The Canadian society for engineering in agricultural, food, and biological systems

CSAE — SCGR

La société canadienne de génie agroalimentaire et biologique

Paper No. 05-050

Application of the Green-Ampt and Curve Number Models to Runoff from Cattle Feedlot Pens

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Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 – 29, 2005

Abstract

Open-air feedlots are required to accommodate runoff within storage ponds and thus avoid environmental problems with the high nutrient loads entering outside water sources. The size of the storage ponds are based upon that of the occurrence of rain events of a certain return period (e.g., 1-in-25 year, 24 hr storm) or that of a specific sized run off event (e.g., 76 mm). Towards that of improved understanding of feedlot runoff and development of predictive models our study applied two models, the Green-Ampt infiltration model and the Soil Conservation Society curve number model, to measured runoff from a feedlot in Saskatchewan. The Green-Ampt model was calibrated with measured soil properties (soil surface 50 mm depth porosity 0.31 m^3 m^{-3} and Ksat 0.1 mm hr^{-1}) and using a rainfall simulator. For that of the presence of a manure pack the Green-Ampt model was applied to underlying soil surface and used an assumption of not allowing any runoff from the manure pack until it was saturated. For the curve number model we used literature values of the curve number (90 for an active or recently scraped feedlot and 75 for an inactive feedlot with manure pack still present). These models were compared to our measured runoff data. Due to dry conditions and events flow rainfall amount during the operation of the weirs the only event that produced runoff was less than 0.1 mm from a 17 mm event. Both models were in general agreement as they produced runoff close to zero for that of when the weir was operational. For a 1 in 25 year, 24 hr storm of 70 mm the Green-Ampt model showed that runoff would be 21 mm and 34 mm with low and high antecedent moisture conditions respectively and if no manure pack was present then runoff would be at least 64 mm (if surface detention were not considered). For a 70 mm rain event the curve number model resulted in runoff of 19 mm and 43 mm for CN values of 75 (moist conditions) and 90 (active wet feedlot) respectively. Although the agreement between models was not good (usually more than 50% error) their improvement could likely be greatly improved if antecedent conditions were better represented. The study indicated that the manure pack, with regards to depth, moisture, content, and areal coverage plays a major role in controlling runoff occurrence and amount.

INTRODUCTION

Western Canadian cattle feedlots are generally built uncovered and with earthen floors. The pens must be designed such that runoff flows away from the pen area and towards a central collection pond. The pen and storage pond design must accommodate large flow volumes such that overflow does not occur with resulting contamination. General design consideration is for the storage pond to accommodate runoff from that for a one in 25 year 24 hour rain event (typical for U.S. feedlots), a one in 30 year rain event (Alberta) or for that of a 76 mm (3 inch) runoff event (Saskatchewan). Of concern is the timing and occurrence of runoff events and the adequacy of current design regulations; are they too little or too much. Towards development of improved feedlot design, siting guidelines and regulations our study addresses that of the occurrence and amount of runoff from rainfall events. Several studies have been conducted upon determination of the amount of runoff that occurs from rain events and matching it to a Soil Conservation Society curve number (CN) runoff model (Kennedy et al. 1999; Parker et al. 1999; Kizil and Lindley 2002; and Miller et al. 2003), however no study has looked to that of modeling the runoff process and using a model to predict the occurrence and amount of runoff given a rain event. The intent of our study is to explore two models and their applicability to simulating a cattle feedlot pen and predicting runoff occurrence and amount. Although the CN runoff model has been used by other studies its use has been limited to that of calculating the CN value for a measured runoff event. We wish to extend this knowledge further. In addition we wish to utilize the Green-Ampt infiltration model (GA). The GA model is more physically based model than the CN model and thus will encourage a better understanding of the feedlot system. To our knowledge the GA model has not been utilized before for feedlot runoff. For the purpose of runoff investigation the objectives of this study were:

1. to measure the amount and occurrence of rainfall runoff from feedlot pens;
2. to develop and calibrate a Green-Ampt infiltration model to feedlot runoff;
3. to apply the calibrated Green-Ampt infiltration model to measured feedlot runoff;
4. to apply the Soil Conservation Service Curve Number model to measured feedlot runoff;
5. to use both models to predict runoff using just climatic data; and
6. to improve upon the understanding of manure and soil properties controlling runoff.

The occurrence and amount of runoff, from rain events, is dependent upon rainfall intensity, rainfall amount, rainfall duration, antecedent moisture, and the infiltration characteristics of the surface layer. The surface of a feedlot pen is essentially that of a porous organic layer overlying a compacted relatively impermeable soil-manure interface layer (Kennedy et al. 1999). Antecedent conditions will thus be controlled by the depth and moisture content of the manure pack, which in turn is affected by stocking density, frequency of manure removal from the pens, and rate of bedding addition.

STUDY SITE

Description

The study feedlot (River Ridge Feedlot) is located about 20 km south of Eston, 60 km SE of Kindersley, and about 180 km SW of Saskatoon on the north side of the South Saskatchewan River at 50°58’48”N and 108°44’24”W. The feedlot was first established in 1996 as a community co-op venture consisting of 8 pens, each 75 by 75 m in area. The pens, arranged on either side of a central road, had a 1.5% slope away from the road towards storage ponds. During 2001 another 8 pens were established immediately to the north of the previous pens. The storage ponds ran parallel the length of the feedlot on both sides (600 m, 8 pens x 75 m), were 3 m deep, 35 m wide at the top with 3:1 slopes. The storage pond had a volume of about 5800 m^3 per pen, however had been designed to accommodate feedlot future expansion. These 8 new pens were stocked by the end of summer 2001. Stocking rates were about 100 head per pen of backgrounding cattle weighing about 360 kg each. Bedding consisted of straw that was added to the middle of the pen. The pens were cleaned in the fall of each year. Cattle were present in the pens until the end of July 2003, after which they were removed due to general economic conditions of western Canadian feedlots. There were no cattle in the pens from the July 31, 2003 to the end of our study, fall of 2004. At our request manure was left in the study pens. For that of 2003 and 2004 about 15% of the pen surface was of bare soil or a compacted manure layer, about 25% was the manure mound that varied between 200 and 450 mm in thickness, and about 55% was a manure pack that varied between 50 and 150 mm in thickness.

General Climate
The feedlot is located in one of the drier parts of the province. Long term precipitation, as recorded at Eston is 297 mm of which 63 mm occurs during the winter (Nov thru March) and 181 mm during the four summer months of May thru August (Canadian Climate Normals 1971-2000). Long term average annual temperature is 3.0°C with January being the coldest month (-14.5 °) and July being the warmest (18.1°C). The Eston climatic station, operational from 1951 to 1995, was located 20 km to the north of the feedlot. The Kindersley climatic station, which was used to supplement climatic data collected at the feedlot, is located 60 km to the northwest.

Surface features and geology
The land about the feedlot, is of glaciolacustrine material with hummocky surficial features (Surficial Geology Map of the Prelate Area, Map 72K). SEACOR (1995) drilled a number of 8 to 9 m core holes and found the profiles to consist primarily of sand and silt with interbedded deposits of clay and clayey till. The groundwater table is estimated to be between 5 to 8 m in depth as this was the depth that seepage conditions were encountered. Elevation in the SW ¼ of section 28 is 648 m (2125 ft) and varies by 1 to 2 m across the site.

