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A Runoff and Sediment Routing Model for Open Lot Beef Feeding Facilities

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Abstract

Feedlot runoff is a potential environmental contaminant and requires proper management to minimize impact on water quality. In designing runoff management systems, accurately assessing the amount of runoff that will be generated is of foremost importance. Along with overall quantity of runoff, the temporal pattern, both throughout the year and within an individual storm event, can have important implications for sizing control system components, in determining the performance the control system achieves, and in the overall pollution potential of the feedlot. This review summarizes the hydraulic properties of the feedlot surface, specifically focusing on variables that impact the total volume of effluent generated and the resulting amount of sediment transported. The work cumulates in development of a feedlot runoff routing model, presented as a series of equations that are implemented within the updated Iowa State University-Vegetative Treatment Area model, with a sediment transport/erosion component. Overall, the results indicated that a curve number of 91 was best for estimating runoff volumes, but substantial variation about this value could occur. The calibrated model was able to accurately estimate average total solids concentrations of lots of different size, shape, and surface condition under different hydraulic situations (R^2 = 0.92 for calibration and the slope of the measured vs. modeled data was not different than one during model validation). Most calibration and validation feedlots were earthen, had the majority of runoff from rainfall events, had mounds within the pen, and were scraped only once or twice per production cycle; thus model performance may be limited for other situations. The feedlot runoff and sediment routing components were used to assess the impact of various feedlot design characteristics, including feedlot area, aspect ratio, and slope, on solids transport from the feedlot surface. This model can be used to evaluate the risk that feedlot runoff poses to water quality for prioritizing feedlots that are in need of enhanced runoff control systems, and to evaluate the hydraulic and sediment loadings that a runoff control system is required to handle.

Keywords

Cattle manure, Erosion, Feedlot hydrology, Feedlot runoff, Modeling, Solids transport

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Environmental Indicators and Impact Assessment

Comments

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A RUNOFF AND SEDIMENT ROUTING MODEL FOR OPEN LOT BEEF FEEDING FACILITIES

D. S. Andersen

ABSTRACT. *Feedlot runoff is a potential environmental contaminant and requires proper management to minimize impact on water quality. In designing runoff management systems, accurately assessing the amount of runoff that will be generated is of foremost importance. Along with overall quantity of runoff, the temporal pattern, both throughout the year and within an individual storm event, can have important implications for sizing control system components, in determining the performance the control system achieves, and in the overall pollution potential of the feedlot. This review summarizes the hydraulic properties of the feedlot surface, specifically focusing on variables that impact the total volume of effluent generated and the resulting amount of sediment transported. The work cumulates in development of a feedlot runoff routing model, presented as a series of equations that are implemented within the updated Iowa State University-Vegetative Treatment Area model, with a sediment transport/erosion component. Overall, the results indicated that a curve number of 91 was best for estimating runoff volumes, but substantial variation about this value could occur. The calibrated model was able to accurately estimate average total solids concentrations of lots of different size, shape, and surface condition under different hydraulic situations (R^2 = 0.92 for calibration and the slope of the measured vs. modeled data was not different than one during model validation). Most calibration and validation feedlots were earthen, had the majority of runoff from rainfall events, had mounds within the pen, and were scraped only once or twice per production cycle; thus model performance may be limited for other situations. The feedlot runoff and sediment routing components were used to assess the impact of various feedlot design characteristics, including feedlot area, aspect ratio, and slope, on solids transport from the feedlot surface. This model can be used to evaluate the risk that feedlot runoff poses to water quality for prioritizing feedlots that are in need of enhanced runoff control systems, and to evaluate the hydraulic and sediment loadings that a runoff control system is required to handle.*

