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TRANSPORT OF POTENTIAL POLLUTANTS IN RUNOFF WATER FROM LAND AREAS RECEIVING ANIMAL WASTES: A REVIEW*

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Abstract—A state-of-the-art review is presented concerning the transport of nutrients (N and P), oxygen demanding compounds (BOD and COD), indicator organisms and pathogens in runoff from land areas receiving animal wastes. Three different land areas are considered: pastures and rangelands, land application sites, and feedlots. For land application sites, results of a linear regression analysis indicated highly significant correlations between constituent (N or P) loading rate and its concentration in runoff water, and also between constituent loading rate and its mass yield rate. Field plots receiving manure during winter and spring, and subject to snowmelt runoff followed a different relationship compared to those receiving applications during summer and fall, and not subject to snowmelt runoff. Effects of various factors, such as time and method of application, soil and cropping management practices, in relation to transport of nutrients are discussed. The limitations of the available data are discussed in terms of identifying future research needs. The greatest need appears to be that of relating the limited data on small plots to larger watersheds, and edge-of-field losses to receiving waters.

INTRODUCTION

Almost one-third of the pollutants entering the national waterways are derived from nonpoint sources (Agee, 1974). The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) require each state to submit a plan which shall identify agriculturally related nonpoint sources of pollution and define procedures and methods to control, to the extent feasible, these sources of pollution. Concerns about nonpoint source pollution are based on concentrations of nutrient elements such as nitrogen (N), phosphorus (P), oxygen demanding compounds (C), and pathogens in runoff water. Animal wastes are a major potential source of water quality degradation; they contain decomposable organic matter and nutrients (ASCE, 1977). Several studies have been conducted relating the losses of N and P in runoff waters from land areas receiving animal wastes. The objectives of this paper are to summarize the available information on the quality of agricultural discharges from areas receiving animal wastes, and to critically review the effects of climate, manure application rates, timing of application, and management practices relative to transport of potential pollutants such as N, P, oxygen demanding compounds, and pathogens via surface runoff. Attempts are also made to obtain relationships between nutrient (N and P) loadings due to manure application and constituent concentrations and mass yields in runoff water. For purposes of this review, three different land areas are considered: (1) croplands and other lands where animal wastes are mechanically spread; (2) pastures and rangelands where the animals, mainly beef and dairy, deposit wastes directly; and (3) feedlots.

N, P, AND C LOSSES FROM LAND APPLICATION SITES

Animal wastes are applied with an objective of either supplying plant nutrients (N and P) or for disposal purposes. When applied for crop utilization of N and P, application rates are usually low compared to those for disposal purposes. Under both conditions the amount of pollutants transported is dependent on climatic conditions, time of application, method of application, and soil and cropping management practices. The availability of N and P at the soil surface is also influenced by several biochemical processes. Processes affecting the availability of inorganic N at the soil surface include (i) mineralization of organic N (Reddy *et al.*, 1979a); (ii) ammonia volatilization (Reddy *et al.*, 1979b); and (iii) denitrification. Phosphorus availability at the soil surface is affected by (i) adsorption characteristics of the soil (Reddy *et al.*, 1979c); and (ii) mineralization of organic P. The rate at which these biochemical processes function is affected by soil and environmental factors; chemical composition; and rate, time, and method of application of animal wastes. Other factors affecting the

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Table 1. Transport of total N and P in runoff water from plot areas receiving animal wastes

Location	Type of manure	Time of application	Total N applied	Total N* runoff	Total P applied	Total P runoff	BOD runoff	COD runoff	Remarks	Reference
			kg ha^{-1} yr^{-1}							
Wisconsin	Fresh dairy	Winter	120	12.7	41.5	2.9	—	—	8 plots @ 3.0 × 12.2 m,	Minshall *et al.* (1970)
	Fermented	Spring	115	4.0	42.4	0.8	—	—	10–12% slope, silt	
	Liquid	Spring	95	3.6	35.8	1.0	—	—	loam soil, corn, 3 yr study	
Wisconsin	Dairy	Fall	128	13.1	22.5	3.5	—	—	10 plots @ 3 × 13.2 m,	Converse *et al.* (1976)
		Winter	121	18.7	24.8	2.4	—	—	10–12% slopes, silt	
		Spring	114	9.1	25.9	1.6	—	—	loam soil, alfalfa, 3 yr study	
N. Carolina	Swine		1344	23.4	605	11.6	—	202	9 plots @ 2.8 × 4.6 m,	Overcash (1976,
	lagoon		672	9.4	312	2.8	—	156	1–3% slope, sandy loam,	Unpublished data)
	effluent		336	8.0	151	3.0	—	124	coastal bermuda grass, 2 yr study	
Alabama	Liquid dairy		5661	13.8	1943	9.0†	39.1	208	12 plots @ 1.5 × 3.0 m,	McCaskey *et al.* (1971)
			3774	8.5	1296	5.2	22.9	125	3.3% slope, sandy loam	
			1782	11.0	612	5.0	25.3	120	soil, grassland, 1 yr	
	Semi-liquid		2416	8.2	1034	5.0	19.1	84	study	
	dairy		1611	6.5	689	2.2	13.7	60		
			805	8.2	345	2.6	17.7	56		
	Dry dairy		7769	18.3	—	7.6	25.4	107		
			5179	17.7	—	4.6	22.9	165		
			2590	7.5	—	1.4	12.5	48		
Ottawa	Dairy liquid	Winter	224	16.0	58	9.0	—	—	14 plots @ 75.6 × 11.6 m,	Phillips *et al.* (1975)
			560	54.8	149	8.5	—	—	sandy loam soil, 0.8% slope	
			897	97.7	235	12.0	—	—	1 yr study	
Minnesota	Dairy	Fall 1972	285	37.6	55.3	7.4			Alfalfa 8 plots @	Young & Mutchler (1976)
		Fall 1973	265	15.6	48.0	6.7			Alfalfa 4 × 23 m, 9%	
		Spring 1972	206	22.1	30.8	3.7			Alfalfa slope, 3 yr study	
		Spring 1973	371	0.4	62.4	0.1			Alfalfa	
		Fall 1972	285	4.9	55.3	0.6			Corn, manure plowed under	
		Fall 1972	285	5.2	55.3	1.6			Corn, manure on frozen ground	
		Spring 1972	206	5.4	30.8	0.6			Corn, manure on snow	
		Spring 1974	339	1.0	14.8	0.1			Corn, manure on snow	
	Liquid beef	Fall and Spring 1974	558	31.8	24.8	6.2			Alfalfa	
New York	Dairy	Winter	170	0.9‡	42.7	0.3			24 plots @ 61.0 × 53.5 m,	Klausner *et al.* (1976)
			478	18.4	117.3	3.6			continuous corn, 3 yr	
			924	3.1	213.0	1.5			study	
Alabama	Dairy		800	3.2‡	—	—	15.8	—	2 plots @ 0.04-ha, <2% slope, manure incorporated, 3 yr study	Lund *et al.* (1975)

* Total N = Organic N + NH_4–N + NO_3–N.
† Includes only PO_4.
‡ Includes only inorganic N (NH_4–N + NO_3–N).

availability of nutrients in runoff are (1) transport by leaching and (2) plant uptake.