MATERIALS AND METHODS

Introduction
Measurements at the feedlot were done between fall of 2002 and fall of 2004 (Fig. 1). Climatic measurements (temperature, humidity, rainfall intensity, solar radiation) was done at the feedlot from Sept 2002 to Aug 2004 with temperature and daily rainfall from the Kindersley climate station (Environment Canada 2004) supplementing missing data. Soil moisture was done only once in June 2002, several times in 2003 and six times in 2004. Soil and manure physical properties (bulk density, texture, porosity and laboratory hydraulic conductivity) were done from samples taken in September 2003. Runoff weirs were setup and operational from July to October 2004. The focus of the measurements (Objective 1) is upon the summer of 2004 when climatic,

soil moisture, and weir runoff measurements were all taken simultaneously. The focus of the modeling (Objective 5) is from April 1, 2002 to Oct 31, 2004.

Manure and Soil Physical Properties

Undisturbed samples for soil texture, bulk density, porosity and saturated hydraulic conductivity measurements were taken during September 2003 via clods and cores. Five samples from each depth, from each of two pens were taken. The soil material and the dried manure material in the upper 100 mm was too hard to obtain undisturbed cores, thus clods (approximately 50 mm wide and 20 to 40 mm thick) representing 0 to 50 and 50 to 100 mm were taken. Core samples were taken by driving the sleeve (sharpened aluminum sleeves, 50 mm high, 75 mm dia.), as mounted onto a metal plate, into the soil with a hammer. Soil cores were obtained at 200-250 mm and 400-450 mm. Five sets of undisturbed core samples of wet manure were taken from each of two pens. The cores were obtained by pushing thin walled steel sleeves (300 mm long steel sleeves, 75 mm dia) into the manure using a hammer. The cores, including the steel casing, were then cut (while still wet) with a band saw into 50 mm increments. Where the manure pack had dried and was in loose granular form, about one liter of manure was collected. Where the manure pack was hard, dry and compacted, clod samples were taken.

Soil sand and clay contents were determined by modified pipette method (Indorante et al. 1990). Soil bulk densities and moisture contents were determined by drying for at least 24 hrs at 105°C and then weighing and dividing the total volume of the sleeve or clod. Manure bulk densities and moisture contents were obtained by drying for at least 24 hrs at 65°C. For soil and manure clods, the clod was wrapped tightly in a thin layer of plastic wrap and then immersed in water to obtain volume by displacement. For the dry granular manure bulk density, samples were 'poured' into a 75 mm dia. clear acrylic column to between 70 and 95 mm height, the depth found in the field. During the pouring, the sides were tapped to aid settling. The volume and oven dried mass (65°C) were used for bulk density. Saturated volumetric moisture contents of all cores (including the dried granular manure in the acrylic column) were obtained by immersing the bottom of the core sleeve or column in water and allowing saturation from the bottom up. The bottoms of the cores were tied off with a piece of cloth so as to retain the sample, but allow the water to enter. Saturated hydraulic conductivities were measured by using a falling head apparatus (Jury et al. 1991). Clod samples were embedded in wax in a 75 mm dia. metal sleeve. All metal sleeves were held in the falling head apparatus.

Antecedent Moisture Content

During the summer and fall of 2004 hand auger (25 mm dia.) samples of the manure pack and underlying soil were taken for soil moisture analysis (oven drying 105°C for soil and 65°C for manure). Samples were taken where no manure pack existed (three per pen in each of two pens), where the manure pack was 200 mm thick (one per pen in two pens) and where the manure pack was 400 mm thick (three per pen in two pens). Samples were at 200 mm deep intervals for both manure and soil. The soil was sampled to a depth of 600 mm, however only the top 200 mm is reported here.

Runoff

Measurements of runoff from natural precipitation events proved the most difficult to determine, due to the infrequency of large rainfall events (> 20 mm d^{-1}) and the lack of proper well maintained monitoring instrumentation. Initially it was planned to measure the depth of water in the holding ponds, however runoff events were infrequent to non-existent and the infiltration in the holding ponds was too great to hold any runoff waters. During the April to October period no standing water, resulting from rain runoff, was ever observed in the holding ponds, however due to the infrequency of our visits, we could have been missed some occurrences.

Runoff Weirs_A pen runoff collection and monitoring system was established for two pens from July 1st to October 30th of 2004. Soil material along the bottom of each pen was bermed so to funnel runoff towards a centrally located V-notch weir. One weir for each of the two study pens was established. The V-notch weir was 406 mm high, 337 mm wide, and was angled at 22.5°. When water flowed, the height of water in the stilling well was to be measured every five minutes by a pressure transducer. During this time period there were no cattle in the pens, however a manure pack (from fall 2002 to July 2003) was present.

Green-Ampt Infiltration Model The Green-Ampt (GA) infiltration model (Rawls et al. 1993) used measured soil and manure properties and was calibrated with a rainfall simulator tests done within the feedlot. We structured the GA model such that rainfall intensity was constant and the first calculation was to calculate the amount of infiltration necessary for runoff to begin (Fs):

$$Fs = \frac{Md\ \psi}{(1 - i\ Ks^{-1})} \qquad (1)$$

Following that the infiltration rate (f) was calculated. This required that the cumulative infiltration (F) be known. For this we added a small increment (about 0.10 Ks) first to Fs, then to successive F values and calculated f, then that of time:

$$f = Ks\ (1 - Md\ \psi\ F^{-1}) \qquad (2)$$

where:

Fs, cumulative infiltration (mm) at which point runoff first begins;

Md, soil moisture deficit (saturated minus antecedent, $m^3\ m^{-3}$) determined by field measurement.

Ψ, soil water tension at the wetting front (mm) was estimated from soil properties (Rawls and Brakensiek, 1985):

$$\Psi = 10 \exp(6.5309 - 7.32561\ n + 0.001583\ C^2 + 3.809479\ n^2 + 0.000344\ S\ C - 0.049837\ S\ n + 0.001608\ S^2\ n^2 + 0.001602\ C^2\ n^2 - 0.0000136\ S^2\ C - 0.003479\ C^2\ n - 0.000799\ S^2\ n) \qquad (3)$$

Where n is the soil porosity ($m^3\ m^{-3}$), C is the percent clay content and S is the percent sand content.

Ks, saturated hydraulic conductivity ($mm\ hr^{-1}$) was determined using 2 different methods: that obtained from a rainfall simulator and that obtained from undisturbed cores or clods in a falling head apparatus (Jury et al. 1991);

i, rain intensity, $mm\ hr^{-1}$, rain gauge or tipping bucket measurements; and

f, infiltration rate, $mm\ hr^{-1}$.

This data with rainfall simulation tests and that of the soil and manure pack measurements were used to calibrate and develop a working Green-Ampt model for the feedlot (**Objective 2**). The rainfall simulator was a modified Guelph Rainfall Simulator (Tossell et al. 1987, 1990). A 14W ¼" nozzle set 1.1 m above the ground and operating at a pressure of approximately 100 kPa.

Variations in nozzle height (1 to 2 m) and operating pressure (45 to 100 kPa) resulted in the rainfall rate being varied between 30 and 80 mm/hr. The time it took for runoff to occur and the runoff rate (until steady-state runoff) was measured.

