Bacterial Pollution in Runoff from Agricultural Lands

WANADA R. BAXTER-POTTER* AND MARTHA W. GILLILAND

ABSTRACT

A review of the literature reporting the methods and results of studies concerned with the nature of nonpoint source microbial pollution leads to several conclusions: (i) Comparison of data from different studies may be complicated by variation in the choice of indicator organisms, variation in watershed size and homogeneity, and variation in media and procedures for determining fecal streptococcus densities. (ii) The ratio of fecal coliform to fecal streptococcus densities can be used to help identify particular sources of fecal pollution, but its usefulness declines with age. Its usefulness may also be affected by media and procedures used to determine fecal streptococcus densities, particularly when data derived from different media or procedures are compared. (iii) Bacterial densities in runoff from agricultural lands often exceed water quality standards. This is true of virtually all types of agricultural land. (iv) Although some connection between bacterial densities and stream discharge during storm events is apparent, the relationship is not simple. Factors such as temperature, hydrologic proximity of pollution sources, livestock management practices, wildlife activity, fecal deposit age, and channel and bank storage, all affect bacterial densities in runoff. Of these factors, only the influence of fecal deposit age on bacterial releases has been studied and quantified. (v) There is in the literature no loading function to predict bacterial densities in runoff that satisfactorily considers the factors listed above; however, typical density values may be used in a simple loading function to estimate probable density ranges.

Additional Index Words: **Coliforms, Fecal streptococcus, Nonpoint source pollution, Water quality, Feedlot management.**

In the 1970s it became apparent that the streams, lakes, estuaries, and aquifers of our nation were receiving significant pollutant loads from nonpoint sources. Today, nonpoint sources are the principal sources of the conventional pollutants for which the USEPA has established water quality criteria (Gianessi and Peskin, 1981). Agricultural lands are now the principal nonpoint sources of such conventional pollutants as biochemical oxygen demand (BOD), P, suspended solids, and bacteria (Gianessi and Peskin, 1981). In many central and western states, where very high percentages of the land are used for cattle (*Bos* sp.) production, fecal coliform bacteria are a prominent and troublesome conventional pollutant (Nebraska Dep. of Environmental Control, 1982).

Many studies offer insights into the nature of nonpoint source bacterial pollution, but no review of these studies is currently available. This review summarizes the methods and results of such studies.

First, factors that must be considered when evaluating or comparing data from different studies are discussed, and the use of the ratio of fecal coliform density to fecal streptococcus density (FC/FS) is described. Next, significant studies of bacteriological characteristics of agricultural runoff are reviewed in roughly chronological order, and feedlots are briefly discussed as a particular agricultural source of bacteria. Finally, a simple method suggested by McElroy (1976) for predicting bacterial densities is described.

FACTORS INFLUENCING DATA COMPARISON AND EVALUATION

Microbial water quality is not commonly determined by testing for specific microbial pathogens, but by testing for the presence and concentration of some indicator organism. Total coliforms (TC), fecal coliforms (FC), and fecal streptococci (FS) are the bacterial groups most commonly used as indicators of the presence of fecal contamination. Study reports may include data on one or all of these bacterial groups. Which bacterial groups are selected depends on the objectives of the research and on when the study was conducted. Fecal coliform densities are nearly always reported since FC are presently the preferred indicator organisms for water quality criteria and standards (Dep. of Interior, 1968; USEPA, 1976). Reports describing older studies tend to include TC data also, since early attempts to establish bacteriological water quality criteria relied on TC as indicator organisms (McKee and Wolf, 1963). Reports describing recent studies often include FS as well as FC data. Specific FS biotypes are sometimes identified in an attempt to identify the source of fecal pollution. This variation in the selection of indicators can complicate the comparison of data from different studies.

Some researchers sample established streams that drain large watersheds containing diverse agricultural lands. Others sample direct runoff from small watersheds that are relatively homogeneous in agricultural use and practice. This distinction is not clear-cut, yet it is important when evaluating and comparing the results of different studies. In studies sampling large watersheds the data reflect the combined effect from several indistinguishable sources. In addition, the fecal contamination detected has been subjected to instream conditions for an unknown period of time. The data collected tell more about the affected stream than about the pollution source. In studies sampling small watersheds distinct sources may be identified and samples collected before significant aging or stress occurs. The data collected tell more about the characteristics and possible significance of particular sources than about the condition of the affected stream.

Further complicating comparison of data from different sources, there is no general agreement on best laboratory procedures for measuring FS densities. Different media and procedures yield different results, making comparisons difficult, particularly where authors do not clearly state which methods were used. Three media (KF agar, Pfizer's Selective Enterococcus [PSE] agar, and

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Both authors, Civil Engineering Dep., Univ. of Nebraska-Lincoln, Omaha, NE 68182-0178. W.R. Baxter-Potter, current address: 1532 Rosemary Lane, Apt. D, South Bend, IN 46637. This work was funded through a grant from the Jane Layman Fund of the Univ. of Nebraska-Lincoln. Received 22 Sept. 1986. *Corresponding author.

