Quantity and Quality of Runoff from a Beef Cattle Feedlot in Southern Alberta

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ABSTRACT

Southern Alberta, which has a cold climate dominated by strong chinook winds, has the highest density of feedlot cattle in Canada. However, the quantity and quality of runoff from beef cattle (*Bos taurus*) feedlots in this unique region has not been investigated. Our objectives were to compare runoff quantity (1998–2002) with catch-basin design criteria; determine concentrations of selected inorganic chemical parameters (1998–2000) in runoff in relation to water quality guidelines and the potential implications of irrigating adjacent cropland; and determine if total heterotrophs, total coliforms, and *Escherichia coli* (1998–2000) persisted in the catch-basin water and soil. Runoff (<0.1 to 42.5 mm) for a 24-h duration that included maximum peak discharge was less than the recommended design criteria of 90 mm based on runoff from 24 h of rainfall with a 30-yr return period. We found that curve numbers between 52 and 96 (mode of 90) were required to match the USDA Natural Resources Conservation Service predicted runoff and actual runoff volumes. Total P posed the greatest threat to water quality guidelines, and K posed the greatest threat for exceeding crop fertilizer requirements if catch-basin effluent was used as irrigation water. Water in the catch basin had continually high populations of *E. coli* throughout the study, with values ranging between $\log_{10}$ 2 and $\log_{10}$ 8 100 mL^{-1}. In contrast, soil in the catch basin generally had low populations of *E. coli* that were <$\log_{10}$ 2 g^{-1} wet wt., but at times higher populations between $\log_{10}$ 2 and $\log_{10}$ 6 g^{-1} wet wt. were also found.

Runoff from beef cattle feedlots contains numerous pollutants that must be controlled and prevented from entering surface waters and ground waters. Research on the quantity and quality of feedlot runoff has been conducted in Texas (Clark et al., 1975a), Nebraska (Swanson, 1972; Gilbertson et al., 1972, 1979), Kansas (Miner et al., 1966), southern Ontario (Coote and Hore, 1977), Saskatchewan (Laksham, 1982), and Alberta (Goatcher et al., 1991). A review of the literature on feedlot runoff was conducted by Gilbertson et al. (1981) and later by Sweeten (1998). More recent research on feedlot runoff has been conducted in Australia (Lott, 1996) and central Alberta (Kennedy et al., 1999). We are unaware of studies conducted on the quantity and quality of feedlot runoff in southern Alberta, which has the highest concentration of feedlot cattle in Canada. There were approximately 700 000 head of beef cattle in the County of Lethbridge in 2003 (T. Ormann, personal communication, 2003). Bedding material is commonly used in feedlot pens, due to a cold climate dominated by strong chinook winds.

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Controlling runoff from feedlots requires a knowledge of feedlot hydrology. Runoff from unpaved feedlots, which is the most common type in the Canadian prairies, depends on the amount of rainfall and snowmelt, the area of the feedlot, and the proportion of precipitation that is stored on the feedlot (Intensive Livestock Operations Committee, 1995). In Alberta, the Agricultural Operations Practices Act (Province of Alberta, 2001) specifies that a catch basin (also known as a retention pond or runoff holding pond) be designed to hold the runoff from a 24-h rainstorm with a return period of 30 yr. Snowmelt runoff may be an important component of the total annual runoff in areas north of 42° latitude (Gilbertson et al., 1981). However, few studies have been conducted on feedlot runoff in northern climates. While most researchers have reported runoff contributions from snowmelt and rainfall (Swanson, 1972; Coote and Hore, 1977; Laksham, 1982), others have found only runoff from rainfall (Kennedy et al., 1999). A positive linear relationship has generally been reported between rainfall and runoff from feedlots (Gilbertson et al., 1981; Coote and Hore, 1977). The proportion of rainfall as runoff (yield) for unpaved feedlots ranges from 36 to 86% for the USA (Coote and Hore, 1977; Gilbertson et al., 1981), 22 to 50% for Australia (Lott, 1995), 19 to 25% for eastern Canada (Coote and Hore, 1977), and 16 to 40% for central Alberta (Kennedy et al., 1999).

Runoff from feedlots has been predicted using the USDA Natural Resources Conservation Service (NRCS) runoff equation (Soil Conservation Service, 1972):

$$Q = [(P - 0.2S)^2]/(P + 0.8S) \quad [1]$$

where Q is rainfall excess or runoff (mm), P is precipitation (mm), and S is maximum soil retention parameter or storage factor (mm). Storage is dependent on the slope of the pens, pen manure management, the depth and antecedent water content of the manure pack, depression storage in cattle hoof prints, and the amount and type of bedding used (Intensive Livestock Operations Committee, 1995; Kennedy et al., 1999). The S value is inversely related to a curve number (CN) that can vary from 0 to 100. The parameter S (mm) is calculated by:

$$S = (25400/\mathrm{CN}) - 254 \quad [2]$$

Abbreviations: CN, curve number; EC, electrical conductivity; TAH, total aerobic heterotrophs; TC, total coliforms.

where CN is runoff curve number. In the USA, a CN value of 90 has been recommended for the design criteria for feedlot catch basins (Gilbertson et al., 1981; Sweeten, 1998), even though lower CN values (82) have been reported (Hauser, 1975). In Alberta, Kennedy et al. (1999) reported CN values ranging from 55 to 83.

Runoff contains chemical contaminants that can impair water quality (Miner et al., 1966; Clark et al., 1975b; Coote and Hore, 1977; Kennedy et al., 1999). The wide range in transported chemicals in runoff may be due to the type of ration fed, the type of feedlot surface, climate, antecedent water content of feedlot floor, as well as storm intensity and duration (Gilbertson et al., 1981). If runoff from feedlots is not properly managed to prevent off-site transport, chemical constituents in runoff have the potential to harm surrounding surface waters in terms of aquatic life, as well as recreational and drinking water use by humans. In addition, because adjacent cropland is often irrigated with catch-basin effluent, the chemical quality of the effluent may affect the soil and crop.

Persistence of bacteria in feedlot runoff or catch basins has been examined in the USA (McCoy, 1967; Hrubrant et al., 1972; Rhodes and Hrubrant, 1972; Crane et al., 1983), but few studies have been conducted north of 49° latitude in feedlots where bedding is commonly used (Kennedy et al., 1999). McCoy (1967) found that the bacterial indicator species for fecal contamination (coliform, enterococci) died off rapidly in the catch basin. Rhodes and Hrubrant (1972) reported that runoff contained a suite of bacteria similar to feedlot manure, but the populations were more variable due to changes in volume of liquid in the runoff. Kennedy et al. (1999) found maximum populations of fecal coliforms in catch-basin effluent during August compared with July and September. Catch basins in southern Alberta may not contain effluent during years of low precipitation or high evaporation, so bacteria may also persist in catch-basin soil, which might be an environmental concern.

The objectives of this study were to compare feedlot runoff quantity with catch-basin design criteria; determine concentrations of selected inorganic chemical parameters in runoff in relation to water quality guidelines; ascertain the potential implications of irrigating adjacent cropland with catch-basin effluent; and determine if total heterotrophs, total coliforms, and *Escherichia coli* bacteria persisted in the catch-basin water and soil.