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Concern over water pollution associated with animal waste has increased with the intensification of livestock production. The passage of the Federal Water Pollution Control Act Amendments in 1972 placed the U.S. Environmental Protection Agency (EPA) in charge of developing runoff control guidelines (Anschutz et al., 1979). As a result, the EPA released the Effluent Limitation Guidelines (ELGs), which described the design and operating criteria for concentrated animal feeding operation (CAFO) waste treatment systems (Sweeten et al., 2003). Designing waste management systems that meet these guidelines while minimizing construction costs requires accurate estimation of the amount of waste generated. Along with understanding the hydraulic constraints placed on the waste management system it is also necessary to estimate the nutrient and solids, suspended and dissolved, loadings the system's treatment components will encounter. As shown in Andersen et al. (2011), many nutrient concentrations can be estimated based on knowledge of total solids content, thus physically based process models that link erosion to feedlot hydrology could be used to estimate nutrient losses from the feedlot.

A feedlot is subject to the same erosion-producing rainfall as the adjacent land, and although conditions of the feedlot and the surrounding surface may differ drastically, the effects of rainfall on solids transport and the erosion process are similar (Swanson et al., 1971). On an average annual basis, erosion is a function of slope angle and length, infiltration rate, and physical properties of the soil (Zing, 1940). However, the intensity, amount, and duration of rainfall can have a profound effect on the runoff rate, and therefore erosion (Ayers, 1936). Thus, the objective of this work was to develop a model of the feedlot surface, using inputs of feedlot surface type (earthen or concrete), average slope, feedlot size, aspect ratio, and a precipitation hyetograph that is capable of predicting runoff volumes and sediment mass transport. This information could then be used to aid in the design of solid settling basins and runoff control systems. The specific objectives are: (1) to discuss the hydraulic properties of the feedlot surface, (2) to discuss the various methodologies that have been used in modeling runoff volumes, (3) to propose a methodology for constructing a hydrograph from the feedlot surfaces, (4) to

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develop a relationship between sediment transport and runoff flow rate, and (5) to evaluate the implications this model has for designing feedlot to minimize sediment transport and evaluating existing lots.

FEEDLOT HYDRAULIC PROPERIES

PROPERTIES OF THE FEEDLOT SURFACE

The physical properties of the soil and manure pack (thickness, bulk density, water holding capacity, moisture content, hydraulic conductivity, infiltration rate, etc.) determines the water balance in the feedlot and is responsible for partitioning precipitation into storage in the manure pack, surface runoff, and leaching volume. Mielke et al. (1974) suggested that three layers develop in the soil profile in a feedlot; a layer of manure accumulation, a black interface layer of mixed organic and mineral soil, and the native soil (often this is the "C" horizon, i.e., underlying parent material as top soil is often removed during lot construction). Moreover, he suggested that this interface layer was primarily responsible for limiting hydraulic conductivity. This self-sealing layer forms through physical, chemical, and biological processes such as compaction from hoof traffic, plugging of soil pores, dispersion of clays from the high sodium and potassium levels accumulating at the interface of the feedlot soil and manure pack, and biofilm development (Mielke et al., 1974; Schuman and McCall, 1975; Miller et al., 1985; Rowsell et al., 1985; Barrington et al., 1987; McConkey et al., 1990).

This description of the feedlot soil profile has generally been accepted (Maule and Chi, 2006; Olson et al., 2006; Miller et al., 2008). However, more recent work by Cole et al. (2009) divided the manure accumulation into two layers, an upper dryer layer and lower wetter layer, although they propose that this division may be weather dependent with the boundary changing due to environmental conditions. Underneath this manure accumulation layer, Cole et al. (2009) found a black interface layer that would limit seepage. In either case (i.e., the profile of Mielke et al., 1974 or that of Cole et al., 2009), the manure-soil hydrologic response expected would be similar; the upper layers (manure) would act as a sponge soaking up added moisture and the compacted soil-manure interface as an impermeable, or very slowly permeable, layer (Mielke et al., 1974). This is not to say leaching from a feedlot surface does not or cannot occur, but rather that on the timescale of the precipitation event seepage through this interfacial layer should be negligible in the overall water balance. For instance, Mielke and Mazurak (1976) reported feedlot infiltration rates of 0.12 cm/day while values from McCullough et al. (2001) ranged from 0.05 to 0.16 cm/day. This is also true of concrete lots as no infiltration could occur; although in both cases significant fractions of precipitation could be stored in the accumulated manure depending on its moisture holding characteristics and its current moisture content.

