are edited to contain the desired monthly average temperatures. Use of this option will greatly shorten computer time, but the results will not reflect uncertainty due to temperature variation.

The resulting bacteria yields from the four area classes are added together and divided by the runoff volume. A counter is incremented if the log bacteria concentration exceeds the USEPA recreational water quality standard of 2.3/100 mL (the base ten logarithm of 200 FC/100 mL) (USEPA, 1976). The log bacteria concentration is stored in array **LCONC**, and the loop is repeated for the desired number of trials.

The desired number of trials is specified in the options file "read" ouside the outermost loop. The greater the number of trials made, the greater the probability of simulating a rare event, and the greater the number of points available for describing the statistical distribution of the output. The extremely rare event, simulated by conducting a very large number of trials, is not of interest because waste management structures could not be built to prevent such an event. Thus, the number of trials conducted should reflect the degree of "rarity" that is of interest. However, the required computer time places a practical constraint on the number of trials conducted. The topic of determining an "appropriate" number of trials for Monte Carlo simulation is discussed in depth by Hahn and Shapiro (1967).

Upon re-entering the second loop, the values stored in array **LCONC** are ranked from smallest to largest. The Julian hour, minimum, maximum, average, and standard deviation of the log bacteria concentration, and the percentage of water quality standard violations are written to an output file. Histogram plotting points are also computed for the values in array **LCONC** for one of the simulation hours as specified in the options file read before entering the outermost loop. Thus, one output file containing the bacteria concentration results and one histogram file are generated for each scenario. A separate software package (not included in COLI) can be used to import the output files and present the results graphically.

MODEL APPLICATION

The Owl Run watershed in Fauquier County, Virginia, is currently being monitored as part of a study to determine the effects of animal waste BMPs on water quality in the Chesapeake Bay. Out of this study grew the need to develop a bacteria model so that the study results could be used for BMP planning on other watersheds as well. The proposed model, COLI, is applied to a subwatershed of Owl Run to gain insight concerning the model's potential.

Site Description

The 1153 ha watershed, shown in Figure 12, is located in Calverton, Virginia and is transversed by the Warrenton Branch of the Southern Railroad. Streams flow only during the wetter periods of the year and can be considered to be predominantly storm runoff. Presently, five major dairy operations are located on the watershed which must manage the wastes from a total of about 1250 head of cattle (Payne, 1988). A high erosion rate on much of the agricultural land is blamed on the fact that a large area must be left without protective vegetative cover over the winter to provide land for spreading manure (VDCHR, 1986).

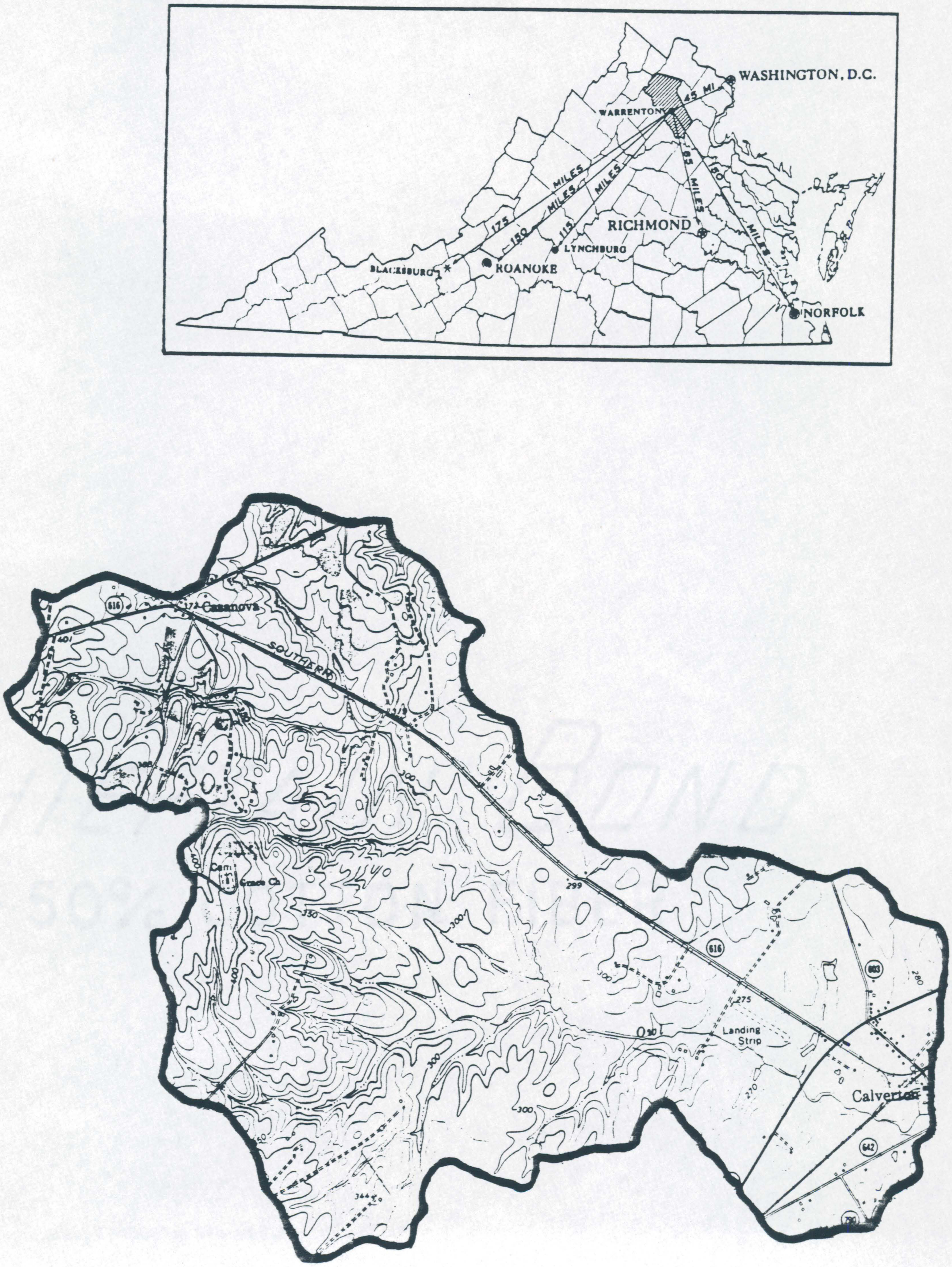


Figure 12. Owl Run watershed.

Land use

Over 90% of the 1153 ha watershed is used for agriculture. The remainder is used primarily for residential, commercial, and transportation purposes. The percentages of the watershed area dedicated to each landuse category are presented in Table 8.

Table 8. Owl Run watershed land use (VDCHR, 1986).

Land Use Category	Percentage of Watershed Area
Corn (conventional till)	15
Corn (no-till)	11
Rotational hay	20
Pasture (active)	18
Pasture (idled)	7
Woodland	20
Non-agricultural	9

Soils

The soils are generally shallow (0.3-0.6 m deep), silt loams, overlying Triassic shale (VDCHR, 1986). The shale layer is exposed in some areas, and the more intensely used fields are thought to be eroding at a rate of 34-45 Mg/ha/year (Payne, 1988; VDCHR, 1986). Specific soil types are presented in Table 9.

Table 9. Owl Run watershed soil types (VDCHR, 1986).

Soil Type	Percent Slope	Percent of Watershed Area
Bowmansville silt loam	0 - 2	1.2
Bucks silt loam, undulating phase	2 - 7	16.3
Calverton silt loam, undulating phase	2 - 7	8.2
Croton silt loam	0 - 5	8.8
Kelley silt loam, level and undulating phase	2 - 7	2.4
Montalto silt loam, undulating moderately shallow phase	2 - 7	14.4
Montalto stony silt loam, rolling moderately shallow phase	7 - 14	2
Penn silt loam, undulating phase	2 - 7	35.7
Penn silt loam, rolling phase	7 - 14	4.1
Rowland silt loam	0 - 2	2.9
Wadesboro silt loam, undulating phase	2 - 7	1.4
Others	0 - 25	2.6

Field Investigations

Data collection for the Owl Run watershed began in 1985. Installations of such animal waste BMPs as waste storage tanks and stream protection is expected to be complete in late 1988 (Payne, 1988). Monitoring is planned to continue for the next ten years to evaluate the effectiveness of the implemented BMPs.

The data collection sites are shown in Figure 13. Precipitation data is collected from the stations with an identifier beginning with the letter "P". Stream flow data and bacteriological samples are collected at stations with an identifier beginning with the letter "Q". Fecal coliform, fecal streptococcus, and total bacteria are enumerated in the bimonthly bacteriological grab samples using the MF technique (APHA, 1985). Samples collected in May, June, and July of 1988 were also tested for the presence of *Salmonella* species using an enzyme linked immunosorbent assay (ELISA) technique described by Emswiler-Rose et al. (1984). All *Salmonella* samples tested negative. Further details concerning data collection and management for the Owl Run watershed are provided by Carr et al. (1988).

To minimize the spatial variation of the study area, a subwatershed was selected for demonstrating the model. Subwatershed D, represented by the shaded portion of Figure 13, was chosen over the other subwatersheds because of its high concentration of dairy cattle (approximately 358 animals on 45 ha of pasture). The outlet of the 324 ha subwatershed is located at station QOD.

Random Input

Rainfall duration and amount and temperature were modeled using the results of studies conducted by Rojiani et al. (1984, 1985) and Kline et al. (1982) for data collected from Blacksburg, Virginia. Although these parameters vary with geographic location, the length of data record (2.5 years) for Fauquier County is presently insufficient to adequately describe the statistical distributions of the parameters. Blacksburg is located approximately 280 km from the Owl Run watershed. It is judged that the locational differences between Blacksburg and Fauquier County conditions are small compared to the random variations in time for the variables used in model COLI.

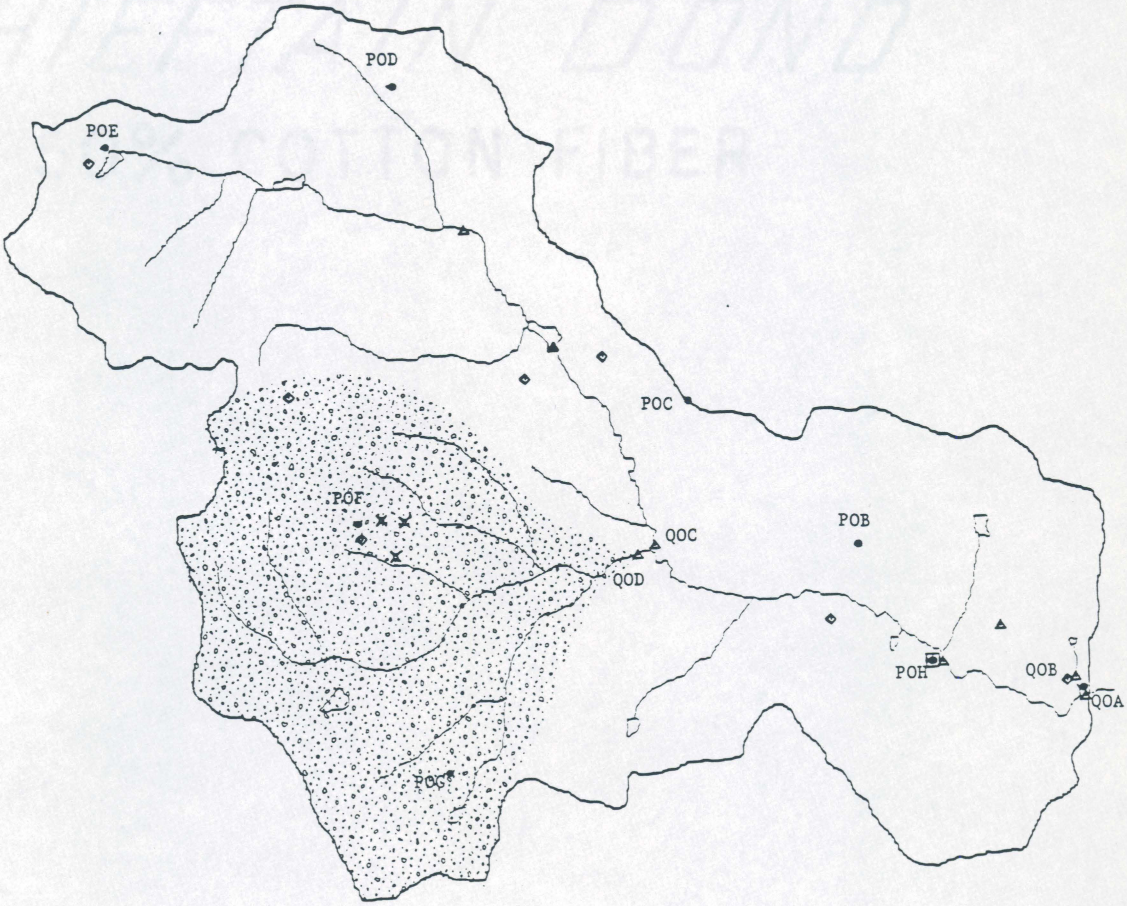


Figure 13. Sampling sites on the Owl Run watershed.

Rainfall duration is thus modeled using a gamma distribution for winter months and a lognormal distribution for summer months based on a period of record of 28 years, as described by Rojiani et al. (1984, 1985). The appropriate regression equation is then employed to calculate correlated rainfall amounts (Rojiani et al., 1985). Rainfall intensity is calculated and then compared to a 25-year return period intensity as listed for Culpeper, Virginia (approximately 40 km from the Owl Run watershed) by Shanholtz and Lillard (1973). A 25-year return period roughly corresponds with the length of data record used by Rojiani et al. (1984, 1985) to develop the rainfall distributions. Nevertheless, the return period of 25 years was selected somewhat arbitrarily for the purpose of demonstration; it is the task of regulatory agencies to define the "sufficiently rare" event. 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 (Kline et al., 1982). KLINE was developed using data collected over a period of nine years. Since hourly temperature data is being collected for Fauquier County, KLINE could eventually be modified, if deemed justified, once a comparative length of record has accumulated.

Single-Valued Input

A sample input file which lists the values used to apply COLI to the subwatershed study site is provided in Figure 14. The input file includes parameters describing the watershed, manure quanity, bacteria quantity and die-off, soil properties, and waste management practices. Determination of these values is described below. Information collected for Fauquier County from various sources is not consistent in the system of measurement units used. Some quantities are more conveniently reported using one system of units than another. Therefore, the input values for COLI are in the units as reported by their source. The computer program then makes the necessary unit conversions to output log FC/100 mL.

```
                    INPUT FILE FOR PROGRAM COLI

WATERSHED PARAMETERS.

  AREA OF WATERSHED (HA):            AW    =    324.0
  LANDUSE FRACTIONS:   FSPD = 0.43  FINC = 0.00  FPST = 0.21  FSOL = 0.36

  SCS CURVE NUMBERS FOR EACH AREA TYPE:
      CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
      CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
      CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

  HYDRAULIC LENGTH (M):     L  =  2160.0
  AVERAGE LAND SLOPE (%): SE  =    3.0
  AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

  INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

  USLE ERODIBILITY FOR MANURE (SI UNITS):            KEM =  0.0066
  USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):  KES =  0.28
  LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

  COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
               FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
               MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
               APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
               OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
               NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

  PRACTICE FACTORS:      PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0

MANURE PARAMETERS.

  ANIMAL DAYS ON PASTURE:                       ANDAY  =   34905.0
  NO. DEFECATIONS PER DAY:                      PIRATE =  12.0
  AREA OF A FECAL DEPOSIT (SQ. M):              APIE   =  0.093
  NONUNIFORMITY CONSTANT:                       KEX    =   2.0

BACTERIA PARAMETERS.

  BACTERIA CELLS PER GRAM OF FRESH MANURE:      CELLM  =  2.3E05
  BACTERIA CELLS PER GRAM OF SOIL:              CELLS  =  4.0E02
  DIE-OFF RATE AT 20 DEGREES CELSIUS:           K20    =  0.3
  TEMPERATURE CORRECTION FACTOR:                THETA  =  1.07

SOIL PROPERTIES.

  SUSPENDED SOLIDS FRACTION OF SOIL:            TSS    =  0.40
  SOIL DENSITY (MG/CUBIC M):                    DENS   =  1.6
  DEPTH OF INCORPORATION OF MANURE (CM):        DEPTH  = 10.0

WASTE MANAGEMENT PRACTICES.

  MANURE SPREAD AT A TIME (MG/HA):    MLOAD  =    2.2
  MANURE INCORP. INTO SOIL (MG/HA):   MLOADI =    2.2
  MANURE STORAGE TIME (HRS):          STOR   =   24.0
  INC. MANURE STORAGE TIME (HRS):     STORI  =    2.0

  BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
  BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
```

Figure 14. Sample input file for the study site.

Watershed parameters

Area of the subwatershed, AW, and landuse fractions for the four area classes (manure spread, manure incorporated, pasture, and non-manured areas) were estimated from descriptions in literature concerning the watershed (VDCHR, 1986) and from personal communications with SCS representatives (Payne, 1988).

The SCS curve numbers for AMC Class II were estimated using values provided by the USSCS (1972). The soils of the subwatershed were assumed to belong to Hydrologic Group C (moderately high runoff potential), based on the soil characteristics provided in VDCHR (1986). The AMC class I and III curve numbers were then determined using the conversion table published by the USSCS (1972). Hydraulic length, **L**, and land slope, **SE**, 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, **KEM**, was reported as 0.0066 kg h/(N m^2) by Khaleel et al. (1979b). **KES**, the erodibility factor for the non-manured soil, was estimated to be 0.28 ton ac h/[hundreds of ac ft-ton(force) in] or 0.0553 kg h/(N m^2) based on the predominance of silt loam soils in the watershed (VDCHR, 1986). Values are input in the units most convenient to the user. Thus, **KEM**, for which little information is available, is input using SI units, the units reported by Khaleel et al. (1979b). The soil erodibility factor (**KES**), however, is input in US Customary units since this system is more familiar to intended users such as SCS representatives. Unit conversion is performed by COLI, using a multiplying factor of 0.1317 to convert ton ac h/[hundreds of ac ft-ton(force) in] to kg h/(N m^2) (Foster et al., 1981).