In recent years, several studies have measured runoff water quality from areas receiving animal wastes (Minshall *et al.*, 1970; McCaskey *et al.*, 1971; Lund *et al.*, 1975; Klausner *et al.*, 1976; Phillips *et al.*, 1975; Converse *et al.* 1976; Young & Mutchler, 1976; Overcash, 1976 (unpublished data*)). The results of these studies are summarized in Table 1. They cover a broad range of climatic conditions, soil and manure types, and cropping and management practices. As indicated in Table 1, very little data are available on transport of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in runoff water.

Time of application

Application of wastes on snow during winter results in low biological activity and therefore, little or no transformation of applied N and P occurs. The runoff water quality from wastes applied in winter and spring and subject to snowmelt runoff, essentially consists of high concentrations of organic bound N and P, and oxygen demanding compounds. Animal wastes applied in summer and fall, and not subject to snowmelt runoff, readily undergo decomposition, thereby reducing concentrations of organic components in runoff water.

Several researchers have documented effects of winter and spring applied manures on nutrient losses. Minshall *et al.* (1970) reported that when dairy manure was spread on frozen ground during 1966–67, up to 20 and 13%† of applied N and P, respectively, were lost under conditions favoring maximum early spring runoff. They also found that nutrient losses in surface runoff from plots receiving manure incorporation in summer were less than those from check plots which received no manure.

Runoff and nutrient losses from alfalfa plots receiving manure applications in fall, winter and spring were monitored for a three-year period by Converse *et al.* (1976). The total N and P losses showed no significant difference between treatments, but losses for 1973–74 were significantly higher than those for the first 2 years for all plot conditions. This was believed to be related to the high percentage of runoff that occurred as surface runoff during the winter months in 1973–74 compared to earlier years.

Klausner *et al.* (1976) evaluated surface runoff losses of inorganic N and total soluble P from fields receiving winter applications of dairy manure. Average runoff values of inorganic N for the three rates of manure application (35, 100, and 200 metric tons ha^{-1}) were 16, 1, and 0.2 kg ha^{-1} for 1972, 1973, and 1974, respectively; phosphorus losses averaged 3.5, 0.7, and 0.01 kg ha^{-1} for the three respective years. Adverse weather conditions during the winter application in 1972 were largely responsible for increased nutrient discharges in runoff. This was especially true for the 100 metric tons ha^{-1} (478 kg N ha^{-1}) treatment (Table 1), which was applied on 15–20 cm of dense melting snow overlying frozen soil.

Young & Mutchler (1976) measured nutrient losses in snowmelt runoff from manure applied frozen plots in which corn and alfalfa were grown. Snowmelt losses from alfalfa plots receiving manure in fall on frozen ground and in spring on top of snow, were 3–10 times the N losses from nonmanured areas; the P losses were as high as 67 times the nonmanured P losses for the 1973 fall application. The N losses from fall applied manured corn plots never exceeded that of nonmanured check plot; the P losses ranged from 3 to 8 times that of check plot.

The importance of timings of surface manure application with respect to runoff events was illustrated by Ross *et al.* (1978). A 1-day delay period between application of liquid manure and simulated rainfall event reduced yield of the pollution parameters (COD, N) in runoff by at least 80%, and in some cases by as much as 97%. This phenomenon is due primarily to reduced solid loss. Concentration of total solids declined rapidly with increasing time before runoff, probably due to a drying of the waste material and increased infiltration.

High nutrient losses appear to result from runoff occurring shortly after application, such as when manure is spread on melting snow, or when rain follows application on frozen soil or snow. For example, Hensler *et al.* (1970) found that 10 and 6% of applied N and P, respectively, of winter-applied manure were lost in runoff. These losses, however, were entirely a result of runoff from a 1.9-cm rain that fell within 24 h after the manure had been applied to frozen ground.

Method of application

Manure application methods affect nutrient loss in two ways. First, surface-applied animal wastes undergo less rapid decomposition compared to soil-incorporated wastes. Runoff water from surface application sites may therefore contain higher concentration of manure particles carrying N, P, and COD compared to runoff water from areas receiving soil-incorporated wastes. Second, incorporation of animal wastes improves the soil physical properties such as bulk density, water holding capacity, hydraulic conductivity, and infiltration rate (Khaleel *et al.*, 1979), thus decreasing runoff volume and accompanying erosion.

Reddell *et al.* (1971) evaluated the quality of irrigation water runoff from deep plowed manured plots receiving one-time applications of 0, 336, 672, and 1008 metric tons ha^{-1} of dry manure. Three different treatments were used: 76-cm moldboard, 46-cm moldboard, and 69-cm trencher. Results indicated no sig-

* Overcash, M. R. 1976. Unpublished data. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, NC.

† Per cent of applied N or P lost or transported = (Total N or P in kg ha^{-1} in runoff/Total N or P in kg ha^{-1} in applied manure) × 100.

nificant difference among treatments in terms of nitrates, nitrites, dissolved solids, or chlorides in the irrigation water runoff. The greatest potential for polluting surface water was from ammonia and phosphate which increased to 140 and 15 mg l^{-1}, respectively, with an application rate of 1008 metric tons ha^{-1}, for the first irrigation. With the second irrigation, however, ammonia and phosphate levels reduced to 35 and 5 mg l^{-1}, respectively.