MATERIALS AND METHODS

Feedlot Design and Management

The Lethbridge Research Centre Feedlot was used for this study (Fig. 1). The research feedlot was constructed in 1996 according to existing provincial guidelines in 1995 (Intensive Livestock Operations Committee, 1995). The topsoil was stripped from the area and clay material excavated from the catch basin and used to construct the surface topography of the feedlot. Pens have about 2% slope from feed bunk to drainage alley, and the drainage alleys have 1% slope. The feedlot consists of 48 smaller (14 × 20 m) pens (Pens 1–48; Fig. 1) that hold approximately 15 beef cattle (*Bos taurus*)

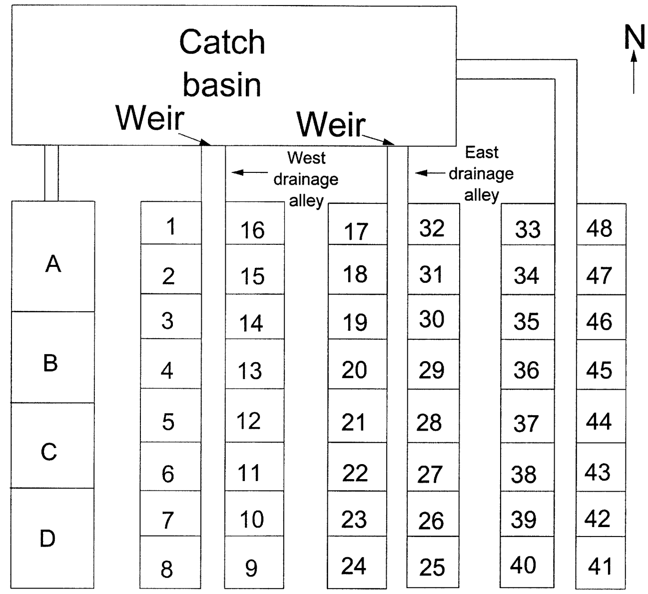

Fig. 1. Layout of the beef cattle feedlot in southern Alberta that was used in this study.

each for a cattle density of 18 m^2 per head. In addition, there are four larger (28 × 40 m) pens (Pens A–D; Fig. 1) that hold approximately 40 cattle each for a cattle density of 28 m^2 per head. The recommended cattle density for finishing feeder cattle and backgrounding calves in southern Alberta feedlots is 18 to 23 and 16 to 18 m^2 $head^{-1}$, respectively (Alberta Agriculture, Food and Rural Development, 1997). Kennedy et al. (1999) reported an average density of 17 m^2 per head for a commercial feedlot near Vegreville, AB. Cattle were not present in Pens 33 to 41 and Pens A to D (Fig. 1) in 1998–1999. Cattle were stocked in the pens from 24 Nov. 1997 to 2 July 1998; 7 Dec. 1998 to 17 June 1999; 14 Oct. 1999 to 11 Aug. 2000; and 31 Oct. 2001 to 15 July 2002. The diet for the beef cattle generally consisted of 70% barley (*Hordeum vulgare* L.) silage and 30% barley grain for a 70- to 80-d backgrounding period, followed by 85 to 90% barley grain and 10 to 15% barley silage for the remainder of the feeding period. All pens were bedded with barley straw with the following exceptions. Wood-chip bedding was used in Pens 1 to 3 in 1998–1999, Pens 9 to 12 in 1999–2000, and in Pens 29 to 32 in 2000–2002. The wood chips were a mixture of sawdust and bark peelings derived from 80% lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and 20% white spruce [*Picea glauca* (Moench) Voss]. Bedding material was used as required during the winter. All pens were cleaned out by the end of August in each year, except for 2002 (wet year), when all pens were cleaned out by the end of September.

Runoff Collection and Analysis

The feedlot catch basin (approximately 135 × 24 × 1.37 m) had a design capacity of approximately 4439 m^3 (4.4 × 10^6 L). Runoff from the 16 pens on the west side of the feedlot (Pens 1–16; Fig. 1) was diverted through the west-side drainage alley into the catch basin; and runoff from the 16 pens on the east side of the feedlot (Pens 17–25; Fig. 1) was diverted through the east-side drainage alley into the catch basin. Runoff from Pens 33 through 48 and Pens A through D also entered the catch basin, but was not measured. A V-notch weir was installed on the west- and east-side drainage alleys to measure the quantity of surface runoff. Each weir drained an area of approximately 0.50 ha. The wiers were instrumented with a float assembly, potentiometer, and datalogger (Foroud and Hlibka, 1989) to measure water-level height in a digital form every 5 to 10 min. The west-side weir was also instrumented with an ISCO (Lincoln, NE) automatic water sampler to collect runoff samples for analyses of various chemical parameters. Samples were collected hourly when flow was continuous and >1.7 L min^{-1}. Runoff quantity and quality were measured from early spring to late fall from 1998 to 2002. Hourly precipitation was determined from the weather station located about 700 m from the feedlot at the Lethbridge Research Centre. The five-day antecedent rainfall index was calculated using the equation (Linsley et al., 1975):

$$\text{FDARI} = (R_{n-1} \times 0.9) + (R_{n-2} \times 0.9^2) + (R_{n-3} \times 0.9^3) + (R_{n-4} \times 0.9^4) + (R_{n-5} \times 0.9^5) \quad [3]$$

where FDARI is the five-day antecedent rainfall index (mm); R_{n-1} is 24-h rainfall (mm) one day before runoff; R_{n-2} is the 24-h rainfall two days before runoff, etc.; and 0.9 is a dimensionless recession factor. Runoff water samples collected from 1998 to 2000 (but not 2002) from the automatic water sampler on the weir were analyzed for electrical conductivity (EC), pH, temperature, ammonia N, nitrate N, ortho-P, total N, total P, total C, inorganic C, and soluble salts (Ca, Mg, Na, K, Cl, SO_4). The EC, pH, and temperature were measured using a portable water quality meter and associated probes (MultiLine P4; Wissenschaftlich-Technische, Werkstätten, Germany). Total dissolved solids (TDS) were estimated by multiplying EC by 640 (Bohn et al., 1979). Ammonia N was determined using the automated phenate method (Technicon Industrial Systems, 1973a) in 1998 and the automated salicylate method (Rhine et al., 1998) thereafter. Nitrate N was determined using the automated cadmium reduction method (Technicon Industrial Systems, 1978) in 1998 and the automated hydrazine reduction method (Kempers and Luft, 1988) thereafter. Changes were made in the methods mainly because of safety concerns with the existing chemicals (i.e., phenol and cadmium). Quality control checks revealed good agreement between the former and latter methods. Ortho-P was determined using the automated ascorbic acid method (Technicon Industrial Systems, 1973b). Total N was determined using the persulfate digestion method (Method 4500-N_{org} D; American Public Health Association, 1995), followed by analysis of nitrate using the methods outlined above. Total P was determined using the persulfate digestion method (Method 4500-P B; American Public Health Association, 1995). Soluble Ca and Mg were analyzed using atomic absorption spectroscopy, and Na and K were determined using flame emission spectroscopy. The sodium adsorption ratio (SAR) was calculated using the equation of Bohn et al. (1979). Chloride was determined using the automated mercuric thiocyanate method (Technicon Industrial Systems, 1974), and SO_4 using the automated barium chloride method (Technicon Industrial Systems, 1972).