Slope length was approximated using a USGS 1:24,000 topographic map of the area, and the length-slope factors for the spread, incorporated, pasture, and nonmanured areas (**LSM**, **LSI**, **LSP**, and **LSS**, respectively) were calculated using Equation [32] (Mitchell and Bubenzer, 1980).

$$LS = \left(\frac{x}{22.13} \right)^m (0.065 + 0.045s + 0.0065s^2) \qquad [32]$$

where LS = length-slope factor (LSM, LSI, LSP, LSS)

x = the average slope length in meters

m = an exponent

$m = 0.5$ for slopes $\geq 5\%$

$m = 0.4$ for slopes $< 5\%$ and $> 3\%$

$m = 0.3$ for slopes $\leq 3\%$ and $\geq 1\%$

$m = 0.2$ for slopes $< 1\%$

s = average slope gradient in percent

Cover factors were determined on a monthly basis for each of the four area classes using guidance provided in Agriculture Handbook Number 537 (Wischmeier and Smith, 1978) and cropstage information for the site (Payne, 1988). For areas where manure is spread, surface conditions at the time of spreading are assumed to resemble those of fallow land for all months since manure is not spread on growing crops. The cover factor is also considered to be constant for areas where manure is incorporated, with the assumption that conditions immediately after incorporation resemble those of a seedbed cropstage. USLE conservation practice factors (**PM** for manure spread areas, **PIN** for incorporated areas, **PP** for pasture, and **PS** for nonmanured areas) are all assumed to be 1.0 since there is no indication that any erosion control practices are currently being employed.

Manure parameters

Bacteria yield from pasture areas is dependent on the number of livestock on the pasture multiplied by the number of days the animals are on the pasture (**ANDAY**), the number of defecations per animal per day (**PIRATE**), the area of an average fecal deposit (**APIE**), and a non-uniformity coefficient (**KEX**). The values selected for these parameters are shown in Figure 14. **KEX** is a measure of the spatial nonuniformity of fecal deposits in a pasture and is used in the calculation of the fraction of pasture area covered with manure. The number of animal days in a year was calculated assuming that the 358 cattle of the study site are on pasture 12 hr/day for five months (summer), 6 hr/day for three months (spring and fall), and 0 hr/day for four months (winter) (VDCHR, 1986; Payne, 1988). Thus, **ANDAY** is estimated to be 34,905 animal days. **ANDAY** was calculated on a yearly basis for convenience and because bovine fecal deposits are believed to shelter viable bacteria cells for a year or longer (Thelin and Gifford, 1983). The values suggested by Khaleel et al. (1979b) were used to estimate **PIRATE**, **APIE**, and **KEX**.

Bacteria parameters

CELLM, the number of cells per unit mass of fresh manure, was estimated to be 2.3×10^5 FC/g based on the value for cow manure reported in Table 3 (Geldreich, 1978). A value of 400 FC/g was used to estimate **CELLS**, the number of cells per unit mass of soil, based on the work of Faust (1982). The base die-off rate constant, **K20**, was estimated to be 0.3/day, as reported by Moore et al. (1988) for fecal coliforms in stored manure. The temperature correction factor of 1.07 reported by Mancini (1978) was selected for **THETA**.

Soil properties

The fraction of soil mass consisting of particles small enough to be suspended in water (**TSS**) 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 (**DENS**) and the depth of incorporation

(**DEPTH**) must be determined. Soil density was measured for surface samples collected from the area. The value of 1.6 Mg/m^3, listed in Figure 14 for **DENS**, is an average of these measurements. A depth of 10 cm was selected for **DEPTH** since the erodibility relationship (Equation [7]) developed by Mazurak et al. (1975) was based on an incorporation depth of 10 cm.

Waste management practices

Parameters related to waste management practice include the amount of manure spread on the land or incorporated into the soil at a time (**MLOAD** and **MLOADI**, respectively), the time the manure is stored before spreading or incorporating (**STOR** and **STORI**, respectively), and the width of buffer strips associated with fields where manure is spread or incorporated (**BWIDM** and **BWIDI**, respectively). The values chosen for these inputs are listed in Figure 14. For the study site, approximately 2.2 Mg of manure are spread per hectare on almost a daily basis (until installment of storage facilities is complete) (Payne, 1988). Thus, **MLOAD** is estimated to be 2.2 Mg/ha and **STOR** is assumed to be 24 hours. Since presently no manure is incorporated into the soil, the values for **MLOADI** and **STORI** will not affect the output. The buffer strip widths are set equal to 0.0 since none are employed in association with areas where manure is spread or incorporated.

Results and Discussion

Model COLI was used to simulate various scenarios pertaining to subwatershed D of Owl Run (Figure 13). The input data for the first scenario is given by the input file of Figure 14. This scenario is used as the "base" and represents conditions for the Owl Run subwatershed prior to the implementation of any animal waste BMPs. The other scenarios are used to determine the hypothetical effects of employing such BMPs as buffer strips, manure storage, and incorporation of manure into the soil. Input files for all scenarios are provided in Appendix D; corresponding output files created by COLI are provided in Appendix E.

Base results

The simulated results of employing no animal waste BMPs on subwatershed D are presented in Figure 15. The bars in the upper plot represent the hypothesized range of results of applying animal waste to the land on a particular date given that a runoff event occurs immediately after application. Each bar represents the range of log fecal coliform concentrations of runoff determined from 100 trials. The horizontal line inside each bar marks the location of the average value of the 100 trials. The number of trials chosen represents a compromise between the number needed to "adequately" describe the full range of possible outcomes and the number that can be conducted within a reasonable amount of computer time. 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 BMPs.

As shown in Figure 15, average log fecal coliform concentrations lie above the suggested water quality goal for all 12 simulated dates. Whether or not the predicted ranges can be considered "high" for nonpoint source runoff is not known. However, it is not surprising that the predicted averages fall above 2.3 log FC/100 mL, considering that the input file reflects a lack of animal waste BMPs and a large percentage of land designated for receiving livestock wastes. In addition, the "worst" case is modeled in that a runoff event is assumed to occur immediately after land application of manure. The winter range bars are shorter than the summer bars partly due to modeling winter and summer storms with different distributions. 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 as temperatures become warmer.

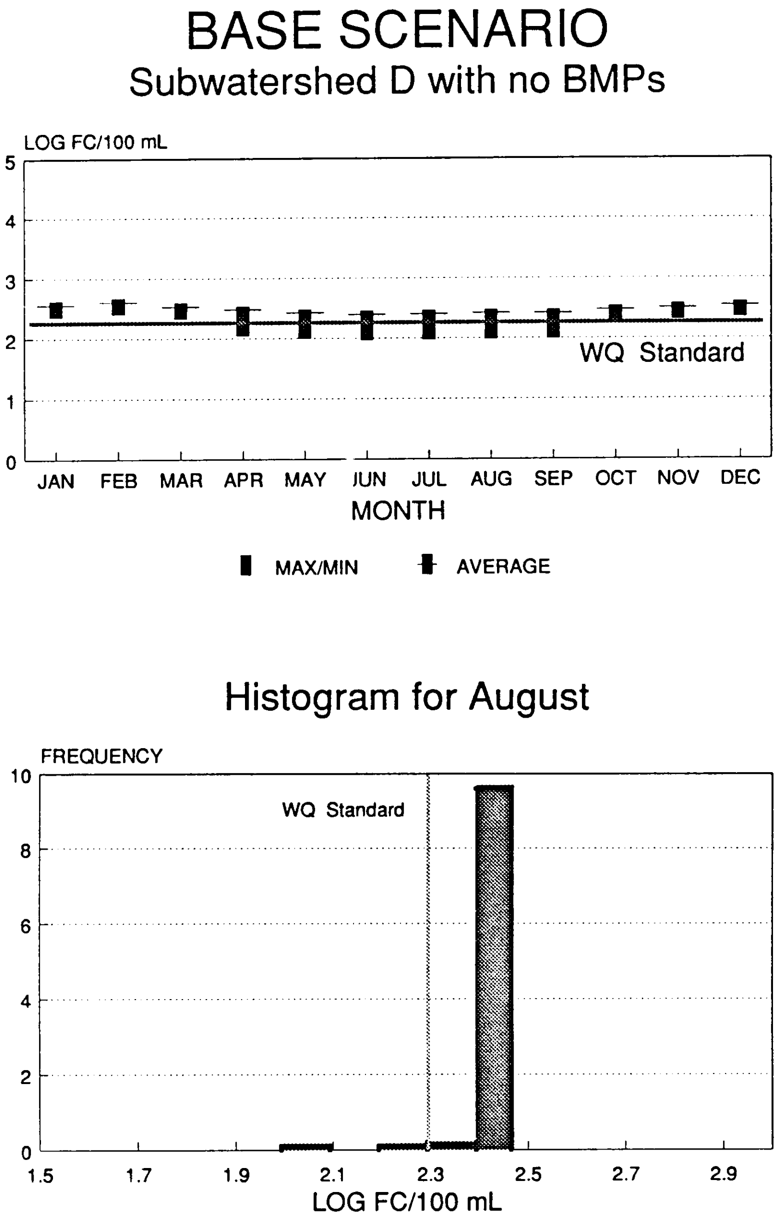


Figure 15. Simulated results for the Owl Run subwatershed assuming no animal waste BMPs are employed.

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 cause the less frequently occurring low bacteria concentrations, which determine 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 (lower plot) of Figure 15, in which the results for August are presented. Of the 100 trials conducted, 98% yielded log FC concentrations in excess of the recommended standard. A majority (approximately 96%) of the computed bacteria concentrations fell in the range of 2.39 to 2.47 log FC/100 mL.

The histograms are generated by COLI to aid in estimating the probability of exceeding a design goal, such as the recreational water quality standard of 2.3 log FC/100 mL, on a particular simulation date. Ideally, a cost could be assigned to the risk of exceeding the design goal and compared to the cost of implementing an animal waste BMP sufficient for reducing that risk. However, determination of the risk cost is complicated by the fact that the occurrence of illness (in humans or animals) due to bacteria in contaminated food or water is dependent on a wide range of factors. In addition, other advantages of waste management practices, such as odor control and nutrient management, would have to be accounted for. The histograms, therefore, serve only to provide insight concerning the distribution of the data resulting from the number of trials conducted.

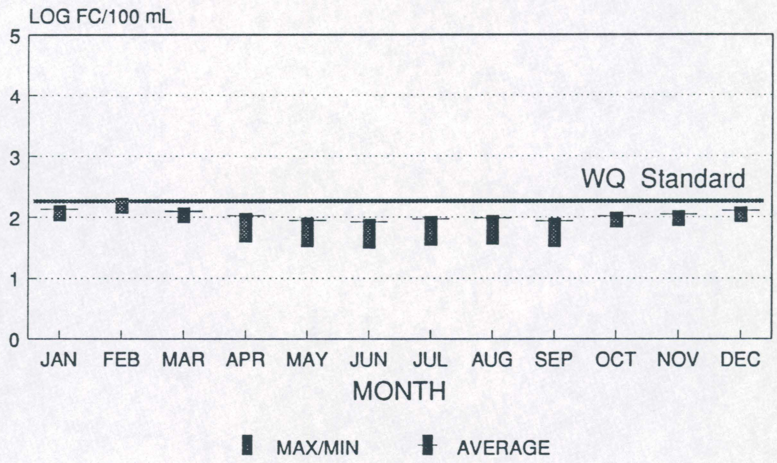
Effects of buffer strips

Buffer strips reduce bacteria in runoff by trapping sediment and associated cells. Model COLI reduces the number of cells eroded by a factor dependent on the buffer strip width. This factor is determined from the regression relationship of Equation [2] (Moore et al., 1988). Comparison of the base scenario represented in Figure 15 with the results presented in Figure 16, illustrates the effect of using 30.48 m (100 ft) buffer strips with all areas where manure is spread. As would be expected from the linear relationship of Equation [2], the effect of using buffer strips is to shift the base scenario results closer to the suggested water quality goal. The seasonal trend and the relative position of the average values are not changed in the upper plot of Figure 16. The August histogram bars are merely shifted to the left in comparison with the base scenario. The model follows the recommendations of Moore et al. (1988) and does not allow buffer strips to reduce bacteria yield by more than 75% (on the linear scale). The restriction suggested by Moore et al. (1988) prevents extrapolation beyond the limited range of the data collected for developing the regression relationship of Equation [2] and recognizes the contribution of background levels of bacteria by the buffer strips themselves. As calculated from Equation [2], a buffer strip 13.56 m (44.5 ft), with assumed slope of 3%, causes a 75% removal of bacteria. Thus, increasing the buffer strip width in the scenario represented in Figure 16 would not cause the simulated concentrations to fall any further below the recreational water quality goal. Thus, for the subwatershed modeled, the use of buffer strips alone are just barely adequate for meeting the recreational water quality standard of 200 FC/100 mL.

Effects of storage

Die-off of bacteria is modeled using Chick's Law and is thus dependent on storage time and temperature. COLI models the reduction of bacteria cells over a specified storage time. Although not modeled by COLI, waste storage provides the additional advantage of improving field cover conditions. With sufficient storage capacity, fields do not have to be left open during the winter to receive wastes. Thus, if it is assumed that no wastes are spread or incorporated during the winter months, then the log concentrations computed by COLI for this period are unrealistically high.

BUFFER STRIP SCENARIO
Base Conditions with 100' Buffer Strips



Histogram for August

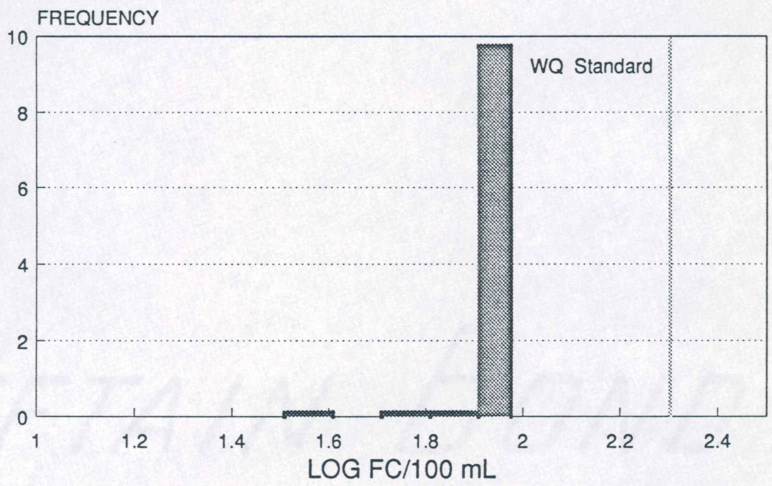


Figure 16. Hypothesized effects of using buffer strips.

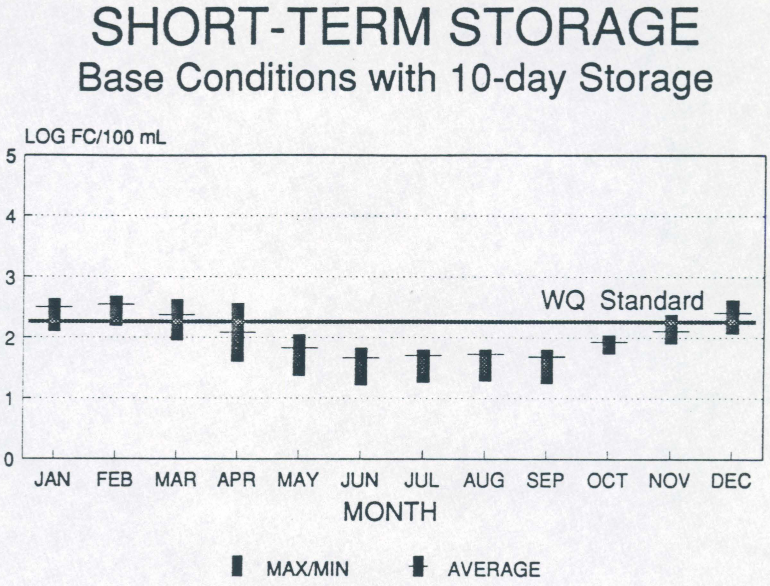
The results of storing manure for ten days are presented in Figure 17. As in the base scenario, 2.2 Mg/ha were assumed to be spread on 43% of the subwatershed. Storage temperature was modeled using subroutine STORAGE which computes a weighted average of simulated air temperatures. The seasonal variation of log bacteria concentration ranges is more pronounced in Figure 17. Concentrations approach the recreational water quality standard as temperatures become warmer. Temperature variation has greater influence on cell die-off as the decay period is increased. Thus, the increased storage time causes the range bars to be wider than those for the base results of Figure 15.

The effects of a six month storage period are shown in Figure 18. Since concrete tanks for providing several months of waste storage are currently being installed in Fauquier County, a scenario with a decay period of six months is of greater interest than the ten day storage scenario. The temperature of the stored waste was modeled using air temperature simulated by KLINE, rather than with subroutine STORAGE, to shorten the lengthly computer time. Log concentration of bacteria, for all months, meets the suggested standard. Due to the graph scale used, the average log concentration for some months appears to correspond almost exactly with the maximum value.

Effects of manure incorporation

For areas where manure is incorporated into the soil, COLI estimates the resulting cell density and erodibility factor for the erodible material. The simulated results of incorporating manure instead of surface spreading are presented in Figure 19. The base input file of Figure 14 was modified by allocating the fraction assigned to the spread area class to the incorporated area class.