McCaskey *et al.* (1971) evaluated the quality of runoff from grassland to which three rates of manure were applied by irrigation, tank spreader (semi-liquid), and conventional (dry) methods. Rates of manure application were different for each treatment. Consequently, it was difficult to compare treatments. The application of waste by the conventional method on permanent disposal sites at rates greater than 7.16 metric tons ha^{-1} (dry basis) once each 3 weeks resulted in marked accumulation of manure solids. The BOD and COD losses under the three methods of application showed no consistent patterns although their average losses under the irrigation (liquid) method of application were highest.

Ross *et al.* (1978) found that compared to surface application, injection of liquid manure into the soil essentially eliminated any pollutant yield in runoff. For example, the concentration of COD in the first liter of runoff, from sodded plots receiving surface application, followed immediately by simulated rainfall was 72 times higher than in the first liter of runoff from the 15-cm injected plots. Likewise the total COD yield in the first 100 l. of runoff was 17 times greater for surface-applied plots than for the 15-cm injected plots. Similarly, for bare soil the first liter of runoff contained approx. 80 times as much COD as in the first liter of runoff from injected plots. The depth of injection had essentially no effect on pollutant yield for the 15- and 30-cm injection depths used in their experiments.

Limited data are available relating nutrient losses to manure application methods. Studies by Ross *et al.* (1978) suggest that incorporated manure is more effective in reducing losses in runoff compared to surface application methods. However, results contrary to this were found by Young (1974) in a simulated rainfall study. For surface applied solid wastes on corn plots, maximum N and P losses were only 16 and 26 percent of those from the non-manured check plot; whereas for the manure incorporated corn plot, maximum N and P losses were as high as 70 and 93% of those from the check plot.

Soil and cropping management practices

Soil management is one of the most important parameters in controlling nutrient losses from manured areas. Zwerman *et al.* (1974) studied runoff quality under two systems of soil management. One involved the removal of all plant residues at harvest, which they defined as poor management. The other involved the reincorporation of plant material with the soil, which they defined as good management. The results indicated, under snowmelt conditions and for all rates of manure application, N and P yields in surface runoff under good soil management were only 1/3 as high as under poorly managed soils. The crop being studied was continuous corn.

The effect of vegetative cover on runoff losses for field plots receiving waste applications was studied by Young & Mutchler (1976). Spreading manure on field plots planted to alfalfa represented more of a pollution hazard than spreading manure on plowed corn plots. Higher N and P losses occurred from the manured alfalfa plots compared to losses from the alfalfa check (nonmanured) plot and the corn plots.

In a study reported by Young (1974), liquid beef and solid dairy wastes were applied within 30 days after planting, to three different corps; corn, oats, and alfalfa. Simulated rainfall was used to generate runoff and soil loss. Alfalfa differed from the corn and oats—the manured alfalfa plots had from 4 to 7 times as much total N loss as the check (nonmanured) plot and 3 times as much total P loss.

Hensler *et al.* (1971), using small runoff plots (1.2 × 1.2 m), studied the N and P losses from winter-applied fertilizer and manure in runoff water from fallow and sod or vegetated soils. The concentration of nutrients in the runoff water was lower for fallow areas compared to vegetated areas. They suggested that although runoff is usually much less for vegetated soil compared to bare soil, vegetation prevents waste components from coming in contact with the soil, thereby increasing the likelihood of waste constituents being removed in the runoff. Ross *et al.* (1978) also found that after a 1-day period between application of liquid manure and the simulated rainfall event, runoff from the bare soil generally contained a much lower percentage of COD and N compared to the runoff from sod. However, results of 0-day delay tests showed no significant differences in terms of pollutant yields from bare and sodded plots.

Research on effects of soil management on nutrient loss tends to indicate that improvement of soil structure will improve the quality of runoff water. This was evident when, spreading manure even under adverse (frozen ground) conditions, a 2/3 reduction in total N and P losses was achieved by maintaining soil structure through return of plant residues (Zwerman *et al.*, 1974). Incorporation of manure after application is generally a good management practice that reduces surface runoff contamination as indicated by Ross *et al.* (1978).

Rate of application

Increasing the rate of application of animal waste increases the availability of potential pollutants at the soil surface, thus increasing their concentrations in surface runoff waters. Data on runoff water quality (McCaskey *et al.*, 1971; Phillips *et al.*, 1975; Zwerman *et al.*, 1974; Young & Mutchler, 1976; Klausner *et al.*, 1976; Converse *et al.*, 1976; Overcash, 1976 (unpub-

Table 2. Relationships between constituent loading rates, constituent concentration in runoff water, and mass yield rates

Time of application	Constituent	Dependent variable, Y§	Equation‡,§	Correlation coefficient, r	Number of observations, n
Winter and spring	N	Concentration	$Y = 2.45 + 0.081\,X$	0.84†	16
Winter and spring	N	Yield	$Y = 0.105\,X - 6.39$	0.93†	14
Winter and spring	P	Concentration	$Y = 3.27 + 0.054\,X$	0.72*	17
Winter and spring	P	Yield	$Y = 1.60 + 0.064\,X$	0.80†	14
Summer and fall	N	Concentration	$Y = 6.6 \ln X - 22.84$	0.84†	20
Summer and fall	N	Yield	$Y = 5.60 + 0.00161\,X$	0.86†	20
Summer and fall	P	Concentration	$Y = 2.29 + 0.0071\,X$	0.81†	22
Summer and fall	P	Yield	$Y = 1.28 + 0.0028\,X$	0.88†	21

* Significant at 99% level.
† Significant at 99.9% level.
‡ Independent variable X: loading rate in kg ha^{-1}yr^{-1} of indicated constituent.
§ Dependent variable Y: concentration in mg l^{-1} or yield in kg ha^{-1} yr^{-1} of indicated constituent in runoff.

lished data)) indicate that land areas receiving low rates of application do not contaminate surface water as much as those receiving high rates of application.

Data on N and P losses in runoff waters, obtained from literature sources, were analyzed in an attempt to determine a relationship between the constituent (N or P) loading rate (kg N or P ha^{-1} yr^{-1}) due to manure application and its concentration in runoff water. Since limited data are available for BOD and COD, loading rate relationships were attempted only for N and P. In upper midwest and north-eastern states, winter and spring manure applications are subject to snowmelt runoff which may constitute as much as 60–70% of annual runoff. Therefore, the water quality data were divided into two categories based on whether the runoff was mainly snowmelt or rainfall-runoff.