Bacterial Enumeration of Catch-Basin Effluent and Soil

Water and soil samples were taken weekly from three locations (east, center, and west locations) within the feedlot catch basin for microbiological analyses between 20 May 1998 and 25 Sept. 2000. Water samples were taken when effluent was present in the catch basin, and soil samples were taken from the catch-basin floor when the catch basin was dry. The upper 30 cm of the water column was sampled using a small bucket attached to a long handle. The 0- to 5-cm depth of soil from the catch-basin floor was sampled using a shovel after the sludge on the catch-basin floor was first removed. Water and soil samples were analyzed for total aerobic heterotrophs (TAH) at 27°, total coliforms (TC), and *E. coli*. All samples were transported to the laboratory within 1 to 2 h and plated within 4 h of collection. Water (10 mL) or soil (10 g) was added to 90 mL of sodium phosphate buffer (pH 6.5, 0.05 *M*). The samples were then blended for 2 min at a medium setting in a Stomacher blender (Model 400; Seward Medical, Mississauga, ON, Canada) and were then serially diluted to the appropriate levels in sodium phosphate buffer. One milliliter of the dilutions was then inoculated into 9 mL of Fluorocult LMX (Merck, Whitehouse Station, NJ) broth tubes for enumeration of coliform and *Escherichia coli* by the three-tube most probable number (MPN) method (Garthwright, 1998). One hundred microliters of the appropriate serial dilution was inoculated onto tryptic soy agar (TSA) plates, in triplicate, for enumeration of the total aerobic heterotrophs at 27°C after 48 h. The Fluorocult LMX broth tubes were incubated aerobically at 37°C for 48 h, and *E. coli* able to hydrolyze 5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside (X-GAL) and 4-methylumbelliferyl-β-D-glucuronide (MUG) were enumerated after 24 and 48 h. Total coliforms able to hydrolyze X-GAL were enumerated after 48 h. For the water samples, the results are presented as log colony forming units (log CFU) per 100 mL or log most probable number (log MPN) per 100 mL. Results for the soil samples are presented as log colony forming units (log CFU) per g wet wt. of soil or log most probable number (log MPN) per g wet wt. of soil. Our minimum detection level for these samples (*E. coli*, coliform) was $\log_{10}$ 1.56 MPN g^{-1}. Positive tubes were also used as a source of single isolates to confirm presumptive enumerations by streaking for single colonies onto LMX agar plates. Selected colonies of presumptive TC and *E. coli* were isolated for confirmation of identity through membrane fatty acid composition (Paisley, 1996), cellular morphology, and biochemical characteristics (Smibert and Kreig, 1994; Garthwright, 1998). The rationale for using generic *E. coli*, TC, and TAH in this study has been previously discussed by Miller et al. (2003).

RESULTS AND DISCUSSION

Surface Runoff

There were six runoff events in 1998, three in 1999, one in 2000, none in 2001, and one in 2002 (Table 1). Rainfall duration ranged from 5 to 59 h, and rainfall amount ranged from 12.2 to 136.9 mm (Table 1). Average hourly rainfall intensity ranged from 1.0 to 2.6 mm h^{-1}, maximum intensity ranged from 3.6 to 15.2 mm h^{-1}, and maximum 5-min intensity ranged from 0.6 to 5.8 mm h^{-1} (Table 1). The five-day antecedent rainfall index ranged from 2.2 mm for Event 2 to 43.0 mm for Event 4 (Table 1), indicating wetter pre-runoff conditions for the latter event. The durations and average intensities for the 11 events were plotted on the rainfall duration–intensity–frequency graph for Lethbridge with return period storms ranging from 2 to 50 yr (data not shown). Rainfall Events 1, 3, 4, 5, and 6 had return periods of <2 yr, and Events 2, 4, 7, 8, and 9 had return periods close to 2 yr. Event 10 had a return period between 2 and 10 yr, and Event 11 had a return period of >50 yr. Rainfall for Event 11 indicated the potential to exceed the catch-basin design volume based on the criteria of one-day rainfall with a 30-yr return period. Monthly rainfall exceeded the monthly long-term normal by 102

Table 1. Summary of rainfall characteristics that caused runoff events (1998–2002) at a beef cattle feedlot in southern Alberta.

Parameter	Rainfall event										
	Event 1, 16 June 1998	Event 2, 26–27 June 1998	Event 3, 28 June 1998	Event 4, 29–30 June 1998	Event 5, 3 July 1998	Event 6, 7–8 July 1998	Event 7, 15 May 1999	Event 8, 3 June 1999	Event 9, 18 July 1999	Event 10, 2–3 Sept. 2000	Event 11, 8 June 2002
Rain start	15 June	26 June	28 June	29 June	3 July	7 July	13 May	2 June	15 July	20 Aug.	8 June
Rain end	16 June	27 June	28 June	30 June	4 July	8 July	15 May	3 June	18 July	3 Sept.	10 June
Duration, h	29	27	9	13	7	5	33	26	19	16	59
Total rain, mm	28.0	34.6	38.6	30.4	17.2	12.2	40.2	35.0	35.2	41.2	136.9
Average intensity, mm h^{-1}†	1.0	1.3	1.1	2.3	2.5	2.4	1.2	1.3	1.9	2.6	2.3
Maximum intensity, mm h^{-1}‡	3.6	4.4	4.4	6.8	6.6	3.8	7.4	5.6	15.2	10.1	5.4
Maximum 5-min intensity, mm	1.4	0.6	0.6	2.2	2.2	3.2	1.8	0.8	5.8	1.6	0.8
Five-day antecedent rainfall index, mm§	32.0	2.2	36.2	43.0	30.4	15.2	37.0	27.1	10.7	17.2	8.2

† Average rainfall intensity for 1 h.
‡ Maximum rainfall intensity for 1 h.
§ Calculated using Eq. [3].

to 382% for the months when the 11 runoff events occurred (Table 2).

All runoff events except one occurred before the manure from the feedlot pens was removed. The exception was Event 10 on 2–3 Sept. 2000, where runoff occurred approximately one month after the pens were cleaned. Hydrographs and rainfall amounts are shown for a 2-yr (Event 2) and >50-yr (Event 11) return period event (Fig. 2). Rainfall rather than snowmelt initiated all 11 runoff events. Similarly, Kennedy et al. (1999) reported that 26 runoff events over 4 yr at a feedlot in central Alberta were all caused by rainfall. Runoff events ranged between 14 and 55 h in duration and depth of runoff ranged from <0.1 to 53.6 mm (Table 3). The runoff yield ranged from 0.1 to 56% (Table 3). In comparison, Kennedy et al. (1999) reported that 16 to 40% of rainfall ran off a feedlot in central Alberta. Although there were significant correlations among some of the rainfall (Table 1) and runoff (Table 3) parameters (data not shown), we observed no linear or nonlinear relationships among the parameters, which was probably due to the small sample size ($n = 11$). Total rainfall depth had the strongest correlation with the various runoff parameters, followed by rainfall duration. Surprisingly, the five-day antecedent rainfall index was uncorrelated with none of the runoff parameters, and we are unsure as to why this occurred.

We used the USDA-NRCS runoff and storage equations (Eq. [1] and [2]) and adjusted the curve number (CN) value until predicted runoff was equal to actual runoff from the feedlot (Table 3). We found that CN values between 52 and 96 (mode = 90) were required to match predicted and actual runoff. Our wide range in CN values suggests that considerable error may result if one CN value is used to predict individual runoff events from feedlots. Therefore, when using the USDA-NRCS equation to predict runoff, we believe that it is best to assume the most frequent or worst-case scenario and use the mode (90) or maximum (96) CN values. In comparison, Kennedy et al. (1999) reported CN values between 55 and 83 for a commercial unpaved feedlot in central Alberta where bedding was used. Our CN mode value of 90 was similar to the value (90) recommended for design criteria of catch basins in the USA (Sweeten, 1998), but was higher than the value of 82 recommended by Hauser (1975). The CN values of <80 observed for some of the runoff events in our Alberta feedlot may be related to straw and wood-chip bedding contributing to greater storage and less runoff. Storage values ranged from 0.4 to 9.2, indicating a wide range in storage of rainfall on the feedlot. This was consistent with extreme seasonal variations in amount of manure and bedding within the feedlot pens because of cleaning of the pens in the summer.

