Attenuation of Runoff and Chemical Loads in Grass Filter Strips at Two Cattle Feedlots, Minnesota, 1995-98

By S.C. Komor and D.S. Hansen

Water-Resources Investigations Report 03-4036

Prepared in cooperation with the Minnesota Pollution Control Agency

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Gale A. Norton, Secretary

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Charles G. Groat, Director

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For additional information write to:
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District Chief
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply metric unit	By	To obtain
Centimeter (cm)	0.3937	inch (in.)
Meter (m)	3.281	foot (ft)
Hectares (h)	2.471	acres
Centimeter per second (cm/s)	0.03281	feet per second (ft/s)
Liter (L)	0.2642	gallon (gal)
Kilogram (kg)	2.205	pound (lb)
Degree Celsius (°C)	(1.8 x temp °C) + 32	Degree Fahrenheit (°F)

Concentrations of substances are given milligrams per liter (mg/L), micrograms per liter (µg/L). A milligram is one thousandth of a gram, a microgram is one millionth of a gram. Electrical conductivity is measured as specific electrical conductance in units of microsiemens per centimeter (µS/cm) at 25 degrees Celsius.

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ABSTRACT

Attenuation of cattle feedlot runoff in two grass-covered filter strips in Minnesota was estimated by measuring chemical loads into and out of the strips. Filter strips of the Bock and Sanborn sites were 60-m long and 20-m wide and received runoff from cattle feedlots that supported 35 and 225 cattle, respectively. Feedlot and filter-strip runoff were measured using flumes with stage sensors. Water samples were collected using automated samplers. Attenuation values were calculated from four storm-runoff events. Ground water sampled beneath and outside the filter strips indicated some infiltration losses of sulfate, chloride, and nitrogen at the Bock site where soil permeability was greater than at the Sanborn site. Chemical constituents in filter-strip runoff, and their corresponding ranges of attenuation were as follows: chemical oxygen demand, 30–81 percent; dissolved chloride, 6–79 percent; dissolved sulfate, -3–82 percent; dissolved ammonia nitrogen, 33–80 percent; suspended ammonia plus organic nitrogen, 29–85 percent; dissolved organic nitrogen, 14–75 percent; suspended phosphorus, 24–82 percent; dissolved phosphorus, 14–72 percent; and fecal coliform bacteria, 18–79 percent. The ranges seem to be affected by barriers of direct contact of the runoff water with the soil. This varies seasonally by coverage of the soil by ice in winter and vegetation in summer months. Greater attenuation values occurred in October and May when mats of wilted, flat-lying grass covered the filter strips; attenuation values were less during the summer when tall growing grass covered the filter strips.

INTRODUCTION

Runoff from animal feedlots commonly contains elevated concentrations of chloride, nitrogen, phosphorous, sediment, and bacteria. The elevated constituent concentrations can affect surface- and ground-water quality. Vegetated-filter strips (filter strips) frequently are installed downslope from feedlots to attenuate feedlot runoff before discharging to ground water and into receiving streams (Hammer, 1992). Filter strips are sloped areas, commonly planted with grass, intended to receive, attenuate, and filter feedlot runoff. Soil berms or other structures along the sides confine runoff within the filter strips. Filter strips remove suspended contaminants by slowing velocities of particles, resulting in deposition, and reduce concentrations of dissolved constituents by adsorption, uptake, infiltration, decomposition and volatilization (Clausen and Meals, 1989; Dickey and Vanderholm, 1981; Edwards and others, 1983; Schwer and Clausen, 1989). The U.S. Geological Survey (USGS), in cooperation with the Minnesota Pollution Control Agency (MPCA), investigated the effectiveness of filter strips to reduce concentrations and loads of feedlot runoff and to determine the effect of filter strips on ground-water quality.

PURPOSE AND SCOPE

The purpose of this report is to describe the results of a study during 1995-98 to determine the attenuation of cattle feedlot runoff and chemical loads in two grass covered filter strips at Bock and Sanborn, Minnesota. Data from 7 storm-runoff events and 10 ground-water monitoring wells collected during 1995-98 were used. Data from four of the seven storm-runoff events were used to compute attenuation of runoff volumes and chemical loads. Data from six ground-water monitoring wells inside the filter strip were compared to data from seven wells outside the filter strips.

PREVIOUS STUDIES

The effectiveness of filter strips can be evaluated using the percent reduction, on a weight basis, of constituents in outflow compared to inflow. Previous studies have found reductions of total suspended solids (TSS) of 33–98 percent, total organic nitrogen of 18–97 percent, total ammonia of 27–97 percent, total nitrogen of 43–92 percent, and total phosphorous of 12–97 percent (Young and others, 1980; Dickey and Vanderholm, 1981; Edwards and others, 1983; Dillaha and others, 1988; Dillaha and others, 1989; Schwer and Clausen, 1989; Schellinger and Clausen, 1992; Chaubey and others, 1994; and Srivastava and others, 1996).

Much of the reduction occurs in the first few meters of the filter strip (Robinson and others, 1996; Srivastava and others, 1996). Filter strips are less effective at removing dissolved constituents than removing suspended constituents. Some studies have found more dissolved nitrate and phosphorus in outflow than in inflow (Dillaha and others, 1988; Dillaha and others, 1989), probably resulting from the remobilization of nutrients in the filter strip. Reductions in fecal coliform bacterial colonies of 58–70 percent have been reported (Young and others, 1980; Chaubey and others, 1994). Other studies have found fecal coliform concentrations were not greatly reduced by filter strips (Dickey and Vanderholm, 1981; Srivastava and others, 1996).

Many of the controlling variables in filter-strip effectiveness have been documented. Filter strips become less effective at removing suspended solids and total nutrient mass when vegetation in the filter strips is short or on steep slopes, or where flow becomes channelized (Edwards and others, 1983; Dillaha and others, 1988; Dillaha and others, 1989; Magette and others, 1989; Chaubey and others, 1994; and Srivastava and others, 1996). Filter strips also are less effective during snowmelt because water flows across the filter strips over frozen ground (Schwer and Clausen, 1989; Schellinger and Clausen, 1992). Effectiveness declines when the filter strips become coated with dry solids from feedlot runoff, which reduce the capacity to accommodate additional solids, and when vegetation is killed or stunted by excessive water or nutrient concentrations because the filtering and adsorption quality is reduced. Other factors that may affect filter strip effectiveness includes the type and quantity of manure; the cleaning schedule of feedlots; the presence of settling basins for removing solids upgradient from the filter strip; the frequency, rate, and timing of rainfall; the vegetation height; antecedent moisture conditions; and soil type.

DESCRIPTION OF STUDY AREA

The two filter strips evaluated were located near the towns of Bock in central Minnesota and Sanborn in southwest Minnesota (fig.1). Average annual precipitation (1961-90) was about 73.4 cm near Bock and 64.5 cm near Sanborn (Midwest Regional Climate Center, Climate data and summaries, accessed February 6, 2003 at: URL http://mcc.sws.uiuc.edu/cgi-bin/greet.cgi/), and about 80 percent of the precipitation falls between April and September. Both filter strips were planted with grass. Feedlot runoff from each contributing catchment flowed into a settling basin to remove solids (fig. 1). Feedlot runoff entered the filter strip through the feedlot-runoff flume. Storm runoff often persisted after rainfall stopped due to ponding in the feedlots and plugging of the wooden filters that conveyed water to the filter strips. Runoff entered the upslope ends of the strips and was spread laterally by gravel strips that extended across the filter strips (fig. 1). Another gravel strip was located midslope in the filter strips. Water was contained within the filter strips by tapered soil berms. Water left the filter strip through the filter-strip runoff flume.