Thus, **FSPD**, the fraction of the subwatershed in the spread area class was set equal to 0.0 and **FINC**, the incorporated fraction, was set equal to 0.43. The manure application rate and the storage period were the same as that for the base scenario (2.2 Mg/ha and 24 hours, respectively). The



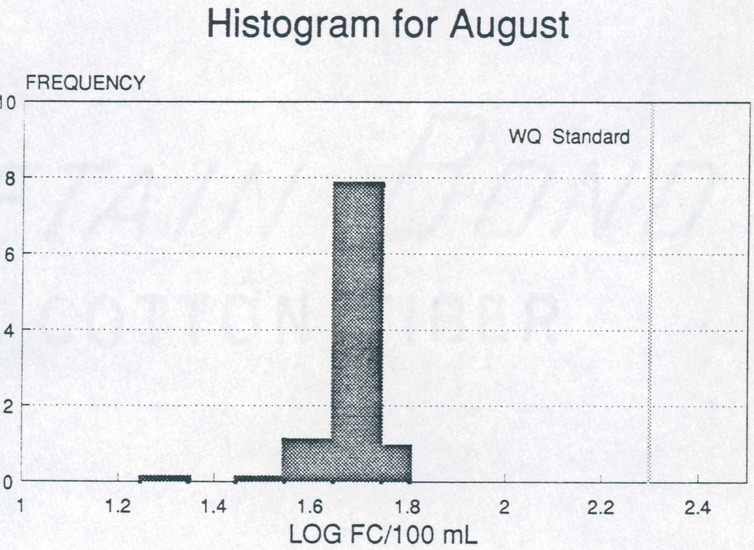
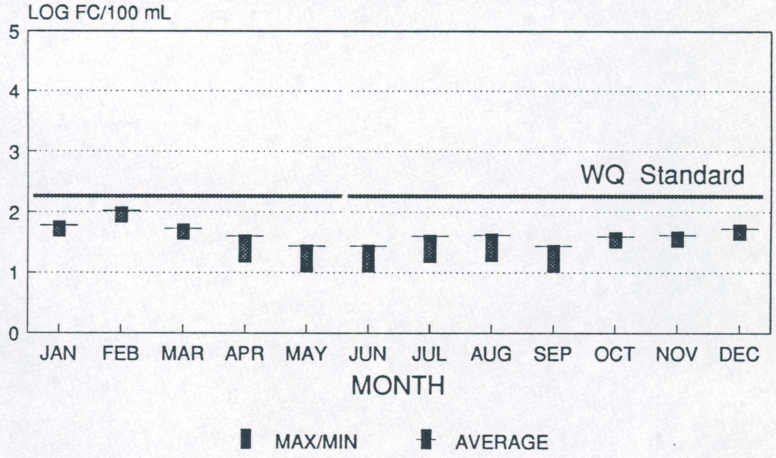


Figure 17. Hypothesized effects of short-term manure storage.

LONG-TERM STORAGE
Wastes Stored for 6 Months



Histogram for August

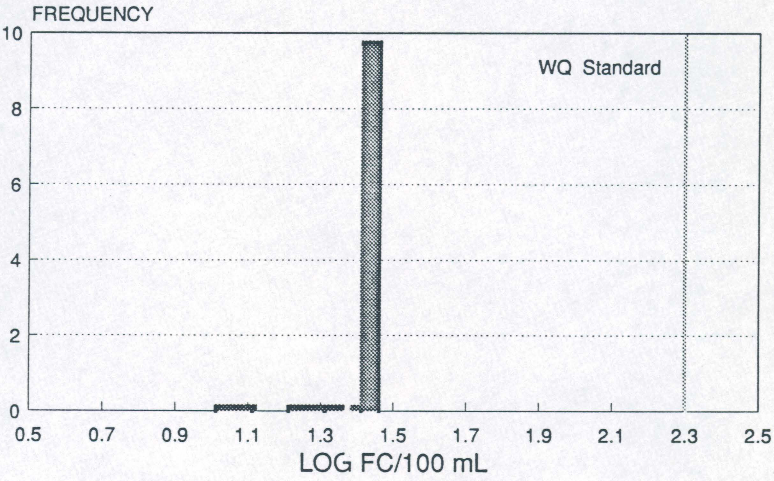


Figure 18. Hypothesized effects of long-term storage.

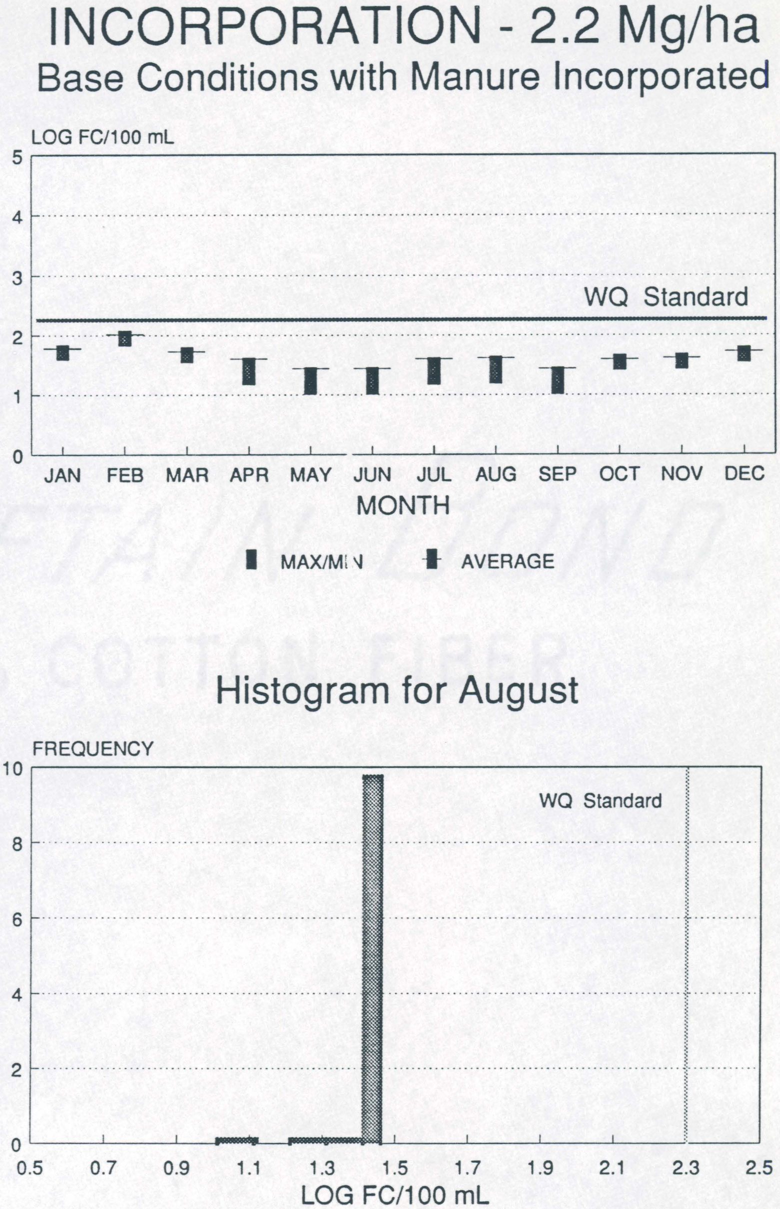


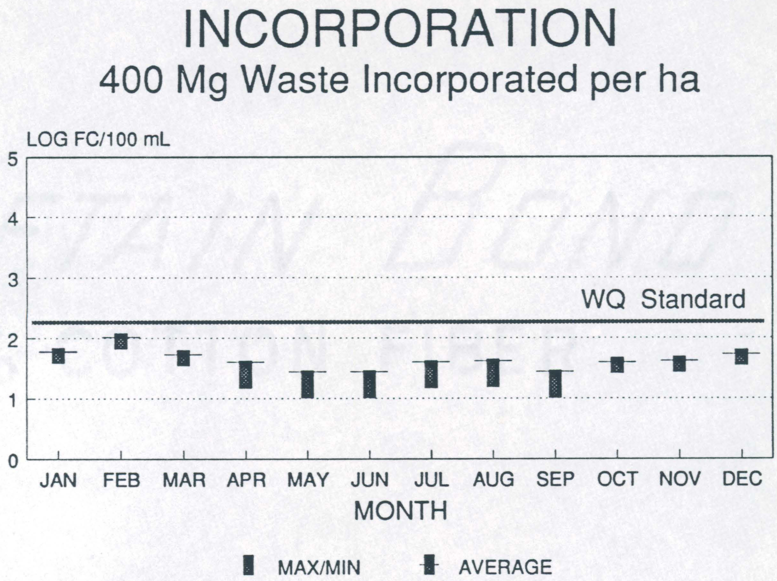
Figure 19. Hypothesized effects of incorporating 2.2 Mg of manure per hectare.

manure applied was assumed to be thoroughly mixed with the soil to a depth of 10 cm. COLI uses a relationship which causes the erodibility factor to increase with increased manure loading, based on the studies conducted by Mazurak et al. (1975) for very high application rates. Thus, the results shown in Figure 19 are conservatively high.

The range bars in Figure 19 all fall below the suggested goal and imply that incorporation is an effective management practice for the conditions described. However, incorporating one day's worth of waste (2.2 Mg/ha for the study site) is not a practical means of waste disposal. It is a more common practice 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. Temperatures were modeled using ambient air temperature (instead of subroutine STORAGE). The results are presented in Figure 20 and are not noticeably different from those of Figure 19. Furthermore, neither of these scenarios in which manure is incorporated differ greatly from the long-term storage scenario of Figure 18 (except in early spring). It is concluded that for the scenarios represented in Figures 18-20, the contribution from the spread and incorporated areas is very small.

Conclusions

Table 10 summarizes the results from the waste management practice scenarios investigated. 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 20 with those of the long-term storage scenario of Figure 18 reveals little difference. Thus, incorporation is not recommended for reducing bacteria concentrations in runoff because it requires additional labor on the part of the farm operator but contributes no significant advantage over long-term storage alone. Nevertheless, incorporation may



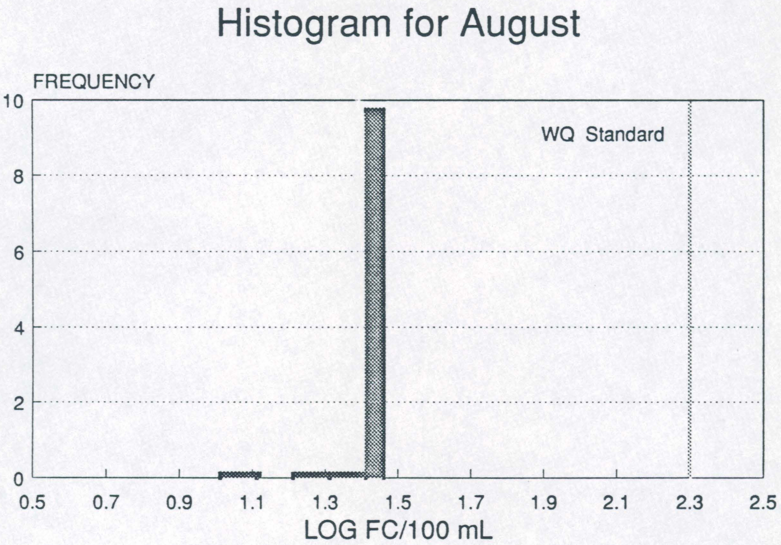


Figure 20. Hypothesized effects of incorporating 400 Mg of manure per hectare.

be advantageous in terms of nutrient management or odor control. Buffer strips are the least expensive of the BMPs examined, and do lower the bacteria concentrations to meet the suggested standard in almost all months. However, the margin for error is small compared to that for long-term storage. Data should be collected to test the appropriateness of the buffer strip relationship (Equation [2]) for Fauquier County.

Table 10. Summary of model results for various management practices.

Management Practice	Average log FC/100 mL				Percent Violations of WQ Standard			
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
No BMPs (Base)	2.56	2.48	2.40	2.47	100	99	98	99
Buffer strips	2.13	2.02	1.97	2.02	0	0	0	0
Short-term storage	2.50	2.09	1.71	1.93	91	7	0	0
Long-term storage	1.78	1.60	1.60	1.60	0	0	0	0
Incorporation	1.78	1.60	1.60	1.60	0	0	0	0

Verification

The scenarios explored above serve only to demonstrate COLI. Because animal waste BMP implementation on the Owl Run watershed has only recently begun, no data has been collected to verify the model's predictions. Thus, at present, COLI should only be used to to determine the relative effects of various BMPs.

Fecal coliform counts were performed on grab samples taken at the outlet of the modeled subwatershed (station QOD) over a period of approximately two and a half years prior to the implementation of BMPs. The results are presented in Figure 21.

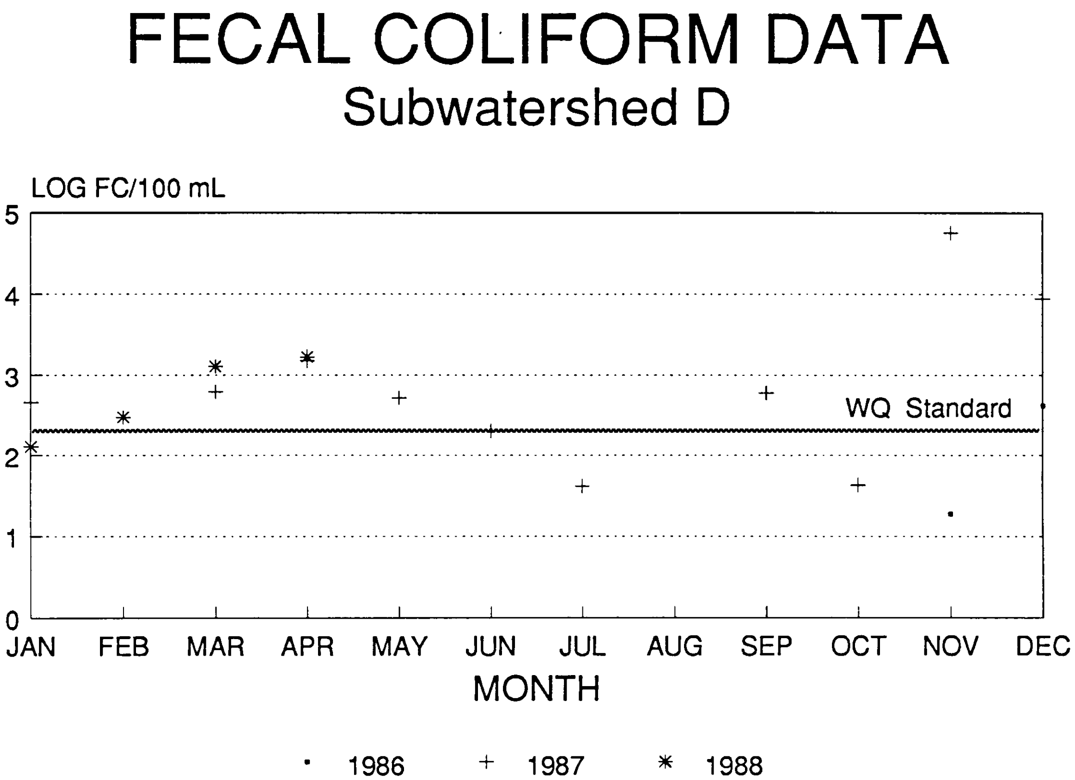


Figure 21. Fecal coliform data for the Owl Run study site.

Direct comparison of the base scenario, representing the effects of using no BMPs, with Figure 21 should not be made due to the variable conditions under which the samples were taken. Some samples were taken during very dry periods from the base flow while others were taken immediately following a storm. However, from Figure 21, it can be concluded that the model does appear to predict the "average" to "bad" case scenario, if not the "worst" case scenario for the study site. The extremely high values shown in Figure 21 could be due to such factors not modeled by COLI as error in performing the enumeration or manure dumped or defecated directly into the stream above the sampling point. In addition, the results produced by COLI may be low due to the fact that only the results of a single manure application are accounted for. Contributions of bacteria from previous manure spreading or incorporation events are not modeled.

MODEL SENSITIVITY ANALYSIS

Because some of the single-valued inputs to COLI are difficult to measure and may, in reality, be highly variable rather than constant, the following analysis and discussion serves to explore the influence of these inputs on the model output. The results of varying certain input values from the base values used in applying the model to Fauquier County, Virginia are shown in Table 11. The base values, presented in Figure 14, assume that no animal waste BMPs are used. Percent change from the base average log fecal coliform concentration was determined using Equation [32] for each month for each of the variables tested.

$$PC_m = \frac{(T_m - B_m)}{B_m} \times 100 \qquad [32]$$

where PC_m = percent change from base average for month m

T_m = test average for month m

B_m = base average for month m

A positive percent change in the average bacteria concentration implies that the adjustment made to the input variable caused the average output to increase from the base average, while a negative value implies a decrease from the base average. Changes in some input values may have greater

Table 11. Influence of selected variables on model output.

				Percent Change from Base Average Log Concentration by Month											
Variable	**Base Value**	**Test Value**	**Percent Change**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
CELLM	2.3E05	2.3E04	-90	-37	-36	-37	-38	-38	-39	-39	-39	-39	-38	-37	-37
		2.3E06	900	39	38	39	40	41	41	41	41	41	40	40	39
CELLS	4.0E02	1.0E02	-75	0	0	0	0	0	0	0	0	0	0	0	0
		4.0E03	900	3	2	3	3	3	3	3	3	3	3	3	3
KEM	0.0066	0.0010	-85	-32	-31	-32	-33	-34	-34	-34	-34	-34	-33	-33	-32
		0.0400	506	31	30	31	32	32	33	33	32	32	32	31	31
KES	0.28	0.10	-64	0	0	0	0	0	0	0	0	0	0	0	0
		0.70	150	0	0	0	0	0	0	0	0	0	0	0	0
KEX	2.0	1.0	-50	0	0	0	0	0	0	0	0	0	0	0	0
		5.0	150	0	0	0	0	0	0	0	0	0	0	0	0
K20	0.3	0.1	-67	0	0	1	2	3	4	4	4	3	2	1	0
		0.7	133	0	-1	-1	-3	-5	-7	-7	-7	-6	-4	-2	-1
MLOAD	2.2	1.0	-55	-10	-8	-10	-11	-12	-12	-11	-11	-12	-11	-11	-10
		10.0	355	23	21	23	24	25	25	25	25	25	24	24	23
THETA	1.07	1.30	21	0	0	1	2	0	-5	-8	-5	0	2	1	1
TLS	57.6	157.6	174	0	0	0	0	0	0	0	0	0	0	0	0
TSS	0.40	0.10	-75	0	0	0	0	0	0	0	0	0	0	0	0
		0.70	75	0	0	0	0	0	0	0	0	0	0	0	0

or lesser effect depending on the scenario used as the basis of comparison. For example, changing **CELLM**, the cell density of manure, would have no effect if all the land were placed in the nonmanured category. Thus, although the general effects of changes to individual input values can be determined from Table 11, the percentages listed are only applicable to the base run used.