A linear regression analysis showed highly significant relationships between the constituent (N or P) loading rate and its concentration in runoff water, and also between constituent loading rate and its mass yield rate (Table 2). The importance of snowmelt runoff is apparent when the relative concentrations or yield rates are compared. For a loading rate of 1000 kg N ha^{-1} yr^{-1}, for areas subject to mainly rainfall-runoff and receiving fall and summer applications of manure, the best fit lines (Table 2) predict a total N concentration of 22.8 mg l^{-1} and a yield rate of 7.2 kg N ha^{-1} yr^{-1}. For the same loading rate of 1000 kg ha^{-1} yr^{-1}, for areas subject to snowmelt runoff, and receiving winter and spring applications of manure, the best fit lines (Table 2) predict a total N concentration of 83.5 mg l^{-1} and a yield rate of 98.6 kg N ha^{-1} yr^{-1}. This represents increases of 2.7 times in total N concentration and 12.7 times in total N yield rates over those areas not receiving snowmelt runoff. Similarly for P, the best fit lines for summer and fall applications predict a total P concentration of 4.1 mg l^{-1} and a yield rate of 2.0 kg P ha^{-1} yr^{-1}, for a P loading rate of 250 kg P ha^{-1} yr^{-1}. For areas subject to snowmelt runoff, a total P concentration of 16.8 mg l^{-1} and a P yield rate of 17.6 kg P ha^{-1} yr^{-1} are predicted for a loading rate of 250 kg P ha^{-1} yr^{-1}. This again represents an increase of 3.1 times in total P concentration and 7.8 times in total P yield rates over those areas not subject to snowmelt runoff.

The conclusions which may be drawn on the effect of loading rates on nutrient losses can be summarized as:

1. There is an influence of loading rate on N and P losses in runoff water. However, the effects of several other factors, such as time of application, method of application, soil and cropping management practices, and their interactions need to be recognized.
2. The plot areas receiving manure during winter and spring, and subject to snowmelt runoff resulted in significantly higher N and P losses compared to those receiving applications during summer and fall, and not subject to snowmelt runoff.
3. As might be expected, some amount of scatter is associated with nutrient data, especially at lower loading rates. This can be attributed to variations in climatic, management and vegetative influences. The nutrient data obtained under extreme climatic conditions were not considered in determining the given relationships.
4. The available data on N and P losses are for small plot-sized areas and should not be interpreted as amounts reaching the streams. Also, in view of limited data being available and because of interaction of several factors, the given relationships should be cautiously used.

N, P, AND C LOSSES FROM PASTURES AND RANGELANDS

Nonpoint pollution from pastured livestock areas and rangelands depends in part upon the stocking density, length of grazing period, average manure loading rate, manure spreading uniformity by grazing livestock, and disappearance of manure with time (Sweeten & Reddell, 1978). Normally, pasture areas have not presented appreciable water quality problems except under special circumstances (Collins, 1975; Robbins *et al.*, 1971). While the manure per unit area of rangeland or pasture is not large, the total

Table 3. Quality of runoff water from pastures and ranglands

Location	Description of the site	Total N* mg l^{-1}	Total N* kg ha^{-1} yr^{-1}	Total P mg l^{-1}	Total P kg ha^{-1} yr^{-1}	BOD mg l^{-1}	BOD kg ha^{-1} yr^{-1}	COD mg l^{-1}	COD kg ha^{-1} yr^{-1}	Reference
Texas	Continuously grazed	0.94	—	0.04	—					Smeins (1976)
	Rotationally grazed	0.64	—	0.07	—					
Oklahoma	Continuously grazed	—	9.73	—	4.60					Olness *et al.* (1975)
	Rotationally grazed	—	2.09	—	1.27					
Tennessee	Heavily grazed pasture I	4.5†	—	7.1‡	—					Sewell & Alphin (1975)
	Heavily grazed pasture II	5.1	—	1.2	—					
S. Dakota	Pasture (with animals)	—	1.52	—	0.25					Dornbush *et al.* (1974)
	Grassland	—	0.97	—	0.10					
	Cultivated land	—	1.28	—	0.30					
N. Carolina	Site F—control	1.2	3.8	0.2‡	0.6‡	2.0	6.0	—		Robbins *et al.* (1971)
	Site E—200 sows on 1.2 ha of drylots plus wastes spread on 2 ha	1.1	2.8	1.2	3.0	4.7	11.0	—		
	Site K—200 hogs on 2.5 ha of drylots	1.4	2.8	1.9	3.8	6.4	13.0	—		
	Site H—dairy cows on 22 ha of pasture and wastewater from milking area followed directly into stream	7.1	14.1	4.6	9.2	17.0	34.0	139	276	
	Site J—dairy cows on 5 ha of pasture and wastewater from milking area followed directly into stream	19	145	18	143	165	1260	504	3918	
	Site P—54 mt of poultry wastes plus shavings spread on 6 ha, yearly	1.9	3.7	1.2	2.0	5.2	9.4	63	117	
	Site D—150 sows on 4 ha of drylot plus discharge from 100 confined hogs	13	78	6.9	40.9	73	429	—	—	
	Site Z—35 dairy cows on 6 ha pasture	1.2	2.1	1.1	2.0	9.8	17	149	264	
	Site X—20 mt of poultry wastes spread on 1.6 ha, once	60	159	—	—	265	679	600	1395	
S. Carolina	Site A—50 to 600 m above major farm drainage area§	2.5	—	2.5	—	12.4	—	17.7	—	Janzen *et al.* (1974)
	Site B—adjacent to major farm drainage area	3.6	—	3.8	—	50.5	—	68.3	—	
	Site C—50 to 600 m downstream of major farm drainage area	3.0	—	2.8	—	19.4	—	27.7	—	
Florida	Average of two pasture sites	—	5.3	—	0.3	—	—	—	—	Wanielista *et al.* (1975)

* Total N = Organic N + NH_4-N + NO_3-N.
† Includes only NO_3-N.
‡ Includes only Ortho-P.
§ Average of three disposal systems.

area in parts of the United States devoted to this land use is very large; hence initial concern existed for the nonpoint source impact of such areas. Potential problems also increase in cases where animals tend to congregate around feeding, watering, and resting areas, in proximity to streams or waterways.