Bock Site

The Bock filter strip was 79 m long by 24 m wide and had a downslope gradient of 1.2 percent. The ratio of filter strip area to feedlot area was 0.20. The Bock site generally was mowed twice during the summer.

Soils in the Bock filter strip consisted of Adolph silt loam (mixed, frigid, Typic Epiaquoll) (U.S. Department of Agriculture, 1977). The top 13 cm of soil is black or dark gray-brown, silty clay, and clay with sand and roots. Soils from 13- to 32-cm depth are poorly drained black and gray silty clay and silt loam. On average, the water table was 1.3 m below land surface during the study, although during wet periods the water table was at land surface. Soil Engineering Testing of Bloomington, Minnesota conducted permeability tests on undisturbed soil cores. Saturated hydraulic conductivities were 7.6 x 10^{-7} cm/s at the upslope end of the strip and 2.9 x 10^{-7} cm/s at the downslope end.

The contributing catchment included the feedlot, feeding barns and cement manure-storage pad. The contributing catchment to the Bock filter strip was 0.97 h. Approximately 30 percent of the catchment was paved. The feedlot was designed to accommodate 150–200 cattle, but only about 35 cattle occupied the feedlot during most of the study.

Night time temperatures varied between –2.8 and 1.7°C from October 17 to October 23, 1995, and the grass began wilting. During May 1996, shoots of new green grass were sprouting through a mat of the previous season’s brown, flat-lying grass.

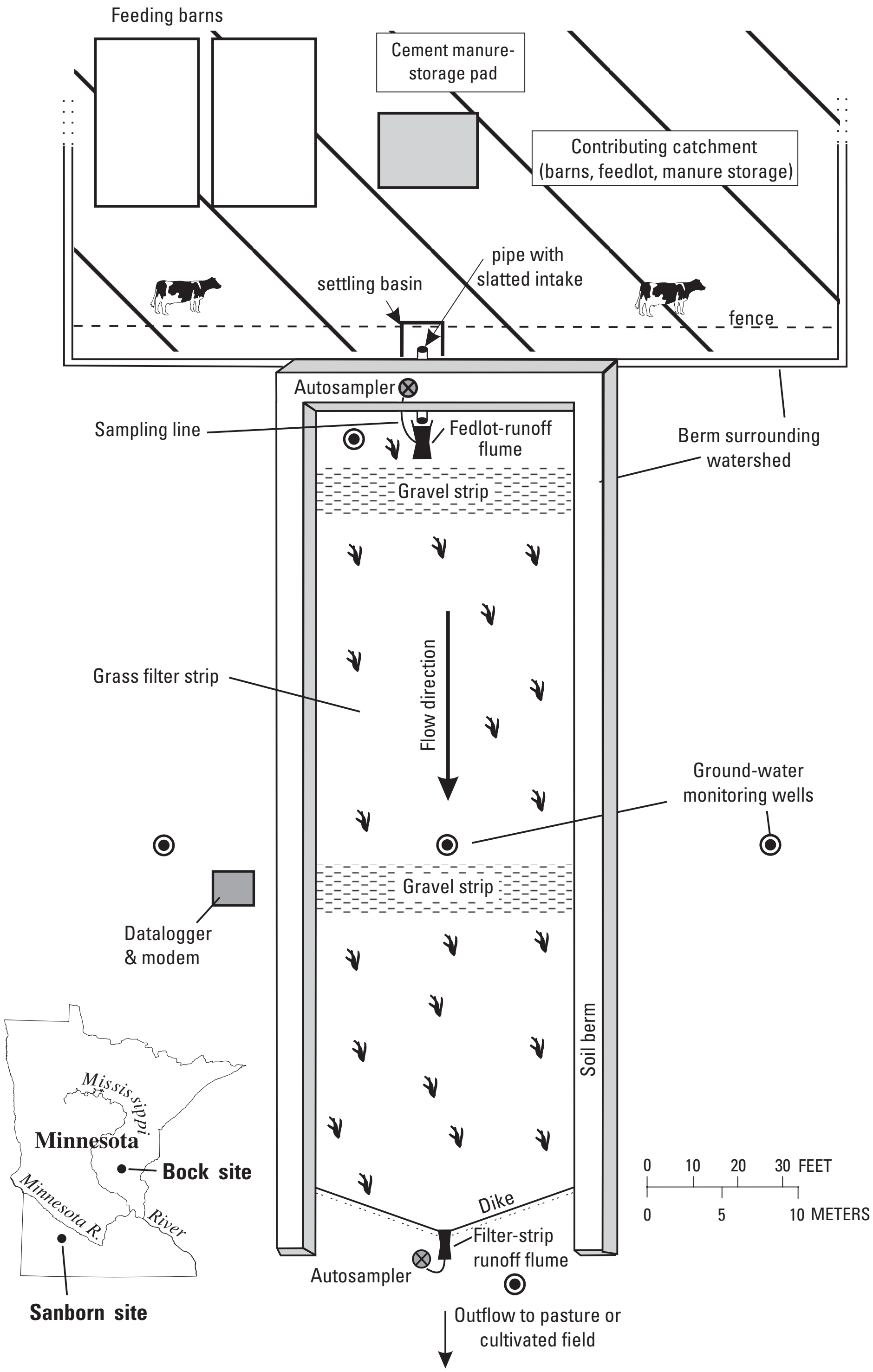

Figure 1. Plan view of filter strips at Bock and Sanborn, Minnesota sites.

Three storm-runoff events were monitored at the Bock site: October 23, 1995; May 5, 1996; and May 14, 1996. The filter strips were designed to accommodate peak runoffs from 25-year, 24-hour rainfalls, having water depths of 1.3 cm in the filter strips and minimum detention times of 15 minutes. The design storm was 11.7 cm for the Bock site.

Sanborn Site

The Sanborn filter strip was 59 m long by 18.3 m wide and had a downslope gradient of 0.5 percent. The ratio of filter-strip area to feedlot area was 0.20. The previous year's vegetation was burned in the spring at the Sanborn site.

Soils in the Sanborn filter strip consisted of Normania loam (mixed, mesic, Aquic Haplustoll) (U.S. Department of Agriculture, 1985). The top 13 cm of soil was black and dark grayish-brown, silty clay, and clay with sand and roots. Soils from the 13- to 40-cm depth were black and dark gray clay loam. Saturated hydraulic conductivities were 2.0 x 10^{-7} cm/s at the upslope and downslope ends of the filter strip. The water table averaged 0.81 m below land surface during the study. Under natural conditions, surface soils have organic-matter contents of 4–8 percent (United States Department of Agriculture, 1985). Organic contents in the filter strips were probably greater due to input of manure-laden water from the feedlots.

The contributing catchment at the Sanborn site was 0.55 h. About 48 percent of the catchment was paved and the feedlot typically contained 225 cattle. The manure-storage pad was about 15 m from the inlet of the filter strip. The site was periodically cleaned.

Four storm-runoff events were monitored at the Sanborn site: July 27, 1996; October 17, 1998; June 2, 1998; and June 27, 1998. During June 1996 and 1998, and July 1996, there were thick growths of waist-high grass. Hard frosts (temperatures between -4 and -5°C) on October 3, 4, 10, and 11, 1996 caused the grass to wilt so that by the storm on October 17, it was brown and mostly lying flat. The design storm was 12.2 cm for the Sanborn site.