As this black interface layer was presumed to be responsible for limiting leaching through the feedlot soil profile, Mielke et al. (1974) attempted to quantify its characteristics. However, he found that feedlots with a black interface layer had infiltration rates that were too slow to measure. Southcott and Lott (1996) reported a similar problem with very low infiltration rates, but found that hydraulic conductivities decreased from 3.1×10^{-5} cm/s before stocking to 2.3×10^{-6} cm/s after six months in a clayey gravel soil and from 2.5×10^{-4} to 1.4×10^{-6} cm/s after six months in a feedlot in a silty sand soil. More recently, McCullough et al. (2001) found conductivity went from 1.4E-5 cm/s to 1.2E-6 cm/s after 9-months use as a feedlot. These authors reported approximately an order of magnitude reduction in hydraulic conductivity, which is similar to the self-sealing effect often reported in earthen lined manure storages. However, if this self-sealing layer is removed or damaged during pen cleaning, it may lead to higher infiltration rates for a period of time as the layer reforms. Unless the entire layer is removed it is unlikely to have a large impact on overall hydrology in terms of changes to the runoff water balance, but could have implications for groundwater quality beneath the feedlot. This is supported by the work of Maule and Fonstad (2002) who suggested moisture fluxes of about 2 to 5 mm/yr below a feedlot, indicating that seepage would have little influence on estimating runoff volume. Despite this, concern over the potential of any seepage water to impact groundwater quality beneath the feedlot carefully as Maule and Fonstad (2000) found evidence of contamination of four of the five sites they studied.

Another unique property of the feedlot surface is that in addition to precipitation, it also receives moisture through cattle defecation and urination. The ASABE manure characteristics standard (*ASABE Standards*, 2005) can be used to provide an estimate of the average annual addition of water to the feedlot surface. This is a function of animal stocking density and is presented as such in figure 1 (assumes two cattle feed out cycles per year). As can be seen, the moisture addition in feces and urine can be quite large; even at 25 m^2/head (typical stocking density for earthen lots in Iowa, Euken et al., 2012) approximately 40 cm/year of water are added to the feedlot surface through cattle excretion. At concrete lots, which often stock at densities of around 12 m^2/head (Euken et al., 2012, up to 82 cm/yr of water can be added from the cattle manure. This amount of added moisture is important to consider

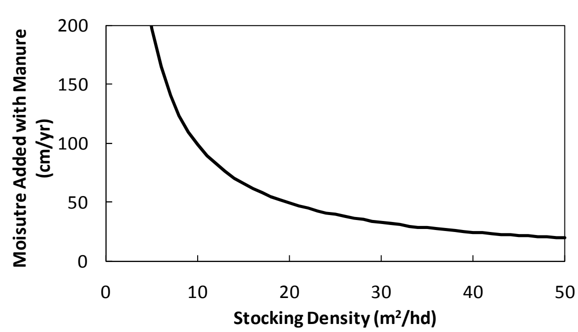


Figure 1. Moisture additions to the feedlot surface resulting from cattle defecation. Calculated based on ASABE Standard 384.2 (2005) assuming two cattle grow outs per year.

when evaluating feedlot surface properties as it can increase moisture levels; for instance in Iowa annual precipitation (NOAA, 2015) ranges from 63 to 102 cm (25 to 40 in.) thus moisture from animal defecation can account for between 30% and 60% of the average annual moisture the feedlot surface receives.