Several studies have been reported concerning total N and P losses in runoff from pastures and rangelands containing grazing animals. Table 3 summarizes data from several sources. Smeins (1976) studied the effect of various rangeland livestock grazing management programs on the quantity and quality of surface runoff. The highest total N concentration from a heavy continuously grazed pasture was $0.94\,mg\,l^{-1}$, while a pasture with a deferred rotation grazing scheme had a total N concentration of $0.64\,mg\,l^{-1}$ on the same date. Nutrient losses appeared to be more related to sediment loss than to animal waste loadings. Generally, less sediment loss occurred on better vegetated watersheds.

Olness *et al.* (1975) found that rangelands where animals were continuously grazed contributed at least four times more N and P in runoff compared to rotationally grazed rangelands. These findings emphasize that grazing management systems influence water quality through erosion/sediment control, that pollutant yields are directly proportional to runoff amounts, and that grazing may decrease infiltration rates, and thereby, increase runoff and pollutant yields (Robbins, 1978).

The contribution of pollutants from pastured livestock areas may sometimes be so small compared to, and so completely confounded with, background or other pollutants, that the contribution due to animal activity is not possible to establish. Dornbush *et al.* (1974) evaluated runoff quality from different land-use areas, and found no significant differences in N and P yields from cultivated areas, pasture, and grasslands.

Sewell and Alphin (1975) studied problem areas associated with unconfined animal production systems. Average nitrate–nitrogen concentration in runoff from two sites on a heavily grazed dairy pasture system exceeded those from all other sites, including those of an aerobic lagoon and drainage from cultivated lands. Mean orthophosphate concentrations in runoff from the dairy pasture were exceeded only by those of aerobic lagoon waters.

Janzen *et al.* (1974) sampled streams above, adjacent to, and below 22 dairies. Disposal systems included lagooning, dry disposal, and liquid manure handling. In case of dry disposal systems, increased NO_3–N (from *ca.* 2.3 to *ca.* $3.9\,mg\,l^{-1}$) and phosphate (from *ca.* 2.4 to $3.6\,mg\,l^{-1}$) levels existed between upstream and adjacent sampling sites. Average concentrations of both these indices were *ca.* $2.9\,mg\,l^{-1}$ at sampling points 50–600 m below the dairies. Increased levels of BOD and COD were present at sampling points adjacent to the dairies.

From a study of 12 agricultural watersheds, Robbins *et al.* (1971) found that distinguishing between pollutants from farm animal production units and natural pollutants in receiving streams is difficult or impossible. Results from studies of three pasture areas, along with the control, are summarized in Table 3. A comparison of total N yields per unit watershed area from the sites (F vs E, K, and Z) suggest that no increase occurred due to animal activity. The researchers attributed the increased N yield from site E to the hog wastes spread in the watershed, increasing the NO_3–N content of the groundwater and base flow in the stream, rather than to the sow drylot operation.

The review on pollutant yields from pastured production units indicates that total N and P yields from these areas are not related to the number of animals involved, and therefore, they are not related to either the amount or the characteristics of animal wastes involved (Robbins, 1978). Rather, yields are intimately related to hydrological and management factors. Control of the quality of water discharged from pastures and rangelands is thus dependent on: (1) control of management practice, like continuous grazing or rotational grazing; (2) control of erosion and sediment transport; and (3) control of direct runoff.

TRANSPORT OF N, P, AND C FROM FEEDLOTS

Normal stocking rates in feedlots range from 10 to $50\,m^2$ per animal (Clark *et al.*, 1975). Because of these large concentrations of cattle, large amount of wastes accumulate which create a potential for pollution when storm runoff occurs. The quantity of pollutants discharged from a feedlot depends upon the runoff volume and the pollutant concentration in the runoff. Runoff volume from a feedlot depends upon: (a) amount and intensity of precipitation; (b) soil moisture conditions; (c) topography including slope and surface cover; and (d) soil characteristics. Stocking rates, which are determined in part by local precipitation patterns such as humid or arid conditions, affect the degree of compaction of the surface and thus the runoff volume. The available data (Madden & Dornbush, 1971; Kreis *et al.*, 1972; White, 1973; Clark *et al.*, 1974; Clark *et al.*, 1975; Wise & Reddell, 1973; Manges *et al.*, 1975; Gilbertson *et al.*, 1975) on feedlot runoff characteristics are summarized in Table 4. Most data are from the Great Plains region.

As indicated in Table 4, the range of concentrations is wide. The average total N concentration ranged from a low of $50\,mg\,l^{-1}$ at Bellville, TX to a high of *ca.* $2100\,mg\,l^{-1}$ at Mead, NB. Similarly the average COD ranged from $4000\,mg\,l^{-1}$ at Bellville, TX to $41{,}000\,mg\,l^{-1}$ at Mead, NB. Snowmelt runoff resulting from winter thawing conditions produced higher concentrations of pollutants than those produced by rainfall-runoff (Manges *et al.*, 1975; Gilbertson *et al.*, 1975). The average total N concentration for snowmelt runoff was almost 2.5 times that of rainfall-runoff at Mead, NB. The greatest difference in values between snowmelt and rainfall-runoff was for the

Table 4. Transport of pollutants from feedlots at various locations, ranges in concentration and average concentrations

Location	Runoff type	Total N (mg l^{-1})	Total P (mg l^{-1})	BOD (mg l^{-1})	COD (mg l^{-1})	Remarks	Reference
Pratt, KS	Rainfall runoff	85–1580 (583)*	9–482 (83)	—	860–16,100 (6855)	Average of runoff data from two areas: area 119 (0.82 ha, 1% slope) and area 2 (11.1 ha, 1.3% slope). Average stocking rate 28 m^2/animal; 2 yr study period	Manges *et al.* (1975)
	Snowmelt runoff	590–2340 (1240)	65–459 (190)	—	7300–35,760 (14,915)		
Mead, NB	Rainfall runoff	11–8593 (854)	2–1425 (151)	—	1300–8200 (3100)	0.11 ha area, 3%, 6%, 9% slopes; stocking rate 19 m^2/animal, 5 yr study period	Gilbertson *et al.* (1975)
	Snowmelt runoff	190–6528 (2105)	5–917 (292)	—	14,100–77,100 (41,000)		
Coshocton, OH	Rainfall runoff	—	—	9–744	350–6340	0.17 ha unpaved barnlot, 13% slope, stocking rate 28 m^2/animal, 2 yr study	White (1973)
Sioux Falls, SD	Rainfall and Snowmelt	277	184	942	4093	Average of 6 feedlot sites, ranging from 0.13 ha to 21.3 ha, 2 to 15% slopes, stocking rate 53 m^2/animal on site No. 15. Approximately 30% of total annual runoff is snowmelt, 2 yr study.	Madden & Dornbush (1971)
McKinney, TX	Rainfall runoff	31–493 (228)	21–223† (69)	1075–3450 (2201)	1439–16,320 (7210)	13 ha area, average slope 13%, stocking rate 9 m^2/animal, 2 yr study	Kreis *et al.* (1972)
Bellville, TX	Rainfall runoff	4–125 (50)	5–305 (85)	—	500–14,000 (4000)	7.5 ha area, avg. slope 3%, stocking rate 35 m^2/animal, 1 yr study	Wise & Reddell (1973)
Bushland, TX	Rainfall runoff	600–2400 (1083)	100–500 (205)	—	10,000–20,000 (15,700)	4 ha area, slope 1.5%, stocking rate 12 m^2/animal, 3 yr study	Clark *et al.* (1974)
Ft. Collins, CO	Rainfall and Snowmelt	1153*	93	—	17,800	0.4 ha area, slope 6%, stocking rate 19 m^2/animal, 3 yr study	Clark *et al.* (1975)