METHODS

Monitoring systems measured runoff volumes entering and exiting each filter strip and collected water samples for chemical analyses. Feedlot runoff that entered each filter strip was measured with a Parshall flume (feedlot-runoff flume) attached to PVC pipe that conveyed water from the feedlot to the strip (fig. 2). Filter-strip runoff was routed by a dike into a second flume (filter-strip runoff flume). Water levels (stage) in the flumes were measured continuously with pressure transducers (Accubar 5600-1025) and converted to discharges with stage-discharge rating curves verified with discharge measurements. Water samples were drawn through Teflon tubing from the base of the flumes into 1-liter plastic bottles by automatic samplers. Sampling lines were back flushed with runoff before each sample was collected. Samplers began collecting samples when the stage in the flumes rose above 2.3 cm. During most runoff events, samples were collected every 10 minutes for the first hour and every half hour (or longer) thereafter. Samples were taken more frequently during the initial stages of a runoff event to better characterize the first flush of runoff. Some runoff events were sampled at a constant frequency (one sample every half hour) after the threshold depth was exceeded. Because auto samplers held only 24 sample bottles, runoff events longer than about 10–12 hours were not sampled in their entirety. Chemical load calculations were not extended beyond the sample period. Incremental rainfall volumes were measured with tipping-bucket rain gages installed at the site. Sampling and measuring equipment was controlled by programmable data loggers (fig. 1).

Rainfall was scarce at the Sanborn site during 1998. Consequently, a dam was installed at the feedlot outlet, just upgradient of the feedlot-runoff flume. When sufficient feedlot runoff from rainfall had accumulated upgradient of the dam, the water was released into the filter strip through the feedlot-runoff flume (fig. 3). These events, which occurred June 2 and 27, 1998, are different tests of filter-strip performance than the natural runoff events monitored July 27 and October 17, 1996. The runoff rate from the filter strip at the Sanborn site for June 27, 1998 was not great enough to activate the autosamplers, so two grab samples were collected near the middle of the filter strip and the filter-strip flume.

The volume of rain on filter strips was calculated from the measured rain depths and the filter-strip areas. The volume retained in the filter strip was the volume of rain falling on the filter strips plus the volume of feedlot runoff entering the flume minus the volume exiting the filter strip. Attenuation value (Av), in percent, in the filter strip (percent of water retained) was determined by the following equation:

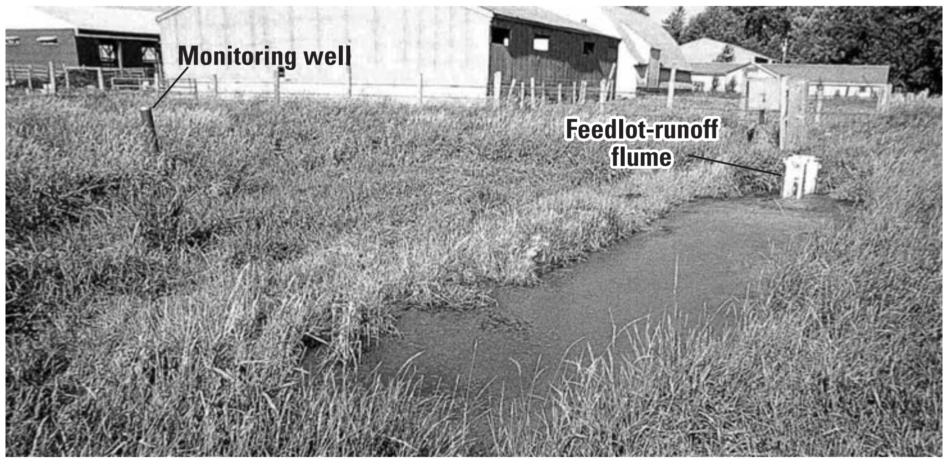

Figure 2. Feedlot runoff in the settling basin at the upslope end of Sanborn filter strip. Photo by M.A. Menheer, U.S. Geological Survey.

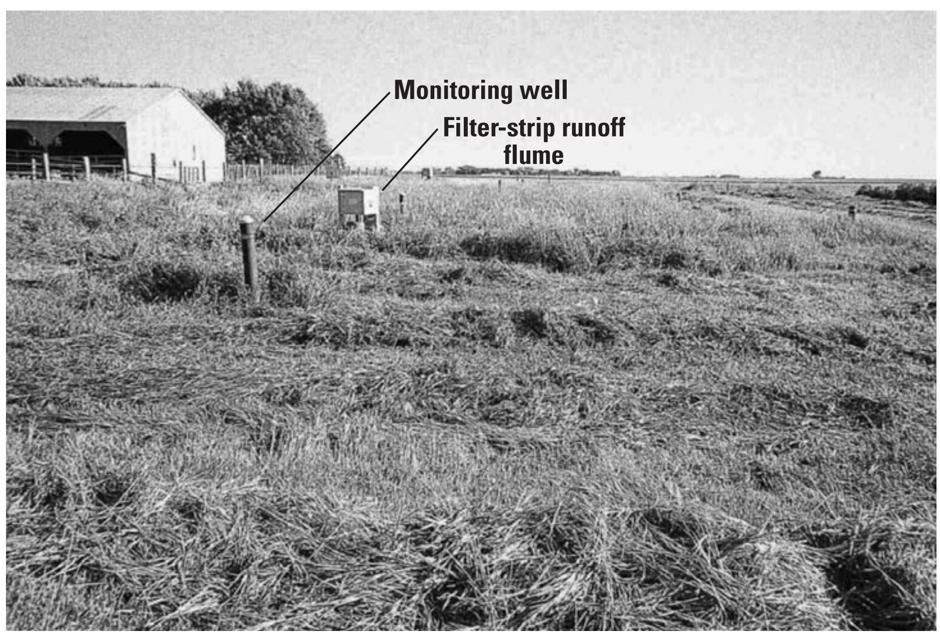

Figure 3. The Sanborn site Looking north from near the filter-strip runoff flume. Photo by M.A. Menheer, U.S. Geological Survey.

$$\mathrm{Av} = 100 \bullet \left[1 - \left(\frac{\text{volume of filter strip runoff}}{\text{volume of feedlot runoff + volume of rain}}\right)\right] \tag{1}$$

Water samples were removed from autosamplers within a few hours after collection and chilled to preserve their compositions. Samples were analyzed for chemical oxygen demand, sulfate, chloride, nitrite plus nitrate nitrogen, ammonia nitrogen, ammonia plus organic nitrogen, and phosphorus at the USGS National Water-Quality Laboratory (NWQL) in Lakewood, Colorado using protocols of Frishman and Friedman (1989). The Minnesota Department of Health (MDH) measured concentrations of fecal coliform bacteria in most samples within 24 hours of sample collection using a membrane-filter technique (American Public Health Association, 1985).

Chemical loads (kg) in runoff were calculated by multiplying chemical concentrations (mg/L) by the volume of discharge accumulated since the previous sample had been collected. For example, a load occurring between 10:00 and 10:30 would be calculated by multiplying the chemical concentrations in the 10:30 sample by the volume of discharge occurring between 10:00 and 10:30. Loads for an entire storm were calculated by summing the incremental loads. Mean storm runoff concentrations (mg/L) were calculated by dividing the total loads by the total volumes of water measured in the feedlot-runoff flume. The resulting values represent the weighted constituent concentrations of each event. Attenuation values for chemical loads were calculated as follows:

$$\mathrm{Av} = \left(\frac{\text{feedlot runoff load} - \text{filter strip runoff load}}{\text{feedlot runoff load}}\right) \bullet 100 \tag{2}$$

Ground water was sampled throughout the study period to evaluate the effect of infiltration from the filter strips. Samples were collected from shallow water-table wells inside and outside the strips (fig.1). Most well screens were from 60- to 90- cm long to allow for variations in the water-table level. A peristaltic pump was used to pump ground water from the wells into flow-through chambers in which pH, specific conductance, temperature, and dissolved oxygen were monitored until stabilized then recorded. Samples were then filtered through 0.45-µm in-line cartridges and collected for analyses of sulfate, chloride, nitrate, nitrite, ammonia nitrogen, organic nitrogen; and phosphorous by the USGS NWQL in Lakewood, Colorado. The MDH analyzed unfiltered samples for fecal-coliform bacteria counts.