A plot of runoff versus rainfall (Fig. 3) revealed no linear relationship as previously reported by others (Clark et al., 1975a; Coote and Hore, 1977). Runoff Events 2, 4, 5, and 6 exhibited a linear trend with rainfall, and were associated with higher CN values (84–96) and lower S values (0.4–1.9). In contrast, Events 1, 3, 7, 8, 9, and 10 exhibited no trend, and were associated with lower CN values (52–96) and greater S values (0.4–9.2). Mean values of rainfall duration, total rainfall, and maximum hourly rainfall intensity were 43 to 69% higher

Table 2. Rainfall (1998–2002) at Lethbridge Research Centre in relation to long-term mean rainfall.

Month	1998	1999	2000	2001	2002	Long-term mean
	mm					
May	53.4 (103)†	58.3 (112)	11.2 (22)	10.0 (19)	56.4 (109)	51.9
June	148.4 (233)	65.1 (102)	44.6 (70)	42.9 (67)	243.7 (382)	63.8
July	57.4 (134)	64.2 (150)	5.5 (13)	10.2 (24)	38.0 (89)	42.8
August	36.2 (76)	39.3 (82)	27.3 (57)	0 (0)	79.1 (165)	47.9
September	13.7 (39)	10.8 (31)	41.9 (120)	7.1 (20)	66.9 (191)	35.0
Total	309.1 (128)	237.7 (98)	130.5 (54)	70.2 (29)	484.1 (201)	241.4

† Numbers in parentheses are percentage values of long-term mean (monthly or total rainfall/monthly or total long-term mean × 100). Long-term mean is based on years 1971–2000.

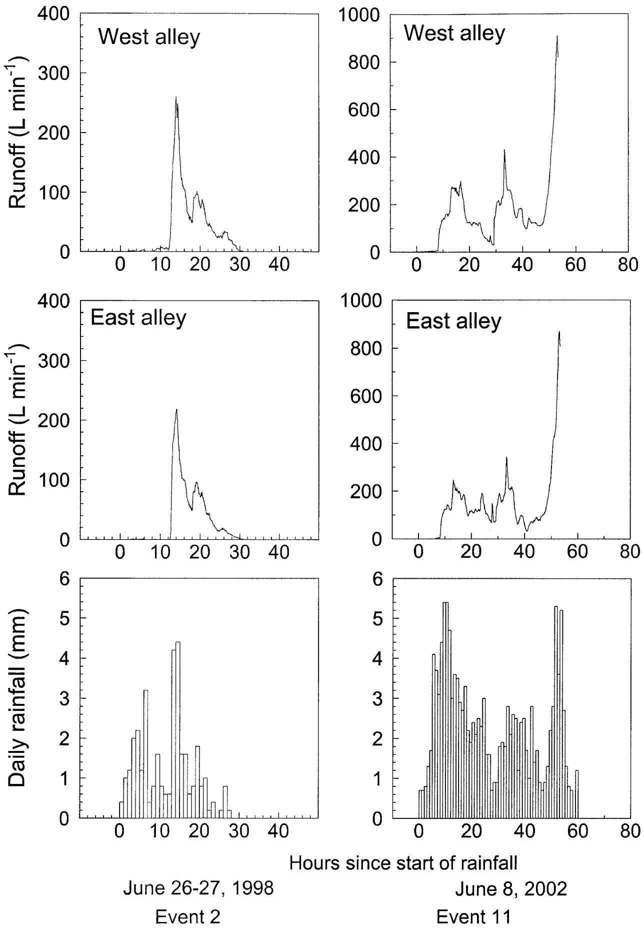

Fig. 2. Runoff hydrographs for 2-yr (Event 2) and >50-yr (Event 11) return period events in relation to daily rainfall for a beef cattle feedlot in southern Alberta. The hydrographs for west and east alleys for Event 11 on 8 June 2002 are incomplete because water in the catch basin rose to the level of the weir, and runoff could not be measured thereafter. Note that the scales for the *y* axis are different for Events 2 and 11.

for the six non-trend events than the four linear events (data not shown). The differences in total runoff between the west and east alleys were less than 100% for 10 of the 11 events (Table 3), indicating that the west and east pens were relatively good replicates. The exception was Event 9, where the total runoff was 1267% higher for the east than west alley. We speculate that some temporal management factor must have caused the large differences in total runoff from the west and east pens for Event 9 on 18 July 1999, because runoff from these pens was similar for the previous Event 8 on 3 June 1999.

We determined the recommended catch-basin storage volume for Lethbridge using the most recent Agricultural Operations Practices Act (Province of Alberta, 2001), and then compared this with the runoff volumes from the west and east drainage alleys to determine if the actual runoff volumes were less than the recommended catch-basin design volume. One-day rainfall runoff volume (ODRRV) in m^3 was calculated from the following equation (Province of Alberta, 2001):

$$\text{ODRRV} = A \times R \times C \qquad [4]$$

where A is the feedlot drainage area (m^2), R is the one-day rainfall depth (m) with a 30-yr return period, and C is a runoff coefficient. The feedlot area contributing runoff through each of the west and east alleys is 4987 m^2, and includes concrete aprons connecting feedlot and catch basin. One-day rainfall for a 30-yr return period at Lethbridge is 0.090 m (Province of Alberta, 2001). The runoff coefficient or proportion of rainfall as runoff was taken as the average (0.53) of the range (0.40–0.65) given for unpaved feedlots (Province of Alberta, 2001). The ODRRV was calculated to be 238 m^3. The 24-h runoff volumes that included maximum peak discharge and that had runoff durations of ≥24 h were determined for Events 2 to 4, 6, 8, 10, and 11 for the west alley, and for Events 1, 2, 4, 6, and 8 to 11 for the east alley (data not shown). All seven runoff events for the west alley and all eight events for the east alley had volumes (0.1–212 m^3) or depths (<0.1 to 42.5 mm) that were less than the recommended design criteria of 238 m^3 or 90 mm. This indicated that the existing design criteria based on 24-h rainfall with a 30-yr return period was adequate for the 3 yr of our study.

Chemical Quality of Feedlot Runoff

The chemical content of the runoff entering the catch basin is shown in Table 4. Because concentrated catch-basin effluent entering lakes or streams via surface runoff is generally diluted before it can potentially affect aquatic life or be used by humans for drinking water, we examined the effect of dilution on the maximum concentration of selected chemicals in relation to the water quality guidelines (Canadian Council of Ministers of the Environment, 2002). These dilution scenarios indicated that to meet the water quality guidelines for aquatic life or drinking water by humans, greatest dilution of the effluent would have to occur for total P (1224 times), followed by total N (173 times), NH_3–N (120 times), Cl, Na, and total dissolved solids (<10 times) (Table 4). In contrast, maximum concentrations of NO_3–N and SO_4 indicated that the effluent would not have to be diluted to meet the water quality guidelines for these two parameters (Table 4).

Most feedlots on irrigated land in southern Alberta empty their catch basins at least once a year by mixing and diluting the effluent into a sprinkler irrigation system (O. Kenzie, personal communication, 2003). We estimated the dilution required for mixing our catch-basin effluent with clean irrigation water containing no nutrients into a center-pivot system to irrigate 54 ha. An irrigation application depth of 167 mm yr^{-1} was chosen, which corresponds to the mean depth of water applied to an irrigated silage barley crop over 20 yr at Lethbridge (Chang and Janzen, 1996). The dilution ratio for mixing the effluent with the irrigation water was adjusted until the amounts of N, P, K, and S (kg ha^{-1} yr^{-1}) applied in the irrigation water matched the maximum fertilizer recommendations of 150 (N), 22 (P), 100 (K), and 20 (S) kg ha^{-1} yr^{-1} (Alberta Agriculture, Food and Rural Development, 1993). Nitrogen in the catch basin potentially available to the crop was considered to

Table 3. Hydrological characteristics of eleven runoff events (1998–2002) at a beef cattle feedlot in southern Alberta.