* Averages.
† PO_4 only.

COD. The COD concentration in snowmelt runoff was almost 13 times that in rainfall-runoff (Mead, NB) indicating that materials contained in snowmelt runoff are composed primarily of undecomposed manure (Gilbertson *et al.*, 1975).

Loehr (1974) reported runoff losses (areal yield rates) from feedlot areas ranging from 100–1600 kg N ha^{-1} yr^{-1} and 10–620 kg P ha^{-1} yr^{-1} for total N and P, respectively. The BOD and COD losses averaged 1560 and 7200 kg ha^{-1} yr^{-1}, respectively. When compared to runoff losses from land application sites, available data (Table 1) indicate ranges of 1–98 kg N ha^{-1} yr^{-1} and 1–12 kg P ha^{-1} yr^{-1} for total N and P, respectively. The BOD and COD losses for land application sites range from 13–39 and 48–208 kg ha^{-1} yr^{-1}, respectively (Table 1). These illustrate the pollution potential of runoff from feedlot areas compared to land application sites.

PATHOGENS AND INDICATOR ORGANISMS

Pathogenic organisms are largely retained at or near the soil surface thus creating greater potential for pollution of surface runoff waters. Transport of organisms in runoff water depends on survival periods of pathogens, and their release from soil particles into runoff water. Pathogen contamination of runoff water is usually based on the number of indicator organisms, such as total coliforms (TC), fecal coliforms (FC), fecal streptococci (FS) or enterococci. Runoff water quality with respect to pathogen contamination is considered for: (i) land application sites and feedlots; and (ii) pastures and rangelands.

Land application sites and feedlots

Most of the available data on runoff water quality do not contain information on pathogen contamination of surface water. The data obtained from a few available sources are summarized in Table 5.

Transport of indicator organisms in runoff water was demonstrated by Van Donsel *et al.* (1967), who simulated soil contamination by periodically introducing 'tracer' strains of coliform bacteria to outdoor plots and measuring losses of the indicator bacteria in runoff resulting from natural rainfall. Organisms isolated from runoff were in direct relation to counts in the soils. Generally counts in the soil below 10,000 per gram of soil resulted in no isolation of coliform bacteria in the runoff water.

Application of liquid dairy manure in winter resulted in higher concentration of fecal coliform and fecal streptococci in runoff water compared to application in spring or fall (Phillips *et al.*, 1975). This is due to long survival periods of FC and FS in winter, compared to spring or fall. Other studies reported by McCaskey *et al.* (1971) and Reddell *et al.* (1971) showed elevated levels of FC and FS in runoff water from land application sites compared to runoff water from control (nonmanured) plots. The concentration of fecal coliform and fecal streptococci in feedlot runoff is about 10^4 times the concentration in runoff water from land application sites (Smith & Miner, 1964).

Pastures and rangelands

Pathogen and indicator organisms concentration at the soil surface essentially depends upon livestock density on these watersheds. Available data on indicator organisms from pastures and rangelands are presented in Table 6. Colthrap and Darling (1975) found significantly increased levels of total coliform, fecal coliform, and fecal streptococci in streams draining grazed areas compared to ungrazed areas. The FC/FS ratio ranged from 0.15 to 0.38.

Milne (1976) also observed significant bacteriological counts in the stream located near greatest livestock activity compared to counts taken upstream. The stream water before entering the wintering area had average total coliform and fecal coliform counts of 7 and 18 per 100 ml, respectively, whereas just downstream from wintering area, the respective average counts were 1431 and 997 per 100 ml. Khare *et al.* (1975) also observed greater concentration of FC and FS downstream from cattle pens compared to upstream.

Dickey & Mitchell (1975) observed that coliform bacteria levels were highest in those ponds having livestock on the watersheds (Table 6). Mean fecal coliform counts increased to as high as 7200/100 ml with application of manure to cultivated watersheds. Fecal streptococci counts essentially paralleled the FC counts. Stephenson & Street (1978) also observed that presence of cattle on rangelands increased FC concentration from zero to 2500 counts/100 ml at several sites.

Total coliform concentration in runoff from a hay field, without any livestock, was found to be similar to the runoff from a grazed area (Kunkle, 1970). However, fecal coliform concentration in runoff from a grazed area was higher compared to an ungrazed area. These results indicate that fecal coliform group is a much better indicator of animal pollution than total coliforms.

Literature data present evidence of increases in fecal coliform and fecal streptococci counts in the surface soil, due to animal waste application, thus resulting in elevated levels of these organisms in runoff waters. However, it is not clear how these organisms are transferred from soil to runoff water during rainfall-runoff. Are pathogen and indicator organisms transported along with manure and sediment particles in an adsorbed phase, or transported in runoff water upon desorption from the manure and soil particles? No literature data are available describing the partition coefficient between the soluble fraction and adsorbed fraction for pathogen and indicator organisms. Future research needs to be directed toward describing quantitatively the mode of transport of pathogens during rainfall-runoff.