PREDICTING RUNOFF VOLUMES

Researchers (Gilbertson et al., 1980; Clark et al., 1975a) have suggested that the Soil Conservation Service (SCS) Curve Number (CN) method and linear regression equations are both viable methods of predicting runoff volumes from beef feedlots. Clark et al. (1975b) utilized the regression method to show rainfall-runoff relationships from six feedlot locations. Based on these equations Gilbertson et al. (1980) stated that between 0.75 and 1.5 cm of rainfall will be retained on the feedlot surface and between 36 and 86% of any additional rainfall will cause runoff, with values fluctuating due to lot antecedent moisture conditions, feedlot shape, slope, and the type of feedlot surface. As an alternative method, numerous researchers have utilized the CN method. Vanderholm et al. (1979) recommended values of 95 to 99.9 for concrete dairy lots and in additional work a value of 90 for paved beef cattle lots (Dickey and Vanderholm, 1977), suggesting that the greater manure accumulation on the surface of the beef lot resulted in greater retention of precipitation. Work from Gilley et al. (2011) suggested similar results, finding that for wet earthen feedlots a CN of 90 was appropriate and that greater accumulation of unconsolidated surface materials reduced runoff volumes. Miller et al. (2003) studied runoff from unpaved lots near Alberta, Canada, finding that CN varied from 52 to 96 for runoff events, mostly due to different amounts of water storage within the feedlot manure pack, which they propose acted like a sponge, absorbing the initial rainfall until it became saturated. This follows the suggestion of Clark et al. (1975a) that the percentage of rainfall that runs off is proportional to the moisture deficit (evaporation minus precipitation) of the region. Similarly many researchers have found that feedlot curve numbers can vary substantially (table 1) with different weather and storm patterns. This analysis is supplemented with figure 2, which used the precipitation and runoff data of Swanson et al. (1971), Swanson and Mielke (1973), Miller et al. (2004), Andersen (2012), and Kreis et al. (1972) to determine which CN and linear equation best fit the relationship between storm size and runoff depth. Both the CN and linear equation fit the data similarly, explaining 73% of the variation in runoff depth. The ideal CN was determined to be 91 and the linear regression equation suggested that 1.2 cm of precipitation was required to initiate runoff at which point 74% of all additional precipitation became runoff. However, there was again substantial variability about these relationships. This has led researchers to question the use of a standardized curve number for modeling feedlot runoff, and instead investigate the use of antecedent rain indexes and water balances on the manure pack to estimate runoff and speculate about the use of models to simulate the dynamic process of infiltration and runoff.

One such water balance model is that of Maule and Chi (2006), and although their model met with only limited success, it provides a framework for physically based feedlot runoff models. Their model used a moisture balance on the manure pack to calculate the retention factor used in the SCS CN method. The water balance was performed by accounting for water inputs from both precipitation and cattle defecation and losses to evaporation. These inputs caused changes to the moisture content of the manure pack The available water holding capacity of the manure pack, calculated based on these inputs, was used as the SCS retention factor in the curve number method. In developing this moisture balance, Maule and Chi (2006) assumed that seepage, i.e., leaching of water through the black interface layer, from the manure pack was negligible. Although the water balance method showed promise and was more successful than either a constant CN or a CN based on an antecedent precipitation index (Maule and Chi, 2006), more information on the hydraulic properties (conductivity, water retention, evaporative drying characteristics, porosity, wetting suction, rewetting characteristics) of the manure pack are needed, limiting implementation of this methodology.

However, to address challenges in temporal variability of curve numbers, and to provide a mechanistic based modeling of the impacts of manure scraping, addition of bedding to the manure pack, and the effect of weather preceding the storm even, a more sophisticated approach will be required. Future work should seek to quantify properties that control moisture loss rates from the manure pack as well as its moisture retention characteristics. Work by Miller and Berry (2005) provides insight into some of the properties that may influence evaporative water losses, as it was related to both the current moisture level and the manure to soil content of the media. However, based on the current information available, it appears that a curve

Table 1. Runoff curve numbers reported in literature for describing the volume of feedlot runoff from sites with varying stocking densities, feedlots surfaces, and weather conditions.