The resulting calibrated Green-Ampt model was then run using 30 minute rainfall amounts from rainfall events that resulted in runoff (**Objective 3**) and from rainfall data for the feedlot in which runoff data was not available (**Objective 5**). For the latter we arbitrarily decided that events that rained more than more than 15 mm within a 24 hour period would be considered in the model. As the pen surface consists of three components; surface bare of loose manure pack, manure pack, and manure mound, these three components were run separately with the GA model for each rain event. The total runoff from a pen would then be the summation of each of these, weighted as to the area they occupy within the pen. Antecedent moisture conditions were set by using a five day antecedent precipitation index (API):

$$API = 0.9P_{i-1} + 0.9^2\, P_{i-2} + 0.9^3\, P_{i-3} + 0.9^4\, P_{i-4} + 0.9^5\, P_{i-5} \quad (4)$$

Where P is the amount of rainfall (and cattle excreted water) added the day before the current day (P_{i-1}) to that added five days previous (P_{i-5}). Cattle excreted water was assumed to be 0.32 mm per day, as based upon the stocking density (100 head until July 31, 2003), their mass (360 kg per head), and the assumption that they excrete 5 L of moisture per day per 100 kg (ACFA 2002).

SCS Curve Number Model The USDA runoff estimation method uses the Soil Conservation Service (SCS) Curve Number model (USDA 1973) to obtain an estimate of runoff (Eqs. 5 and 6). Estimated runoff was compared to instances of rainfall that both runoff and did not generate runoff measurements recorded by the weir so to calibrate curve numbers.

$$Q = \frac{(P - 0.2 \bullet S)^2}{(P + 0.8 \bullet S)} \quad (5)$$

where;
Q = total runoff (mm depth)
P = 24 hr rainfall (mm)
S = rain storage in mm of water before onset of runoff

$$S = 25400\ CN^{-1} - 254 \quad (6)$$

CN is soil conservation curve number

The SCS Curve Number model was to be calibrated with literature based values and then applied to daily rainfall events to predict runoff from 2002 to 2004 (**Objectives 4 and 5**).

Potential Evaporation

For the purpose of considering wet conditions (high rainfall and low potential evaporation) we calculated daily potential evaporation (PE) by the standardized reference Penman-Monteith method (ASCE 2002) when a full data set was available. For periods where only temperature was available the Hargreaves equation (ASCE 2002) was used.

RESULTS AND DISCUSSION; MEASUREMENTS

Manure and Soil Properties

During the study period, including after the cattle were removed, the manure pack (including the manure mound) in the pens varied in thickness from 0 to 450 mm deep. About 25% of the surface area of both pens was taken up with a central manure mound that averaged 400 mm deep. The manure mound had more straw mixed in it then the surrounding manure pack. About 10-15% of the pen was bare soil surface and the remainder (55 to 60%) had a thin manure pack, 50 to 150 mm. During 2003, after the removal of the cattle, it was noticed that the thin manure pack had dried to a loose granular form. Underlying the manure mound and manure pack (wet or dry) was a thin (1-3 mm) black manure-soil-interface (MSI) layer. The MSI was more visible with the wet manure. For the dry manure pack there was a granular layer (averaging about 60 mm in depth) overlying a compacted manure layer (about 50 mm in depth). In some places the granular material had been removed, by wind, leaving the underlying compacted manure layer exposed.

The average bulk density of the wet manure pack was 0.22 g cm^{-3} and its average porosity, as judged by saturation was 0.71 m^3 m^{-3}(Table 1). The loose dried granular manure layer had a bulk density of 0.44 g cm^{-3} and a higher volumetric saturation than wet manure (0.82 m^3 m^{-3}). The saturated hydraulic conductivity (Ks) of the wet manure pack averaged 76 x 10^{-7} m s^{-1}, whereas the dry compacted layer was 0.6 x 10^{-7} m s^{-1}.

Table 1. Manure and soil properties

Material	Depth (mm)	Sand %	Clay %	Bulk density (g/cm^3)	θ_s m^3/m^3	Ks (x 10^{-7} m/s)
Wet manure	na	na	na	0.22 (0.03)	0.71 (0.06)	76 (20)
Granular Dry manure	0-60	na	na	0.44 (0.12)	0.82 (0.08)	na
Compacted Dry manure	60-110	na	na	0.78 (0.11)	0.44 (0.12)	0.63 (2.7)
MSI		na	na	0.93 (0.32)	na	0.20 (0.38)
Soil	0-50	50 (4)	17 (2)	1.65 (0.18)	0.31 (0.04)	0.51 (8.5)
Soil	50-100	51 (10)	17 (4)	1.68 (0.15)	0.39 (0.07)	3.4 (120)
Soil	200-250	55 (3)	16 (0.5)	1.35 (0.19)	0.47 (0.06)	3.9 (10)
Soil	400-450	45 (1)	21 (4)	1.49 (0.05)	0.44 (0.04)	2.3 (6.9)

'wet' and 'dry' manure refers to state of manure pack during sampling. $\theta_{s;}$ saturated volumetric moisture content. Ks; saturated hydraulic conductivity, Ks averages are from log-values of Ks. MSI manure-soil interface. Values in brackets are standard deviations.

Wet manure measurements were done on 50 mm high cores taken at various manure pack depths between manure surface to 200 mm beneath the surface.

Number of samples: wet manure pack 9 samples for bulk density 6 samples for saturated moisture 9 samples for Ks; granular dry manure 10 for all properties; compacted dry manure 4 for all properties; MSI 4 for all properties; Soil (with exception of texture) 10 soil 0-50 mm, 6 soil 50-100 mm, 10 200-250 mm , 8 400-450 mm; Soil texture 6 for 0-50-100 mm, 4 200-250 mm, and 3 400-450 mm.

The soil texture of the pens (upper 50 mm) averaged about 50 % sand and 17 % clay content. On average soil bulk density was the highest at 50-100 mm depth (1.68 g cm^{-3}) and decreased to that of an average of 1.5 g cm^{-3} at 400 to 450 mm depth. Soil porosity, as determined by saturation, was the least near the surface and increased with depth. The lowest hydraulic conductivities were in the compacted manure layer, the manure-soil-interface, and the upper 50 mm of soil. These values were lower by almost an order of magnitude than the 50 to 100 mm layer despite both layers having similar bulk densities, perhaps organic clogging or chemistry account for the differences in Ks. The Ks values for the manure-soil-interface and the surface 50 mm of soil are higher than that reported by other studies (Kennedy et al 1999 reported double ring infiltrometer rates of less than 1.8 x 10^{-9} m s^{-1}; McCullough et al. 2001 reported falling head Ks values between 5.3 x 10^{-9} m s^{-1} and 1.9 x 10^{-8} m s^{-1}; and Miller et al., 2003 reported double ring infiltrometer rates of 6.6 x 10^{-9} m s^{-1}). The stocking density at our feedlot was about 56 m^2 $head^{-1}$, whereas that reported by Kennedy et al. (1999) and Miller et al. (2003) was about 17 to 18 m^2 $head^{-1}$.