Table 5. Indicator organism population in runoff water from land areas receiving wastes

Type of waste/ Description of the site	TC	Organisms FC counts 100 ml^{-1}	FS	FC/FS Ratio	Remarks	Reference
Liquid dairy manure applied in						
Fall	37	16	7	2.28	Dairy manure applied at 224, 560 and 897 kg N ha^{-1}. Values are average of all loading rates and rainfall events.	Phillips *et al.* (1975)
Winter	1623	72	12,940	0.006		
Spring	374	3	104	0.029		
Spring-Fall	132	5	55	0.091		
Control (no waste applied)	1098	2	58	0.034		
Feedlots (Kansas)	33×10^6–348×10^6	35×10^6–240×10^6	13×10^6–240×10^6	1.00–2.69	Feedlot runoff characteristics in Kansas.	Smith & Miner (1964)
Liquid dairy waste	197	27	68*	0.40	Liquid dairy waste applied by irrigation. Values are average of all loading rates.	McCaskey *et al.* (1971)
Semi-liquid dairy waste	151	91	305*	0.30	Semi-liquid dairy waste applied by tank spreader. Values are average of all loading rates.	
Dry dairy waste	1074	132	600*	0.22	Dry waste applied by conventional spreader. Values are average of all loading rates.	
Control (no waste applied)	20	10	11*	0.91		
Beef waste	32,850	1412			Applied by deep plowing. Values presented are average of all treatments.	Reddell *et al.* (1971)
Control (no waste applied)	1969	175	—	—		
Feedlots (Texas)						
A		0.026×10^6	0.36×10^6	0.1	All feedlots (A to F) are unsurfaced lots.	Geldreich (1976)
B		0.074×10^6	0.21×10^6	0.4		
C		0.21×10^6	0.46×10^6	0.5		
D		0.22×10^6	0.54×10^6	0.4		
E		0.31×10^6	3.20×10^6	0.1		
F		1.70×10^6	26.0×10^6	0.1		
Runoff—Ohio watershed						
113	—	8	1500	0.01	Corn, wheat, meadow	Geldreich (1976)
118	—	2	610	0.003	Corn, wheat, meadow	
185	—	20	3700	0.01	Corn, wheat, meadow	
192	—	18	1000	0.02	Corn, wheat, meadow	
196	—	1200	8400	0.14	Corn, wheat, meadow	
Runoff—Vermont watershed						
A-8	—	170	140	1.21	Pasture, hay fields	Geldreich (1976)
M-12	—	1700	2800	0.61	Dairy barns	
T-1	—	800	1100	0.73	Pasture, meadows	
T-5	—	290	3000	0.10	Pasture, meadows	
T-8	—	1400	390	3.60	Farmsteads, barns	
W-2	—	170	140	1.21	Pasture, meadows	
W-3	—	38	140	0.27	Forest, meadows	

* Enterococci.

FUTURE RESEARCH NEEDS

The primary purpose of this study was to critically review the literature and analyze research needs relative to transport of potential pollutants, like N and P, in runoff water from land application sites, pastures, and rangelands. An additional purpose was to obtain relationships between constituent (N or P) loading rate and its average concentration in runoff water, and also between constituent loading rate and its mass yield rate. The relationships presented earlier tend to show an influence of loading rate on concentrations and mass yield rates. However, additional data, replications and a wider geographical sampling are needed to further corroborate these relationships. As a result of this review, some guidelines may be suggested for future research.

Land application areas

Table 1 lists available data for small plot-sized areas. The greatest need appears to be that of relating the limited data on small plot-sized areas to larger watershed areas. Will the small or large watershed areas behave similar to small plot-sized areas? With climatic conditions, soil and cropping management practices remaining same, will the nutrient concentrations be same for small and large areas? The effects of various factors, like time of application, methods of application, soil and cropping management practices, on nutrient losses need to be evaluated for larger watershed areas. Recently the United States Environmental Protection Agency has begun an intensive, three-year monitoring program for selected pastures and rangeland watersheds in Ohio, Nebraska, Oklahoma, and Washington, to adequately characterize nonpoint source runoff water quality as affected by hydrologic conditions and livestock and agronomic management practices. The selected watersheds vary in sizes from 0.51 ha in Ohio to 70 ha in Oklahoma. These studies will provide detailed hydrologic, chemical, and bacteriological data for each runoff event. A similar monitoring program should also be undertaken for land application sites, on a watershed basis, to assess the nonpoint pollution from these areas.

The available data in Table 1 contain only edge-of-field losses on N and P. These losses may not necessarily be interpreted as amounts reaching surface waters, and can be altered during overland flow, and transport across or through soil. Therefore, it is necessary to extrapolate these losses to receiving water.

The available data indicate an increase in N and P losses in runoff with increased nutrient loading rates. However, for relatively low application rates, hydrologic impact and vegetative influences outweigh the impact of loading rates. At higher application rates, the available data show a definite increase in N and P losses. For large manure applications, are the hydrologic impacts then overshadowed by loading rates?

Most data show lower runoff volumes from manured areas compared to nonmanured or control areas (Young, 1974; Young & Mutchler, 1976; Hensler *et al.*, 1970; McCaskey *et al.*, 1971). The lower runoff volumes are related to higher infiltration capacity, larger water holding capacity, improved hydraulic conductivity, and bulk density. It would, therefore, be appropriate to document the effects of manure applications on soil physical properties' changes, and quantitatively estimate these changes as functions of management practices and loading rates. How do the soil physical properties change with time? Is the effect of manure immediate? What would be the impact of manure on soil physical properties in 1 year? In 2 years? Over a long term application period of 10 years?

The manure on the surface is assumed to behave like a mulch (Young, 1974). Manure applications have been found to reduce the loss of total solids, because the runoff is less, and the concentration of total solids in the runoff is low (Gunther, 1974). More studies are needed to evaluate the effect of manure on sediment transport from manured areas (Khaleel *et al.*, 1978). The solids in the runoff from manured areas originate from two different sources; the soil and the manure. How much of total solids in runoff is due to manure itself? A series of manure erodibility factors, similar to soil erodibility factors as defined in the universal soil loss equation, are needed for various manure types to determine the manure detachment and transport rates. The land application experiments suggested earlier can provide these data. How does the sediment and nutrient loss vary for different manure application modes, i.e. surface-applied or soil-incorporated? How do the nutrients get attached to the sediment by particle size?

The manure type for most of the experiments listed in Table 1 was dairy; only one was with swine lagoon effluent. Poultry and swine are generally considered to produce waste higher in nitrogen content. Will the nutrient losses in runoff water from areas receiving poultry wastes be more compared to those receiving other type of wastes? Also, will beef feedlot manure behave similar to dairy manure with respect to nutrient losses?