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M-enterococcus medium) are commonly used in one of two procedures (membrane filter or pour plate).

Pavlova et al. (1972) evaluated five media for the isolation, enumeration, and identification of FS from several natural sources. Neither the membrane filter nor the pour plate procedure was used for comparison. Instead, 0.1 mL of each sample dilution was spread directly on each medium in triplicate plates. Pavlova et al. (1972) found that KF and PSE agars yielded the highest recovery of FS. The KF agar exhibited slightly better recovery of the strains *Streptococcus bovis* and *Streptococcus equinus*, the predominant but short-lived streptococcus strains in fresh cattle feces. The KF agar also supported a lower percentage of non-FS colonies (19%) than PSE agar (23%). However, Pavlova et al. (1972) pointed out that the PSE agar offered the advantage of a shorter incubation period (24 vs. 48 h).

In a comparison of media, Geldreich (1976) found that KF agar used in the membrane filter procedure consistently recovered higher densities of FS than M-enterococcus medium used in the membrane filter procedure. At least four of the studies reported by Geldreich (1976) indicated that both KF and PSE agars used in the pour plate procedure were "more sensitive for detecting FS in general, and *S. bovis* and *S. equinus* in particular." This conclusion is reasonably consistent with that of Pavlova et al. (1972).

Switzer and Evans (1974) found that KF broth used in the membrane filter procedure gave $<1\%$ recovery of *S. bovis*, but that PSE agar gave good recovery. They suggested that the omission of agar from the PSE formulation might improve recovery. This appears to be inconsistent with the conclusions of Pavlova et al. (1972) and Geldreich (1976) regarding the KF medium, but Switzer and Evans (1974) used a different form (broth) of KF medium in a different procedure.

When testing sewage samples, Pavlova et al. (1972) used KF agar in both the membrane filter procedure and the procedure described above. When used in the membrane filter procedure, KF agar recovered only 30 to 40% of the number of organisms recovered by the procedure used for comparison of media.

Though KF and PSE media appear, in general, to be preferable for recovery of FS, they may not perform identically. Their performance may depend on the predominant FS strains present, the procedure in which they are employed, and whether they are used in the agar or broth form.

THE FC/FS RATIO

Geldreich (1976) suggested that the ratio of FC/FS might be a useful tool for characterizing fecal pollution. He compiled literature data on measured FC and FS densities and calculated FC/FS ratios typical of feces from warm-blooded animals. His results suggested that FC/FS is 4 or higher for human fecal material and 0.6 or less for other warm-blooded animals. A range of 0.1 to 0.6 is typical of domestic animals, and values <0.1 are typical of wildlife.

Geldreich (1976) cautioned, however, that FC/FS in receiving waters gradually shifts as organisms age, because of differences in die-off rates. Since the predominant FS strains in domestic wastes are more persistent than FC, the FC/FS ratio for such wastes tends to decrease with time. In contrast, the FS strains that are more common in animal feces (*S. bovis* and *S. equinus*) are short-lived, thus FC/FS for wastes from animal sources tends to rise with time. This is particularly true of cattle and horse (*Equus* sp.) feces in which *S. bovis* and *S. equinus* predominate. Geldreich (1976) pointed out that aging fecal pollution in a stream from either type of source is often characterized by FC/FS ratios between 0.7 and 3.0.

The medium and procedure used to determine FS densities may also affect the usefulness of FC/FS. Geldreich (1976) suggests that both KF and PSE agars are suitable. However, they may produce results that are different enough to be misleading if data from studies using different methods or media are compared.

BACTERIOLOGICAL CHARACTERISTICS OF AGRICULTURAL RUNOFF

The following significant studies are reviewed in roughly chronological order. The evolution of both water quality standards and research objectives is reflected in the progression of the studies. The contemporary water quality criteria used by each researcher are given in the text when needed. Most commonly referred to are the TC and later FC criteria for primary contact (also referred to as bathing or swimming). They are: 1000 organisms per 100 mL (1000/100 mL) for TC, and 200 organisms per 100 mL (200/100 mL) for FC.

Weidner et al. (1969) studied six agricultural watersheds in southern Ohio in an attempt to correlate several water quality parameters with soil losses. Within each watershed, a single land use and management practice was employed. Land uses included corn (*Zea* sp.) fields, wheat (*Triticum* sp.) fields, meadows, and orchards. No mention is made of manure spreading. Correlations were developed for BOD, some chemical pollutants, and suspended solids but not for bacterial pollutants. However, Weidner et al. (1969) did observe that TC densities in runoff from all watersheds exceeded 1000/100 mL (the predominant bathing water criteria at that time) in at least 50% of the samples taken, and that TC densities in runoff from some watersheds exceeded the criteria in 90% of the samples taken. They also observed that FS densities exceeded FC densities, suggesting that sources of bacterial pollutants were animal rather than human.