As shown in Table 11, adjusting the cell density of manure, **CELLM**, by an order of magnitude caused an approximate 40% change in the averaged outputs. Cell density of the soil, **CELLS**, is fairly low in comparison to manure cell density, thus increasing **CELLS** by an order of magnitude had little effect on the output for the particular situation modeled. Similarly, varying the manure erodibility factor, **KEM**, affected the output by 30-34%, while varying the soil erodibility factor, **KES**, within reasonable ranges resulted in no change from the base averages. For the particular area class distribution studied, variation of the nonuniformity coefficient for fecal deposit coverage of pasture, **KEX**, had no effect on the output averages. Decreasing **K20**, the cell die-off rate at 20° C, from 0.3 to 0.1/day resulted in a 0-1% increase over the base average output during the winter months and a 2-4% increase during the summer months. Increasing **K20** to 0.7/day resulted in slight decreases of the average output values ranging from 0-2% in the winter and 5-7% in the summer.

Lowering the manure application rate, **MLOAD**, to a practical minimum resulted in a 8-12% decrease in average log bacteria concentration. Increasing the application rate to 10 Mg/ha increased the average output value by 21-25% Simulation with higher and higher application rates, however, would not result in continually increasing output values since the amount of bacteria eroded by a single storm becomes limited by the severity of the storm rather than the amount of manure available on the land. An increase in **THETA**, the temperature correction factor for adjusting the cell decay rate, caused little change in average log concentration during the winter months and a decrease during the summer months. Such a trend is predictable from Equation [3], assuming **THETA** is greater than 1.0. A correction factor less than 1.0 would imply that the decay rate increases with decreasing temperature, which is contrary to nature. The test on **TLS**, the time since the last storm, is actually a test on the effect of assuming AMC class I (dry conditions) for all 100 trials. When **TLS** is assigned a value greater than 120 hours (five days), then the AMC I curve numbers are used in computing the runoff. For this study, such an adjustment to **TLS** caused no deviation from the base averages. Thus, using the average time between storms for Blacksburg, Virginia instead of for Fauquier County did not contribute any significant error. The fraction of the soil mass consisting of particles small enough to be suspended in a water sample (**TSS**) was roughly estimated by laboratory analysis to be 0.4 for non-manured soils of the study site. If the true value were as small as 0.1 or as large as 0.7, the error due to using 0.4 would be insignificant for the case study, probably due to the small number of cells associated with soil in comparison to manure.

Overall, the variables which did affect the model output when changed, did so to a greater extent in the summer months than in the winter, due to the accelerated die-off during warmer weather. Manure cell density (**CELLM**) and the manure erodibility factor (**KEM**) appear to have the greatest influence on average output. Additional data should be collected for these two variables and the practicality of treating them as random inputs should be investigated. Variables which did not appear to affect the output should be further studied to determine if the ranges tested are appropriate.

SUMMARY AND CONCLUSIONS

Computer model COLI was developed for predicting the log concentration of bacteria in agricultural runoff. The main purpose of the model is to aid in the evaluation of animal waste BMPs for reducing the amount of bacteria transported by runoff to potential food and water supplies. A review of pertinent literature provided insight concerning the factors and processes affecting the concentration of bacteria in runoff from areas receiving livestock wastes. Previous efforts in predicting bacteria yields have provided useful deterministic relationships, but also have revealed a lack of knowledge in the area of describing the variability associated with bacteria populations eroded from the land by storm runoff.

COLI is a probabilistic model which uses Monte Carlo simulation to combine the deterministic relationships developed in previous studies with stochastic information concerning the input variables of storm duration, rainfall amount, and temperature. 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 modeling bacteria die-off. The "worst" case scenario is modeled by assuming that a storm occurs immediately after land application of manure. However, the contributions of bacteria from manure applied prior to the storm date are not modeled.

To account for some spatial variability, the study area was divided into four area classes: a) areas where manure is spread, b) areas where manure is incorporated into the soil, c) pasture, and d) nonmanured areas. Total cell yield from a single storm is the sum of the cells yielded from each of the four classes. Bacteria concentration is determined by dividing the total cell yield by the storm runoff volume. Output is in the form of log fecal coliforms/100 mL. COLI performs multiple trials for each of 12 dates within a year and calculates the minimum, maximum, and average log FC/100 mL for each date.

In developing the probabilistic bacteria model COLI, several assumptions, in addition to those concerning the adequacy of the above deterministic relationships, were made as necessitated by a lack of information and practicality. These additional assumptions are summarized as follows:

1) The indicator bacteria species, particularly the fecal coliform bacteria, are adequate for evaluating the disease potential of runoff contaminated by livestock wastes.

2) Bacteria populations in runoff are predominantly the result of recent environmental conditions such that it is appropriate to model the effects of a single storm rather than accumulated annual effects.

3) Rainfall duration and amount as well as ambient air temperature are appropriately treated as random variables, which, for a limited geographic region, follow the statistical behavior of data collected for Blacksburg, Virginia.

4) There is no overlap among the four area classes. In reality, manure may be mechanically applied to some pasture areas. Also, some areas may shift from one class to another on a seasonal basis.

5) For areas where manure is spread, the fraction of area covered by manure is linearly related to the manure application rate for rates less than or equal to 63 Mg/ha. For higher application rates, the entire spread field is assumed to be covered with a layer of manure.

6) 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.

7) 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 be constantly replenished.

8) Cells die off from the time of defecation until the time at which the manure is applied to the land. If this period is less than or equal to 24 hours, then the temperature of the environment surrounding the bacteria is the same as ambient air temperature. If the manure is stored for a period greater than 24 hours, then the temperature of the waste is a weighted average of the hourly air temperatures of the past two weeks.

The proposed model was applied to a small watershed in Fauquier County, Virginia. The model output for a scenario which assumed no animal waste BMPs in use was compared to output from scenarios in which BMPs were employed. It was determined that long-term storage of wastes is an effective practice for reducing the bacteria concentration in runoff so that it meets the recreational water quality standard of 200 FC/100 mL. Incorporation of a practical amount 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, buffer strips were insufficient for reducing bacteria concentrations to meet the water quality goal.

Single-valued inputs that were particularly difficult to measure were varied within reasonable ranges to determine their influence on the model output. Variables which did have significant influence on the model ouput tended to have greater impact during the summer months than in the winter months. The cell density of manure and the USLE erodibility factor for manure were determined to have the greatest influence on the model output.

As a result of demonstrating COLI, the following conclusions are made:

1) The model predicted log bacteria concentrations that agreed reasonably well with the upper values of the observed data for the Fauquier County study site. Nevertheless, although the model attempts to predict the worst case scenario, observed bacteria concentrations may exceed predicted concentrations. More study is needed to determine if additional sources of variability, such as error associated with the enumeration technique, can be practically incorporated into the proposed model.

2) The effects of long-term storage may be impractical to model using COLI due to the very long computer run time required. However, if ambient air temperature is used to model the temperature of waste stored in a tank or lagoon, then the computer run time is reduced by approximately one order of magnitude, although the results may be less conservative than if storage temperature is simulated.

3) COLI is useful for comparing the relative effects of animal waste BMPs on the bacteria concentration of runoff from a single storm. Because COLI is a probabalistic model, it produces output that acknowledges the highly variable nature of bacteria concentrations and is able to incorporate existing statistical knowledge of rainfall and temperature variation. COLI is not yet useful for aiding risk-based design of animal waste BMPs, but may be useful for establishing water quality criteria that are more appropriate for application to

nonpoint source pollution than the present criteria established for the control of point source pollution.

RECOMMENDATIONS FOR FUTURE STUDY

Model COLI attempts to further the work of previous modeling efforts, particularly through emphasis on the variable nature of bacteria populations in runoff. Nevertheless, because COLI has not yet been thoroughly tested and because it incorporates only a crude body of knowledge, the following recommendations are made for future study:

1) Fecal coliform counts should be continued to be made for samples collected at the outlet of subwatershed D, once waste storage facilities are in use, and compared with the values predicted by COLI. If possible, samples should be collected immediately following a storm to test the hypothesis that COLI models the worst case scenario.

2) Plot studies with simulated rainfall may be appropriate for testing the effects of buffer strips alone. Plot studies may also be useful for determining whether or not the effects of the type of cover used with spread areas can be adequately modeled with the cover factors used by COLI.

3) COLI is site-specific in that the rainfall and temperature variables were statistically described using data collected from Blacksburg, Virginia. Additional study should be done to determine the geographic range for which the model is adequate.

4) The statistical correlation between temperature and rainfall duration and amount should be investigated to determine the adequacy of the stochastic models used in COLI.

5) The relationship between the fraction of spread area covered with manure and the manure application rate should be refined. Spreading equipment, field conditions, and the proximity of a field to the manure collection site may be additional factors which should be considered in determining the fraction of area covered with manure.

6) Fecal bacteria counts should be made for a large number of manure and soil samples to determine if cell density would be more appropriately modeled as a random variable, rather than as a constant.

7) Additional data should be collected to aid in the estimation of the USLE erodibility factor for areas spread with manure. The variable should also be considered for modeling as a random input.

8) The effects on bacteria populations due to pH of bedding material (such as granular lime) and of the soil into which manure is incorporated should be investigated to determine their significance and practicality for inclusion in COLI.

9) The waste storage temperature model should be improved so as to be less time consuming. A physically-based model, rather than the empirical submodel used by COLI, may prove to be more accurate and more computationally efficient. Monitoring the tem-

perature of the wastes within the storage facilities being installed in Fauquier County may aid in the development of such a model.

10) Other empirical models used by COLI, such as those describing the bacteria removing capacity of buffer strips and the influence of manure on the erodibility factor should be further tested and improved upon.

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Appendix A. Variable Listing for COLI

	VARIABLE	DESCRIPTION
	AMT(1000)	Array of simulated rainfall amounts that meet duration and intensity criteria. (mm)
	AMT1(1000)	Temporary array of simulated rainfall amounts. (mm)
*	ANDAY	Product of the number of livestock and the number of days in a year that livestock are on pasture.
*	APIE	Area of a single livestock fecal deposit. (m^2)
	AVG	Average log bacteria concentration for a particular simulation date. (log FC/100 mL)
*	AW	Total area of the watershed. (ha)
*	BWIDI	Width of buffer strip for areas where manure is incorporated into the soil. (ft)
*	BWIDM	Width of buffer strip for areas where manure is spread but not incorporated into the soil.
	CELLI	Number of bacteria cells of a given species present in a gram of a specified mixture of soil and manure.
*	CELLM	Number of bacteria cells of a given species present in a gram of fresh manure.
*	CELLS	Number of bacteria cells of a given species present in a gram of soil.
*	CI(12)	Array of monthly USLE cover factors for areas where manure is incorporated into the soil.
*	CM(12)	Array of monthly USLE cover factors for areas where manure is spread on the land without incorporation.
	CN	Weighted average SCS curve number.
*	CNINC(3)	Array of estimated SCS curve numbers for areas

		where manure is incorporated into the soil. Each element is the estimation for the corresponding AMC class.
*	CNPAS(3)	Array of estimated SCS curve numbers for pasture areas. Each element is the estimation for the corresponding AMC class.
*	CNSOL(3)	Array of estimated SCS curve numbers for areas not receiving livestock manure. Each element is the estimation for the corresponding AMC class.
*	CNSPD(3)	Array of estimated SCS curve numbers for areas where manure is spread on the land without incorporation. Each element is the estimation for the corresponding AMC class.
*	CP(12)	Array of monthly USLE cover factors for pasture areas.
*	CS(12)	Array of monthly USLE cover factors for areas not receiving livestock manure.
	D	Duration of unit excess rainfall. (hours)
	DATE(0:500)	Array of Julian hours for which the simulation is performed.
*	DENS	Density of the soil into which manure is incorporated. (Mg/m^3)
*	DEPTH	Depth to which manure is incorporated into the soil. (cm)
	DET0	Detachment rate for soil with no manure added as calculated by Equation [7]. ($mg/cm^2/h$)
	DETM	Detachment rate for soil with a specified amount of manure added as calculated by Equation [7]. ($mg/cm^2/h$)
*	DLAM	The shape parameter of the distribution for summer storm duration.
*	DSEED	A value that seeds the random number generators.
*	DSCL	The scale parameter of the distribution for winter storm duration.
*	DSHP	The shape parameter of the distribution for winter storm duration.
	DT	Ratio of area covered by fecal deposits to the total pasture area.
	DTHETA	The temperature correction factor saved as a double precision value.
	DUR(1000)	Array containing simulated rainfall durations that meet duration and intensity criteria. (hours)

	DUR1(1000)	Array containing simulated storm durations. (hours)
*	DZETA	The scale parameter of the distribution for summer storm duration.
	EROMAN	Mass eroded from the fraction of the spread area covered with manure. (Mg)
	EROSOL	Mass eroded from the fraction of the spread area not covered with manure. (Mg)
*	EXDAY	Integer value ranging from 1 to 25 indicating the date for which histogram points are to be calculated for the generated values of log bacterial concentration.
	FCINC	Number of bacteria cells eroded from areas where manure is incorporated into the soil.
	FCPAS	Number of bacteria cells eroded from pasture areas.
	FCSOL	Number of bacteria cells eroded from areas not receiving livestock manure.
	FCSPD	Number of cells eroded from areas where manure is spread.
*	FINC	Fraction of watershed area for which manure is incorporated into the soil.
	FPIE	Fraction of pasture area covered by fecal deposits.
*	FPST	Fraction of watershed area that is pasture.
	FREC	Fraction of spread area receiving livestock wastes.
*	FSOL	Fraction of watershed area that does not receive livestock manure.
*	FSPD	Fraction of area watershed area on which manure is spread but not incorporated into the soil.
	FVIOL	Fraction of trials for which the log bacteria concentration exceeds the recreational water quality standard.
	G	An intermediate value used in the calculation of FPIE.
	IAMT	Counter used in the calculation of rainfall amounts from generated storm durations.
	ICN	Integer indicating the AMC class of an SCS curve number.
	IDA	Counter used in the selection of pairs of generated storm durations and amounts that meet duration

	and intensity criteria.
IDAY	Counter used to generate random output for 12 dates within a year for a given scenario.
IHR(8761)	Array output by subroutine KLINE containing the Julian hours for which random temperatures have been generated.
IHR1(8761)	Array of Julian hours occurring prior to January 1st of the simulation year. The array is output by subroutine KLINE.
IHR2(8761)	Array of Julian hours occurring on or after January 1st of the simulation year. The array is output by subroutine KLINE.
ILAST	Number of hours in the decay period.
IM	Integer representing the month (1 = January).
INC	Counter used in the hourly decay of bacteria eroded from areas where manure is incorporated into the soil.
IREP	Counter used in selecting a new pair of storm duration and amount if a given pair fails to meet duration and intensity criteria.
IRST	Counter used to designate the Julian hour corresponding to a temperature.
ISET	Counter used to distinguish between input data sets.
ISPD	Counter used in the hourly decay of bacteria eroded from areas where manure is spread but not incorporated into the soil.
IWRIT	Integer indicating the file to which the Julian hour, minimum, maximum, average, and standard deviation of the generated log bacteria concentrations, and percent violations should be written.
J	Counter used in generating the desired number of output deviates for a given Julian hour.
* K20	Bacterial die-off rate at 20° C. (1/day)
KEI	USLE erodibility factor for areas where manure is incorporated into the soil. (kg hr/[N m^2])
* KEM	USLE erodibility factor for areas where manure is spread but not incorporated into the soil. (kg hr/[N m^2])
* KES	USLE erodibility factor for areas that do not receive livestock manure. (U. S. customary units)

	KESSI	USLE erodibility factor (converted to SI units) for areas that do not receive livestock manure.
*	KEX	Exponent that accounts for the nonuniformity in spatial distribution of livestock fecal deposits.
*	L	Hydraulic length of the watershed. (m)
*	LAVG	Flag set equal to 0 by the user to model temperature with monthly average temperatures (supplied by the user) rather than temperatures simulated by subroutines KLINE and STORAGE.
	LCONC(1000)	Array of log bacterial concentrations for a given scenario and Julian hour. (log [cells/100 mL])
*	LSI	USLE length-slope factor for areas where manure is incorporated into the soil.
*	LSM	USLE length-slope factor for areas where manure is spread but not incorporated into the soil.
*	LSP	USLE length-slope factor for areas pasture areas.
*	LSS	USLE length-slope factor for areas not receiving livestock manure.
*	LSTOR	Flag set equal to 0 by the user if storage temperature is to be modeled using ambient air temperatures simulated by KLINE rather than the temperatures simulated using STORAGE.
	M	Julian hour for which subroutine KLINE begins temperature simulation.
	M1	Julian hour prior to January 1st of simulation year at which subroutine KLINE begins temperature simulation.
	M2	Julian hour on or after January 1st of simulation year at which subroutine KLINE begins temperature simulation.
	MANURE	Amount of manure applied to the land per spreading event. (Mg)
*	MLOAD	Amount of manure applied per hectare per spreading event. (Mg/ha)
*	MLOADI	Amount of manure incorporated into the soil per hectare per incorporation event. (Mg/ha)
	N	Julian hour for which subroutine KLINE ends temperature simulation.
	N1	Julian hour prior to January 1st of simulation

		year for which subroutine KLINE ends temperature simulation.
	N2	Julian hour on or after January 1st of simulation year for which subroutine KLINE ends temperature simulation.
	ND	Number of duration-amount pairs meeting the duration and intensity criteria needed to generate the desired number of output deviates. ND is one greater than NDEV in order to determine initial conditions.
	NDA	Number of duration-amount pairs to be generated. NDA is 50 greater than NDEV in case some pairs fail to meet duration and intensity criteria.
*	NDEV	Number of random output deviates to be generated for each simulation date.
*	NSET	Number of input data sets (scenarios) for which simulation is to be performed.
	NOUT	Integer designating the file to which histogram plotting points are to be written.
	NVIOL	Number of trials for a particular simulation date that exceed the recreational water quality standard.
*	PIN	USLE conservation practice factor for areas where manure is incorporated into the soil.
*	PIRATE	Number of defecations per animal per day.
*	PM	USLE conservation practice factor for areas where manure is spread but not incorporated into the soil.
*	PP	USLE conservation practice factor for pasture areas.
*	PS	USLE conservation practice factor for areas not receiving livestock manure.
	Q	Runoff volume computed using the SCS method of Equation [13]. (mm)
	QP	Peak runoff rate computed using the SCS method of Equation [15]. (m^3/s)
	RATIOC	Ratio of soil detachment rate when no manure is incorporated into the soil to that when manure (MLOADI) is added.
	REDI	Bacterial yield reduction factor due to use of buffer strips on areas where manure is incorporated into the soil.
	REDM	Bacterial yield reduction factor due to use of buffer

		strips on areas where manure is spread but not incorporated into the soil.
	REMAIN	Amount of material eroded from areas where manure is spread that is not manure. (Mg)
	RFMAX	Maximum height of histogram bar computed by subroutine HISTO.
	RINTEN(1000)	Array of simulated rainfall intensities. (mm/hr)
*	R1D	Rainfall intensity for storm of 1 day duration for desired return period. (in/hr)
*	R1H	Rainfall intensity for storm of 1 hour duration for desired return period. (in/hr)
*	R2D	Rainfall intensity for storm of 2 day duration for desired return period. (in/hr)
*	R2H	Rainfall intensity for storm of 2 hour duration for desired return period. (in/hr)
*	R2M	Rainfall intensity for storm of 2 minute duration for desired return period. (in/hr)
*	R3D	Rainfall intensity for storm of 3 day duration for desired return period. (in/hr)
*	R3H	Rainfall intensity for storm of 3 hour duration for desired return period. (in/hr)
*	R4D	Rainfall intensity for storm of 4 day duration for desired return period. (in/hr)
*	R5D	Rainfall intensity for storm of 5 day duration for desired return period. (in/hr)
*	R5M	Rainfall intensity for storm of 5 minute duration for desired return period. (in/hr)
*	R6D	Rainfall intensity for storm of 6 day duration for desired return period. (in/hr)
*	R6H	Rainfall intensity for storm of 6 hour duration for desired return period. (in/hr)
*	R9H	Rainfall intensity for storm of 9 hour duration for desired return period. (in/hr)
*	R10M	Rainfall intensity for storm of 10 minute duration for desired return period. (in/hr)
*	R12H	Rainfall intensity for storm of 12 hour duration for desired return period. (in/hr)