QUALITY OF WATER

Hydrologic and chemical characteristics of runoff events at the Bock (tables 1 and 2) and Sanborn sites (tables 3 and 4) characterize runoff from the filter strips. The runoff duration from the feedlot value represents the time the stage remained above 2.3 cm in the flumes.

Ground-water quality is a concern where feedlot-runoff infiltration is significant. Chemical constituent concentrations in water from wells installed inside and outside the filter strips at the Bock and Sanborn sites are listed in table 5. Chemical changes in ground water from wells sampled inside the filter strips indicate that, for some parameters, filter-strip runoff degrades ground-water quality. Ground-water quality differences at

Table 1. Hydrology at the Bock site.

[cm, centimeter; hr, hour; L, liter; L/s, liters per second; --, equipment malfunction]

Hydrology	Storm-runoff event		
	10/23/1995	5/5/1996	5/14/1996
Rain depth (cm)	1.5	1.4	2.3
Rainfall duration (hr)	10.3	6.9	13.9
Runoff duration from feedlot (hr)	18.0	7.6	9.9
Runoff duration at filter-strip exit (hr)	--	2.8	7.5
Maximum discharge from feedlot (L/s)	3.2	2.8	3.0
Maximum discharge at filter-strip exit (L/s)	--	1.2	1.9
Time between first discharges from feedlot and at filter-strip exit (hr)	--	0.2	1.8
Time between hydrograph peaks from feedlot and at filter-strip exit (hr)	--	0.1	1.1
Volume of rain in filter strip (L)	27,470	24,466	40,776
Volume of feedlot runoff (L)	142,333	52,627	58,166
Volume of feedlot runoff plus rain on filter strip (L)	169,803	77,093	98,942
Volume of filter-strip runoff (L)	--	16,812	52,882
Total water retained in filter strip (L)	--	60,281	46,060
Attenuation value (percent of water retained)	--	78	47

Table 2. Constituent concentrations, loads, and attenuation values at the Bock site

[mg/L, milligrams per liter; N, nitrogen; --, equipment failure]

Chemical concentrations

Constituent		Chemical oxygen demand (mg/L)			Sulfate, dissolved (mg/L)			Chloride, dissolved (mg/L)			Nitrate + nitrite, dissolved (mg/L)			Ammonia N, dissolved (mg/L)		
Sample date		10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96
Feedlot runoff	Number of samples	11	6	11	11	6	11	11	6	11	11	6	11	11	6	11
	Maximum	920	5200	--	100	47.0	23.0	190	280.0	270.0	30.0	0.7	0.2	7	100	120.0
	Minimum	10	4400	--	83	4.8	5.0	150	250.0	190.0	17.0	0.2	0.1	0.97	61	89.0
	Average	500	4700	--	94.4	23.9	11.6	170.9	265.0	235.5	27.3	0.4	0.2	3.5	84.8	105.8
	Standard deviation	380	294.4	--	5.3	16.5	6.9	11.4	10.5	30.1	4.2	0.2	0.0	1.8	16.5	11.7
Filter-strip runoff	Number of samples	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12
	Maximum	--	--	--	--	--	8.8	--	--	220.0	--	--	0.1	--	--	65.0
	Minimum	--	--	--	--	--	1.9	--	--	190.0	--	--	0.1	--	--	36.0
	Average	--	--	--	--	--	4.1	--	--	207.5	--	--	0.1	--	--	45.3
	Standard deviation	--	--	--	--	--	6.9	--	--	30.1	--	--	0.0	--	--	9.3

Constituent		Ammonia +organic N, suspended (mg/L)			Organic N, dissolved (mg/L)			Phosphorous, dissolved (mg/L)			Phosphorous, suspended (mg/L)			Fecal coliform (colonies/100 mL)		
Sample date		10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96
Feedlot runoff	Number of samples	11	6	11	11	6	11	11	6	11	11	6	11	11	6	11
	Maximum	34.0	80.0	200.0	16.0	169.0	140.0	15.0	68.0	72.0	9	22.0	48.0	3.90E+06	2.40E+05	5.30E+05
	Minimum	3.6	40.0	0.0	4.2	117.0	70.0	6.9	61.0	45.0	1	10.0	13.0	2.27E+05	9.10E+04	8.60E+04
	Average	24.1	60.0	89.1	12.4	131.8	101.5	12.7	64.3	57.9	6.2	15.8	24.5	2.26E+06	1.67E+05	3.15E+05
	Standard deviation	8.9	14.1	52.4	3.4	19.5	23.3	2.4	3.0	9.5	2.9	4.8	12.7	1.18E+06	6.29E+04	1.21E+05
Filter-strip runoff	Number of samples	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12
	Maximum	--	--	34.0	--	--	110.0	--	--	36.0	--	--	11.0	--	--	2.40E+05
	Minimum	--	--	0.0	--	--	30.0	--	--	17.0	--	--	0.0	--	--	5.80E+03
	Average	--	--	15.4	--	--	50.3	--	--	25.4	--	--	5.0	--	--	1.06E+05
	Standard deviation			10.1			20.5			6.3			3.0			1.21E+05

Chemical loads

Constituent	Chemical oxygen demand			Sulfate, dissolved			Chloride, dissolved			Nitrite plus nitrate, dissolved			Ammonia N, dissolved		
Sample date	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96
Feedlot runoff (kg)	214.30	190.66	--	31.90	1.32	0.78	59.16	10.91	15.32	8.13	0.19	0.01	1.63	3.98	6.14
Filter-strip runoff (kg)	--	--	--	--	--	0.19	--	--	10.35	--	--	0.00	--	--	2.40
Attenuation value, in percent	--	--	--	--	--	75	--	--	32	--	--	84	--	--	61

Constituent	Ammonia + organic N, suspended			Organic N, dissolved			Phosphorous, dissolved			Phosphorous, suspended			Fecal coliform (colonies/100 mL)		
Sample date	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96	10/23/95	5/5/96	5/14/96
Feedlot runoff (kg)	9.89	2.30	5.13	4.45	5.53	5.60	4.58	2.61	1.86	2.61	0.58	1.41	3.753E+06	8.180E+10	1.206E+11
Filter-strip runoff (kg)	--	--	0.75	--	--	2.87	--	--	1.40	--	--	0.25	--	--	4.60E+10
Attenuation value, in percent	--	--	85	--	--	49	--	--	25	--	--	82	--	--	62

Table 3. Hydrology at the Sanborn site

[cm, centimeter; hr, hour; cm/hr, centimeters per hour; L, liter; L/s, liters per second; --, equipment malfunction; †, release of dammed water]

	Date sampled			
	7/27/96	10/17/96	6/2/98	6/27/98
Rain depth (cm)	9.1	3.6	0.5	0.6
Rainfall duration (hr)	52	6.5	45	82
Rainfall intensity (cm/hr)	0.54	0.47	†	†
Runoff duration from feedlot (hr)	14.9	16.5	40	7.25
Runoff duration at filter-strip exit (hr)	27.1	11.2	--	2.2
Maximum discharge from feedlot (L/s)	9.8	4.5	13.5	10.3
Maximum discharge from filter-strip-exit (L/s)	7.7	1.5	--	1.34
Time between first discharges from feedlot and at filter-strip exit (hr)	2.0	5.3	41.0	40.2
Time between hydrograph peaks from feedlot and at filter-strip exit (hr)	10.8	3.7	--	41.1
Volume of rain in filter strip (L)	117,048	46,305	6,534	8,232
Volume of feedlot runoff (L)	12,888	97,379	79,574	143,576
Volume of feedlot runoff plus rain on filter strip (L)	129,936	143,684	†	†
Volume of filter-strip runoff (L)	19,273	24941	--	3,160
Volume retained in filter strip (L)	110,662	118,743	--	148,647
Attenuation value (percent of water retained)	85	83	--	98

both sites are not from specific storm events or runoff described in this report, but are the result of storm runoff and infiltration over time.