Author	Feedlot Conditions	Location	Curve No.	% Variation
Kennedy et al. (1999)	Unpaved, 17 m^2/head, Rainfall	Alberta	55-83	51
Kizil and Lindley (2002)	Pond Ash, 46 m^2/head, Rainfall	North Dakota	82-97	18
Swanson et al. (1971)	Unpaved, Rainfall Simulator	Nebraska	76-98	29
Swanson and Mielke (1973)	Unpaved, Rainfall	Nebraska	73-100	37
Miller et al. (2004)	Unpaved, 18 m^2/head, Rainfall	Alberta	59-95	61
Andersen (2012) – CN IA 1	Unpaved, 30 m^2/head, Rainfall	Iowa	77-100	30
Andersen (2012) – CN IA 2	Unpaved, 16 m^2/head, Rainfall	Iowa	77-98	27
Andersen (2012) – NW IA 1	Unpaved, 21 m^2/head, Rainfall	Iowa	94-100	6
Andersen (2012) – NW IA 2	Paved, 7 m^2/head, Rainfall	Iowa	73-100	37
Kreis et al. (1972)	Soft chalky bedrock, 11 m^2/head, Rainfall	Texas	79-99	25

number approach remains the best option for estimating runoff volumes, with a CN of 91 most appropriate for earthen lots and a slightly higher curve number (93) for paved lots.

Modeling the Runoff Hydrograph

Along with knowing the amount of runoff that occurs, proper analysis of settling basin performance and solids, total and suspended, transport from the feedlot requires information on the runoff hydrograph (Lott et al., 1990). Little research has focused on this area; however, work by Swanson et al. (1971) and by Gilley et al. (2011) have shown that erosion from a feedlot surface is proportional to the flow rate of runoff across the surface, i.e., that the movement of sediment from the feedlot surface is in general transport limited. Moreover, Lott et al. (1990) suggested a similar idea, stating that experience in Australia has shown settling basin weirs are more prone to clogging after intense rainfall events, possibly due to increased momentum carrying more manure into and through the settling basin. The link between solids transport and flow rate reported by these researchers seems plausible from a mechanistic standpoint as the feedlot surface is often covered with highly erodible particles; however, utilizing a relationship between flow rate and solids transport to predict feedlot runoff solids content requires a flow routing method be used to generate the runoff hydrographs.

Several methods have been proposed to generate runoff hydrographs including hydrograph fitting, kinematic flow routing, and SCS synthetic hydrograph generation. Using hydrograph fitting would require the generation of large datasets in which both the precipitation hyetograph and the runoff hydrograph are monitored prior to interception by the runoff control system. Although example hydrographs from earthen and concrete lots have been reported in the literature (Miner et al., 1966), insufficient information is provided to construct a unit hydrograph based on their findings and to generalize it to feedlots of differing size and slope. A second approach, using kinematic wave theory was proposed by Lott et al. (1990). Although many of the underlying assumptions of kinematic wave theory are plausible for feedlots (pen surface is relatively uniform with no significant irregularities, precipitation hyetograph across the feedlot surface would be similar, and in most cases backwater effects would be negligible upstream of the sedimentation system), an accurate Manning's coefficient is required (Lott et al., 1990). The value of Manning's coefficient is unknown and probably varies with different pen surface conditions such as frequency of pen cleaning, amount of manure accumulation, and moisture of the manure pack, and factors such as the quantity and size of hoof print depressions on the feedlot surface. Moreover, the addition of mounds within the pen could cause significant irregularities to the feedlot surface, violating one of the driving assumptions of the technique. Thus, at this time the SCS synthetic unit hydrograph approach as outlined by Haan et al. (1994) seems appropriate.