Climate

Climate affects the potential for runoff; wet conditions (high precipitation and low evaporation) create high soil moisture contents which can result in greater chance and amount of runoff given a rain event, whereas dry conditions (low precipitation and high evaporation) creates low soil moisture contents. The relationship of rainfall to potential evaporation (PE) is a general indicator of such wet and dry conditions (Fig. 2). During the April thru October periods of the three years of study, there were 7 weeks (out of 90) in which the rainfall was greater than the PE; 4 weeks during 2002 and 3 weeks during 2004. The April through October period of 2002 had cooler temperatures (10.8°C) but greater rainfall (314 mm) than normal (12.1°C, 218 mm from Eston Climate Normals, 1971-2000, Environment Canada 2004); April through October of 2003 was warmer (13.7°C) and much lower rainfall (181 mm) than normal, while April thru October of 2004 was cooler (11.6°C) and with higher rainfall than normal (268 mm). The wet conditions of 2004 occurred between June 5 and August 10 (Fig. 3).

Of consequence for runoff determination is rainfall amounts that may exceed the infiltration capacity of the soil. The largest daily rainfall events, greater than 20 mm, during the study period (April 1, 2002 to Oct 31, 2004) were 47 mm (July 9, 2002 as recorded at Kindersley), 34 mm (Sept 30, 2002), 26 mm (June 6, 2004), and 24 mm (Sept 7, 2002), with the last three events recorded at the feedlot (Fig. 6). Long-term Kindersley rainfall data (1912 to 2004) found these events to represent a return period of once every 6 years (47 mm), once every 3 years (34 mm), and once every 1.7 years (26 mm). A daily rain of 70 represents a return period of 25 years.

During the period in which the climate station and weir were both operational (Figs 1 and 3) a total rainfall of 112 mm occurred with the largest event being 19 mm on Aug 7. During this period of 2004 were only two other events larger than 10 mm per day; 13.4 mm on July 4, and 10.1 mm on Aug 1 (Fig. 3).

The highest 30 minute event recorded at the feedlot was 9.2 mm on May 26, 2003. There were five 30 minute events between 5 and 10 mm and 18 events between 2.5 and 5 mm. None of these events were exceptional in terms of amount. Thirty minute rainfall intensities recorded at the Kindersley station (1985 through to 1999, Environment Canada, 2004) indicated that on average there can be 2.7 events per year of 5 to 10 mm, at least one event per year of between 10 and 15 mm, and one event of 25 to 30 mm every 15 years. Extrapolation of these events indicates that a one in 25 year event would rain about 40 mm in 30 minutes.

Antecedent Moisture

Manure and soil moisture measurements were taken during mid-summer to fall of 2004 (Figs. 5 and 6). Of this period, July 19 to Aug 10, 2004 was the wettest period with regards to high rainfall relative to potential evaporation (67 mm of rain and 96 mm of PE). For the 400 mm thick manure pack the top 200 mm absorbed most of the rains (35 mm) increasing to near saturation on Aug 10 (Fig. 5), however the 200 mm thick manure pack did not show the highest moisture content values until after most of the rains had passed. Although the 200 mm manure pack was represented by only two sets of samples per date, each set agreed with the general moisture trend shown in Figure 5. All volumetric moisture contents shown for Fig. 5 and 6 are converted from mass moisture using bulk densities reported in Table 1 and thus could be in error from actual vaues. Soil moisture measurements of the top 200 mm beneath the 400 mm manure pack (Fig. 6) showed no measurable change in moisture during July 6 to Oct 8, 2004, while the soil bare of manure increased by 15 mm between July 19 and Aug 24. Soil moisture beneath a 200 mm manure pack showed slight changes indicating that some of the rains and drying conditions percolated through the manure pack. The 5-day API (Eq. 4) for the three highest rainfalls of when the weir was operational was 6.1 mm July 4 (13.4 mm of rain), 3.9 mm on Aug 1 (10.1 mm of rain), and 14.2 mm on Aug 7 (19.3 mm of rain).

Actual Runoff

Monitoring for actual runoff was to have proceeded via two different ways; change in depth of water in the storage ponds, and use of runoff weirs that would record the runoff rate at 10 minute intervals. Due to dry conditions typical of the site and the high permeability of the bottom of the storage pond, the only time that ponded water was observed was during snowmelt when the bottom was frozen. Much of the observed ponded melt water, seemed to have originated from snow drifts within the pond. The sides of the storage pond were of highly erodible soil material (silts to fine sands) and developed rills and small gullies during the 3 years of our study.

The weirs were operational from July to Oct 2004 (Figs. 1 and 3). The only time runoff was recorded at the weir was on Aug 7, when 19 mm of rain occurred, however the runoff amount was very small (less than 0.1 mm) and could be attributed to rain on a small scraped surface immediately in front of the the weir collection system. The lack of recorded runoff is still useful as it provides information about what type of events do not produce runoff.

RESULTS AND DISCUSSION; MODELING

Green-Ampt Method

Model Calibration The Green-Ampt Equation was calibrated using information from manure and soil properties (Table 1) and data from the rainfall simulator (Table 2). The rainfall simulator applied water to a bare (no manure pack) pen surface and to a pen surface with a dried manure pack (50 mm of granular material overlying 50 mm of compacted manure). The rainfall rates varied between 34 and 68 mm hr^{-1}. A rainfall of 35 mm in 60 minutes represents about a 1 in 10 year rain event, 50 mm is one in 30 years, and 65 mm is about one in 90 years (extrapolated Kindersley 60 minute rain fall intensities, 1984 to 1999, Environment Canada 2004). For a dry manure pack runoff took at between 2 ¾ and 8 hrs to occur and for a soil surface with no loose manure pack, runoff occurred within 1 to 7 minutes (Table 2). The resulting final infiltration rates are about two orders of magnitude higher than the Ks values for the surface soil, compacted dry manure layer, or the MSI as measured in the lab (Table 1, an infiltration rate of 20 mm hr^{-1} is

55 x 10^{-7} m s^{-1}). A water balance was performed after the infiltration tests to account for the water rained on the surface. The water balance showed missing water, especially for the tests done on the manure pack. The amount of water held in the manure pack and soil at the end of the rainfall test (subtracting antecedent moisture) plus the amount of runoff was much less than the amount of rain applied. By considering the manure pack tests; the manure pack at antecedent was very dry (0.05 m^3 m^{-3}) and at the end of the test was saturated (0.82 m^3 m^{-3}), thus for the 50 mm deep granular layer, 37.5 mm of rain would saturate the 50 mm granular layer, yet the rainfall rates of 34 to 39 mm hr^{-1} took 2 to 6 hours before runoff occurred. From the higher than expected final infiltration rates and the lack of an agreeable water balance we assume that the boundary plates demarcating the 1 m^2 plot area were not properly sealed and that excessive lateral flow occurred. This would have resulted in lower measured runoff values and thus higher infiltration rates. As the pen floor was very hard it was difficult to install and plates. We recommend that future studies use bentonite to attain a seal.

For the soil texture (52% sand, 16% clay) and porosity (0.31 m^3 m^{-3}) of the surface 50 mm of soil a wetting tension of -339 mm is calculated (Eq. 3). The Green-Ampt model as run on a bare feedlot surface with a hydraulic conductivity of 20 mm hr^{-1}, a rain intensity of 50 mm/hr, a wetting tension of -340 mm, and a soil moisture deficit as measured (Md = 0.21 m^3 m^{-3}) would not produce runoff until after 84 min of rain, much longer than that measured. A Ks of 1 mm hr^{-1} with the other parameters kept the same as above, produces a runoff curve similar to that measured (in both time of runoff initiation and runoff rate, Fig. 7). Reducing Ks to 0.1 mm hr^{-1}, similar to that measured in the lab (Table 2), results in runoff starting within 15 s of rainfall and the runoff rate being slightly higher than that measured (Fig. 7). As measured runoff was when it was collected from the collection plate and not from when ponding was first observed, this could be possible. We assume that the following parameters are representative of the feedlot soil or manure-soil interface for predictive Green-Ampt modeling of a bare (soil or compacted dry manure) feedlot pen surface:

- Ks = 0.1 mm hr^{-1} (0.28 x 10^{-7} m s^{-1});
- Ψ = -340 mm; and
- θs = 0.31 m^3 m^{-3}

Table 2. Summarization of runoff properties from rainfall simulation tests.