Kunkle (1970a) studied a 75-ha Vermont watershed that included pasture, woodland, and hay fields. Stream discharge and TC and FC densities were monitored. A control plot was established in a hay field that had not been grazed, manured, or fertilized for at least 8 yr. Over 90% of his storm runoff observations contained higher densities of both TC and FC than predominant criteria for swimming (1000/100 mL and 200/100 mL, respectively). Kunkle's (1970a) findings indicated that background levels of bacterial pollutants rise during storms. This was particularly true of TC, which are ubiquitous in nature. Total coliform densities in runoff from the control plot were similar to TC densities in runoff from the grazed portion of the watershed. Conversely FC densities in runoff from the control plot were much lower than FC densities in runoff from the grazed portion of the watershed. Therefore, Kunkle (1970a) suggested that FC be used as a more specific and therefore better indicator of fecal pollution than TC.

Kunkle's (1970a) data demonstrated a relationship between bacterial densities and the hydrologic regime of the stream. Both TC and FC densities rose with stream discharge during storm runoff events. Although the bacterial density curves closely resembled the storm hydrograph, particularly the rising limb, no quantified correlation was developed for stream discharge and bacterial density. However, in a later paper discussing several studies concurrent with the one described above, Kunkle (1970b) noted that the relationship of bacterial densities to stream flow plotted as an hysteretic loop (Fig. 1).

Kunkle (1970b) suggested that since bacteria cannot be transported appreciable distances through soils (Romero, 1970), they must be transported in overland flow. He then cited several hydrologic studies which observed that upland areas of permeable watersheds contributed little or no overland flow during storms and that most overland flow occurred on saturated areas along channels. His plot studies confirmed these observations. He also suggested that the banks and bottom of the channel were significant sources of bacteria. He observed that bacterial densities rose sharply with stream flow when upstream releases created wave surges, and that bacterial densities rose with benthic disturbance caused by upstream wading. Kunkle (1970b) concluded that upland contributions of bacteria to streams were "minor" when compared to contributions from activities near the channels and that simple comparisons of watershed censuses of humans and animals with bacterial water quality could be very misleading. He urged that any interpretation of water quality should consider the hydrologic characteristics of the watershed involved and the proximity of possible fecal sources to channels. He also urged that pollution surveillance schemes not be limited to periodic sampling, but that they include storm event data as well.

Robbins et al. (1972) studied 12 typical agricultural sites in the Piedmont region of North Carolina. Five of the six sites were watersheds (2–26 ha) subjected to land-spread wastes, including pasture and feedlot operations. A sixth watershed, described as free from animal wastes, was used for control. Samples were analyzed for TC, FC, FS, 5-d and ultimate BOD, chemical oxygen demand (COD), total solids (TS), volatile solids, total organic carbon (TOC), total Kjeldahl N, ammonia nitrogen, NO_2-N, NO_3-N, total phosphate, orthophosphate, specific conductivity, and pH.

Robbins et al. (1972) reported that average bacteriological quality in streams arising in all six watersheds "greatly exceeded" quality limits generally set for

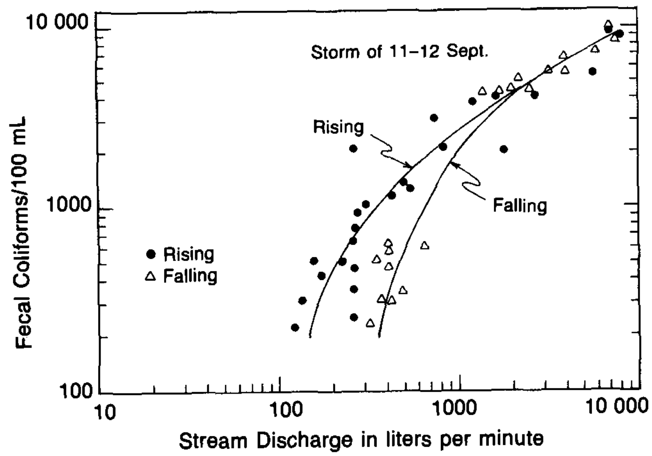

Fig. 1. Relationship of fecal coliform densities to stream flow in a pastured watershed stream during a major storm (Kunkle, 1970b; with permission).

bathing waters. Since bacterial densities from the control watershed were also high, the authors suggested that the pollution effects of animal wastes (when properly spread on watersheds) might be overshadowed by hydrologic factors such as rainfall, temperature, slope, soil permeability, surface culture, drainage pattern, degree of erosion, and antecedent moisture conditions.