*	R15M	Rainfall intensity for storm of 15 minute duration for desired return period. (in/hr)
*	R18H	Rainfall intensity for storm of 18 hour duration for desired return period. (in/hr)
*	R20M	Rainfall intensity for storm of 20 minute duration for desired return period. (in/hr)
	R25	Rainfall intensity of the simulated storm for the desired return period. (mm/hr)
*	R30M	Rainfall intensity for storm of 30 minute duration for desired return period. (in/hr)
*	R45M	Rainfall intensity for storm of 45 minute duration for desired return period. (in/hr)
	S	Retention parameter of Equation [13]. (mm)
*	SE	Average land slope. (%)
*	STOR	Time manure is stored before spreading. (hours)
*	STORI	Time manure is stored before spreading and incorporating into the soil. (hours)
	SUMCON	Sum of the log bacteria concentrations for a particular simulation date (used for computing the average log concentration).
	SUMX2	Sum of the squared log bacteria concentrations (used in computing the standard deviation).
	TC	SCS time of concentration. (hours)
*	THETA	Temperature correction factor for adjusting K20.
	TL	SCS time of lag. (hours)
*	TLS	Average time since the last storm. (hours)
	TP	SCS time to peak runoff. (hours)
*	TSS	Fraction of soil made up of clay and silt particles that become suspended in runoff.
	WI	Histogram bar width. (log [cells/100 mL])
	YIELD	Sum of eroded bacteria cells from each area type. (number of cells)
	Z(8761)	Array of temperatures simulated by KLINE for the Julian hours in array IHR. (° C)
	Z1(8761)	Array of temperatures simulated by KLINE

	for the Julian hours prior to January 1st of the simulation year in array IHR1. (° C)
Z2(8761)	Array of temperatures simulated by KLINE for the Julian hours on or prior to January 1st of the simulation year in array IHR2.

* Indicates variable is an input variable.