Test	Site	Condition	Rain intensity	Time to RO	Test duration	final RO rate	final infil
			mm/hr	min	min	mm/hr	mm/hr
FST#1	Field	stubble	36	NA	150	NA	>36
MPT#0	Pen 6	manure pack	34	NA	105	NA	>34
MPT#1	Pen 4	manure pack	34	NA	155	NA	>34
MPT#2	Pen 4	manure pack	39	165	207	9	30
MPT#3	Pen 6	manure pack	34	480	490	3	31
HPT#1	Pen 4	bare	36	1	26	40	-4*
HPT#2	Pen 4	bare	57	5.5	20	38	19
HPT#3	Pen 4	bare	65	2.8	22	46	19
HPT#4	Pen 6	bare	68	5.5	26	45	23
*HPT#5	Pen 6	bare	51	6.7	26	73*	*
HPT#6	Pen 6	bare	51	4.2	40	21	30

'NA' runoff did not start during test time, thus a final runoff rate is not provided.
'bare' refers to a pen surface with no manure pack.
*runoff rates exceeded rainfall rates, error is expected in rainfall application rate.

Model Development For a Manure Pack For application of the Green-Ampt model to a feedlot with a manure pack, we used the following conceptual model:

- that the manure pack will retain water against draining to the feedlot floor until the field capacity of the manure pack is reached;
- that once the field capacity is reached then added rain water will reach the feedlot manure-soil interface at the same rate that water is applied. At this point the Green-Ampt model can be applied; and
- runoff will not occur until the manure pack is saturated. Runoff could occur via two processes; as interflow between the bottom of the manure pack and the relatively impermeable pen floor or as surface flow which will not occur until the manure pack is saturated. Interflow could occur shortly after the manure pack reaches field capacity. Both of these processes can occur simultaneously. For that of simplicity we assumed that runoff will not occur until the manure pack is saturated;

We estimated runoff from the manure pack using the Green-Ampt model with the parameters already listed above for the soil and with these for the manure pack:

- $\theta ma = 0.05$ m^3 m^{-3} (measured antecedent moisture content of manure pack)
- $\theta ms = 0.71$ m^3 m^{-3} (measured saturated moisture content of manure pack)
- $\theta mfc = 0.45$ m^3 m^{-3} (assumed field capacity of manure pack)
- Zm = 50 mm (measured depth of manure pack)
- i = 35 mm hr^{-1} (measured rainfall rate of rainfall simulator)

Given the above conditions the manure pack will require 20 mm of water (34.2 min) to reach field capacity. At that point the infiltrated water has reached the pen soil or compacted manure surface surface and the Green-Ampt model is applied using the soil parameters. Another 13 mm of rain was required to bring the manure pack from field capacity to saturation, which according to the Green-Ampt model will occur after 25.5 minutes. The total time required for a 50 mm dry manure pack to reach saturation and for surface ponding to commence is 59.6 minutes (assuming that lateral flow at the bottom of the manure pack does not occur). To test the sensitivity of the assumed value of field capacity we ran the GA model with the same above conditions, however we allowed rainwater to immediately reach the feedlot floor under the 50 mm of dry manure pack (e.g., a field capacity is 0.05 m^3 m^{-3}). For this condition then the manure pack will reach saturation and surface ponding will begin after 61.6 minutes. Thus the value that field capacity actually is for manure has little effect upon how long it takes for runoff to occur and for future tests we used the GA model as soon as rain began.

Application of the GA model to the feedlot with measured rainfall events used the following conditions:

- the rainfall intensity of the event will simply be the total rainfall divided by the duration. We assume that this will result in little error due to the low Ks (0.1 mm hr^{-1}) of the pen floor;
- For rain events in which just daily rainfall amount is given the duration will be 24 hours;
- For a rain event to be considered for runoff it must be greater than 15 mm in within 24 hours;
- The five day API (Eq. 4) will be used to calculate the antecedent soil moisture of the top 50 mm and that of the manure pack.

- The starting soil moisture before API is added is 0.20 $m^3 m^{-3}$ and that of the manure pack is 0.30 $m^3 m^{-3}$; and
- It is assumed that 15% of the feedlot pen is bare, that 15% has a 50 mm manure pack, that 15% has a 100 mm manure pack, that 15% has a 150 mm manure pack, that 15% is of 200 mm manure pack, and that the remainder (25%) is the manure mound of 400 mm average depth;

Model Results The above Green-Ampt model and our conceptual feedlot model were thus applied to all rains of greater than 15 mm within 24 hours between April 1, 2002 and Oct 31, 2004. Two of these rain events occurred during the period that we had the weir operational (July 4-5 and Aug 7, 2004). The GA model predicted that the runoff from these two events would be 2 and 4 mm with all or most of the runoff coming from the bare soil portions. Measured manure pack and soil moisture contents (Figs. 5 and 6) during July through August 2004, reflect high antecedent moisture contents. The measured soil moistures were of the top 200 mm and would likely be higher than this in the upper 50 mm immediately following rains. The predicted runoff is greater than what was observed, however the GA model presented here does not have a surface detention term. Surface detention could easily be several mm or more.

Table 3. Observed and modelled runoff of daily rainfalls greater than 15 mm in 2002, 2003, and 2004.

Date	1in25 yr	29 Jn 02	09 Ju 02	26 Ju 02	07 Se 02	30 Se 02	12 Ap 03	06 Jn 04	10-12 Jn 04	15 Jn 04	04-05 Ju 04	07 Au 04
Rain (mm)	70	15	47	16	24	34	18	21	32	30	17	21
Duration (hr)	24	24	24	24	9.5	22.5	10	14	37.5	17	28	24
Observed RO (mm)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0.1
Green-Ampt Model Results												
API (mm)	5	1.2	6.4	1.2	16	1.5	1.2	10	21	21	6	14
Θa	0.30	0.22	0.30	0.22	0.30	0.23	0.22	0.30	0.30	0.30	0.30	0.30
Soil RO	64	2	41	2	20	21	9	17	23	25	10	15
50MP RO	49	0	27	0	16	2	0	6	23	25	0	9
100 MP RO	28	0	6	0	0	0	0	0	4	6	0	0
150 MP RO	7	0	0	0	0	0	0	0	0	0	0	0
Total RO	21	0.3	11	0.3	5	3	1	3	8	9	2	4
SCS Curve Number Model Results												
CN	90	90	90	90	90	90	90	75	75	75	75	75
RO	43	2	25	3	7	14	4	0.7	0.07	0.5	0.2	0.1

Green-Ampt calculated θa based upon API. Total runoff for Green-Ampt assumes that each of the above conditions occupies 15% of the feedlot surface and that there is no surface detention. All runoff (RO) is in mm.
API is 5 day antecedent precipitation index (Eq. 4). θa is antecedent soil moisture and was not allowed to exceed 0.30 $m^3 m^{-3}$. Soil RO is runoff from bare pen surface (no manure pack). 50MP RO, 100 MP RO, and 150 MP RO is the runoff from pen surface with 50, 100, and 150 mm of manure pack. CN is SCS curve number (assigned). RO is calculated SCS runoff as based upon Eqs 5 and 6.