	Runoff event										
Parameter	Event 1, 16 June 1998	Event 2, 26–27 June 1998	Event 3, 28 June 1998	Event 4, 29–30 June 1998	Event 5, 3 July 1998	Event 6, 7–8 July 1998	Event 7, 15 May 1999	Event 8, 3 June 1999	Event 9, 18 July 1999	Event 10, 2–3 Sept. 2000	Event 11, 8 June 2002
	West alley runoff										
Runoff start	16 June	26 June	28 June	29 June	3 July	7 July	15 May	3 June	18 July	2 Sept.	8 June
Runoff end	16 June	27 June	28 June	30 June	4 July	8 July	15 May	4 June	18 July	3 Sept.	10 June
Duration, h:min	14:8	39:52	23:59	39:55	20:50	28:31	20:10	31:55	23:15	38:20	55:10
Total runoff, mm	2.6	15	0.6	11.9	9.5	1.2	0.1	3.3	0.6	3.9	53.6†
Yield, %‡	9.3	43.4	1.6	39.1	55.2	9.8	0.2	9.4	1.7	9.5	39.2
Maximum discharge, L m^{-1}	62	261	11	322	329	38	2	99	126	231	908
CN value§	79	90	85	90	96	90	59	76	52	72	NA¶
Storage factor, *S*#	2.7	1.1	1.8	1.1	0.4	1.1	7.0	3.2	9.2	3.9	NA
	East alley runoff										
Runoff start	16 June	26 June	28 June	29 June	3 July	7 July	15 May	3 June	18 July	2 Sept.	8 June
Runoff end	16 June	27 June	28 June	30 June	4 July	8 July	15 May	4 June	18 July	3 Sept.	10 June
Duration, h:min	23:53	33:2	14:0	40:40	19:5	28:31	15:15	31:30	23:50	32:50	55:10
Total runoff, mm	1.5	12.8	0.2	13.4	5.8	0.1	<0.1	2.8	8.2	0.9	44.9†
Yield, %‡	5.4	37.0	0.5	44.1	33.7	0.8	0.1	8.0	23.3	2.2	32.8
Maximum discharge, L m^{-1}	73	219	5	309	209	16	<1	69	592	184	868
CN value§	76	89	96	91	93	84	57	74	83	63	NA¶
Storage factor, *S*#	3.2	1.2	0.4	1.0	0.8	1.9	7.5	3.5	2.1	5.9	NA

† Total runoff for west and east alleys is actually partial runoff measured until catch basin overflowed.
‡ Yield = total runoff/total rainfall (all runoff events, except Event 10, occurred before the pens were cleaned of manure).
§ USDA-NRCS curve number (CN) required to match predicted and actual runoff (see Eq. [2]).
¶ Not applicable because only partial runoff was measured.
# USDA-NRCS storage factor calculated from Eq. [2].

be the sum of NH_3–N and NO_3–N. Similarly, ortho-P was considered to be the available form to the crop. The calculations revealed that greatest dilution of the effluent would be required for K (nine times) followed by S (six times), and the effluent would not have to be diluted for P and N.

We also estimated the land base required to apply the concentrated effluent to meet the maximum fertilizer recommendations for the nutrients as described above. Our calculations showed that irrigating with concentrated effluent would require the most land for K (1.2 ha) followed by S (0.9 ha), and then N and P (0.1 ha). These two scenarios clearly show that K has the highest potential to exceed the maximum crop fertilizer requirements if adjacent land is irrigated with catch basin effluent.

The EC values of feedlot runoff entering the catch basin ranged from 2.1 to 7.0 dS m^{-1}, and the sodium adsorption ratio (SAR) values of runoff ranged from 0.3 to 9.0 (Table 4). Using the mean EC (4.2 dS m^{-1}) and SAR (4.3) values, and the criteria of Ayers and Westcott (1987), we found that the runoff should not cause any infiltration or percolation problems if the effluent is directly applied as irrigation water to adjacent cropland. In contrast, Miller et al. (2001) found higher EC and Na in clay loam and fine sandy loam soils after application of feedyard effluent in Texas. Although the EC and SAR data of the irrigation water indicated no problem in terms of infiltration, long-term irrigation with this effluent could result in EC values in the root zone that could inhibit crop growth (Maas, 1990). Based on mean values, K was the dominant soluble cation in runoff, followed by Na, Ca, and Mg (Table 4). Chloride was the dominant soluble anion, followed by SO_4. As expected, organic C rather than inorganic C constitutes the majority of total C (Table 4). High organic C in surface waters is undesirable because organic matter contributes to high biological oxygen demand values, which depletes dissolved oxygen. Nitrate and Ca had CV values of >100%, indicating that these two parameters had the greatest variability in concentration for all the runoff events. Ortho-P and Mg had CV values between 50 and 100%, and the remaining parameters had CV values of <50%. Nitrate N concentrations in our feedlot runoff during 1999 and 2000 were higher (>10 mg L^{-1}) than values reported for other studies (Miner et al., 1966; Coote and Hore, 1977), but we are unsure as to why this trend occurred.

Bacterial Quality of Effluent and Soil in the Catch Basin

Thirty presumptive *E. coli* isolates and 50 presumptive coliform isolates were obtained from the catch-

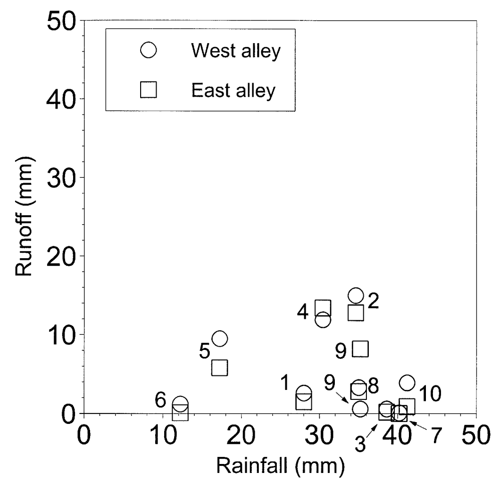

Fig. 3. Relationship of runoff and rainfall for 10 runoff events from a beef cattle feedlot in southern Alberta. Event 11 is not included because only partial runoff was measured.

Table 4. Chemical content of runoff (1998–2000) from a beef cattle feedlot in southern Alberta.

Parameter	Percentile concentration† Chemical constituent‡ TP	OP	TN	NH_3–N	NO_3–N	TC	OC	IC	Na	Ca	Mg	K	Cl	SO_4	TDS	pH	EC	SAR
	mg L^{-1}																dS m^{-1}	
Minimum	2.1	0.9	19.2	0.7	<0.04	32.6	20.8	11.8	8.0	32.5	8.3	13.3	8.5	23.4	1331	7.6	2.1	0.3
25%	25.1	3.9	59.5	26.7	0.1	460	403	49	206	58.6	57.0	431	473	158	2192	7.9	3.4	3.4
Median	33.3	4.6	82.2	34.6	0.1	588	505	70	252	84.0	79.1	495	559	188	2589	8.0	4.0	4.2
75%	49.5	5.7	102	40.2	6.7	728	648	112	284	146	124	574	742	279	3021	8.1	4.7	4.9
Maximum	61.2	22.7	173	85.9	23.5	1142	983	169	443	1760	345	1255	1448	499	4467	8.4	7.0	9.0
Mean	35.3	5.8	85.7	33.0	3.4	604	524	80	246	148	96.1	515	604	217	2671	8.0	4.2	4.3
CV, %	43	68	38	43	180	37	36	49	29	143	57	36	36	43	26	–	26	32
N	50	140	49	140	140	51	51	51	140	140	140	140	140	140	96	101	96	140
WQG§	0.05	–	1.0	0.572	10	–	–	–	200	–	–	–	250	500	500	–	–	–
DF¶	1224	–	173	150	2	–	–	–	2	–	–	–	6	1	9	–	–	–