Appendix B. Program Listing for COLI

```
C
C                               PROGRAM COLI
C
C      THIS PROGRAM USES MONTE CARLO SIMULATION TO DETERMINE A RANGE
C      OF VALUES FOR LOG FC/100 ML RESULTING FROM RUNOFF FROM A SINGLE
C      STORM OCCURRING DURING ANY SEASON OF THE YEAR.  THE DETERMINISTIC
C      EQUATION FOR BACTERIA YIELD IS BASED ON A MODIFIED USLE.
C      BACTERIA YIELD IS CALCULATED FOR FOUR AREAS OF LAND
C      TREATMENT:  AREAS WHERE MANURE IS SPREAD, AREAS WHERE
C      MANURE IS SPREAD AND INCORPORATED, PASTURE AREAS, AND
C      NONMANURED AREAS.  CONCENTRATION IS CALCULATED BY DIVIDING
C      COLIFORM YIELD BY STORM RUNOFF VOLUME.
C
C
C  >>>>>> DIMENSION ARRAYS AND DECLARE CERTAIN VARIABLES AS REAL.
C
      REAL KEM, KEI, KES, LSM, LSI, LSP, LSS, KEX, K20, L
      REAL CNSPD(3), CNINC(3), CNPAS(3), CNSOL(3), AMT1(1000)
      REAL DATE(0:500), AMT(1000), MLOAD, MANURE, DUR1(1000)
      REAL DUR(1000), Z1(8761), Z2(8761), Z(8761), MLOADI, TEMP(8761)
      REAL RINTEN(1000), LCONC(1000), CM(12), CI(12), CP(12), CS(12)
      REAL JAN, MAR, MAY, JUN, JUL, NOV
      INTEGER IHR1(8761), IHR2(8761), IHR(8761), EXDAY
      DOUBLE PRECISION DSEED,DTHETA,FCSPD,FCINC,FCPAS,FCSOL,YIELD
C
C
C  >>>>>> SPECIFY NUMBER OF SCENARIOS TO BE MODELED,
C  >>>>>> NUMBER OF TRIALS TO BE RUN FOR EACH DATE,
C  >>>>>> DATE FOR WHICH HISTOGRAM PLOTTING POINTS
C  >>>>>> WILL BE CALCULATED, AVG. TEMP OPTION, LONG OR
C  >>>>>> SHORT RUN TIME WASTE STORAGE TEMPERATURE MODEL.
C
      READ(14,25) NSET, NDEV, EXDAY, LSTOR, LAVG
   25 FORMAT(//47X,I3/52X,I4/65X,I2/65X,I2/////65X,I2)
C
C
C  >>>>>>>>> BEGIN LOOP FOR GENERATING OUTPUT FOR NSET WASTE
C  >>>>>>>>> MANAGEMENT SCENARIOS.
C
      DO 1000 ISET = 1,NSET
C
         WRITE (*,*) '****** STARTING SCENARIO ',ISET,' ******'
C
C
C  >>>>>>>>> READ INPUT FILE FOR SCENARIO ISET.
C
        READ(ISET,20) AW, FSPD, FINC, FPST, FSOL, CNSPD(1), CNINC(1),
     $    CNPAS(1), CNSOL(1), CNSPD(2), CNINC(2), CNPAS(2),
     $    CNSOL(2), CNSPD(3), CNINC(3), CNPAS(3),
     $    CNSOL(3), L, SE, TLS, R2M, R5M, R10M, R15M, R20M, R30M, R45M,
     $    R1H, R2H, R3H, R6H, R9H, R12H, R18H, R1D, R2D, R3D, R4D, R5D,
     $    R6D, KEM, KES, LSM, LSI, LSP, LSS, CM(1), CI(1), CP(1), CS(1),
     $    CM(2), CI(2), CP(2), CS(2), CM(3), CI(3), CP(3), CS(3), CM(4),
     $    CI(4), CP(4), CS(4), CM(5), CI(5), CP(5), CS(5), CM(6), CI(6),
     $    CP(6), CS(6), CM(7), CI(7), CP(7), CS(7), CM(8), CI(8), CP(8),
     $    CS(8), CM(9), CI(9), CP(9), CS(9), CM(10), CI(10), CP(10),
     $    CS(10), CM(11), CI(11), CP(11), CS(11), CM(12), CI(12),
     $    CP(12), CS(12), PM, PIN,
     $    PP, PS, ANDAY, PIRATE, APIE, KEX, CELLM, CELLS, K20, THETA,
     $    TSS, DENS, DEPTH, MLOAD, MLOADI, STOR, STORI, BWIDM, BWIDI
C
   20   FORMAT(/////41X,F9.1/20X,4(9X,F4.2)///3(4X,4(12X,F4.0)/)/31X,
     $    F8.1/32X,F5.1/43X,F6.1////5(2X,4(8X,F8.4)/)/56X,F8.4/56X,F6.2
     $    /23X,4(8X,F3.1)//12(19X,4(7X,F6.4)/)/23X,4(8X,F3.1)/////
     $    54X,F11.1/57X,F4.1/57X,F5.3/57X,F4.1
     $    /////2(54X,E9.1/),56X,F4.1/57X,F4.2/////57X,F4.2/56X,F4.1
     $    /55X,F5.1/////48X,F5.1/48X,F5.1/47X,F6.1/47X,F6.1//
```

```
     $     64X,F6.1/64X,F6.1)
C
C   >>>>>>>>> PERFORM NECESSARY CONVERSIONS ON INPUT.
C
             DTHETA = DBLE(THETA)
             KESSI = KES*0.1317
             CELLM = CELLM * 1.0E06
             CELLS = CELLS * 1.0E06
C
C   >>>>>>>>> CALCULATE CELL DENSITY FOR SOIL MIXED WITH MANURE.
C
             CELLI = (MLOADI*CELLM + DENS*DEPTH*100.*CELLS) /
     $              (MLOADI + DENS*DEPTH*100.)
C
C   >>>>>>>>> CALCULATE BACTERIA REDUCTION FACTOR DUE TO BUFFER STRIPS.
C   >>>>>>>>> (MOORE ET AL., 1988)
C
C   >>>>>>>>>>>> REDUCTION FACTOR FOR SPREAD AREAS:
                IF(BWIDM.GE.10.0) THEN
                   REDM = ( 100. - (11.77 + 4.26*BWIDM/SE) ) * 0.01
                   IF(REDM.LT.0.25) REDM = 0.25
                ELSE
                   REDM = 1.0
                END IF
C
C   >>>>>>>>>>>> REDUCTION FACTOR FOR AREAS WHERE MANURE IS
C   >>>>>>>>>>>> INCORPORATED:
                IF(BWIDI.GE.10.0) THEN
                  REDI = ( 100. - (11.77+4.26*BWIDI/SE) ) * 0.01
                  IF(REDI.LT.0.25) REDI = 0.25
                ELSE
                  REDI = 1.0
                END IF
C
C   >>>>>>>>> DETERMINE FRACTION OF PASTURE AREA COVERED WITH COWPIES,
C   >>>>>>>>> (KHALEEL ET AL., 1979B).
C
        DT = PIRATE * ANDAY * APIE / (FPST * AW * 10000.)
        G = (KEX + DT)/KEX
        FPIE = 1.0 - G**(-KEX)
C
C
C   >>>>>>>>> BEGIN LOOP FOR GENERATING RANDOM OUTPUT FOR EVERY 350TH
C   >>>>>>>>> HOUR OF THE YEAR FOR A GIVEN SCENARIO.
C
                DO 990 IDAY = 0,11
                  WRITE (*,*) '      STARTING DATE ',IDAY,' OF THIS SET'
                  DSEED = 49603957.D0
                  DATE(IDAY) = FLOAT(IDAY)*720.  + 360.
C
C   >>>>>>>>>> DETERMINE MONTH SO THAT APPROPRIATE COVER FACTOR
C   >>>>>>>>>> WILL BE USED.
C
                  IM = 12
                  IF(DATE(IDAY).LE.7920.) IM = 11
                  IF(DATE(IDAY).LE.7200.) IM = 10
                  IF(DATE(IDAY).LE.6480.) IM =  9
                  IF(DATE(IDAY).LE.5760.) IM =  8
                  IF(DATE(IDAY).LE.5040.) IM =  7
                  IF(DATE(IDAY).LE.4320.) IM =  6
                  IF(DATE(IDAY).LE.3600.) IM =  5
                  IF(DATE(IDAY).LE.2880.) IM =  4
                  IF(DATE(IDAY).LE.2160.) IM =  3
                  IF(DATE(IDAY).LE.1440.) IM =  2
                  IF(DATE(IDAY).LE. 720.) IM =  1
C
C   >>>>>>>> GENERATE RANDOM INPUTS.
```

```
C
C   >>>>>>>>>>>>> GENERATE RANDOM STORM DURATIONS AND RAINFALL AMOUNTS.
C
C   >>>>>>>>>>>>> GENERATE DURATIONS FROM THE GAMMA OR LOGNORMAL DISTRIB.
C   >>>>>>>>>>>>> (DEPENDING ON SEASON) AND THEN APPLY APPROPRIATE
C   >>>>>>>>>>>>> REGRESSION EQUATION TO CALCULATE AMOUNT
C   >>>>>>>>>>>>> (ROJIANI ET AL., 1985).
C
C   >>>>>>>>>>>>> IREP IS A COUNTER USED IN GENERATING NEW PAIRS OF
C   >>>>>>>>>>>>> DUR AND AMT WHEN CALCULATED DURATION AND INTENSITY
C   >>>>>>>>>>>>> FALL OUTSIDE OF EXPECTED RANGES.  EXTRA DEVIATES ARE
C   >>>>>>>>>>>>> GENERATED TO REPLACE REJECTED PAIRS.
C
          IREP = NDEV + 2
          NDA = NDEV + 50
C
C   >>>>>>>>>>>>>>>>>>>> SELECT DISTRIBUTION PARAMETERS FOR THE SEASON
C   >>>>>>>>>>>>>>>>>>>> BEING STUDIED.
C
          IF(DATE(IDAY).LT.2160. .OR. DATE(IDAY).GT.6552.) THEN
              DSHP = 2.031
              DSCL = 0.340
              CALL GENGAM(DSCL,DSHP,DUR1,NDA,DSEED)
              DO 90 IAMT = 1,NDA
                 AMT1(IAMT) = EXP(-1.95 + 0.118*DUR1(IAMT)) * 25.4
   90         CONTINUE
C
          ELSE
              DLAM = 0.761
              DZETA = 0.922
              CALL GENLOG(DZETA,DLAM,NDA,DUR1,DSEED)
              DO 95 IAMT=1,NDA
                AMT1(IAMT) = EXP(-1.57 + 0.1*DUR1(IAMT)) * 25.4
   95         CONTINUE
C
          END IF
C
C   >>>>>>>>>>>>>>>>>>>> CHECK DURATION AND INTENSITY TO MAKE SURE
C   >>>>>>>>>>>>>>>>>>>> THEY FALL WITHIN EXPECTED RANGES.
C
              ND = NDEV + 1
              DO 150 IDA = 1,ND
                  DUR(IDA) = DUR1(IDA)
                  AMT(IDA) = AMT1(IDA)
  100             RINTEN(IDA) = AMT(IDA)/DUR(IDA)
C
C   >>>>>>>>>>>>>>>>>>>>>>>>>> DETERMINE INTENSITY FOR APPROPRIATE RETURN
C   >>>>>>>>>>>>>>>>>>>>>>>>>> PERIOD FOR THE GENERATED DURATION.
C
                  IF(DUR(IDA).GT.0.0) R25 = R2M*25.4
                  IF(DUR(IDA).GT.0.058) R25 = R5M*25.4
                  IF(DUR(IDA).GT.0.125) R25 = R10M*25.4
                  IF(DUR(IDA).GT.0.208) R25 = R15M*25.4
                  IF(DUR(IDA).GT.0.290) R25 = R20M*25.4
                  IF(DUR(IDA).GT.0.417) R25 = R30M*25.4
                  IF(DUR(IDA).GT.0.625) R25 = R45M*25.4
                  IF(DUR(IDA).GT.0.875) R25 = R1H*25.4
                  IF(DUR(IDA).GT.1.5) R25 = R2H*25.4
                  IF(DUR(IDA).GT.2.5) R25 = R3H*25.4
                  IF(DUR(IDA).GT.4.5) R25 = R6H*25.4
                  IF(DUR(IDA).GT.7.5) R25 = R9H*25.4
                  IF(DUR(IDA).GT.10.5) R25 = R12H*25.4
                  IF(DUR(IDA).GT.15.0) R25 = R18H*25.4
                  IF(DUR(IDA).GT.21.0) R25 = R1D*25.4
                  IF(DUR(IDA).GT.36.0) R25 = R2D*25.4
                  IF(DUR(IDA).GT.60.0) R25 = R3D*25.4
                  IF(DUR(IDA).GT.84.0) R25 = R4D*25.4
```

```
                  IF(DUR(IDA).GT.108.0) R25 = R5D*25.4
                  IF(DUR(IDA).GT.132.0) R25 = R6D*25.4
C
C  >>>>>>>>>>>>>>>>>>>>>>>>> SELECT A NEW PAIR OF DUR AND AMT IF DUR
C  >>>>>>>>>>>>>>>>>>>>>>>>> AND RINTEN DO NOT FALL WITHIN SPECIFIED
C  >>>>>>>>>>>>>>>>>>>>>>>>> RANGES.
C
                  IF(DUR(IDA).LT.0.0005 .OR. DUR(IDA).GT.144.
     $                 .OR. RINTEN(IDA).GT.R25)  THEN
                      DUR(IDA) = DUR1(IREP)
                      AMT(IDA) = AMT1(IREP)
                      IREP = IREP + 1
                      GO TO 100
                  END IF
  150        CONTINUE
C
C >>>>>>>>>> INITIALIZE WQ STANDARD VIOLATION COUNTER AND
C >>>>>>>>>> BEGIN LOOP FOR GENERATING RANDOM OUTPUT FOR DATE(IDAY).
C
              SUMCON = 0.0
              SUMX2 = 0.0
              NVIOL = 0
              DO 800 J = 1,NDEV
                 IF (MOD(J,100).EQ.0)
     &              WRITE (*,*) '          RAIN #',J
C
C  >>>>>>>>>>>>> DETERMINE AMC SO THAT APPROPRIATE CN CAN BE CHOSEN
C  >>>>>>>>>>>>> FOR EACH AREA TYPE.
C
                 IF (DATE(IDAY).LT.2160. .OR. DATE(IDAY).GT.6552.) THEN
                    IF (TLS.GT.120. .OR. AMT(J).LT.13.) ICN = 1
                    IF (TLS.LE.120. .AND. AMT(J).GE.13.
     $                 .AND. AMT(J).LE.28.) ICN = 2
                    IF (TLS.LE.120. .AND. AMT(J).GT.28.) ICN = 3
                 ELSE
                    IF (TLS.GT.120. .OR. AMT(J).LT.36.) ICN = 1
                    IF (TLS.LE.120. .AND. AMT(J).GE.36.
     $                 .AND. AMT(J).LE.53.) ICN = 2
                    IF (TLS.LE.120. .AND. AMT(J).GT.53.) ICN = 3
                 END IF
C
C  >>>>>>>>>>>>> COMPUTE CURVE NUMBER (WEIGHTED AVERAGE).
C
                 CN = CNSPD(ICN)*FSPD + CNINC(ICN)*FINC +
     $                CNPAS(ICN)*FPST + CNSOL(ICN)*FSOL
C
C  >>>>>>>>>>>>> COMPUTE RUNOFF VOLUME AND PEAK FLOW RATE (SCS METHOD).
C
                 S = 25400./CN - 254.
                 TL = (L*3.281)**0.8 * (1000./CN -10.+ 1.)**0.7 /1900.
     $                 * SE**0.5
                 TC = 1.67*TL
                 D  = 0.133*TC
                 TP = D/2. + 0.6*TC
                 Q = (AMT(J+1) - 0.2*S)**2 / (AMT(J+1) + 0.8*S)
                 QP = 0.0021 * Q * AW / TP
C
C
C  >>>>>>>>> CALCULATE KEI, ERODIBILITY FACTOR FOR MANURE INCORPORATED
C  >>>>>>>>> INTO THE SOIL (MAZURAK, ET AL., 1975).
C
          DETO = 1.12 * RINTEN(J+1)**2 + 46.4*RINTEN(J+1)
          DETM = 1.12 * RINTEN(J+1)**2 + (46.4+0.84*MLOADI)*RINTEN(J+1)
          RATIOC = DETO/DETM
          KEI = KESSI/RATIOC
C
C
```

```
C
C  >>>>>>>>> CALCULATE FC YIELD FROM EACH AREA TYPE.
C  >>>>>>>>> FC YIELD IS EQUAL TO MG SOIL OR MANURE ERODED (MUSLE)
C  >>>>>>>>> MULTIPLIED BY CELLS/MG MULTIPLIED BY A DIE-OFF FACTOR
C  >>>>>>>>> WHERE APPLICABLE.  TIME OF DECAY IS THE TIME THE MANURE
C  >>>>>>>>> IS STORED BEFORE LAND APPLICATION.  SUBROUTINE KLINE
C  >>>>>>>>> IS CALLED SO THAT DIE-OFF RATE, K, CAN BE DETERMINED ON
C  >>>>>>>>> ON AN HOURLY BASIS.
C
C  >>>>>>>>> FOR SPREAD AREA: IF MORE MANURE IS ERODED THAN WAS LAST
C  >>>>>>>>> SPREAD, THEN THE BOTTOM LAYER (REMAIN) WILL BE CONSIDERED
C  >>>>>>>>> AS SOIL.
C  >>>>>>>>> FOR PASTURE AREA:  THE FPIE FRACTION HAS A CELL DENSITY
C  >>>>>>>>> OF CELLM; THE (1-FPIE) FRACTION HAS A CELL DENSITY OF
C  >>>>>>>>> CELLS.
C
C
C  >>>>>>>>>>>>>> COMPUTE BACTERIA YIELDS BEFORE DIE-OFF.
C
C  >>>>>>>>>>>>>>>>>>>>> COMPUTE FRACTION OF SPREAD AREA ACTUALLY
C  >>>>>>>>>>>>>>>>>>>>> RECEIVING WASTES.
C
         FREC = 1.0
         IF(MLOAD.LT.63.0) FREC = MLOAD/63.0
C
         MANURE = MLOAD*AW*FSPD
         EROMAN = 11.8*(Q*10.*AW*QP)**0.56*KEM*LSM*CM(IM)*PM*FSPD*FREC
         EROSOL = EROMAN/FREC*(1.0-FREC)
         IF(EROMAN.GT.MANURE) THEN
             REMAIN = EROMAN - MANURE
             EROMAN = MANURE
         ELSE
             REMAIN = 0.0
         END IF
C
C
         FCSPD = EROMAN*CELLM*REDM + (REMAIN+EROSOL)*TSS*CELLS
     $            * REDM
         FCINC = 11.8*(Q*10.*AW * QP)**0.56 * KEI*LSI*CI(IM)*PIN * FINC
     $                 * CELLI * REDI
         FCPAS = 11.8*(Q*10.*AW * QP)**0.56 * KEM*LSP*CP(IM)*PP * FPST
     $                 * ( FPIE*CELLM + (1.-FPIE)*CELLS*TSS )
         FCSOL = 11.8*(Q*10.*AW*QP)**0.56 * KESSI*LSS*CS(IM)*PS * FSOL
     $              * TSS * CELLS
C
C
C  >>>>>>>>>>>>>>>  MODEL DIE-OFF FOR SPREAD AREA.
C  >>>>>>>>>>>>>>>  IF DECAY PERIOD IS GREATER THAN 24 HOURS, CALL
C  >>>>>>>>>>>>>>>  STORAGE TO MODEL LAGOON TEMPERATURES UNLESS
C  >>>>>>>>>>>>>>>  LSTOR HAS BEEN SET TO 0.  IF LSTOR IS GREATER
C  >>>>>>>>>>>>>>>  THAN 0, THE VERY TIME CONSUMING SUBROUTINE 'STORAGE'
C  >>>>>>>>>>>>>>>  WILL BE USED TO MODEL STORED WASTE TEMPERATURE.
C  >>>>>>>>>>>>>>>  IF LSTOR IS 0, THEN AMBIENT TEMPERATURE WILL BE
C  >>>>>>>>>>>>>>>  USED TO MODEL STORED WASTE TEMPERATURE, AND RESULTS
C  >>>>>>>>>>>>>>>  WILL TEND TO BE UNDERESTIMATED.
C  >>>>>>>>>>>>>>>  IF LAVG = 0, AVG. MONTHLY TEMP., INPUT BY THE USER,
C  >>>>>>>>>>>>>>>  WILL BE USED TO ADJUST K20.
C
C
         M = INT(DATE(IDAY)-STOR)
         N = INT(DATE(IDAY))
C
CNEW
C
      IF(STOR.GT.24. .AND. LSTOR.GT.0) THEN
              CALL STORAGE(DSEED, M, N, TEMP)
      ELSE
```

```
          IF(M.LE.0) THEN
            M1 = M + 8760
            N1 = 8760
            M2 = 1
            N2 = N
              IF(LAVG.EQ.0) THEN
                CALL AVERAGE(M1,N1,Z1)
                CALL AVERAGE(M2,N2,Z2)
              ELSE
                CALL KLINE(DSEED,M1,N1,IHR1,Z1)
                CALL KLINE(DSEED,M2,N2,IHR2,Z2)
              END IF
            ITIME = 0
            DO 250 IRST = M1,N1
              ITIME = ITIME + 1
              TEMP(ITIME) = Z1(IRST)
              IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
 250        CONTINUE
            DO 260 IRST = M2,N2
              ITIME = ITIME + 1
              TEMP(ITIME) = Z2(IRST)
              IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
 260        CONTINUE
         ELSE
              IF(LAVG.EQ.0) THEN
                CALL AVERAGE(M,N,Z)
              ELSE
                CALL KLINE(DSEED,M,N,IHR,Z)
              END IF
            ITIME = 0
            DO 270 IRST = M,N
              ITIME = ITIME + 1
              TEMP(ITIME) = Z(IRST)
              IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
 270        CONTINUE
         END IF
      END IF
C
C  >>>>>>>>> ENTER DECAY LOOP.
C
      ILAST = N - M + 1
      DO 500 ISPD = 1, ILAST
        FCSPD = FCSPD*DEXP(-K20/24.*DTHETA**DBLE(TEMP(ISPD)-20.))
 500 CONTINUE
C
C
C  >>>>>>>>>>>>>>> MODEL DIE-OFF FOR MANURE INCORPORATED AREA.
C
       M = INT(DATE(IDAY)-STORI)
C
       IF(STORI.GT.24. .AND. LSTOR.GT.0) THEN
           CALL STORAGE(DSEED, M, N, TEMP)
       ELSE
           IF(M.LE.0) THEN
             M1 = M + 8760
             N1 = 8760
             M2 = 1
             N2 = N
               IF(LAVG.EQ.0) THEN
                 CALL AVERAGE(M1,N1,Z1)
                 CALL AVERAGE(M2,N2,Z2)
               ELSE
                 CALL KLINE(DSEED,M1,N1,IHR1,Z1)
                 CALL KLINE(DSEED,M2,N2,IHR2,Z2)
               END IF
             ITIME = 0
             DO 520 IRST = M1, N1
```

```
                ITIME = ITIME + 1
                TEMP(ITIME) = Z1(IRST)
                IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
  520       CONTINUE
            DO 530 IRST = M2, N2
                ITIME = ITIME + 1
                TEMP(ITIME) = Z2(IRST)
                IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
  530       CONTINUE
          ELSE
               IF(LAVG.EQ.0) THEN
                  CALL AVERAGE(M,N,Z)
               ELSE
                  CALL KLINE(DSEED,M,N,IHR,Z)
               END IF
            ITIME = 0
            DO 540 IRST = M,N
                ITIME = ITIME + 1
                TEMP(ITIME) = Z(IRST)
                IF(TEMP(ITIME).LT.3.0)  TEMP(ITIME)= -200.0
  540       CONTINUE
          END IF
       END IF
C
C  >>>>>>>>> ENTER DECAY LOOP.
C
      ILAST = N - M + 1
      DO 600 INC = 1, ILAST
         FCINC = FCINC*DEXP(-K20/24.*DTHETA**DBLE(TEMP(INC)-20.))
  600 CONTINUE
C
C
C  >>>>>>>>> DETERMINE TOTAL CELL YIELD AND COMPARE TO WQ STANDARD.
C
         YIELD = FCSPD + FCINC + FCPAS + FCSOL
         LCONC(J) = DLOG10( YIELD*0.0001 / (Q*10.*AW) )
         IF(LCONC(J).GT.2.3) NVIOL = NVIOL + 1
         SUMCON = SUMCON + LCONC(J)
         SUMX2 = SUMX2 + LCONC(J)**2
C
  800 CONTINUE
C
         AVG = SUMCON/FLOAT(NDEV)
         STD = SQRT( (FLOAT(NDEV)*SUMX2  - SUMCON**2)
     $             /FLOAT(NDEV*(NDEV-1)) )
         FVIOL = FLOAT(NVIOL)/FLOAT(NDEV)  * 100.
         IWRIT = 7 + ISET
         CALL RANK(NDEV,LCONC)
         WRITE(IWRIT,985) DATE(IDAY), LCONC(1), LCONC(NDEV), AVG, STD,
     $     FVIOL
  985    FORMAT(2x,F5.0,4F10.5,2X,F4.0)
C
C
C  >>>>>>>> CREATE HISTOGRAM FOR LOG CONCENTRATION.
C
      IF(IDAY.EQ.EXDAY) THEN
      WI = 0.1
      NOUT = 10 + IWRIT
      CALL HISTO(NDEV,LCONC,LCONC(1),LCONC(NDEV),WI,RFMAX,NOUT)
      END IF
  990 CONTINUE
 1000 CONTINUE
C
      STOP
      END
C************************************************************************
C*****                                                             *****
```

```
C*****  THIS SUBROUTINE SIMULATES HOURLY DRY BULB TEMPERATURES FOR *****
C*****  A MAXIMUM OF ONE YEAR (8760 HOURS) OR A PORTION OF A YEAR. *****
C*****                                                              *****
C***********************************************************************
C
C        THIS SUBROUTINE IS LIMITED TO 8760 HOURS.
C
C        THE SUBROUTINE MULTM IS REQUIRED.
C
C        THE STANDARD NORMAL RANDOM NUMBER GENERATOR GGNML
C                FROM THE IMSL ROUTINE LIBRARY IS USED.
C
C        DSEED = INPUT/OUTPUT DOUBLE PRECISION VARIABLE
C                ASSIGNED AN INTEGER VALUE IN THE
C                EXCLUSIVE RANGE (1.D0,2147483647.D0).
C                DSEED IS REPLACED BY A NEW VALUE TO BE
C                USED IN A SUBSEQUENT CALL.
C
C        M     = THE HOUR OF THE YEAR AT WHICH THE
C                SIMULATION BEGINS (M IS AN INTEGER)
C
C        N     = THE HOUR OF THE YEAR AT WHICH THE
C                SIMULATION ENDS (N IS AN INTEGER)
C
C        IHR   = THE OUTPUT ARRAY OF HOURS WITH
C                DIMENSION N-M+1.
C
C        Z     = THE OUTPUT ARRAY OF HOURLY DRY BULB
C                TEMPERATURES THAT CORRESPOND TO IHR.
C
C
      SUBROUTINE KLINE (DSEED,M,N,IHR,Z)
CJAB+
CJAB       DIMENSION AX(9),DELY(8762),XHATT(1,9),S(3),IHR(8761),Z(8761)
      DIMENSION AX(9),DELY(8762),XHATT(1,9),S(8761),IHR(8761),Z(8761)
      INTEGER SPTR
CJAB-
      DIMENSION DEL(1,1)
      DOUBLE PRECISION DSEED
      DATA PI/3.141592654/
C
C        THE FUNCTIONS ARE SPECIFIED FOR THE PERIODIC VARIATIONS
C
      A1(R)=1.0
      A2(R)=SIN(2.*PI*R/8760.)
      A3(R)=COS(2.*PI*R/8760.)
      A4(R)=SIN(2.*PI*365.*R/8760.)
      A5(R)=COS(2.*PI*365.*R/8760.)
      A6(R)=SIN(2.*PI*730.*R/8760.)
      A7(R)=COS(2.*PI*730.*R/8760.)
      A8(R)=SIN(2.*PI*1095.*R/8760.)
      A9(R)=COS(2.*PI*1095.*R/8760.)
C
C        THE COEFFICIENTS FOR THE REGRESSION EQUATION ARE SPECIFIED.
C
      XHATT(1,1)= 0.512987E+02
      XHATT(1,2)=-0.551939E+01
      XHATT(1,3)=-0.195574E+02
      XHATT(1,4)=-0.616349E+01
      XHATT(1,5)=-0.458292E+01
      XHATT(1,6)= 0.125612E+01
      XHATT(1,7)= 0.821104E+00
      XHATT(1,8)= 0.201078E+00
      XHATT(1,9)=-0.145084E+00
      DELY(M)=0.
      XBAR=0.017600E+00
```

```
      NN=N+1
CJAB+
      CALL GGNML (DSEED,NN-M+1,S)
      SPTR = 0
CJAB-
      DO 10 I=M,NN
      II=I-1
      IF(I.EQ.M) GO TO 100
      IHR(II)=I-1
  100 R=FLOAT(I)-1.0
      AX(1)=A1(R)
      AX(2)=A2(R)
      AX(3)=A3(R)
      AX(4)=A4(R)
      AX(5)=A5(R)
      AX(6)=A6(R)
      AX(7)=A7(R)
      AX(8)=A8(R)
      AX(9)=A9(R)
C
C        THE TIME VARIATIONS OF THE STANDARD DEVIATION AND HOUR TO
C                 HOUR CORRELATION ARE CALCULATED
C
      B=SIN(2.*PI*R/8760.)
      BB=COS(2.*PI*R/8760.)
      RX1=0.97196+0.01289*B+0.01525*BB
      SD=9.01+2.07*B+2.35*BB
C
C        MULTM CALCULATES THE PERIODIC TEMPERATURE AND GGNML SELECTS A
C                 RANDOM NUMBER FROM THE STANDARD NORMAL DISTRIBUTION.
C
      CALL MULTM(XHATT,AX,DEL,1,9,1)
CJAB+
CJAB      CALL GGNML(DSEED,1,S)
      SPTR = SPTR + 1
C
C        THE MARKOV CHAIN CALCULATES THE RANDOM PART OF THE TEMPERATURE.
C                 IT IS ADDED TO THE PERIODIC TEMPERATURE.
C
CJAB      RES=S(1)*SD*SQRT(1.0-(RX1**2))
      RES=S(SPTR)*SD*SQRT(1.0-(RX1**2))
CJAB-
      XMARK=XBAR+RX1*(DELY(I)-XBAR)
      DELY(I+1)=XMARK+RES
      IF(I.EQ.M) GO TO 10
      Z(II)=( DELY(I)+DEL(1,1) - 32. ) / 1.8
   10 CONTINUE
      RETURN
      END
C************************************************************************
C*** MULTM ACCEPTS MATRIX A (N BY M),MULTIPLIES A BY MATRIX B (M BY L)
C*** TO YIELD MATRIX C (N BY L).
C************************************************************************
C
      SUBROUTINE MULTM(A,B,C,N,M,L)
      DIMENSION A(N ,M ),B(M ,L ),C(N ,L )
      DO 10 IN=1,N
         DO 10 IL=1,L
            SUM=0.0
            DO 20 IM=1,M
               SUM=SUM+A(IN,IM)*B(IM,IL)
   20       CONTINUE
         C(IN,IL)=SUM
   10 CONTINUE
      RETURN
      END
C
```

```
C     PROGRAM TO GENERATE A GAMMA DISTRIBUTION FOR ANY ETA.
C     FROM HAAN (1977), EQUATION 13.7.
C
C     XX   = ARRAY WITH N GENERATED GAMMA DEVIATES
C     N    = NUMBER OF DEVIATES DESIRED
C     DLAM = SCALE PARAMETER
C     ETA  = SHAPE PARAMETER
C     DSEED= DOUBLE PRECISION SEED FOR IMSL GGUBS ROUTINE
C
C
      SUBROUTINE GENGAM(DLAM,ETA,XX,N,DSEED)
      REAL XX(N),RU(3),RU2(20)
      DOUBLE PRECISION DSEED
      IETA=IFIX(ETA)
      FETA=ETA-FLOAT(IETA)
      DO 40 I=1,N
      YF=0.0
      IF (FETA.EQ.0.0) GOTO 20
   10 CALL GGUBS(DSEED,3,RU)
      S1=RU(1)**(1./FETA)
      S2=RU(2)**(1./(1.-FETA))
      IF(S1+S2.GT.1) GOTO 10
      Z=S1/(S1+S2)
      YF=-Z*ALOG(RU(3))/DLAM
   20 YI=0
      IF(IETA.EQ.0)GOTO 35
      CALL GGUBS(DSEED,IETA,RU2)
      DO 30 J=1,IETA
   30 YI=YI-ALOG(RU2(J))
      YI=YI/DLAM
   35 XX(I)=YF+YI
   40 CONTINUE
      RETURN
      END
C
C  SUBROUTINE GENLOG:  THIS SUBROUTINE GENERATES DEVIATES FROM A
C                      LOGNORMAL DISTRIBUTION.
C
C      DMU = SCALE PARAMETER
C      DSIGMA = SHAPE PARAMETER
C      N = NUMBER OF DEVIATES TO BE GENERATED
C      XX = VECTOR CONTAINING THE GENERATED DEVIATES.
C      DSEED = SEED FOR RANDOM NUMBER GENERATOR.
C
C
C
       SUBROUTINE GENLOG(DMU,DSIGMA,N,XX,DSEED)
       REAL RNORM(1000), XX(1000)
       DOUBLE PRECISION DSEED
       CALL GGNML(DSEED,N,RNORM)
       DO 500 J = 1, N
          XX(J) = EXP( DSIGMA*RNORM(J) + DMU )
  500     CONTINUE
          RETURN
          END
      SUBROUTINE HISTO(N,X,XMIN,XMAX,WI,RFMAX,NOUT)
C
C     THIS PROGRAM CALCULATES HISTOGRAM PLOTTING POINTS.
C
C     X = INPUT ARRAY OF (N) POINTS RANKED FROM SMALL TO LARGE
C     XMIN = MINIMUM X VALUE - INPUT
C     XMAX = MAXIMUM X VALUE - INPUT
C     WI = HISTOGRAM BAR WIDTH IN UNITS OF X - INPUT
C     RFMAX = MAXIMUM HEIGHT OF THE HISTOGRAM BARS - OUTPUT
C        THE HEIGHT OF EACH HISTOGRAM BAR IS GIVEN BY:
C        NO. OF DATA POINTS IN THAT INTERVAL / N * WI
```

```
C      NOUT=OUTPUT OPTION
C
       DIMENSION X(N)
C      DATA N,WI,XPMIN,XPMAX/14,0.25,0.0,6.0/
       CALL RANK(N,X)
       XPMIN=XMIN
       XPMAX=XMAX
       RFMAX=0.0
       K=0
       I=1
C       WRITE(6,30)
C30     FORMAT('           XP        YP')
5      CONTINUE
       IF(X(I).LE.(XPMIN+WI)) GO TO 2
       GO TO 3
2      I=I+1
       IF(I.LE.N) GO TO 5
3      I=I-1
       RF=(FLOAT(I)-FLOAT(K))/(FLOAT(N)*WI)
       IF(RF.LT.0.0) RF=0.0
       IF(RF.GT.RFMAX) RFMAX=RF
       XP=XPMIN
       YP=0.0
       WRITE(NOUT,20) XP,YP
       YP=RF
       WRITE(NOUT,20) XP,YP
       XP=XPMIN+WI
       IF(XP.GT.XPMAX) XP=XPMAX
       WRITE(NOUT,20) XP,YP
       YP=0.0
       WRITE(NOUT,20) XP,YP
20     FORMAT(2F10.5)
       XPMIN=XP
       K=I
       I=I+1
       IF(I.LE.N) GO TO 5
25     XP=XP+WI
       IF(XP.GT.XPMAX) GO TO 15
       DO 22 I=1,4
   22  WRITE(NOUT,20) XP,YP
       GO TO 25
15     RETURN
       END
       SUBROUTINE RANK(N,XX)
C
C      THIS ROUTINE RANKS ONE DIMENSIONAL ARRAY OF DATA FROM SMALL TO
C         LARGE.
C
C      XX = INPUT ARRAY OF N POINTS
C
       DIMENSION L5(20),XX(N)
       INTEGER R4(20),P2
       N1=N
       L5(1)=1
       R4(1)=N1
       P2=1
  216  IF(L5(P2).LT.R4(P2)) GO TO 219
       P2=P2-1
       GO TO 254
  219  I=L5(P2)
       J=R4(P2)
       P1=XX(J)
       M4=(I+J)/2
       IF (J-I.LT.6) GO TO 232
       IF ((P1.GT.XX(I)).AND.(P1.LT.XX(M4))) GO TO 232
       IF ((P1.LT.XX(I)).AND.(P1.GT.XX(M4))) GO TO 232
       IF ((XX(I).LT.XX(M4)).AND.(XX(I).GT.P1)) GO TO 230
```

```
      IF ((XX(I).GT.XX(M4)).AND.(XX(I).LT.P1)) GO TO 230
      H1=XX(J)
      XX(J)=XX(M4)
      XX(M4)=H1
      GO TO 231
  230 H1=XX(J)
      XX(J)=XX(I)
      XX(I)=H1
  231 P1=XX(J)
  232 IF(I.GE.J) GO TO 243
  233 IF(XX(I).GE.P1) GO TO 236
      I=I+1
      GO TO 233
  236 J=J-1
  237 IF (.NOT.((I.LT.J).AND.(P1.LT.XX(J)))) GO TO 240
      J=J-1
      GO TO 237
  240 IF (I.GE.J) GO TO 242
      H1=XX(J)
      XX(J)=XX(I)
      XX(I)=H1
  242 GO TO 232
  243 J=R4(P2)
      H1=XX(J)
      XX(J)=XX(I)
      XX(I)=H1
      IF(I-L5(P2).GE.R4(P2)-I) GO TO 250
      L5(P2+1)=L5(P2)
      R4(P2+1)=I-1
      L5(P2)=I+1
      GO TO 253
  250 L5(P2+1)=I+1
      R4(P2+1)=R4(P2)
      R4(P2)=I-1
  253 P2=P2+1
  254 IF (P2.GT.0) GO TO 216
      RETURN
      END
C
C ######################################################################
C
C                              SUBROUTINE STORAGE
C
C     THIS SUBROUTINE DETERMINES THE TEMPERATURE OF WASTE INSIDE A
C     LAGOON OR STORAGE TANK FOR A PARTICULAR HOUR BASED ON THE
C     AMBIENT AIR TEMPERATURE OF THE PAST 360 HOURS (2 WEEKS).  THE
C     MODEL IS BASED ON THE WORK OF SMITH AND FRANCO (1985).
C
C     DSEED = RANDOM NUMBER GENERATOR SEED USED BY KLINE       (INPUT)
C     IST = BEGINNING JULIAN HOUR OF TEMPERATURE SIMULATION    (INPUT)
C     IEND = ENDING JULIAN HOUR OF TEMPERATURE SIMULATION      (INPUT)
C     TL = ARRAY OF LAGOON TEMPERATURES FOR SIMULATION PERIOD (OUTPUT)
C
C ######################################################################
C
         SUBROUTINE STORAGE (DSEED, IST, IEND, TL)
         REAL TA(8761), TA1(8761), TA2(8761), TAK(8761), ILAG(8761)
         REAL ILAG2(8761), TL(8761)
         DOUBLE PRECISION ALPHA(0:719), B, DSEED
         B = DBLE(0.2/24.)
         MS1 = IST - 359
         NS1 = IEND
         IF(MS1.LE.0) THEN
               MS1 = MS1 + 8760
               NS1 = 8760
               MS2 = 1
               NS2 = IEND
```

```
               CALL KLINE(DSEED,MS1,NS1,ILAG,TA1)
               CALL KLINE(DSEED,MS2,NS2,ILAG2,TA2)
               ITA = 0
               DO 1200 JTA = MS1,NS1
                  ITA = ITA + 1
                  TA(ITA) = TA1(JTA)
 1200          CONTINUE
               DO 1300 JTA = MS2,NS2
                  ITA = ITA + 1
                  TA(ITA) = TA2(JTA)
 1300          CONTINUE
         ELSE
               CALL KLINE(DSEED,MS1,NS1,ILAG,TAK)
               ITA = 0
               DO 1400 JTA = MS1, NS1
                  ITA = ITA + 1
                  TA(ITA) = TAK(JTA)
 1400          CONTINUE
         END IF
           IHOUR = 0
           DO 2000 JUL = IST,IEND
             IHOUR = IHOUR + 1
             SUMA = 0.0
             SUMT = 0.0
             ITOP = IHOUR + 359
             DO 1500 LT = 0, 359
               ITIME = ITOP - LT
               ALPHA(LT) = DEXP(-B*FLOAT(LT))
               SUMA = SUMA + ALPHA(LT)
               SUMT = SUMT + TA(ITIME) * ALPHA(LT)
 1500        CONTINUE
             TL(IHOUR) = SUMT/SUMA
             IF(TL(IHOUR).LT.3.0)  TL(IHOUR)= -200.0
 2000      CONTINUE
         RETURN
         END
C
C
C
C
C                        SUBROUTINE AVERAGE
C
C    THIS SUBROUTINE ALLOWS THE USER TO INPUT MONTHLY AVERAGE
C    TEMPERATURES SO THAT TRENDS AND RELATIVE PERFORMANCE OF BMPS
C    CAN BE DETERMINED.
C
C
C
         SUBROUTINE AVERAGE(M,N,Z)
C
         REAL Z(8761), JAN, MAR, MAY, JUN, JUL, NOV
C
C   SPECIFY AVERAGE MONTHLY TEMPERATURES
C
         DATA JAN /-1.5/
         DATA FEB /-0.5/
         DATA MAR /10.6/
         DATA APR /8.7/
         DATA MAY /16.0/
         DATA JUN /19.4/
         DATA JUL /22.8/
         DATA AUG /21.1/
         DATA SEP /17.2/
         DATA OCT /11.2/
         DATA NOV /5.0/
         DATA DEC /4.0/
C
```

```
      DO 100 HR = M,N
         IF(HR.LE.8760) Z(HR) = DEC
         IF(HR.LE.8064) Z(HR) = NOV
         IF(HR.LE.7320) Z(HR) = OCT
         IF(HR.LE.6576) Z(HR) = SEP
         IF(HR.LE.5856) Z(HR) = AUG
         IF(HR.LE.5112) Z(HR) = JUL
         IF(HR.LE.4368) Z(HR) = JUN
         IF(HR.LE.3624) Z(HR) = MAY
         IF(HR.LE.2880) Z(HR) = APR
         IF(HR.LE.2160) Z(HR) = MAR
         IF(HR.LE.1416) Z(HR) = FEB
         IF(HR.LE.744) Z(HR) = JAN
         IF (Z(HR).LT.3.0) Z(HR) = -200.0
100   CONTINUE
      RETURN
      END
```