During these 3 years of simulation the runoff from these events was 20 mm, 1, and 26 mm for the years 2002, 2003, and 2004 respectively. Runoff did not occur from any portion of the manure pack that was 150 mm or thicker and only upon three occasions did it occur from a 100 mm thick manure pack. The amount of runoff that occurred was strongly controlled by the amount of rain within the event and the API. The API essentially worked to increase the soil and manure pack moistures. A high API could essentially bring the manure pack to saturation resulting in most of the rain event water in running off. It should be cautioned that the total runoff calculated for the Green-Ampt model in Table 3 does not include surface detention. If surface detention was 5 mm then there would only be 3 events that resulted in runoff.

A one in 25 year rain storm with relatively dry pre-conditions (API = 5 mm) would result n 21 mm of runoff. If wet conditions had existed before (API = 30 mm) then the runoff would be 34 mm. If the pen had been recently scraped of all manure then the one in 25 year rain storm (API = 5 mm) could result in 64 mm of runoff. The proper assessment of the contribution of a 1 in 25 year rain storm should also consider the likelihood of what the API would be, that of surface detention, and that of the proportion of the pen covered in manure as opposed to being bare.

SCS Curve Number Model

The Soil Conservation Curve Number method by USDA (1973) has been used in other feedlot studies (Table 4). The curve number (CN), varies according to surface, infiltration, and antecedent moisture conditions.

Table 4. Summary of curve numbers for unpaved active feedlots.

Author	Curve Number	Area
Kennedy et al. (1999)	55 to 83	Alberta
Parker et al. (1999)	91 to 97	Nebraska
Kizil and Lindley (2002)	82 to 91	North Dakota
Miller et al. (2003)	52 to 96	Alberta

Although we do not have weir runoff data supporting selection of appropriate curve numbers for this feedlot, we assumed the following CN values;

- For a very wet manure pack in an active feedlot a CN of 90 to 95;
- For a dry manure pack a CN of 50 to 75; and
- For a recently scraped pen (wet or dry surface) a CN of 90 to 95.

Using the above assumptions; CN values were chosen such that daily runoff could be estimated from that of daily rain events during the study period of April 2002 to Oct 2004 (Table 4). Although runoff can occur from rain events smaller than 15 mm within 24 hours only those events tested for the Green-Ampt model were run for the SCS model (Eqs 5 and 6). For events that occurred when the weir was operational (June 4-5 and Aug 7, 2004) runoff amounts of 0.2 and 0.1 mm were predicted (Table 3). Essentially these can be considered as zero and this agrees with that of the observed values. However, it must be cautioned that the chosen CN values were done so very arbitrarily and actual CN values are very dependent upon antecedent conditions.

For the events during 2002, 2003, and 2004 the rain runoff was 51, 4, and 1 mm consecutively. The year 2004 was low because of the low CN value chosen and perhaps given the wet conditions of that summer it would have been appropriate to have chosen a higher CN value.

The effect of varying the curve number from 65 to 95 upon runoff from 24 hr rainfall amounts of different return periods for Kindersley is shown in Fig. 8. A one in 25 year 24 hr rainfall of 70 mm with a CN of 95 (very wet antecedent conditions) would produce 56 mm of runoff. Saskatchewan regulations require that the runoff ponds accommodate 76 mm of runoff (3 inches). This is more than adequate given the occurrence of a one in 25 year rainfall for wet antecedent conditions. However future studies should consider the likelihood of wet conditions occurring for a 1 in 25 year rainfall and that of runoff water already present in storage ponds.

SUMMARY AND CONCLUSIONS

Cattle feedlot soil and hydrology measurements were taken with the intent of understanding the parameters that control the occurrence and amount of pen runoff from rain events and then improving upon the application of models to feedlot runoff. Rainfall intensity and amount was monitored with a tipping bucket on site and supplemented with data from an Environment Canada climate station about 60 km away. During the three year period there were three rain fall events greater than 20 mm (24, 26, 37, and 47 mm) representing return periods of once very 6 years (47 mm) to about once every 1.5 years (24 mm). The greatest 30 minute event was 9.2 mm, which is within the range of yearly occurrence. Of the three summers two were wetter than normal and one was drier than normal, but normal for this region is relatively dry (146 mm) to the rest of the province. There were seven weekly periods during the three April thru October periods where weekly rainfall exceeded weekly potential evaporation. These periods should have the greatest antecedent moisture conditions.

Runoff weirs, established during the summer of 2004 only recorded runoff from one event, 19 mm of rain) and the runoff was less than 0.1 mm. During the period of recording there were three events greater than 10 mm with the greatest being 19 mm. Measured soil and manure moisture conditions indicated near saturation during part of the summer and a relatively high API for the 19 mm rainfall.

Measured soil and manure properties, along with that of runoff measurements from a rainfall simulator, was used to calibrate the Green-Ampt infiltration model for that of feedlot pen surface with no loose manure pack. Due to suspected leakage under the rainfall simulator runoff plates and lack of measured water balance, the calculated final infiltration rates were reasoned to be in error. Operation of the Green-Ampt model with appropriate soil input parameters indicated that measured final infiltration rates of 20 mm hr-1 would not be appropriate and that leakage would be the explanation. Saturated hydraulic conductivity values as measured in the lab, 0.1 mm hr-1 were thus used with the model. A conceptual manure pack model that allowed for the presence of a manure pack was developed such that the Green-Ampt infiltration model could be used. The conceptual model considered that the manure pack in no way hindered water flow to the soil surface and that runoff would not occur until the manure pack was saturated.

Application of the conceptual pack model with the Green-Ampt infiltration equation to the two heavy rain fall events while the wier was operational in 2004 produced near zero runoff if it was assumed that surface detention was more than 4 mm, and that bare soil surface accounted for not more than 15% of the pen surface.

The Soil Conservation Service Curve Number model was operated with CN values chosen from the literature, 90 for an active feedlot and 75 for an inactive feedlot. For the two highest rain events while the period while the weir was operational (CN of 75) runoff of 0.2 and 0.1 mm was produced. This is within that recorded, 0 and 0.1 mm, however the CN values strongly control antecedent conditions and should be chosen as based upon such.

Application of both the Green-Ampt and curve number models to high rainfall (greater than 15 mm per event) amounts of 2002 and 2003 resulted in generally poor agreement of total runoff amounts. This lack of agreement could be easily improved if antecedent conditions were used to derive the CN number. A one in 25 year, 24 hr rain storm of 70 mm could result in 21 mm of runoff (Green-Ampt with a low API of 5 mm), 34 mm of runoff (Green-Ampt with a high API of 30 mm), or 43 mm of runoff with the curve number model with a CN of 90. The Green-Ampt model could produce much greater runoff values if a greater proportion of the pen surface was bare of manure.