BOCK SITE

Three storm-runoff events were monitored at the Bock site on October 23, 1995; May 5, 1996; and May 14, 1996. Due to equipment malfunctions, only flow volumes exiting the filter strip were measured during storm-runoff events on May 5, 1996, and May 14, 1996, and filter-strip runoff quality was evaluated for May 14, 1996 (table 1).

The storm-runoff event of October 23, 1995 generated the greatest volume of feedlot-runoff (142,333 L). Feedlot runoff from the storm of October 23, 1995, measured at the feedlot-runoff flume, contained the smallest loads of dissolved ammonia nitrogen, organic nitrogen, and fecal coliform bacteria compared to the other storm-runoff events (table 2). Sulfate, chloride, and nitrite plus nitrate loads were much larger in the October 23, 1995 storm than in other storms.

The storms of May 5, 1996 and May 14, 1996 were approximately equivalent in terms of the feedlot-runoff volumes through the feedlot-runoff flume (52,627 and 58,166 L, respectively). However, the storms differed substantially in the volume of water that exited the filter strip and the percentages of water retained in the filter strip (78 percent and 47 percent, respectively) (table 1; fig. 4). The average depth to the water table beneath the filter strip decreased from 0.6 m on April 19, 1996 to 0.2 m on May 16, 1996. The smaller percentage of retained water on May 14, 1996 probably reflects the presence of shallower saturated soils compared to the event on May 5, 1996. Feedlot-runoff loads tended to be larger on May 14, 1996 than on May 5, 1996, with the exceptions of dissolved nitrite plus nitrate, dissolved phosphorus, and sulfate.

Ground water from wells sampled inside the filter strips at the Bock site had elevated specific conductance, dissolved sulfate, dissolved chloride, dissolved nitrate, dissolved ammonia nitrogen, and dissolved organic nitrogen concentrations beneath the filter strip when compared to ground water in wells outside the filter strip (table 5). The average chemical constituent concentrations in water from wells installed inside the filter strip was generally larger than the concentrations of chemical constituents in water from wells located outside the filter strip (table 5). Average dissolved sulfate, chloride, and nitrate were 62, 167, and 2.6 mg/L, respectively, inside the filter strip and 53, 123, and 0.35 mg/L, respectively, outside the filter strip. The greater effect on ground water at the Bock site likely is due to the greater hydraulic conductivity of soil compared to the Sanborn site.

Table 4. Constituent concentrations, loads and attenuation values at the Sanborn site

[mg/L, milligrams per liter; colonies/100 mL, colonies per 100 milliliter; --, equipment malfunction; N, nitrogen; E, multiplyed by 10 to the indicated power]

Chemical concentrations

Constituent		Chemical oxygen demand (mg/L)				Dissolved sulfate (mg/L)				Dissolved chloride (mg/L)			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff	Number of samples	13	10	8	10	13	10	8	10	13	10	8	10
	Maximum	3,300	4,900	21,000	2,320	68	280	174.5	83	120	700	857.5	244.7
	Minimum	560	150	16,000	1,385	33	110	137.3	58.4	49	210	792.5	137.3
	Average	1,058	3,470	17,788	1,764	45.8	160	164.2	72	69.8	374	836.9	165.4
	Standard deviation	831	1,798	1,723	282	9.3	55.8	12.8	9.2	17.7	168.1	21.5	34.7
Filter-strip runoff	Number of samples	15	5	--	2	15	5	--	2	15	5	--	2
	Maximum	710	3,300	--	1,640	63	140	--	102.3	76	260	--	231.1
	Minimum	470	2,900	--	1,535	41	27	--	80.8	58	200	--	217.4
	Average	574	3,120	--	1,588	49.8	109.4	--	91.5	65.3	234	--	224.3
	Standard deviation	66	148	--	74	6.2	46.6	--	15.2	5.1	23	--	9.7

Constituent		Dissolved nitrate + nitrite as N (mg/L)				Dissolved ammonia N (mg/L)				Suspended ammonia + organic N (mg/L)			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff	Number of samples	13	10	8	10	13	10	8	10	13	10	8	10
	Maximum	0.2	0.3	0.1	0.6	25	65	0.7	31.7	71	185	709.8	113.5
	Minimum	0	0.1	0.1	0.1	4.2	25	0.6	17.3	6	2	0	74.8
	Average	0.1	0.1	0.1	0.3	6.8	35.9	0.6	25.6	23.1	103.7	264.9	95.3
	Standard deviation	0	0.1	0	0.2	5.7	12.3	0.0	5.5	16.6	50.2	275.2	13.4
Filter-strip runoff	Number of samples	15.0	5.0	--	2.0	15	5	--	2	15	5	--	2
	Maximum	15.4	0.3	--	0.1	62	41	--	23.9	25	183	--	122
	Minimum	0	0.1	--	0.1	25	21	--	8.7	0	60	--	100.9
	Average	1.3	0.1	--	0.1	37.1	25.6	--	16.3	14.7	115.8	--	111.4
	Standard deviation	4.1	0.1	--	0	8.1	8.6	--	10.7	6.2	45.5	--	14.9

Chemical loads

Constituent	Chemical oxygen demand				Dissolved sulfate				Dissolved chloride			
Sample date	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff (kg)	254.96	394.34	677.54	251.97	14.48	12.69	6.29	10.4	21.86	25.94	31.95	25.45
Filter-strip runoff (kg)	127.03	73.87	--	176.3	11.02	2.27	--	10.71	15.76	5.36	--	23.9
Attenuation value, in percent	50	81	--	30	24	82	--	-3	28	79	--	6

	Dissolved nitrite + nitrate as N				Dissolved ammonia N				Suspended ammonia + organic N			
	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff (kg)	0.02	0.01	0	.03	1.72	2.9	0.02	3.72	6.5	10.25	9.35	15.99
Filter-strip runoff (kg)	0.07	0	--	.02	1.15	0.59	--	1.24	2.96	2.55	--	11.38
Attenuation value, in percent	-235	63	--	42	33	80	--	67	54	75	--	29

Table 4. Constituent concentrations, loads and attenuation values at the Sanborn site--Continued