Appendix C. Example Options File

```
                      INPUT FILE FOR PROGRAM COLI

SPECIFY NO. OF SCENARIOS TO BE MODELED: NSET =    4
NUMBER OF DEVIATES TO BE GENERATED PER DATE: NDEV =  100
RUN FOR WHICH EXAMPLE HISTOGRAM WILL BE GENERATED:       EXDAY =  8
SPECIFY WASTE STORAGE TEMPERATURE MODEL (FOR STOR>24):   LSTOR =  1
  IF LSTOR = 0, RUN TIME WILL BE SHORTENED CONSIDERABLY
                BUT RESULTS MAY TEND TO BE UNDERESTIMATED.
  IF LSTOR > 0, RUN TIME MAY BE QUITE LONG (ON THE ORDER OF DAYS)
IF AVERAGE TEMPERATURES ARE TO BE USED, SPECIFY
     LAVG = 0, OTHERWISE SPECIFY LAVG >= 1 :             LAVG   =  2
```

Appendix D. Example Input Files

Base Scenario

```
                         INPUT FILE FOR PROGRAM COLI

WATERSHED PARAMETERS.

  AREA OF WATERSHED (HA):             AW   =    324.0
  LANDUSE FRACTIONS:  FSPD = 0.43  FINC = 0.00  FPST = 0.21  FSOL = 0.36

  SCS CURVE NUMBERS FOR EACH AREA TYPE:
      CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
      CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
      CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

  HYDRAULIC LENGTH (M):     L  =  2160.0
  AVERAGE LAND SLOPE (%): SE  =    3.0
  AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

  INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

  USLE ERODIBILITY FOR MANURE (SI UNITS):          KEM =  0.0066
  USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):  KES =  0.28
  LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

  COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
               FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
               MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
               APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
               OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
               NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

  PRACTICE FACTORS:      PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0

MANURE PARAMETERS.

  ANIMAL DAYS ON PASTURE:                     ANDAY  =   34905.0
  NO. DEFECATIONS PER DAY:                    PIRATE =  12.0
  AREA OF A FECAL DEPOSIT (SQ. M):            APIE   =  0.093
  NONUNIFORMITY CONSTANT:                     KEX    =   2.0

BACTERIA PARAMETERS.

  BACTERIA CELLS PER GRAM OF FRESH MANURE:    CELLM  =  2.3E05
  BACTERIA CELLS PER GRAM OF SOIL:            CELLS  =  4.0E02
  DIE-OFF RATE AT 20 DEGREES CELSIUS:         K20    =  0.3
  TEMPERATURE CORRECTION FACTOR:              THETA  =  1.07

SOIL PROPERTIES.

  SUSPENDED SOLIDS FRACTION OF SOIL:          TSS    =  0.40
  SOIL DENSITY (MG/CUBIC M):                  DENS   =  1.6
  DEPTH OF INCORPORATION OF MANURE (CM):      DEPTH  = 10.0

WASTE MANAGEMENT PRACTICES.

  MANURE SPREAD AT A TIME (MG/HA):    MLOAD  =    2.2
  MANURE INCORP. INTO SOIL (MG/HA):   MLOADI =    2.2
  MANURE STORAGE TIME (HRS):          STOR   =   24.0
  INC. MANURE STORAGE TIME (HRS):     STORI  =    2.0

  BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
  BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
```

Buffer Strip Scenario

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                    INPUT FILE FOR PROGRAM COLI

WATERSHED PARAMETERS.

  AREA OF WATERSHED (HA):          AW   =   324.0
  LANDUSE FRACTIONS:  FSPD = 0.43  FINC = 0.00  FPST = 0.21  FSOL = 0.36

  SCS CURVE NUMBERS FOR EACH AREA TYPE:
     CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
     CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
     CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

  HYDRAULIC LENGTH (M):     L  =  2160.0
  AVERAGE LAND SLOPE (%): SE  =     3.0
  AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

  INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

  USLE ERODIBILITY FOR MANURE (SI UNITS):            KEM =  0.0066
  USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):   KES =  0.28
  LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

  COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
               FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
               MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
               APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
               OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
               NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

  PRACTICE FACTORS:       PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0

MANURE PARAMETERS.

  ANIMAL DAYS ON PASTURE:                  ANDAY  =   34905.0
  NO. DEFECATIONS PER DAY:                 PIRATE =  12.0
  AREA OF A FECAL DEPOSIT (SQ. M):         APIE   =  0.093
  NONUNIFORMITY CONSTANT:                  KEX    =   2.0

BACTERIA PARAMETERS.

  BACTERIA CELLS PER GRAM OF FRESH MANURE:  CELLM  =  2.3E05
  BACTERIA CELLS PER GRAM OF SOIL:          CELLS  =  4.0E02
  DIE-OFF RATE AT 20 DEGREES CELSIUS:       K20    =  0.3
  TEMPERATURE CORRECTION FACTOR:            THETA  =  1.07

SOIL PROPERTIES.

  SUSPENDED SOLIDS FRACTION OF SOIL:        TSS    =  0.40
  SOIL DENSITY (MG/CUBIC M):                DENS   =  1.6
  DEPTH OF INCORPORATION OF MANURE (CM):    DEPTH  = 10.0

WASTE MANAGEMENT PRACTICES.

  MANURE SPREAD AT A TIME (MG/HA):    MLOAD  =    2.2
  MANURE INCORP. INTO SOIL (MG/HA):   MLOADI =    2.2
  MANURE STORAGE TIME (HRS):          STOR   =   24.0
  INC. MANURE STORAGE TIME (HRS):     STORI  =    2.0

  BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM = 100.0
  BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
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Ten-Day Storage Scenario

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                    INPUT FILE FOR PROGRAM COLI

WATERSHED PARAMETERS.

  AREA OF WATERSHED (HA):           AW   =     324.0
  LANDUSE FRACTIONS:  FSPD = 0.43  FINC = 0.00  FPST = 0.21  FSOL = 0.36

  SCS CURVE NUMBERS FOR EACH AREA TYPE:
      CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
      CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
      CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

  HYDRAULIC LENGTH (M):     L   =  2160.0
  AVERAGE LAND SLOPE (%): SE   =     3.0
  AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

  INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

  USLE ERODIBILITY FOR MANURE (SI UNITS):          KEM =  0.0066
  USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):  KES =  0.28
  LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

  COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
               FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
               MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
               APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
               OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
               NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

  PRACTICE FACTORS:      PM   = 1.0  PIN = 1.0  PP   = 1.0  PS   = 1.0


MANURE PARAMETERS.

  ANIMAL DAYS ON PASTURE:                        ANDAY   =    34905.0
  NO. DEFECATIONS PER DAY:                       PIRATE  =   12.0
  AREA OF A FECAL DEPOSIT (SQ. M):               APIE    =   0.093
  NONUNIFORMITY CONSTANT:                        KEX     =    2.0


BACTERIA PARAMETERS.

  BACTERIA CELLS PER GRAM OF FRESH MANURE:       CELLM   =   2.3E05
  BACTERIA CELLS PER GRAM OF SOIL:               CELLS   =   4.0E02
  DIE-OFF RATE AT 20 DEGREES CELSIUS:            K20     =   0.3
  TEMPERATURE CORRECTION FACTOR:                 THETA   =   1.07


SOIL PROPERTIES.