Robbins et al. (1972) observed a strong relationship of pollutant concentrations with the storm hydrograph. In particular, TC and FC densities rose with stream discharge and receded at a somewhat slower rate. However, the magnitude of peak bacterial densities seemed to be more a function of season or temperature than of stream discharge. Figures 2 and 3 depict the hydrologic data and bacterial density data, respectively, from a stream draining a 14-ha watershed receiving wastes from 500 hogs (*Sus* sp.). The figures illustrate the relationship of bacterial densities with stream discharge. Bacterial densities were plotted for two storms. Densities for the May storm were higher than those for the March storm, even though stream flow was much lower in May. The authors attributed these higher densities to warmer temperatures.

Robbins et al. (1972) also attempted to develop predictive relationships. They reported that, of the pollution indices studied, TOC proved "particularly promising" as an indicator. Simple regression analysis revealed a "high" correlation of several pollutant indices with TOC. In particular, correlation coefficients for FC with TOC ranged from 0.050 for a watershed where poultry wastes had been spread, to 0.895 for a watershed where cattle grazed. The average of the correlation coefficients for the other four watersheds (including the control) was 0.532 with a median value of 0.464. Multiple regression analyses with such independent variables as number of animals, flow rate, and temperature did not produce statistically significant equations for predicting stream pollution.

Harms et al. (1975a, b) collected surface runoff from snowmelt and rainfall from seven agricultural sites in eastern South Dakota. Total coliform densities in snowmelt runoff exceeded the recommended limits for

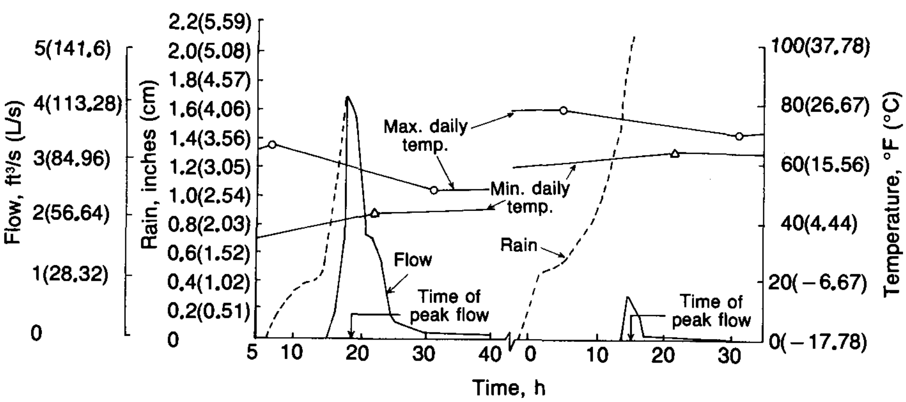

Fig. 2. Hydrologic data for two storms: 18 to 19 March and 19 to 20 May (Robbins et al., 1972; with permission).

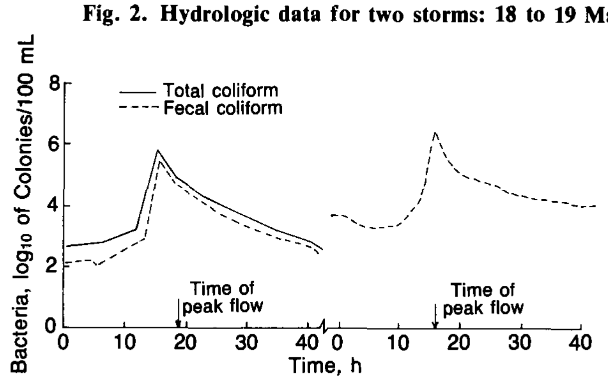

Fig. 3. Bacterial density data for two storms: 18 to 19 March and 19 to 20 May (Robbins et al., 1972; with permission).

treated public water supply (10 000/100 mL) with a frequency of 25% for oat (*Avena* sp.) stubble and alfalfa-bromegrass (*Medicago* sp.-*Bromus* sp.) hay field, 35% for pasture, 85% for fall-plowed fields, and >95% for grazed corn stubble. Fecal coliform densities in snowmelt runoff exceeded recommended limits for treated public water supply (2000/100 mL) with a frequency of 9% for grazed corn stubble, 15% for alfalfa-bromegrass hay field, and 50% for pasture. Sites with minimum ground cover (e.g., fall-plowed and corn stubble) yielded higher densities of FS in snowmelt runoff than well-covered fields (e.g., oat stubble). Rainfall runoff from cultivated fields bore FC densities that exceeded recommended limits for primary contact recreation (200/100 mL) with a frequency of 90%. FS densities were comparable to TC densities; both exceeded 5000/100 mL with a frequency of 90%. Harms et al. (1975a, b) concluded that surface runoff waters from agricultural lands carry indicator organism densities that frequently exceed water quality standards, and suggested that the contributions of nonpoint sources be considered when estimating the water quality benefits to be derived from further point source regulation. Nonpoint source pollution from agricultural runoff was regarded as unredressable and the authors suggested that water quality parameters be reviewed.