Chemical concentrations									
Constituent		Dissolved organic N (mg/L)				Dissolved phosphorus (mg/L)			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff	Number of samples	13	10	8	10	13	10	8	10
	Maximum	74	195	2745	56.5	21.0	36.0	251.2	35.1
	Minimum	8.8	51	890.4	31.9	3.6	19.0	154.2	22.1
	Average	20	97.4	1326.1	38.9	6.5	22.6	196.5	27.4
	Standard deviation	17	46.4	591.4	9.2	4.9	5.3	29.0	4.5
Filter-strip runoff	Number of samples	15	5	--	2	15.0	5.0	----	2
	Maximum	21	99	--	77.7	10.0	30.0	--	40.9
	Minimum	10.6	53	--	40.8	4.5	19.0	--	18.4
	Average	16.3	64.6	--	59.2	6.7	23.0	--	29.7
	Standard deviation	3.1	19.3	--	26	1.5	4.5	--	16.0
Constituent		Suspended phosphorus (mg/L)				Fecal coliform (colonies/100ml)			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff	Number of samples	13	10	8	10	10	10	8	10
	Maximum	17	54	151	32.1	3.70E+07	2.4E+8	2.6E+7	6.0E+6
	Minimum	0.9	4	23.7	19.3	5.80E+06	7.9E+7	1.0E+7	3.0E+5
	Average	5.4	27.6	95.6	25.6	1.10E+07	1.3E+8	2.1E+7	2.0E+6
	Standard deviation	4.1	13.4	51.5	4.4	8.60E+06	4.8E+7	5.2E+6	2.0E+6
Filter-strip runoff	Number of samples	15	5	--	2	15	5	--	2
	Maximum	6	42	--	36.2	1.30E+07	2.8E+8	--	4.0E+6
	Minimum	0	12	--	29.3	7.50E+06	1.5E+8	--	1.1E+6
	Average	2.2	30.4	--	32.7	9.60E+06	1.9e+8	--	2.6E+6
	Standard deviation	1.7	11.8	--	4.8	1.3E+6	5.5E+7	--	2.1E+6
Chemical loads									
Constituent		Dissolved organic N				Suspended phosphorus			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/26/96	10/17/96	6/2/98	6/27/98
Feedlot runoff (kg)		4.69	6.55	48.2	6.09	1.43	2.58	3.19	4.35
Filter-strip runoff (kg)		4.04	1.64	--	5.15	0.89	0.68	--	3.32
Attenuation value, in percent		14	75	--	15	38	74	--	24
Constituent		Dissolved phosphorus				Fecal coliform bacteria (colonies/100 mL)			
Sample date		7/27/96	10/17/96	6/2/98	6/27/98	7/27/96	10/17/96	6/2/98	6/27/98
Feedlot runoff (kg)		1.60	2.03	7.82	4.07	2.8E+13	1.3E+14	8.2E+5	3.8E+5
Filter-strip runoff (kg)		1.38	.56	--	2.43	2.7E+13	2.7E+13	--	1.8E+5
Attenuation value, in percent		14	72	--	40	18	79	--	53

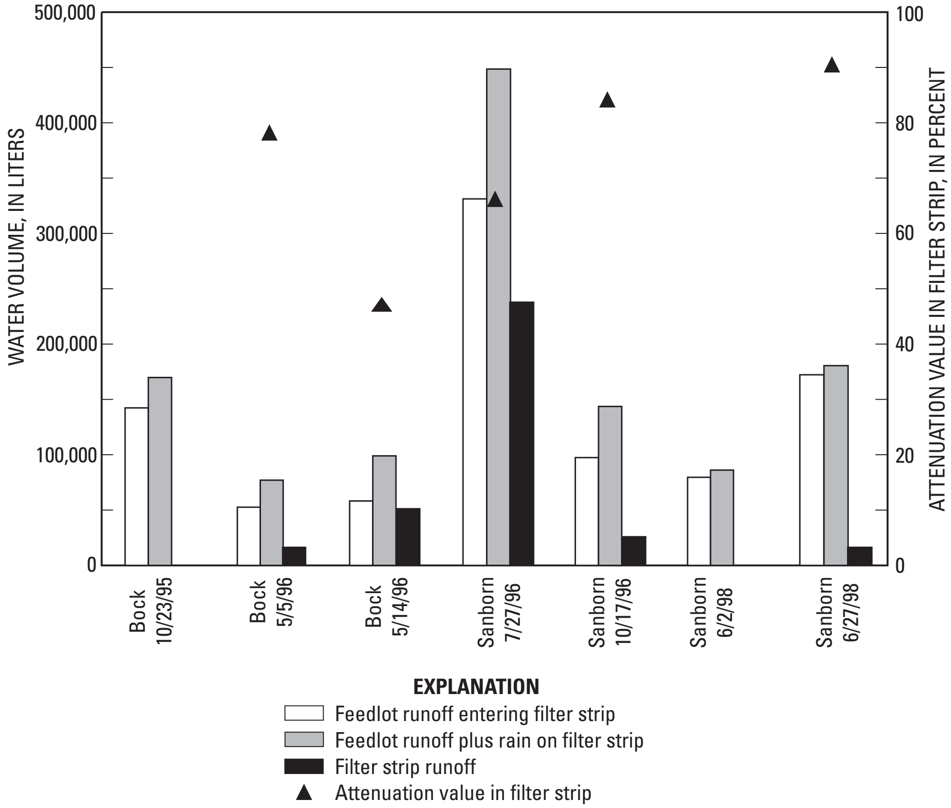

Figure 4. Volumes of feedlot runoff, feedlot runoff plus rain on the filter strip, filter-strip runoff, and attenuation value in the filter strip.

SANBORN SITE

Four storm-runoff events were monitored at the Sanborn site: July 27, 1996; October 17, 1996; June 2, 1998; and June 27, 1998. Due to equipment malfunctions, flow volumes exiting the filter strip were not measured during the storm-runoff event on June 2, 1998. Percentages of water retained in the strip ranged from 83 percent on October 17, 1996 to 98 percent on June 27, 1998. The storm of July 27, 1996 generated the most rain (9.1 cm) and the greatest volume of rain on the filter strip (table 3). Excluding the partially monitored storm of June 2, 1998, the storm of June 27, 1998 produced the least rain (0.6 cm) and the smallest flow volumes. The storm of October 17, 1996 was intermediate in rainfall (not flow volumes), with 3.6 cm of rain.

Average specific conductance of water from wells inside the filter strip was 2,603 µS/cm compared to 2,160 µS/cm outside the filter strip. Average chemical constituent concentration in water from wells located inside the filter strip is similar to average chemical constituent concentrations in water from wells located outside the filter strip.

ATTENUATION OF RUNOFF AND CHEMICAL LOADS

Attenuation values for runoff in the filter strips ranged from 47 to 98 percent (tables 1 and 2; fig. 4). The smallest value was at the Bock site on May 14, 1996 where the soils were wet from previous rainfalls, which limited the ability to absorb new water. The largest value was at the Sanborn site on June 27, 1998 (table 3).

Constituent concentration, loads from feedlot and filter-strip runoff, and attenuation values for the Bock and Sanborn sites are listed in tables 2 and 4, respectively. Periodically, some constituent concentrations were greater in the filter-strip than in feedlot runoff. For example, filter-strip runoff had greater concentrations for all constituents sampled than feedlot runoff except chemical oxygen demand. Filter-strip runoff could contain greater concentrations of certain constituents than the feedlot runoff because any given runoff event can entrain settled and adsorbed constituents left behind by preceding events.

Dissolved chloride concentrations were the dominant inorganic constituent in feedlot runoff and undoubtedly comes primarily from the urine component of manure. Sulfate loads were large in certain samples, particularly at the Bock site on October 23, 1995 (table 2). Mammals excrete approximately 40 percent of ingested sulfate (A.N. Pell, Cornell University, written, commun., 2000). This excretory component is the likely source of sulfate in feedlot runoff.