  SUSPENDED SOLIDS FRACTION OF SOIL:             TSS     =   0.40
  SOIL DENSITY (MG/CUBIC M):                     DENS    =   1.6
  DEPTH OF INCORPORATION OF MANURE (CM):         DEPTH   =  10.0


WASTE MANAGEMENT PRACTICES.

  MANURE SPREAD AT A TIME (MG/HA):     MLOAD  =     2.2
  MANURE INCORP. INTO SOIL (MG/HA):    MLOADI =     2.2
  MANURE STORAGE TIME (HRS):           STOR   =   240.0
  INC. MANURE STORAGE TIME (HRS):      STORI  =     2.0

  BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
  BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
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Six-Month Storage Scenario

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                         INPUT FILE FOR PROGRAM COLI

 WATERSHED PARAMETERS.

   AREA OF WATERSHED (HA):           AW    =    324.0
   LANDUSE FRACTIONS:  FSPD = 0.43   FINC = 0.00   FPST = 0.21   FSOL = 0.36

   SCS CURVE NUMBERS FOR EACH AREA TYPE:
       CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
       CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
       CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

   HYDRAULIC LENGTH (M):     L   =   2160.0
   AVERAGE LAND SLOPE (%): SE   =    3.0
   AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

   INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

     R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
     R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
     R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
     R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
     R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

   USLE ERODIBILITY FOR MANURE (SI UNITS):             KEM =  0.0066
   USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):   KES =  0.28
   LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

   COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
                FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
                MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
                APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
                MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
                JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
                JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
                AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
                SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
                OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
                NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
                DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

   PRACTICE FACTORS:      PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0

 MANURE PARAMETERS.

   ANIMAL DAYS ON PASTURE:                          ANDAY  =    34905.0
   NO. DEFECATIONS PER DAY:                         PIRATE =   12.0
   AREA OF A FECAL DEPOSIT (SQ. M):                 APIE   =   0.093
   NONUNIFORMITY CONSTANT:                          KEX    =    2.0

 BACTERIA PARAMETERS.

   BACTERIA CELLS PER GRAM OF FRESH MANURE:         CELLM  =   2.3E05
   BACTERIA CELLS PER GRAM OF SOIL:                 CELLS  =   4.0E02
   DIE-OFF RATE AT 20 DEGREES CELSIUS:              K20    =   0.3
   TEMPERATURE CORRECTION FACTOR:                   THETA  =   1.07

 SOIL PROPERTIES.

   SUSPENDED SOLIDS FRACTION OF SOIL:               TSS    =   0.40
   SOIL DENSITY (MG/CUBIC M):                       DENS   =   1.6
   DEPTH OF INCORPORATION OF MANURE (CM):           DEPTH  =  10.0

 WASTE MANAGEMENT PRACTICES.

   MANURE SPREAD AT A TIME (MG/HA):     MLOAD  =    2.2
   MANURE INCORP. INTO SOIL (MG/HA):    MLOADI =    2.2
   MANURE STORAGE TIME (HRS):           STOR   = 4320.0
   INC. MANURE STORAGE TIME (HRS):      STORI  =    2.0

   BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
   BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
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Incorporation of 2.2 Mg Manure per ha

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                              INPUT FILE FOR PROGRAM COLI

 WATERSHED PARAMETERS.

   AREA OF WATERSHED (HA):             AW   =    324.0
   LANDUSE FRACTIONS:  FSPD = 0.00  FINC = 0.43  FPST = 0.21  FSOL = 0.36

   SCS CURVE NUMBERS FOR EACH AREA TYPE:
       CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
       CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
       CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

   HYDRAULIC LENGTH (M):      L   =  2160.0
   AVERAGE LAND SLOPE (%): SE   =    3.0
   AVERAGE TIME BETWEEN STORMS (HRS):  TLS =  57.6

   INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

   USLE ERODIBILITY FOR MANURE (SI UNITS):            KEM =  0.0066
   USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):  KES =  0.28
   LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

   COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
                FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
                MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
                APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
                MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
                JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
                JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
                AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
                SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
                OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
                NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
                DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

   PRACTICE FACTORS:      PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0


 MANURE PARAMETERS.

   ANIMAL DAYS ON PASTURE:                     ANDAY  =    34905.0
   NO. DEFECATIONS PER DAY:                    PIRATE =   12.0
   AREA OF A FECAL DEPOSIT (SQ. M):            APIE   =   0.093
   NONUNIFORMITY CONSTANT:                     KEX    =    2.0


 BACTERIA PARAMETERS.

   BACTERIA CELLS PER GRAM OF FRESH MANURE:   CELLM  =   2.3E05
   BACTERIA CELLS PER GRAM OF SOIL:           CELLS  =   4.0E02
   DIE-OFF RATE AT 20 DEGREES CELSIUS:        K20    =   0.3
   TEMPERATURE CORRECTION FACTOR:             THETA  =   1.07


 SOIL PROPERTIES.

   SUSPENDED SOLIDS FRACTION OF SOIL:         TSS    =   0.40
   SOIL DENSITY (MG/CUBIC M):                 DENS   =   1.6
   DEPTH OF INCORPORATION OF MANURE (CM):     DEPTH  =  10.0


 WASTE MANAGEMENT PRACTICES.

   MANURE SPREAD AT A TIME (MG/HA):     MLOAD  =     2.2
   MANURE INCORP. INTO SOIL (MG/HA):    MLOADI =     2.2
   MANURE STORAGE TIME (HRS):           STOR   =     2.0
   INC. MANURE STORAGE TIME (HRS):      STORI  =    24.0

   BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
   BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
```

Incorporation of 400 Mg Manure per ha

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                    INPUT FILE FOR PROGRAM COLI

WATERSHED PARAMETERS.

  AREA OF WATERSHED (HA):            AW   =    324.0
  LANDUSE FRACTIONS:  FSPD = 0.00  FINC = 0.43  FPST = 0.21  FSOL = 0.36

  SCS CURVE NUMBERS FOR EACH AREA TYPE:
      CNSPD(1) = 64.  CNINC(1) = 64.  CNPAS(1) = 72.  CNSOL(1) = 57.
      CNSPD(2) = 81.  CNINC(2) = 81.  CNPAS(2) = 86.  CNSOL(2) = 75.
      CNSPD(3) = 92.  CNINC(3) = 92.  CNPAS(3) = 94.  CNSOL(3) = 88.

  HYDRAULIC LENGTH (M):      L   =  2160.0
  AVERAGE LAND SLOPE (%): SE   =    3.0
  AVERAGE TIME BETWEEN STORMS (HRS):   TLS =  57.6

  INTENSITIES FOR DESIRED RETURN PERIOD FOR VARIOUS DURATIONS (IN/HR):

    R2M  = 16.1312  R5M  = 10.9569  R10M =  7.1295  R15M =  5.3155
    R20M =  4.3909  R30M =  3.0062  R45M =  2.0854  R1H  =  1.6873
    R2H  =  1.1110  R3H  =  0.9017  R6H  =  0.5951  R9H  =  0.4696
    R12H =  0.3643  R18H =  0.2578  R1D  =  0.2011  R2D  =  0.1133
    R3D  =  0.0760  R4D  =  0.0571  R5D  =  0.0490  R6D  =  0.0470

  USLE ERODIBILITY FOR MANURE (SI UNITS):           KEM =  0.0066
  USLE ERODIBILITY FOR SOIL (US CUSTOMARY UNITS):   KES =  0.28
  LENGTH-SLOPE FACTORS:  LSM = 2.8  LSI = 2.8  LSP = 2.8  LSS = 2.8

  COVER FACT.: JAN - CM = 0.3600  CI = 0.6000  CP = 0.0921  CS = 0.0403
               FEB - CM = 0.3600  CI = 0.6000  CP = 0.1591  CS = 0.0403
               MAR - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403
               APR - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               MAY - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUN - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0109
               JUL - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0109
               AUG - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               SEP - CM = 0.3600  CI = 0.6000  CP = 0.0423  CS = 0.0403
               OCT - CM = 0.3600  CI = 0.6000  CP = 0.0609  CS = 0.0403
               NOV - CM = 0.3600  CI = 0.6000  CP = 0.0640  CS = 0.0403
               DEC - CM = 0.3600  CI = 0.6000  CP = 0.0827  CS = 0.0403

  PRACTICE FACTORS:      PM  = 1.0  PIN = 1.0  PP  = 1.0  PS  = 1.0


MANURE PARAMETERS.

  ANIMAL DAYS ON PASTURE:                    ANDAY  =    34905.0
  NO. DEFECATIONS PER DAY:                   PIRATE =   12.0
  AREA OF A FECAL DEPOSIT (SQ. M):           APIE   =   0.093
  NONUNIFORMITY CONSTANT:                    KEX    =    2.0


BACTERIA PARAMETERS.

  BACTERIA CELLS PER GRAM OF FRESH MANURE:   CELLM  =   2.3E05
  BACTERIA CELLS PER GRAM OF SOIL:           CELLS  =   4.0E02
  DIE-OFF RATE AT 20 DEGREES CELSIUS:        K20    =   0.3
  TEMPERATURE CORRECTION FACTOR:             THETA  =   1.07


SOIL PROPERTIES.

  SUSPENDED SOLIDS FRACTION OF SOIL:         TSS    =   0.40
  SOIL DENSITY (MG/CUBIC M):                 DENS   =   1.6
  DEPTH OF INCORPORATION OF MANURE (CM):     DEPTH  =  10.0


WASTE MANAGEMENT PRACTICES.

  MANURE SPREAD AT A TIME (MG/HA):    MLOAD  =     2.2
  MANURE INCORP. INTO SOIL (MG/HA):   MLOADI =   400.0
  MANURE STORAGE TIME (HRS):          STOR   =     2.0
  INC. MANURE STORAGE TIME (HRS):     STORI  =  4320.0

  BUFFER STRIP WIDTH FOR AREAS SPREAD WITH MANURE (FT):  BWIDM =   0.0
  BUFFER STRIP WIDTH FOR MANURE INCORPORATED AREAS (FT): BWIDI =   0.0
```

Appendix E. Example Output Files

Base Scenario

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	2.36856	2.61892	2.55839	0.04266	100.
1080.	2.41612	2.66523	2.60488	0.04258	100.
1800.	2.33911	2.58772	2.53152	0.04397	100.
2520.	2.05123	2.52669	2.48080	0.04941	99.
3240.	2.00214	2.47741	2.43064	0.05064	98.
3960.	1.97040	2.45197	2.39865	0.05176	98.
4680.	1.97491	2.45551	2.40403	0.05121	98.
5400.	1.98766	2.46430	2.41755	0.05033	98.
6120.	1.99282	2.46543	2.42302	0.04966	98.
6840.	2.28260	2.52995	2.47322	0.04333	99.
7560.	2.31509	2.56504	2.50670	0.04435	100.
8280.	2.35233	2.59903	2.54430	0.04351	100.

Histogram Plotting Points for August

X	Y
1.99282	0.00000
1.99282	0.10000
2.09282	0.10000
2.09282	0.00000
2.09282	0.00000
2.09282	0.00000
2.19282	0.00000
2.19282	0.00000
2.19282	0.00000
2.19282	0.10000
2.29282	0.10000
2.29282	0.00000
2.29282	0.00000
2.29282	0.20000
2.39282	0.20000
2.39282	0.00000
2.39282	0.00000
2.39282	9.60000
2.46543	9.60000
2.46543	0.00000

Buffer Strip Scenario

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	1.94206	2.19310	2.13201	0.04191	0.
1080.	2.06235	2.31314	2.25174	0.04167	3.
1800.	1.90693	2.15678	2.09865	0.04261	0.
2520.	1.59324	2.06054	2.02407	0.04844	0.
3240.	1.51600	1.98486	1.94583	0.04933	0.
3960.	1.49191	1.96523	1.92164	0.04991	0.
4680.	1.53986	2.01009	1.97059	0.04921	0.
5400.	1.55544	2.02279	1.98669	0.04879	0.
6120.	1.50888	1.97558	1.94000	0.04875	0.
6840.	1.82714	2.07594	2.01765	0.04235	0.
7560.	1.85653	2.10395	2.04777	0.04294	0.
8280.	1.91592	2.16480	2.10735	0.04238	0.

Histogram Plotting Points for August

X	Y
1.50888	0.00000
1.50888	0.10000
1.60888	0.10000
1.60888	0.00000
1.60888	0.00000
1.60888	0.00000
1.70888	0.00000
1.70888	0.00000
1.70888	0.00000
1.70888	0.10000
1.80888	0.10000
1.80888	0.00000
1.80888	0.00000
1.80888	0.10000
1.90888	0.10000
1.90888	0.00000
1.90888	0.00000
1.90888	9.70000
1.97558	9.70000
1.97558	0.00000

Ten-Day Storage Scenario

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	2.10210	2.62920	2.49853	0.11863	91.
1080.	2.19375	2.67791	2.54212	0.11901	96.
1800.	1.95192	2.62191	2.37533	0.17777	60.
2520.	1.60323	2.55856	2.08684	0.13002	7.
3240.	1.37545	2.04744	1.83319	0.09056	0.
3960.	1.21862	1.82976	1.66680	0.07120	0.
4680.	1.26594	1.79837	1.70631	0.05478	0.
5400.	1.28892	1.80738	1.72763	0.05300	0.
6120.	1.24595	1.80402	1.68664	0.06085	0.
6840.	1.73389	2.03734	1.93275	0.05565	0.
7560.	1.90624	2.37922	2.10925	0.07190	1.
8280.	2.07439	2.62191	2.41292	0.14970	71.

Histogram Plotting Points for August

X	Y
1.24595	0.00000
1.24595	0.10000
1.34595	0.10000
1.34595	0.00000
1.34595	0.00000
1.34595	0.00000
1.44595	0.00000
1.44595	0.00000
1.44595	0.00000
1.44595	0.10000
1.54595	0.10000
1.54595	0.00000
1.54595	0.00000
1.54595	1.10000
1.64595	1.10000
1.64595	0.00000
1.64595	0.00000
1.64595	7.80000
1.74595	7.80000
1.74595	0.00000
1.74595	0.00000
1.74595	0.90000
1.80402	0.90000
1.80402	0.00000

Six-Month Storage Scenario

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	1.58881	1.84323	1.77897	0.04096	0.
1080.	1.82622	2.08064	2.01638	0.04094	0.
1800.	1.54206	1.79647	1.73222	0.04097	0.
2520.	1.16892	1.61822	1.60279	0.04732	0.
3240.	1.01064	1.45992	1.44451	0.04730	0.
3960.	1.01064	1.45992	1.44451	0.04731	0.
4680.	1.16892	1.61819	1.60278	0.04732	0.
5400.	1.19048	1.63975	1.62435	0.04732	0.
6120.	1.01064	1.45992	1.44451	0.04731	0.
6840.	1.40917	1.66359	1.59933	0.04096	0.
7560.	1.43073	1.68515	1.62089	0.04096	0.
8280.	1.54206	1.79647	1.73222	0.04097	0.

Histogram Plotting Points for August

X	Y
1.01064	0.00000
1.01064	0.10000
1.11064	0.10000
1.11064	0.00000
1.11064	0.00000
1.11064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.10000
1.31064	0.10000
1.31064	0.00000
1.31064	0.00000
1.31064	0.10000
1.41064	0.10000
1.41064	0.00000
1.41064	0.00000
1.41064	9.70000
1.45992	9.70000
1.45992	0.00000

Incorporation of 2.2 Mg Manure per ha

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	1.58881	1.84323	1.77897	0.04096	0.
1080.	1.82622	2.08064	2.01638	0.04094	0.
1800.	1.54206	1.79647	1.73222	0.04097	0.
2520.	1.16892	1.61819	1.60278	0.04732	0.
3240.	1.01064	1.45992	1.44451	0.04731	0.
3960.	1.01064	1.45992	1.44451	0.04731	0.
4680.	1.16892	1.61819	1.60278	0.04732	0.
5400.	1.19048	1.63975	1.62435	0.04732	0.
6120.	1.01064	1.45992	1.44451	0.04731	0.
6840.	1.40917	1.66359	1.59933	0.04096	0.
7560.	1.43073	1.68515	1.62089	0.04096	0.
8280.	1.54206	1.79647	1.73222	0.04097	0.

Histogram Plotting Points for August

X	Y
1.01064	0.00000
1.01064	0.10000
1.11064	0.10000
1.11064	0.00000
1.11064	0.00000
1.11064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.10000
1.31064	0.10000
1.31064	0.00000
1.31064	0.00000
1.31064	0.10000
1.41064	0.10000
1.41064	0.00000
1.41064	0.00000
1.41064	9.70000
1.45992	9.70000
1.45992	0.00000

Incorporation of 400 Mg Manure per ha

Julian hour	Minimum/Maximum log FC/100 mL		Average	Standard deviation	Percent violations
360.	1.58881	1.84323	1.77897	0.04096	0.
1080.	1.82622	2.08064	2.01638	0.04094	0.
1800.	1.54206	1.79647	1.73222	0.04097	0.
2520.	1.16892	1.61819	1.60278	0.04732	0.
3240.	1.01064	1.45992	1.44451	0.04731	0.
3960.	1.01064	1.45992	1.44451	0.04731	0.
4680.	1.16892	1.61819	1.60278	0.04732	0.
5400.	1.19048	1.63975	1.62435	0.04732	0.
6120.	1.01064	1.45992	1.44451	0.04731	0.
6840.	1.40917	1.66359	1.59933	0.04096	0.
7560.	1.43073	1.68515	1.62089	0.04096	0.
8280.	1.54206	1.79647	1.73222	0.04097	0.

Histogram Plotting Points for August

X	Y
1.01064	0.00000
1.01064	0.10000
1.11064	0.10000
1.11064	0.00000
1.11064	0.00000
1.11064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.00000
1.21064	0.10000
1.31064	0.10000
1.31064	0.00000
1.31064	0.00000
1.31064	0.10000
1.41064	0.10000
1.41064	0.00000
1.41064	0.00000
1.41064	9.70000
1.45992	9.70000
1.45992	0.00000

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