Andersen (1977), in a 2.5-yr study of a 2000-ha watershed in eastern Nebraska, sampled the base flow of Dee Creek on a weekly basis. Total coliform densities ranged from 240/100 mL to 3 300 000/100 mL with a mean value of approximately 87 000/100 mL. Fecal coliform densities ranged from <20/100 to 240 000/100 mL with an approximate mean of 4800/100 mL. Fecal streptococcus densities ranged from 60/100 to 28 000/100 mL with an approximate mean value of 1700/100 mL. The FC/FS ratios were not considered useful since samples were collected at the outlet of a large watershed from a stream that may have borne bacteria some distance from their source.

Significant variations were noted in some of the bacteriological data. Andersen (1977) suggested that particularly low densities at unexpected times might be due to the flushing action of preceding runoff events, and that particularly high densities might be due to the discharge of animal wastes in close proximity to the stream. Bacterial densities were generally higher in the spring and summer months and lower in the late fall and winter. This apparent seasonal variation could have been related to several factors such as temperature, livestock management practices, and manure handling practices.

Stephenson and Street (1978) sampled several streams in a 23 400-ha rangeland watershed in southwestern Idaho. Grazing took place in the watershed for about 6 months per year. The study spanned a 3-yr period. Samples were collected at 20 sites in the watershed and two sites downstream from the watershed. Sampling was periodic. Though sampling sometimes coincided with runoff events, the study was not an attempt to characterize runoff in particular, but stream flow in general. Samples were analyzed for TC and FC.

The authors found that the presence of cattle directly affected FC densities in the streams. The FC densities increased rapidly after cattle were introduced and remained high until cattle were removed. When large parcels of rangeland were grazed with a low level of management, FC densities remained high almost 3 months after cattle were removed in late fall. When management was more intense and the rangeland was fenced into allotments for deferred grazing, FC densities decreased rapidly after cattle were removed, though residual organisms were believed to remain in the soil and adjacent to the channels for some time. Stephenson and Street (1978) did not clearly attribute the difference in the rate of bacterial density decline to a difference in management practices nor did they suggest other possible causes.

At all sites, stream flow volume was reported to be more closely related to TC densities than to FC densities.

One site in particular was described where the stream dried up for several months, yet water was available to the livestock from several springs and cattle continued to graze above the sampling site. When stream flow resumed, coliform densities were high. During a period of warm, rainy spring weather a direct relationship (r = 0.85) between TC densities and increased runoff was observed. Yet for this same period, FC densities were reported as "not influenced" by the runoff. In fact, Stephenson and Street's (1978) data indicate that FC densities declined steadily to zero during that period. The high correlation was exceptional. Correlation coefficients of TC and FC densities with stream flow were generally low (r <0.45). Coliform densities usually rose with the rising storm hydrograph but peaked and began to decline rapidly before the storm hydrograph peaked. Stephenson and Street (1978) concluded that typical rangeland cattle grazing operations would probably result in coliform bacterial pollution of streams draining that rangeland, and that FC densities would probably exceed water quality standards frequently. Factors affecting bacterial density in these streams were livestock density, livestock access to streams, stream characteristics, hydrologic characteristics, and climatic characteristics.

Stephenson and Rychert (1982) found that *Escherichia coli* densities in bottom sediments of several rangeland streams in southwestern Idaho were from two to 760 times greater than in overlying waters. They concluded that organisms in bottom sediment were resuspended following disturbance or rainfall and contributed to pollution of the streams.

Doran and Linn (1979) studied the bacteriological quality of runoff from pasture land in eastern Nebraska for a period of 3 yr. Runoff samples from a 48-ha pasture and a 0.11-ha control area were tested for TC, FC, FS, and starch hydrolyzing FS. Starch hydrolyzing FS were presumed to be *S. bovis*, the predominant, though short-lived, microflora in cattle feces. Data from the study were tabulated in a later report (Doran et al., 1981). The TC and FC densities from both the grazed and ungrazed pasture usually exceeded current recommended water quality standards for primary contact (200 FC/100 mL and 1000 TC/100 mL) except when temperatures were low or cattle were absent. The TC densities from the grazed and ungrazed area were comparable but FC densities were five to 10 times higher in runoff from the grazed area. The FS densities in runoff from the control area were three times higher than FS densities in runoff from the grazed area. Doran and Linn (1979) attributed these high FS densities to an observed increase in wildlife activity in the ungrazed area. The FC/FS ratios from the control area were typical of wildlife feces. The FC/FS ratios from the grazed pasture were also typical of wildlife during snowmelt (0.020) but were characteristic of domestic animal feces when cattle were present (0.387).