The field study and the process of model development, calibration, and application has revealed the following information important to understanding and modeling feedlot runoff;

- Antecedent moisture content of the soil surface will have very little effect upon the amount of runoff due to the very low hydraulic conductivity;
- Antecedent moisture content of the manure pack is of major importance in runoff amount; and
- The proportion of the feedlot covered in manure and the depth of manure has a major effect upon controlling the occurrence and amount of runoff;

RECOMMENDATIONS

Towards furthering understanding of feedlot hydrology and towards improvements in management of waters leaving a feedlot there is a need for the following information;

- The role that the manure pack and cattle stocking density has upon retention and release of moisture from wet and dry conditions typical for the prairies;
- The role that the manure pack and cattle stocking density has upon underlying soil moisture changes and drainage; and
- A runoff-simulation model that takes into account day to day antecedent conditions, cattle stocking management, and manure pack conditions.

ACKNOWLEDGEMENTS

Funding for this project is provided by Saskatchewan Agriculture Development Fund. PFRA is acknowledged for drilling and installation of piezometers, drill log interpretation and geotechnical laboratory analysis of core samples. Personnel at the River Ridge Feedlot are thanked for access permission and project support. We wish all cattle producers better times soon. Marc White, Daryl Rinas, and Crystal Halliday are thanked for their patience and sweat for field work. Wayne Morley is thanked for the design and setup of the weir data loggers.

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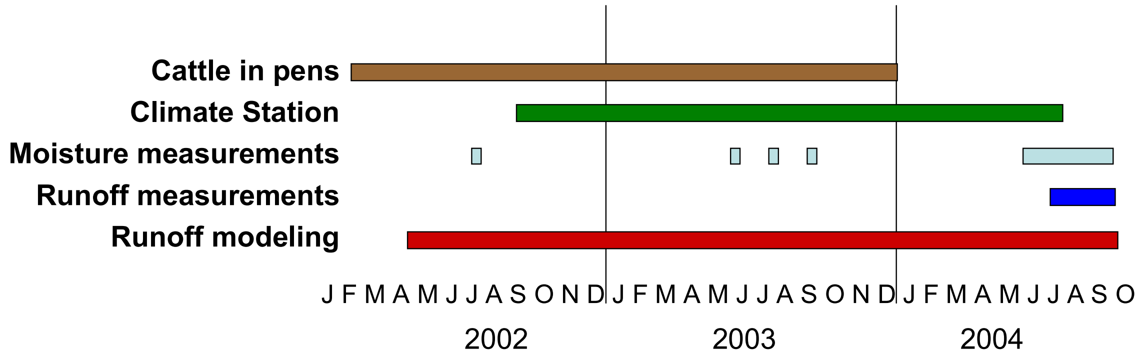

Fig. 1. Schedule of feedlot measurements and modeling period.

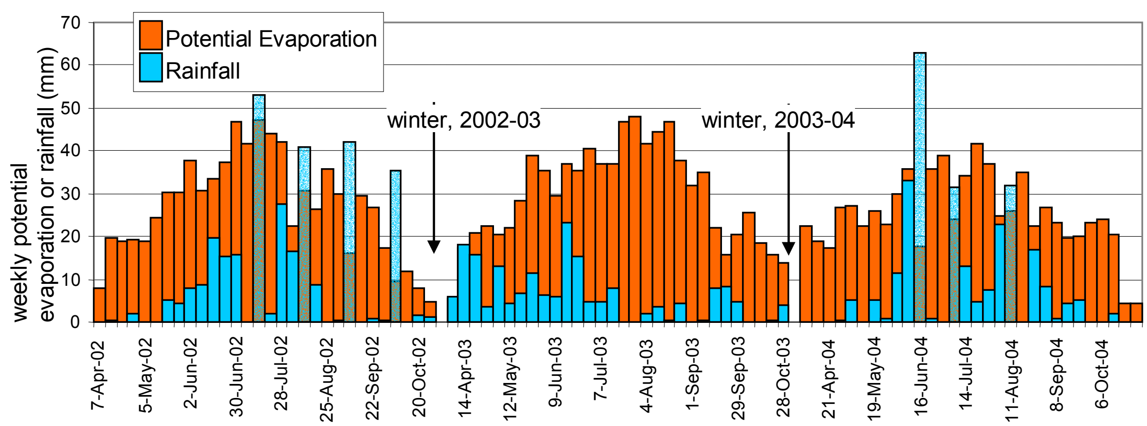

Fig. 2. Weekly potential evaporation and rainfall of April to October, 2002 to 2004.

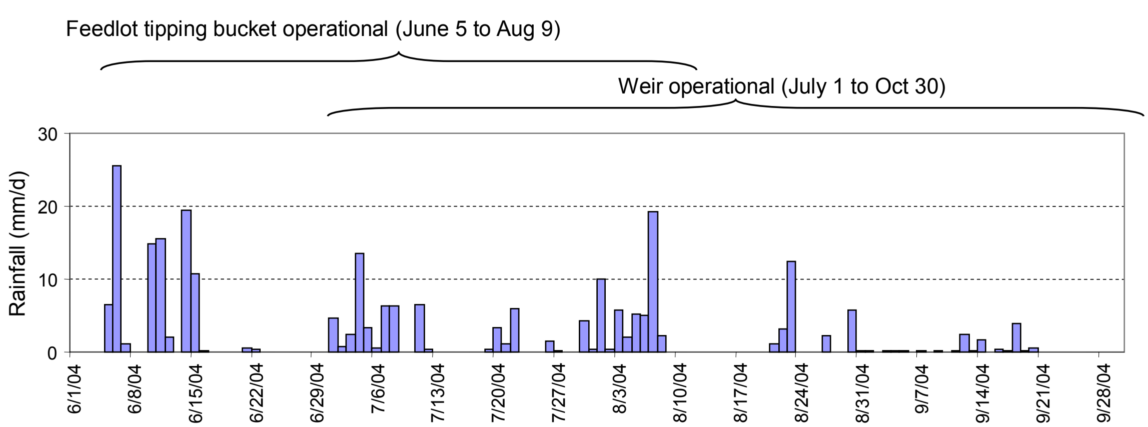

Fig. 3. Daily rainfall during weir operation of July to Sept, 2004. Rain events to Aug 9 were recorded with feedlot tipping bucket. Rain events afterwards are from Kindersley.

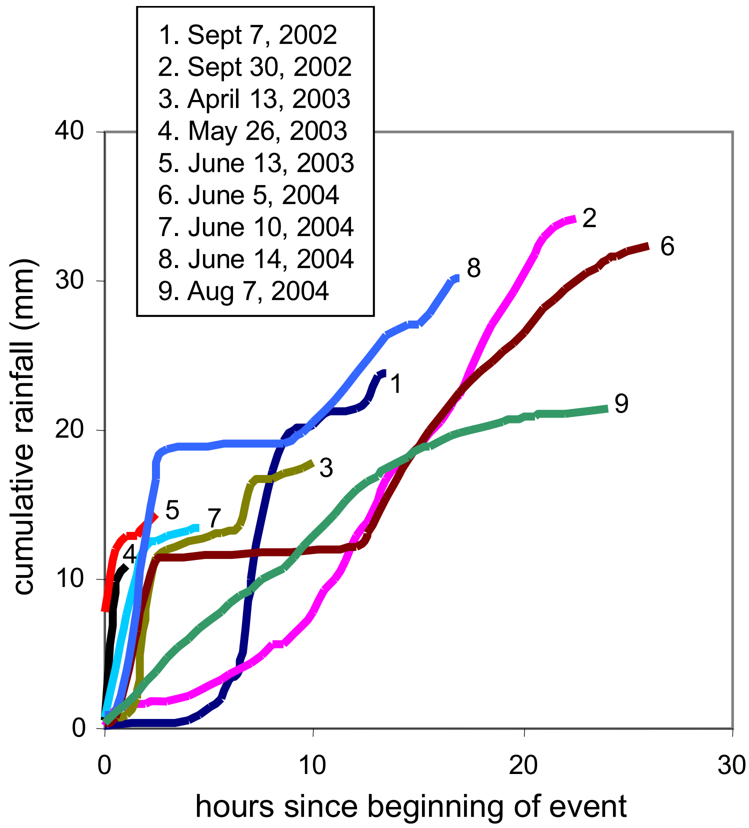

Fig. 4. Selected cumulative rainfall during individual rain events as recorded with tipping bucket at 30 minute intervals. Events that rained greater than 10 mm in one hour or 20 mm within one day were selected from feedlot climate station.