Most of the data listed in Table 1 were collected over a period of 1 to 3 years. Ross *et al.* (1978) reported that yearly applications of manure on sod reduced pollutant concentration in the runoff from test plots. Injected plots receiving manure applications for 3 consecutive years produced no runoff during the latter two years. Plots receiving surface application produced runoff each of the 3 years, but the concentration of pollutants was reduced each consecutive year. Will the same results have occurred if the area had received the same application rate for a period of 5 years? Will the same trend continue if the land application is continued for a period of 10 years, or after the system has reached a point of equilibrium?

Table 6. Indicator organism population in runoff water from pastures and rangelands

Description of the site	TC	Organism FC counts/100 ml	FS	FC/FS Ratio	Remarks	Reference
Grazed watershed	24	88	325	0.27	Stream water quality from rangeland watersheds.	Colthrap & Darling (1975)
Grazed watershed	103	38	101	0.38		
Ungrazed watershed	18	4	27	0.15		
Grassed watershed	—	15	—	—	Pond water quality was tested on these watersheds.	Dickey & Mitchell (1975)
Cultivated watershed	—	145	—	—		
Livestock watershed	—	982	—	—		
Rangelands with beef cattle	2000–400,000	800–80,000	5000–80,000	0.16–1.00	Runoff quality measured from land wintering range cattle.	Dixon *et al.* (1977)
Pasture and woodland area	300–700	330–7000	175–100,000	0.07–1.89	—	Yousef *et al.* (1976)
Pasture K_3	330,000	41,000	—	—	Pasture heavily grazed and resting area near shade.	Sewell & Alphin (1975)
Pasture K_4	158,000	64,000	—	—		
Small farm pond I	600	—	—	—	Small farm ponds heavily used by cattle.	Sewell & Alphin (1975)
Small farm pond II	3400	—	—	—		
Urban runoff—						
wooded hillside	65,415	635	10,473	0.06	Storm water from suburban area of Cincinnati, Ohio was tested. Values presented are averages of samples collected in several seasons.	Geldreich *et al.* (1968)
Street gutters	95,750	13,420	73,825	0.18		
Business district	107,500	14,950	37,000	0.40		
Sampling Station 1	28,870	8,818	14,420	0.61	Tributary of Reynoldsville Creek immediately down stream from cattle feeding pens.	Khare *et al.* (1975)
Sampling Station 2	1528	71	148	0.48	Tributary of Reynoldsville Greek immediately upstream from cattle feeding pens.	

Site F (control)		1–0.8 × 10^6 (10,000)*			Description of sites in Table 3	Robbins *et al.* (1971)
Site E		2–8 × 10^6 (189,000)				
Site K		1450–11 × 10^6 (365,000)				
Site H		1–78 × 10^6 (2.3 × 10^6)				
Site J		28 × 10^3–215 × 10^6 (8.6 × 10^6)				
Site P	—	1–160,000 (9600)	—	—		
Site Z	—	1–460,000 (30,700)	—	—		
Site X	—	50–1050 (235)	—	—		
Stream sampling above major farm drainage area	—	200–230,000 (10,300)	—	—	Average of three different waste disposal systems; lagoons, dry disposal and liquid manure	Janzen *et al.* (1974)
Stream sampling adjacent to farm drainage area	—	100–280,000 (37,000)	—	—	Average of three different waste disposal systems; lagoons, dry disposal and liquid manure	
Stream sampling downstream of farm drainage area	—	200–330,000 (18,000)	—	—	Average of three different waste disposal systems; lagoons, dry disposal and liquid manure	

* Averages.

Pastures and rangelands

The limited data available so far suggest that pasture production of livestock has presented less of a pollutional problem compared to land application areas. However, as in Table 1, nutrient data contained in Table 3 for pastures and rangelands are also edge-of-field losses. These losses need to be extrapolated to receiving waters. Livestock presence on pastures and rangelands can cause changes in infiltration rates and soil physical properties (Gifford & Hawkins, 1978). These changes need to be quantified. In dealing with grazing intensity, data on cover criteria and plant species should be included, as well as the duration of use and animal loading rate (number of animals per unit area). Knowledge of these loading rates would allow estimation of N and P deposited by the pasturing animals. Also, the time and space distributions of excreta by freely grazing cattle in pastures and rangelands need to be investigated in terms of expected animal behavior distribution patterns (Peterson *et al.*, 1956; Sweeten & Reddell, 1978; Gifford & Hawkins, 1978).

SUMMARY AND CONCLUSIONS

Much research has been conducted at various locations, and under a variety of conditions, to determine total N and P loads from land areas receiving animal wastes. The available data on N and P, and also on BOD, COD, indicator organisms and pathogens are summarized for pastures and rangelands, land application sites, and feedlots.

For land application sites, results of a linear regression analysis indicated a highly significant correlation between nutrient (N or P) loading rate and its average concentration in runoff water, and also between nutrient loading rate and its mass yield rate. Plot areas receiving manure during winter and spring, and subject to snowmelt runoff followed a different relationship compared to those receiving applications during summer and fall, and not subject to snowmelt runoff. Nutrient runoff data obtained under extreme weather conditions were not considered in obtaining the regression equations. These relationships, therefore, represent nutrient transport under average climatic conditions of the geographical areas. Effects of several other factors, such as time of application, method of application, soil and cropping management practices, and their interactions need to be recognized. Nearly all data presented are for small plot-sized areas and should not necessarily be interpreted as amounts reaching surface waters. Many of the constituents can be altered during transport across or through soil.

Data on total N and P runoff losses from pastures and rangelands indicate that, in many cases, it may be difficult to distinguish between pollution attributable to animal wastes and natural or "background" levels of pollution. Nutrient discharges in runoff from these areas may be controlled by employing proper management or grazing schedule, controlling erosion and sediment transport, and surface runoff.

The feedlot runoff data suggest that snowmelt runoff contains about two to three times more nutrients compared to rainfall-runoff. Pollutant concentrations for feedlots are greater by several orders of magnitude compared to those for land application sites, and pastures and rangelands. Compared to control (nonmanured areas), higher levels of indicator organisms and pathogens are indicated in runoff from both land application sites, and pastures and rangelands.

Limitations of the available data on nutrient losses are discussed in terms of identifying future research needs. The greatest need appears to be that of relating the limited data on small plot-sized areas to larger watersheds, and edge-of-field losses to receiving waters.

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