Although bacterial densities were described by Doran and Linn (1979) as generally highest in early runoff peaks and decreasing thereafter, no relationship between FC and FS densities and either total rainfall or total runoff was observed. An apparent relationship between bacterial densities (FC and FS) in runoff from the grazed area and both stocking density and air temperature (assumed to be the same as water temperature for runoff) was reported but not quantified.

Doran and Linn (1979) also suggested that FC/FS ratios between 0.7 and 4.0, in runoff from pastures, may indicate situations where cattle have been close to sampling or outflow points, introducing fresh feces in the runoff. These elevated FC/FS ratios were related to differential die-off rates and were characteristic of domestic animal wastes (particularly cattle wastes) of recent origin. These results are consistent with Geldreich's (1976) suggestion that FC/FS ratios for fecal pollution from nondomestic sources would tend to increase with age.

Doran et al. (1981) also compiled data from several sources for TC, FC, and FS densities, and FC/FS ratios in runoff from a variety of nonpoint sources. Their purpose was to illustrate the consistency with which FC densities in runoff exceeded the 200/100 mL standard for primary contact recreation. These and Geldreich's (1976) data can also be used as baseline data when evaluating test results from runoff from similar sources or when attempting to estimate a probable median value for bacterial densities in runoff.

In a 3-yr study, Jawson et al. (1982) studied the bacteriological quality of runoff from a 21.5-ha watershed in the lower panhandle of Idaho. The watershed was characterized by winter precipitation and summer grazing. Most runoff events occurred while cattle were not on the watershed. A control watershed (9.9 ha) was fenced off to prevent grazing. Runoff samples were collected from both watersheds and analyzed for TC, FC, and FS. Fecal coliform densities from the grazed watershed were routinely >200/100 mL, and TC densities from both watersheds routinely exceeded 10 000 mL. Results suggested that TC and FS densities did not correlate well with the recentness of animal grazing. Flow-weighted average densities for TC and FS in runoff from the control watershed did not drop off significantly over the 3-yr period, but remained comparable to densities in runoff from the grazed watershed. The FC densities from the control watershed did decline with time, but slowly. They were as high as 200/100 mL 18 months after exclusion and did not drop to <10/100 mL until 2 yr after the exclusion of cattle. Fecal streptococci were described as more persistent than FC. The FS densities did decline steadily over the 3-yr period; however, they declined on both the grazed and the control watersheds. Although FC/FS ratios were lower in runoff from the ungrazed watershed, the authors did not believe that the dropping ratios could be attributed to a change in the source of fecal pollution, since the "persistence" of FS might have produced the same effect.

All bacterial densities from both watersheds rose each spring after a period of warm weather and before cattle were returned to the watershed. Jawson et al. (1982) did not suggest whether this rise might be due to a change in precipitation characteristics, an increase in bacterial availability due to thawing, or an increase in bacterial reproduction. However, runoff samples taken from

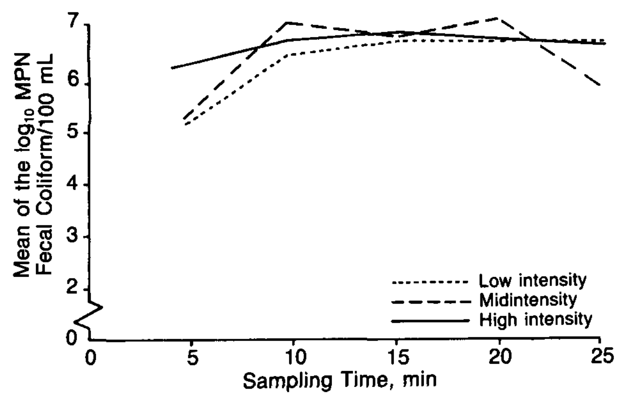

Fig. 4. Fecal coliform count at 5-min intervals for three rainfall intensities (23, 51, and 69 mm/h) using 2-d-old (unrained-on age) standard cowpies (Kress and Gifford, 1984; with permission).

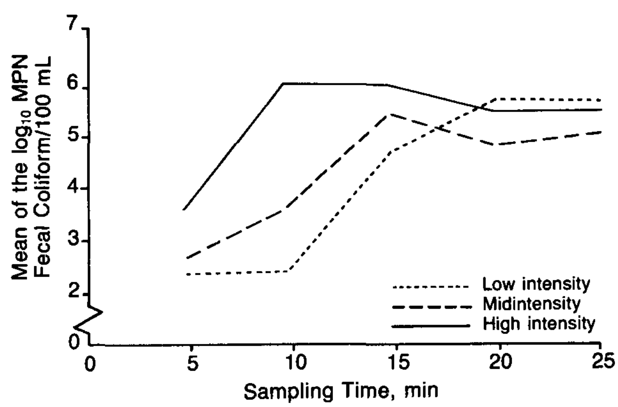

Fig. 5. Fecal coliform count at 5-min intervals for three rainfall intensities (23, 51, and 69 mm/h) using 10-d-old (unrained-on age) standard cowpies (Kress and Gifford, 1984; with permission).