† Percentile concentrations: minimum (0%), 25%, median (50%), 75%, and maximum (100%) percentiles.
‡ EC, electrical conductivity; OP, ortho-phosphorus; IC, inorganic carbon; OC, organic carbon; SAR, sodium adsorption ratio; TC, total carbon; TDS, total dissolved solids; TN, total nitrogen; TP, total phosphorus.
§ Water quality guidelines. Total P and Total N are provincial guidelines for protection of aquatic life (Alberta Environment 1999). Ammonia N is a federal guideline for protection of aquatic life (Canadian Council of Ministers of the Environment, 2002). Nitrate N is a federal guideline (Canadian Council of Ministers of the Environment, 2002) for protection of water for community water supplies (drinking water for humans). Sodium, Cl, SO_4, and TDS are aesthetic guidelines (Canadian Council of Ministers of the Environment, 2002) for protection of water for community water supplies (drinking water by humans).
¶ Dilution factor for maximum value of chemical parameter to meet water quality guideline.

basin water samples. All 30 presumptive *E. coli* isolates were confirmed as *E. coli* by all testing methods. All 50 coliform isolates were confirmed as lactose fermenting Enterobactericeae but not *E. coli*. Thus there were no false negative or false positive isolates. Twenty-six presumptive *E. coli* positive samples and 37 presumptive coliform isolates were obtained from the soil of the catchbasin floor. All presumptive coliform isolates were confirmed as lactose fermenting Enterobactericeae but not *E. coli*. However, only 20 isolates could be confirmed from the 26 samples presumptively positive for *E. coli*, giving a potential false positive rate of 23% for these samples. No presumptive *E. coli* strains were isolated from the LMX broth tubes of these potential false positive samples. The samples could have been positive for *E. coli* but we were simply unable to isolate *E. coli* from the LMX tubes due to high levels of other competing bacteria.

Water was consistently in the catch basin during the summers of 1998 and 1999, but whenever it was present, high levels of *E. coli* and TC populations were detected (Fig. 4). Populations of the two groups of bacteria generally ranged between $\log_{10}$ 2 and $\log_{10}$ 8 100 mL^{-1}. This was consistent with high populations of *E. coli* and TC in the feedlot pen manure at this same feedlot during these same years (Larney et al., 2003; Miller et al., 2003).

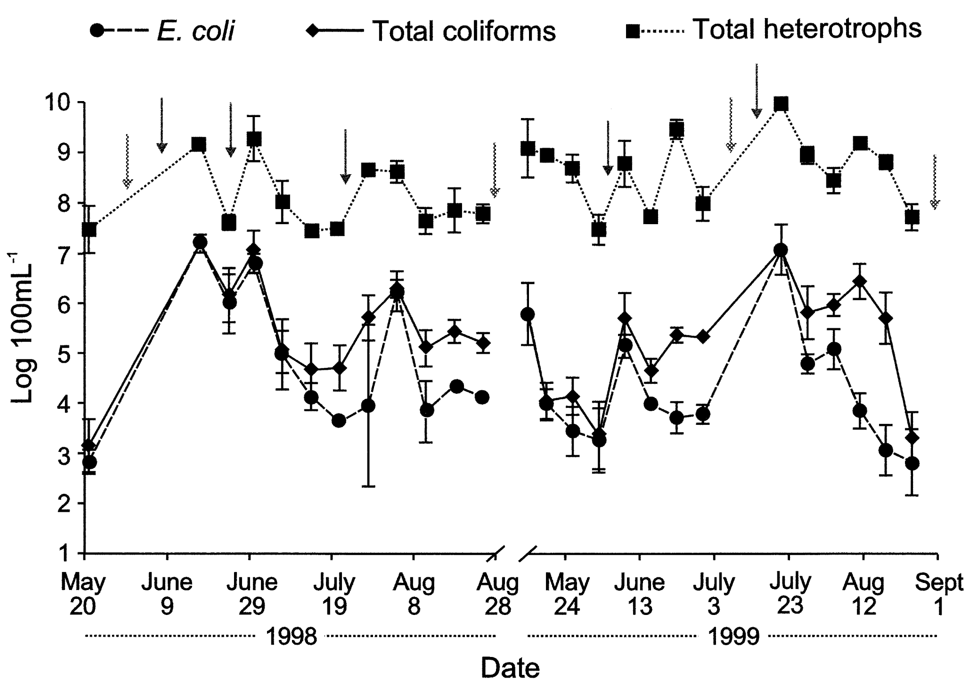

Fig. 4. Persistence of *E. coli*, total coliforms, and total heterotrophs at 27°C in effluent of a feedlot catch basin over a 2-yr (1998–1999) period. Gray arrows indicate times when the catch basin was dry, and black arrows indicate times when the catch basin was replenished with feedlot runoff.

This was true even up to complete evaporation of water from the catch basin. The *E. coli*, TC, and TAH populations displayed broadly similar persistence curves, with peaks following replenishment of the catch-basin runoff water. The *E. coli* population was $>\log_{10}$ 5 100 mL^{-1} following replenishment events, but declined more rapidly and to lower levels than the TC population. Not unexpectedly, the TAH population was generally more stable and did not demonstrate the same intensity of variation in population size.

The high levels and continual persistence of *E. coli* in the catch-basin water are clearly indicative of its poor quality. Persistence of *E. coli* in aquatic environments varies depending on the exact nature of the water environment in question. Under controlled conditions, *E. coli* O157 in bovine fecal slurries survived a minimum of 28 d at 4°C, or as short a period as 5 d at 23°C (Kudva et al., 1998). In pond water at 13°C, inoculated *E. coli* O157 was found to persist for up to 13 d (Porter et al., 1997). Although *E. coli* in the catch basin water of our study showed seasonal variation, it was always easily detectable in the catch-basin water. There were indications, however, that *E. coli* was demonstrating differential and lower persistence characteristics than TC. This suggests that management techniques such as microbial competition could be used to limit *E. coli* in catch-basin water. Nevertheless, the continued presence of *E. coli* in the catch-basin water highlights the continued need for containment of feedlot effluent.

There are environmental concerns about potential persistence of these bacteria on the crop and re-infection of cattle consuming silage when feedlot effluent is applied to adjacent land by irrigation. Yanke et al. (2003) applied effluent from a commercial feedlot in southern Alberta to silage barley plots in 1999 and 2000, and compared persistence of *E. coli* and TC on the crop and in the soil under treated and control plots. They found that in 1999, *E. coli* persisted on the crop and soil for up to 15 d post-application, whereas TC persisted for only 6 d on the crop and only 4 d in the soil. These results suggest that re-infection of cattle may occur if the crop is harvested and fed too soon after effluent is applied. In addition, persistence of these bacteria in surface soil could result in contamination of nearby surface water if runoff occurred soon after application.