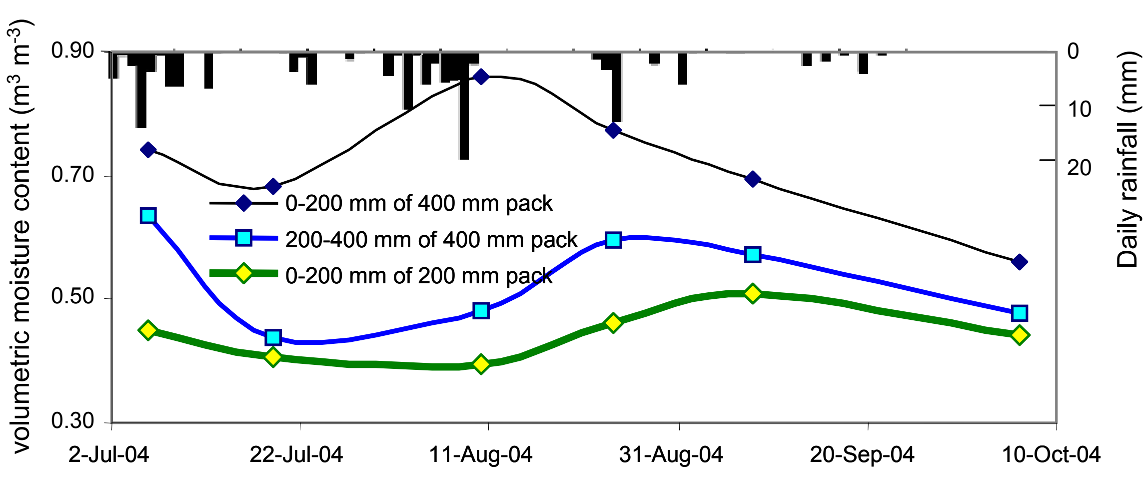

Fig. 5. Manure pack moisture contents where it was 200 and 400 mm deep (measurements in 400 mm pack are average of 4 samples, those in 200 mm pack are average of 2 samples).

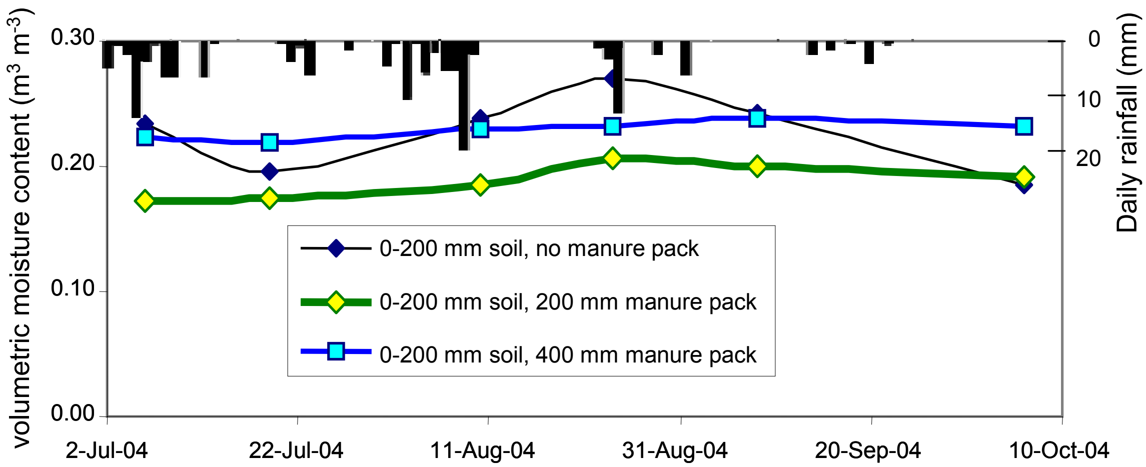

Fig. 6. Soil moisture contents of upper 200 mm of soil for bare soil, that underlying a 200 mm thick manure pack, and that underlying 400 mm manure mound (measuresments in 400 mm pack are average of 4 samples, those in 200 mm pack are average of 2 samples).

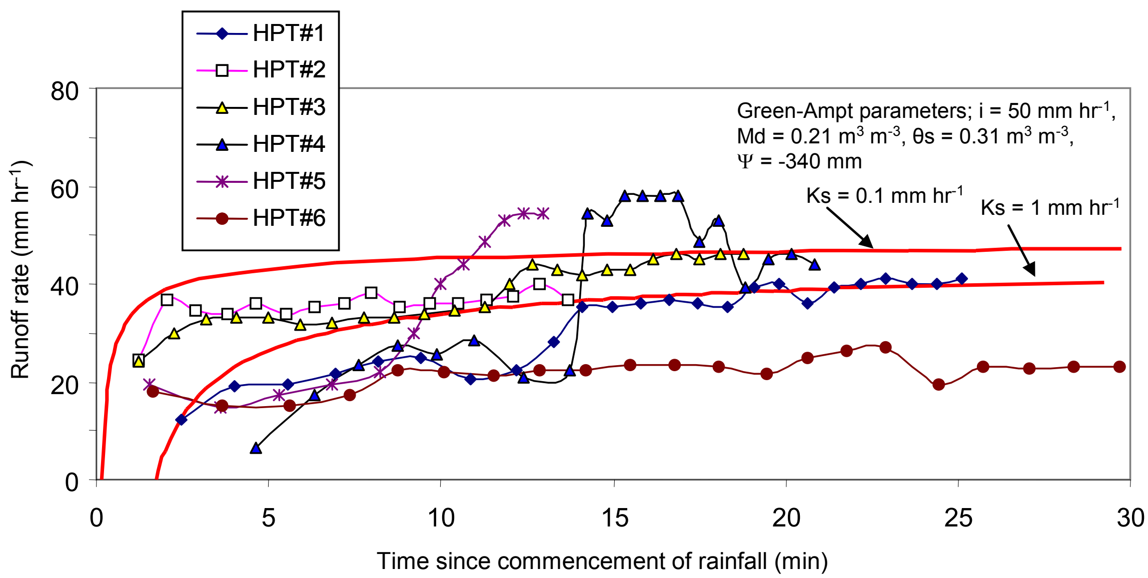

Fig. 7. Runoff rate with time since commencement of rainfall from Guelph rainfall simulator for compacted pen surfaces. Red lines are simulated values using Green-Ampt Model.