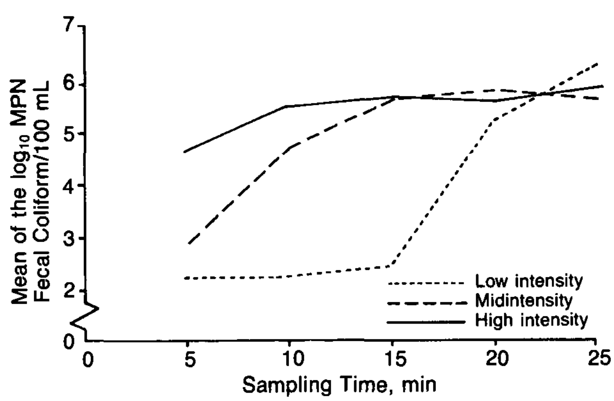

Fig. 6. Fecal coliform count at 5-min intervals for three rainfall intensities (23, 51, and 69 mm/h) using 20-d-old (unrained-on age) standard cowpies (Kress and Gifford, 1984; with permission).

several points within the grazed watershed exhibited the same increase in bacterial densities in warm weather that the main sampling site did, suggesting that the increase was a nonpoint phenomena and not associated just with the stream channel or a pond on the site.

Kress and Gifford (1984) studied FC releases from cattle feces as a function of three environmental factors. Rainfall intensity, fecal deposit age attained before rainfall, and recurrent rainfall were each studied for their effect on FC releases from standard cowpies. Standard cowpies were exposed to ambient temperature and sunlight conditions but were shielded from natural rainfall.

Figures 4, 5, and 6 illustrate the pattern of bacterial release from 2, 10, and 20-d-old fecal deposits subjected to low, medium, and high intensity rainfall. Rainfall intensity had no statistically significant effect on peak FC releases from fecal deposits that were 2 or 10-d-old (and still partially moist). However, on older (completely dry) fecal deposits (20-d-old), peak releases were significantly different. The highest intensity yielded the lowest peak releases and the lowest intensity yielded the highest peak releases.

Peak FC releases declined with the age of the fecal deposit. A log-log regression equation ($R^2 = 0.293$) was developed that described the relationship of fecal deposit age attained before rainfall and peak FC release during rainfall

$$\log Y = 7.57 - 1.97 \log X \qquad [1]$$

where Y = mean peak most probable number (MPN) (FC/100 mL), and X = age of fecal deposit prior to wetting (d).

When the fecal deposits were rewet, peak FC releases were consistently lower than peak releases from once wet deposits. This difference was statistically significant only in the third, fourth, and fifth of six wettings.

FEEDLOTS

The surface characteristics and surface treatments of feedlots are unlike those of other agricultural land uses. Ten thousand beef cattle may produce 330 Mg of excrement per day (McCalla and Viets, 1969) which are deposited on the feedlot surface. Feedlot surfaces are commonly "cleaned" by scraping manure accumulations into mounds or by removing manure altogether. They are devoid of vegetation, and are subject to severe hoof action. All of these surface characteristics and treatments have some effect on the quantity and quality of runoff.

Feedlots have long been identified as a particular agricultural source of severe stream pollution. Smith and Miner (1964) and Smith (1965) described severe slug flow pollution events attributable to feedlot runoff. Research has also established that feedlot runoff may contain pathogens that are harmful to humans (Miner et al., 1967; Bromel et al., 1971). Yet, data for bacterial densities in feedlot runoff are scarce.

Miner et al. (1966) measured bacterial densities for TC, FC, and FS from the two experimental feedlots studied. Kreis et al. (1972) also reported TC, FC, and FS densities as well as FC/FS ratios. Findings from both studies are summarized in Table 1. Bacterial densities vary greatly, even within the same study, but consistently exceed standards for primary contact.