There were small precipitation events during the summer of 2000, but never enough to leave standing water at the time of weekly sampling. Microbial sampling of the 0- to 5-cm depth of catch-basin soil revealed differences among the measured populations (Fig. 5). The TAH population was very constant, regardless of season or replenishment of catch-basin water. The TAH population ranged between $\log_{10}$ 8 and $\log_{10}$ 10 g^{-1} wet wt. In contrast, *E. coli* and TC populations varied considerably, and numbers ranged between $\log_{10}$ 1.56 and $\log_{10}$ 6 g^{-1} wet wt. The *E. coli* population was generally below the detection limit but increased very slightly with the onset of spring, with higher populations in the soil of the catch basin following replenishment events. In particular, the *E. coli* population increase following the fall replenishment was quite dramatic. The TC population demonstrated a similar pattern of persistence, with higher growth in the spring in the absence of any replenishment events from the feedlot pens into the catch basin. However, the levels of both populations did seem to decrease quickly with the absence of water in the catch basin.

Soil from the dry catch-basin floor generally had low levels of *E. coli*, but at times populations of $>\log_{10}$ 4 g^{-1} wet wt. were present (Fig. 5). A positive response by *E. coli* and no response by TAH to environmental stimuli suggests that the *E. coli* population persists in a manner different from the general microbial population. Fenlon et al. (2000) suggested relatively poor persis-

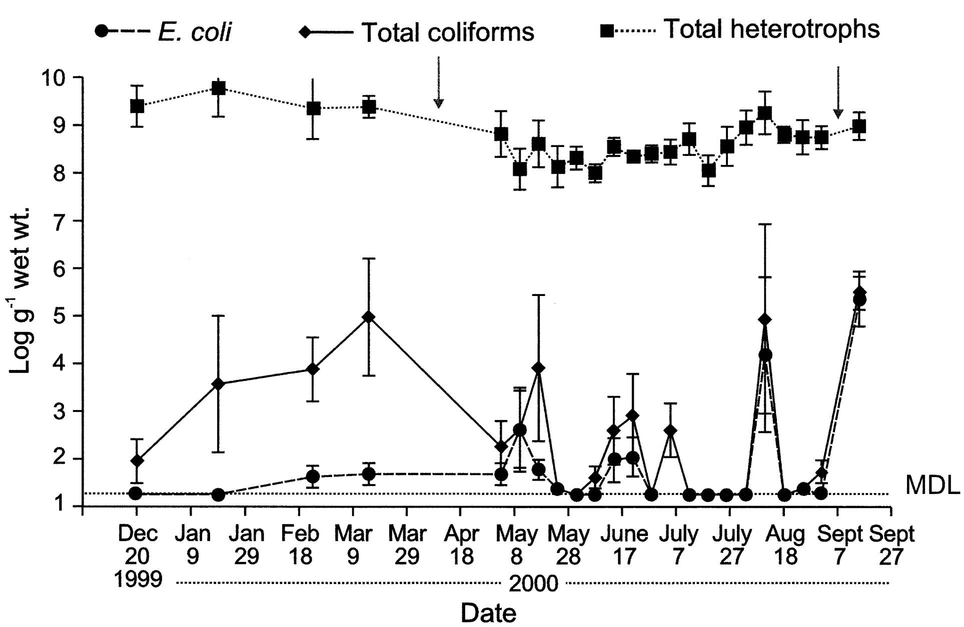

Fig. 5. Persistence of *E. coli*, total coliforms, and total heterotrophs at 27°C in catch-basin soil over a 2-yr (1999–2000) period. Arrows indicate times when the catch basin contained water. The term MDL is the minimum detection limit.

tence of *E. coli* when the population declined to less than 1% of the levels applied within a month of applying cattle manure slurry to land. In contrast, Sjorgen (1995) demonstrated persistence of an inoculated *E. coli* for more than 13 yr in a silty loam soil of test plots. These two studies illustrate that the exact environmental conditions encountered may substantially affect persistence of *E. coli*.

CONCLUSIONS

Feedlot runoff (<0.1 to 42.5 mm) of 24-h duration that included maximum peak discharge was less than the recommended design criteria of 90 mm, indicating that the existing design criteria based on 24-h rainfall with a 30-yr return period was adequate for the 3 yr of our study. Total P in catch-basin water posed the greatest threat to water quality guidelines, and K posed the greatest threat for exceeding crop fertilizer requirements if catch-basin effluent was used as irrigation water. Water in the catch basin had continually high populations of total heterotrophs, total coliforms, and *E. coli* bacteria, indicating the need for containment of this effluent. Soil in the catch basin had high populations of total heterotrophic bacteria. Total coliforms and *E. coli* in the catch-basin soil were generally low, but at times higher populations were also found. The *E. coli* in the feedlot water seemed to be demonstrating differential and lower persistence characteristics than those of the total coliform population, indicating that management techniques such as microbial competition might be used to limit *E. coli*.

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REFERENCES

Alberta Agriculture, Food and Rural Development. 1993. Fertilizing irrigated grains and oilseed crops. Agdex 100/541-1. AAFRD, Edmonton, AB, Canada.

Alberta Agriculture, Food and Rural Development. 1997. Alberta feedlot management guide. Feeders Assoc. of Alberta, Barrhead, AB, Canada.

Alberta Environment. 1999. Surface water quality guidelines for use in Alberta. Environ. Sci. Div., Alberta Environ., Edmonton, AB, Canada.

American Public Health Association. 1995. Standard methods for the examination of water and wastewater. 19th ed. APHA, Washington, DC.

Ayers, R.S., and D.W. Westcott. 1987. Water quality for agriculture. Irrig. Drain. Paper no. 29, Rev. 1. FAO, Rome.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1979. Soil chemistry. John Wiley & Sons, New York.

Canadian Council of Ministers of the Environment. 2002. Canadian environmental quality guidelines. Update 2002. CCME, Winnipeg, MB.

Chang, C., and H.H. Janzen. 1996. Long-term fate of nitrogen from annual feedlot manure applications. J. Environ. Qual. 25:785–790.

Clark, R.N., C.B. Gilbertson, and H.R. Duke. 1975a. Quantity and quality of beef feedyard runoff in the Great Plains. p. 429–431. *In* 3rd Int. Symp. on Livestock Wastes Proc., Univ. of Illinois, Urbana-Champaign, IL. Am. Soc. Agric. Eng., St. Joseph, MI.

Clark, R.N., A.D. Schneider, and B.A. Stewart. 1975b. Analysis of runoff from southern Great Plains feedlots. Trans. ASAE 18:319–322.

Coote, D.R., and F.R. Hore. 1977. Runoff from feedlots and manure storages in southern Ontario. Can. J. Agric. Eng. 19:116–121.

Crane, S.R., J.A. Moore, M.E. Grismer, and J.R. Miner. 1983. Bacterial pollution from agricultural sources: A review. Trans. ASAE 26:858–866.

Fenlon, D.R., I.D. Ogden, A. Vinten, and I. Svoboda. 2000. The fate of *Escherichia coli* and *E. coli* O157 in cattle slurry after application to land. J. Appl. Microbiol. Symp. Suppl. 88:149S–156S.

Foroud, N., and D.A. Hlibka. 1989. Instrumentation for simultaneous recording of water level in digital and graphical forms. Trans. ASAE 32:465–470.

Garthwright, W.E. 1998. Food and Drug Administration bacteriological analytical manual. 8th ed. Rev. A, Appendix 2. AOAC Int., Gaithersburg, MD.

Gilbertson, C.B., J.A. Nienaber, J.L. Gartung, J.R. Ellis, and W.E. Splinter. 1979. Runoff control comparisons for commercial beef cattle feedlots. Trans. ASAE 22:842–849.

Gilbertson, C.B., J.A. Nienaber, T.M. McCalla, J.R. Ellis, and W.R. Woods. 1972. Beef cattle feedlot runoff, solids transport and settling characteristics. Trans. ASAE 15:1132–1134.

Gilbertson, C.B., J.C. Nye, R.N. Clark, and N.P. Swanson. 1981. Controlling runoff from livestock feedlots—A state of the art. Agric. Info. Bull. 441. USDA, Washington, DC.