Decrease of chloride concentrations in filter-strip runoff compared to feedlot runoff may be due to two processes. First, chloride is an essential plant nutrient that has a role in photosynthesis, adenosine triphosphate production, and phosphorylation reactions (Kadlec and Knight, 1996). Plant uptake is therefore a potential chloride sink. Second, increases of chloride concentration in ground water at both sites indicates that chloride infiltrated through the soil substrate into ground water. Although only the Bock site has greater chloride concentrations in ground water underlying the filter strips than ground water outside of the filter strip, it is possible that chloride at the Sanborn site did not infil-

Table 5. Ground-water chemistry of the Bock and Sanborn site

[m, meter, µS/cm, micorsiemens per centimeter; °C degrees Celsius; mg/L, milligrams per liter; mL, milliliter; --, no data]

	Number of wells	Number of samples	Average water level below ground surface (m)	Average value												
				Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Nitrate, dissolved (mg/L)	Nitrite, dissolved (mg/L)	Ammonia, dissolved (mg/L)	Organic nitrogen, dissolved (mg/L)	Phosphorous, dissolved (mg/L)	Phophorous, ortho, dissolved (mg/L)	fecal coliform (colonies/100mL)
Bock site																
Wells inside filter strip	3	14	--	1194	7.1	8.7	2.9	62	167	2.60	0.16	0.09	0.81	0.03	0.02	9 to 72
Standard deviation	--	--	--	520	0.3	4.0	1.9	36	110	4.73	0.32	0.10	0.63	0.05	0.02	--
Wells outside filter strip	2	9	--	890	7.3	7.8	2.9	53	123	0.35	0.02	0.04	0.29	0.02	0.02	<9
Standard deviation	--	--	--	95	0.3	3.7	2.0	11	22	0.37	0.01	0.03	0.14	0.01	0.01	--
Sanborn site																
Wells inside filter strip	3	15	0.39	2603	6.9	10.1	1.0	408	272	0.13	0.03	0.48	0.95	0.03	0.02	<9
Standard deviation	--	--	--	405	0.4	1.4	1.2	173	72	0.13	0.06	0.20	0.72	0.03	0.01	--
Wells outside filter strip	5	21	1.29	2160	7.1	8.6	2.5	414	237	0.16	0.02	0.25	0.67	0.04	0.03	<9
Standard deviation	--	--	--	483	0.4	2.2	1.9	102	70	0.33	0.03	0.33	0.45	0.06	0.03	--

trate completely to the water table and was stored in the soil.

Sulfate is another plant essential nutrient that in its reduced form, sulfhydryl (SH^-), is used to synthesize amino acids (Kadlec and Knight, 1996). Sulfate may also be reduced to volatile H_2S gas. Increased sulfate concentrations in ground water beneath the Bock site filter strip indicates that sulfate infiltrated into ground water.

Nitrogen species in most feedlot runoff were dominated by organic nitrogen and ammonia plus organic nitrogen; while dissolved ammonia concentrations were comparatively smaller (tables 2 and 4). Such results are typical for runoff from cattle feedlots (Vellidis and others, 1996; Reaves and DuBowry, 1997). Exceptions occurred in feedlot runoff at the Bock site on May 5, 1996, and May 14, 1996 when dissolved ammonia loads are approximately equivalent to the other two nitrogen species. Suspended phosphorous loads were larger than dissolved phosphorus loads in some samples, but the reverse was true in other samples. It is likely that suspended phosphorus was adsorbed to manure and soil particles. Sharpley and Smith (1995) indicated that suspended, adsorbed phosphorus is converted to inorganic phosphorus in soils receiving manure. The variability in the ratios of organic suspended and dissolved phosphorus species may reflect this process.

Phosphorous is an essential plant nutrient and major cellular constituent. Plant uptake of dissolved orthophosphate may cause decreases of dissolved phosphorus loads in filter-strip runoff. Suspended phosphorous also may be bound to manure and soil particles. Decomposition of manure and release of phosphorus from soils would make it available for plant uptake. Suspended phosphorous also may be removed by filtration and sedimentation.

Fecal coliform bacteria are not disease causing, but are indicators of pathogens. Fecal-coliform contaminated surface water typically contains 200 to greater than 2,000,000 colonies/100 mL (Myers and Sylvester, 1999). Feedlot runoff at the Sanborn site contained as much as 2.8×10^{13} colonies/100 mL. The decrease of fecal coliform colony counts in filter-strip runoff compared to feedlot runoff may be due to physical filtration, or prolonged exposure to sunlight, which can kill bacteria.

Loads of all constituents except two were less in filter strip runoff than in feedlot runoff at both sites (tables 2 and 4). Nitrite plus nitrate nitrogen loads increased at the Sanborn site on July 27, 1996, but the feedlot runoff and filter-strip runoff loads were so small as to be practically indistinguishable. Sulfate loads also increased by 3 percent at the Sanborn site on June 27, 1998, but this small increase probably was within the error of the load calculation.

Decreases in ammonia loads in the filter strip may be due to plant uptake or volatilization. Oxidation of ammonia to nitrate is unimportant judging from the small nitrite plus nitrate loads. A source of ammonia is conversion from organic nitrogen by mineralization. Mineralization may be the cause of decreases in dissolved and suspended organic nitrogen. Organic nitrogen also may have decreased due to physical filtration by grass in the filter strip.

Loads of fecal coliform bacteria were largest in the Sanborn samples from 1996 and smallest in the Sanborn samples from 1998. Despite the large fecal coliform loads in runoff, ground water beneath the filter strips contains only small concentrations of these bacteria (table 5).

Attenuation of chemical loads could be evaluated for four events, three at the Sanborn site and one at the Bock site (fig. 5; tables 2 and 4). Attenuation values were uniformly largest for the storm of October 17, 1996 at the Sanborn site and ranged from 72 to 82 percent (except for nitrate; table 4). The storm of July 27, 1996 had attenuation values of 14 to 54 percent (except for nitrate), and the storm of June 27, 1998 had values of 6 to 67 percent (except for sulfate). Attenuation was greatest at colder temperatures (storm of October 17, 1996) probably because freezing temperatures affected the filter-strip vegetation by causing the grass to wilt and lay close to the ground. The storm of May 14, 1996 at the Bock site had the next largest overall attenuation values, which ranged from 25 to 85 percent (table 2). Dissolved chloride, which is generally conservative in surface water, was attenuated 32 percent. The chloride lost in the filter strip may have infiltrated. Attenuation values for suspended constituents (62–85 percent) tended to be larger than those for dissolved constituents (25–75 percent).

The time that feedlot runoff remains in the filter strip seems to have little systematic effect on attenuation values. For example, the duration of filter-strip runoff at the Sanborn site was 27.1 hours on July 27, 1996, and 2.2 hours on June 27, 1998 (table 3). Although runoff remained in the filter strip about 25 hours longer on July 27, 1996, attenuation values were 85 percent on July 27, 1996 and 98 percent on July 27, 1998. Despite these differences in retention time, attenuation values were not demonstrably related to retention times.