PREDICTING BACTERIAL DENSITIES

None of the preceding studies presented a relationship that might be used as a loading function to predict

Table 1. Bacterial densities in feedlot runoff.†

Indicator organism	Miner et al. (1966) Unsurfaced lot‡	Miner et al. (1966) Concrete lot‡	Kreis et al. (1972) Bedrock and crushed stone base§
TC	22–348	33–348	12.5
FC	8–79	35–240	1.35
FS	8–79	13–24	73.7
FC/FS			0.003–0.08

† All densities reported as 10^6 organisms/100 mL.
‡ Ranges reported are 70% confidence limits of data.
§ Mean values.

bacterial densities in runoff. McElroy (1976) considered bacterial pollutant loading from uncontrolled feedlots and suggested that current data on known ranges of bacterial densities in feedlot runoff be used in a simple loading function where pollutant loading in a stream is expressed as

$$Y = aQCDA \quad [2]$$

where
Y = bacterial yield (organisms/d);
a = a dimensional constant (0.1 metric, 0.23 English);
Q = direct runoff (cm/d or in./d);
C = concentration of bacteria in runoff (organisms/L);
D = delivery ratio (a function of distance between source and receiving stream); and
A = area of livestock facility (ha, acres).

Table 2 summarizes the typical range of bacterial densities for three distinct types of agricultural land use: corn field, pasture, and feedlot. These values are taken directly from the literature cited. Typical density values such as these might be used in Eq. [2] to expand its applicability to include other land use types.

McElroy's (1976) equation assumes that bacterial density (C) does not vary with runoff rate or rainfall intensity, and no mention is made of temperature, seasonal, or stocking factors. The equation might be modified to consider indirectly the seasonal fluctuations apparent in Jawson et al.'s (1982) and Andersen's (1977) data by developing the C factor as a function of season. Similarly, C might be expressed as a function of temperature, in keeping with Doran and Linn's (1979) observations. In either case the value used for C would be a gross estimate based on wide-ranging data from a variety of sources.

SUMMARY AND CONCLUSIONS

Certain variable factors complicate the comparison and evaluation of data from different studies: (i) The choice of indicator organisms reported may vary and is primarily a function of the era and objectives of the study. (ii) Watershed size and homogeneity may vary. (iii) Selection of medium and procedure for determining FS densities may affect results.

The ratio FC/FS suggested by Geldreich (1976) has proved useful for identifying sources of fecal contamination (Doran and Linn, 1979; Doran et al., 1981; Jawson et al., 1982; Kreis et al., 1972; Weidner et al., 1969), particularly when the pollution has not aged in the stream. Its usefulness may also be affected by the media and procedures used to determine FS densities.

Table 2. Typical values from the literature for three land uses.†

Indicator organism	Literature
Corn field	
TC	15 800‡–145 000§
FC	5 400§–14 300‡
FS	16 200§–39 000§
Pasture	
TC	6 000§–329 000¶
FC	1 000§–57 000¶
FS	1 750§–172 000¶
Feedlot	
TC	22 000 000#–348 000 000#
FC	1 350 000††–79 000 000#
FS	8 000 000#–79 000 000#

† All densities reported as organisms/100 mL.
‡ Sewell and Alphin (1975).
§ Harms et al. (1975b).
¶ Doran et al. (1981).
# Miner et al. (1966).
†† Kreis et al. (1972).

Bacterial densities in runoff from agricultural lands often exceed water quality standards. This is true of virtually all agricultural land uses. Weidner et al. (1969), Kunkle (1970a), Robbins et al. (1972), Harms et al. (1975a, b), Andersen (1977), Stephenson and Street (1978), Doran and Linn (1979), Doran et al. (1981), Jawson et al. (1982), Miner et al. (1966), and Kreis et al. (1972) all reported TC and FC densities frequently in excess of primary contact standards. The agricultural lands studied included corn fields, wheat fields, fall-plowed fields, meadows, pasture, range land, feedlots, woodlands, and lands subject to manure-spreading.

The hydrologic proximity of potential fecal pollution sources to a stream is significant (Kunkle, 1970b; Stephenson and Street, 1978). If potential sources are deposited where organisms may not travel in overland flow to the receiving stream, their contribution to fecal pollution in the stream will be minor.

It is apparent that there is some relationship between bacterial densities and stream discharge during storms. Kunkle (1970a, b), Robbins et al. (1972), and Stephenson and Street (1978) reported that bacterial densities rose as stream discharge rose, and Doran and Linn (1979) observed that bacterial densities were generally highest during early runoff peaks. However, no quantified relationship was established. Other factors such as temperature (Robbins et al., 1972; Doran and Linn, 1979), hydrologic proximity of sources (Kunkle, 1970b), livestock density and proximity (Robbins et al., 1972; Stephenson and Street, 1987; Andersen, 1977; Doran and Linn, 1979), wildlife activity (Doran and Linn, 1979), fecal deposit age (Kress and Gifford, 1984), and channel and bank storage (Kunkle, 1970b; Stephenson and Rychert, 1982) affect bacterial densities in runoff. Kress and Gifford (1984) have made the only controlled study of a single factor's influence on bacterial releases.

There is in the literature no loading function to predict bacterial densities in runoff that explicitly considers the factors listed above. However, McElroy's (1976) approach might be expanded to other agricultural land uses by using typical values taken from the literature, such as those in Table 2.

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