Goatcher, L.J., L.R. Goodwin, A.K. Sharma, M.R. Bennett, B.S. West, F.P. Dieken, and A.A. Qureshi. 1991. Impact of cattle feedlot wastes on surface water quality in Alberta: Microbiological and chemical surface water quality. Rep. AECV91-R2. Alberta Environ. Centre, Vegreville, AB, Canada.

Hauser, V.L. 1975. Design runoff volume from feedlots in the southwestern Great Plains. p. 426–428. *In* Proc. of 3rd Int. Symp. on Livestock Wastes, Univ. of Illinois, Urbana, IL. Am. Soc. Agric. Eng., St. Joseph, MI.

Hrubrant, G.R., R.V. Daugerty, and R.A. Rhodes. 1972. Enterobacteria in feedlot waste and runoff. Appl. Microbiol. 124:378–383.

Intensive Livestock Operations Committee. 1995. Code of practice for the safe and economic handling of animal manures. Agdex 400/27-2. Alberta Agric., Food and Rural Development, Edmonton, AB, Canada.

Kempers, A.J., and A.G. Luft. 1988. Re-examination of the determination of environmental nitrate as nitrite by reduction with hydrazine. Analyst (Cambridge, UK) 113:1117–1120.

Kennedy, B., R.N. Coleman, G.M. Gillund, B. Kotelko, M. Kotelko, N. MacAlpine, and P. Penney. 1999. Feedlot runoff: Volume 1: Quantity and quality of rainfall and snowmelt runoff from pens. CAESA Res. Project Rep. 109-94. Alberta Agric., Food and Rural Development, Vegreville, AB, Canada.

Kudva, I.T., K. Blanch, and C.J. Hovde. 1998. Analysis of *Escherichia coli* O157:H7 survival in ovine or bovine manure and manure slurry. Appl. Environ. Microbiol. 64:3166–3174.

Laksham, G. 1982. Surface water pollution from intensive livestock operations. p. 30–48. *In* A.A. Qureshi and R.N. Coleman (ed.) Cattle Feedlot Workshop Proc., Vegreville, AB, Canada. 8–9 Dec. 1981. Rep. AECV82-P1. Alberta Environ. Centre, Vegreville.

Larney, F.J., L.J. Yanke, J.J. Miller, and T.A. McAllister. 2003. Fate of coliform bacteria in composted beef cattle feedlot manure. J. Environ. Qual. 32:1508–1515.

Linsley, R.K., M.A. Kohler, and J.L.H. Paulhus. 1975. Hydrology for engineers. 2nd ed. McGraw-Hill, New York.

Lott, S.C. 1995. Australian feedlot hydrology. Part I (data). *In* Proc. Feedlot Waste Manage. Conf., Gold Coast, QLD, Australia. 12–14 June 1995. Queensland Dep. of Primary Ind., Gold Coast.

Lott, S.C. 1996. Feedlot hydrology. Ph.D. thesis. Univ. of Southern Queensland, Toowoomba, Queensland, Australia.

Maas, E.V. 1990. Crop salt tolerance. p. 262–304. *In* K.K. Tanji (ed.) Agricultural salinity assessment and management. ASAE, New York.

McCoy, E. 1967. Lagooning of liquid manure (bovine): Bacteriological aspects. Trans. ASAE 10:784–785.

Miller, B.L., D.B. Parker, J.M. Sweeten, and C. Robinson. 2001. Response of seven crops and two soils to application of beef cattle feedyard effluent. Trans. ASAE 44:309–315.

Miller, J.J., B.W. Beasley, L.J. Yanke, F.J. Larney, T.A. McAllister, B.M. Olson, L.B. Selinger, D.S. Chanasyk, and P. Hasselback. 2003. Bedding and seasonal effects on chemical and bacterial properties of feedlot cattle manure. J. Environ. Qual. 32:1887–1894.

Miner, J.R., L.R. Fina, J.W. Funk, R.I. Lipper, and G.H. Larson. 1966. Stormwater runoff from cattle feedlots. p. 23–26. *In* Proc. Natl. Symp. on Animal Waste Manage., East Lansing, MI. 5–7 May 1966. Am. Soc. Agric. Eng., St. Joseph, MI.

Paisley, R. 1996. MIS whole cell fatty acid analysis by gas chromatography: Training manual. MIDI, Newark, DE.

Porter, J., K. Mobbs, C.A. Hart, J.R. Saunders, R.W. Pickup, and C. Edwards. 1997. Detection, distribution and probable fate of *Escherichia coli* O157 from asymptomatic cattle on a dairy farm. J. Appl. Microbiol. 83:297–306.

Province of Alberta. 2001. Agricultural Operation Practices Act. Queen's Printer, Edmonton, AB, Canada.

Rhine, E.D., G.K. Sims, R.L. Mulvaney, and E.J. Pratt. 1998. Improving the Berthelot reaction for determining ammonium in soil extracts and water. Soil Sci. Soc. Am. J. 62:473–480.

Rhodes, R.A., and G.R. Hrubrant. 1972. Microbial population of feedlot waste and associated sites. Appl. Microbiol. 24:369–377.

Sjorgen, R.E. 1995. Thirteen-year survival study of an environmental *Escherichia coli* in field mini-plots. Water Air Soil Pollut. 81:315–335.

Smibert, R.M., and N.R. Kreig. 1994. Phenotypic characterization. p. 607–654. *In* P. Gerhardt et al. (ed.) Methods for general and molecular bacteriology. Am. Soc. for Microbiol., Washington, DC.

Soil Conservation Service. 1972. National engineering handbook. Section 4. Hydrology. USDA, U.S. Gov. Print. Office, Washington, DC.

Swanson, N.P. 1972. Hydrology and characteristics of feedlot runoff. p. 71–80. *In* Proc. of Seminar on Control of Agricultural-Related Pollution, Lincoln, NE. 24–25 July 1972. Great Plains Agric. Council, Lincoln, NE.

Sweeten, J.M. 1998. Cattle feedlot manure and waste management practices. p. 125–156. *In* J.L. Hatfield and B.A. Stewart (ed.) Animal waste utilization: Effective use of manure as a soil resource. Ann Arbor Press, Chelsea, MI.

Technicon Industrial Systems. 1972. Sulfate in water and wastewater. Industrial Method 118-71W. Technicon Ind. Syst., Tarrytown, NY.

Technicon Industrial Systems. 1973a. Ammonia in water and wastewater. Industrial Method 98-70W. Technicon Ind. Syst., Tarrytown, NY.

Technicon Industrial Systems. 1973b. Orthophosphate in water and seawater. Industrial Method 155-71W/Tentative. Technicon Ind. Syst., Tarrytown, NY.

Technicon Industrial Systems. 1974. Chloride in water and wastewater. Industrial Method 99-70W/B. Technicon Ind. Syst., Tarrytown, NY.

Technicon Industrial Systems. 1978. Nitrate and nitrite in water and wastewater. Industrial Method 100-70W/B. Technicon Ind. Syst., Tarrytown, NY.

Yanke, L.J., J.J. Miller, T.A. McAllister, F.J. Larney, B.M. Olson, L.B. Selinger, D.S. Chanasyk, and P. Hasselback. 2003. Persistence of bacteria on silage barley and soil after irrigation with catch basin effluent. p. 9–1 to 9–22. *In* J.J. Miller (ed.) Managing feedlot manure to protect water quality and human health. Canada-Alberta Beef Ind. Development Fund Project no. 97AB061 final report. Alberta Agric. Res. Inst., Alberta Agric., Food and Rural Development, Edmonton, AB, Canada.