Some studies reported that suspended constituents are attenuated more efficiently than their dissolved equivalents (Dillaha and others, 1986). This relation is apparent in the single set of attenuation values (May 14, 1996) available for the Bock site (fig. 5; table 2). Attenuation values of nitrogen species are 61 percent for

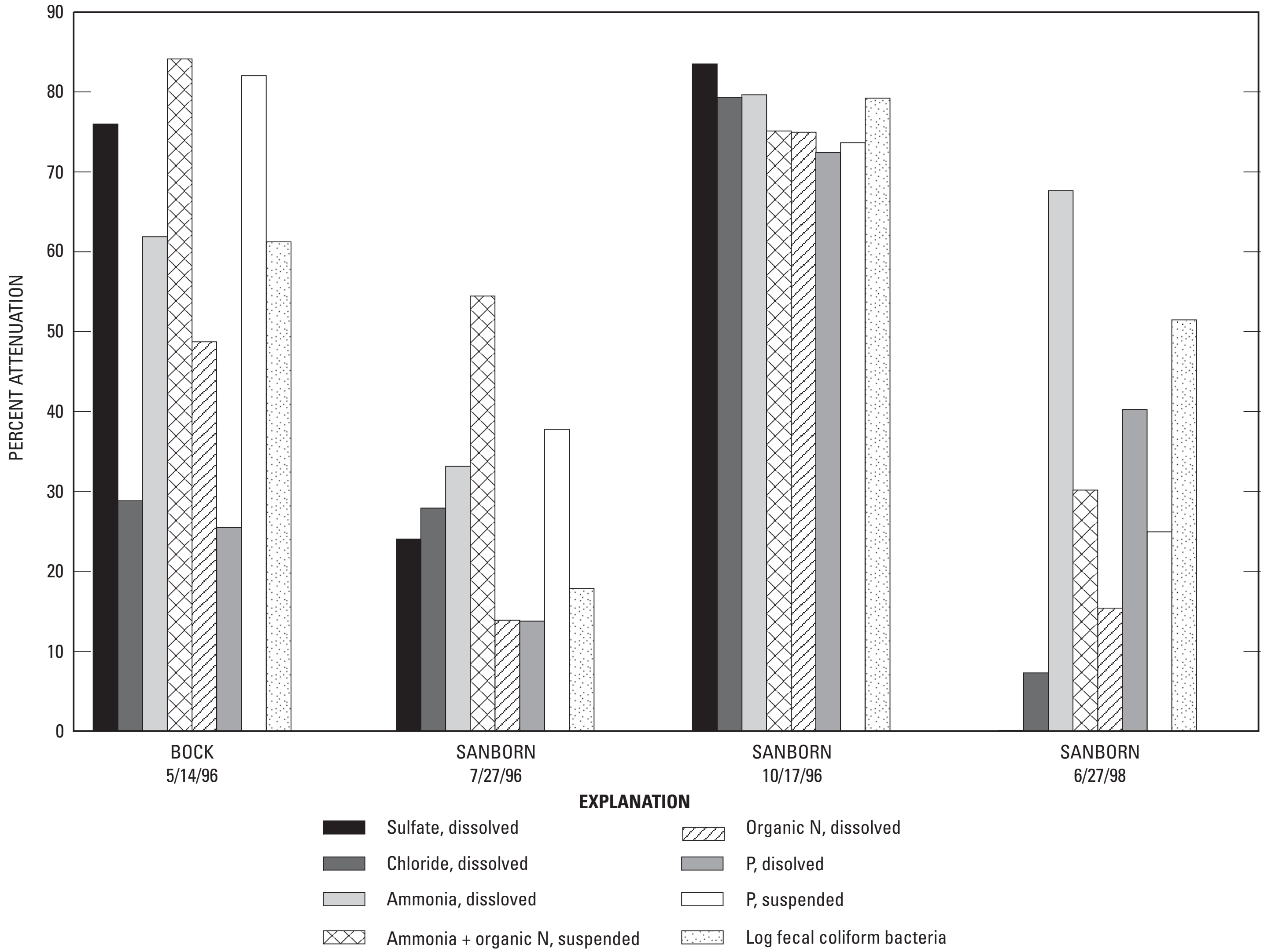

Figure 5. Attenuation values for chemical constituents in four runoff events.

dissolved ammonia-nitrogen and 49 percent for dissolved organic nitrogen, but 85 percent for suspended ammonia plus organic nitrogen. Similarly, attenuation of dissolved phosphorus is 25 percent compared to 82 percent for suspended phosphorus. At the Sanborn site on July 27, 1996, attenuation values of dissolved nitrogen species were less than those of suspended nitrogen species. On October 17, 1996, attenuation values of dissolved and suspended nitrogen species were generally equivalent. On June 27, 1998, the attenuation value for dissolved ammonia nitrogen was greater than for suspended ammonia plus organic nitrogen, but the attenuation value for dissolved organic nitrogen was less than the attenuation value for the suspended species. A similar pattern of dissolved greater than suspended was expressed for phosphorus species. The attenuation value for dissolved phosphorus was less than the attenuation value for suspended phosphorus on July 27, 1996, was nearly equivalent to the attenuation value for suspended phosphorus on October 17, 1996, and was greater than the attenuation value for suspended phosphorus on June 27, 1998. These complex patterns show that no single statement can be made concerning relative attenuation values of dissolved and suspended nitrogen and phosphorus species.

Attenuation of fecal coliform bacteria indicate that deposition of bacteria is increased when grass is flat lying (tables 2 and 4). There may also be an effect in which bacterial survival is improved at greater temperatures, perhaps because of beneficial physiological effects on bacteria.

SUMMARY

The attenuation efficiency of cattle feedlot runoff in two grass-covered filter strips in Minnesota was estimated by measuring chemical loads entering and leaving the filter strips. The Bock and Sanborn filter strips measured 60-m long and 20-m wide and received runoff from cattle feedlots that housed 35 and 225 cattle, respectively. Feedlot and filter-strip runoff was measured using flumes with stage sensors. Water samples were collected using automated samplers.

Ground-water quality is a concern where feedlot-runoff infiltration is significant. Chemical changes in ground water from wells sampled inside the filter strips indicate that, for some parameters, filter-strip runoff degrades ground-water quality. Ground water from wells sampled inside the filter strips at the Bock site had elevated specific conductance, dissolved sulfate, dissolved chloride, dissolved nitrate, dissolved ammonia nitrogen, and dissolved organic nitrogen concentrations compared to ground water from wells outside the filter strip. Ground water from wells inside the Sanborn filter strip had increased ground-water levels, temperature, and dissolved ammonia nitrogen concentrations, and decreased dissolved oxygen concentrations beneath the filter strip compared to ground water from wells outside the filter strip. The greater effect on ground water at the Bock site likely is due to the greater hydraulic conductivity of soil compared to the Sanborn site.

Attenuation efficiencies from four storm-runoff events were calculated. Ground water sampled beneath and outside the filter strips indicated some infiltration losses of sulfate, chloride, and nitrogen at the Bock site where soil permeability was greater than the Sanborn site. Chemical constituents in filter-strip runoff, and their corresponding ranges of attenuation efficiency were as follows: chemical oxygen demand, 30 to 81 percent; dissolved sulfate, -3 to 82 percent; dissolved chloride, 6 to 79 percent; dissolved ammonia nitrogen, 33 to 80 percent; suspended ammonia plus organic nitrogen, 29 to 85 percent; dissolved organic nitrogen, 14 to 75 percent; suspended phosphorus, 24 to 82 percent; dissolved phosphorus, 14 to 72 percent; and fecal coliform bacteria, 18 to 79 percent. The ranges seem to be affected by barriers of direct contact of the runoff water with the soil. This varies seasonally by coverage of the soil by ice in winter and vegetation in summer months. Greater attenuation values occurred in October and May when mats of wilted, flat-lying grass covered the filter strips; values were less during the summer when tall growing grass covered the filter strips.

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