In the SCS synthetic unit hydrograph approach the first step is to estimate the time to peak of the hydrograph. This can be estimated using the SCS Method (1975) as shown in equation 1. In this equation T_p is the time-to-peak of the hydrograph in minutes, Δt is the duration of the unit excess rainfall in minutes, L is the length of the longest flow path in meters, CN is the runoff curve number (which could be adjusted based on the available water holding capacity of the feedlot surface), and *slope* is the average slope of the feedlot in m/m. This value can then be used in equation 2 to calculate the peak flow rate. In this equation q_p is the peak flow rate in cubic meters per second per centimeter of effective precipitation, A is the area of the feedlot in square meters, and T_p is the time of concentration in minutes. The SCS Dimensionless Unit Hydrograph can then be used to generate a unit hydrograph specific to the feedlot. Equation 3 provides a normalized equation which can be used to approximate the SCS hydrograph at different points in time, in this equation U is the flow rate of the unit hydrograph, in m^3/s per cm effective precipitation, q_p is the peak flow rate (m^3/s-cm effective precipitation) as calculated in equation 2, t is the time in minutes, and t_p is the peak time (minutes) as

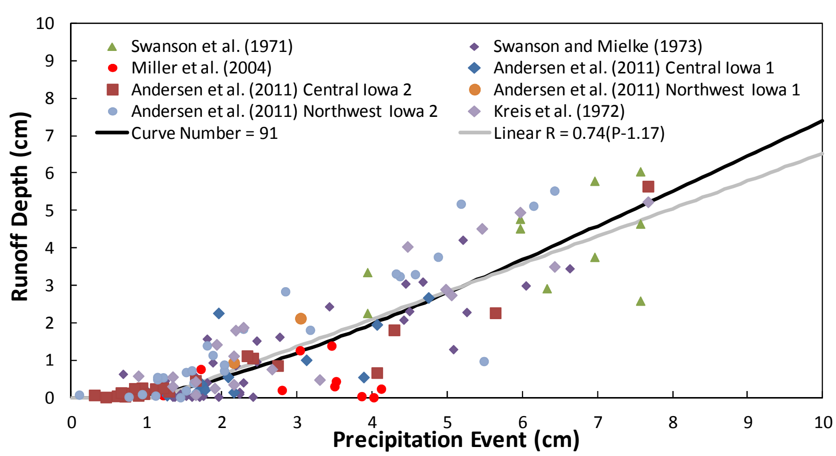


Figure 2. Monitored runoff depth vs. precipitation event size. Data from Swanson et al. (1971), Swanson and Mielke (1973), Miller et al. (2004). Andersen (2012), and Kreis et al. (1972). The SCS curve number and a linear regression equation were fit to the observed data. Model fitting suggested that the best curve number to use was 91 and the linear relationship indicated that 1.17 cm of precipitation were required to initiate runoff and thereafter 74% of all additional precipitation was converted to runoff; both equation had R2 values of 0.79.

calculated in equation 1. To facilitate programming, the time to peak should be adjusted to occur at the closest multiple of the time-step used in the model and total flow for the unit hydrograph should be adjusted to ensure that it is equal to the equivalent of 1 cm of runoff from the contributing drainage area. Total flow is checked using equation 4, where Q should be 1 cm, Δt is the time-step used in the model in minutes (chosen as 5 min here), U_i is the flow rate of the unit hydrograph at each point in cubic meters per second per cm, A is the area of the feedlot in square meters, and 6000 is a conversion from meters to centimeters and minutes to seconds. If this equation is not within the desired tolerance (0.0001) the peak flow is adjusted and then tolerance rechecked. This process should be iterated until the tolerance criterion is satisfied.

$$T_p = \frac{\Delta t}{2} + \left[\frac{L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{73.45\sqrt{slope}} \right] \tag{1}$$

$$q_p = \frac{A}{8000T_p} \tag{2}$$

$$U = q_p\left(\frac{t}{t_p}\exp\left(1 - \frac{t}{t_p}\right)\right)^{3.822} \tag{3}$$

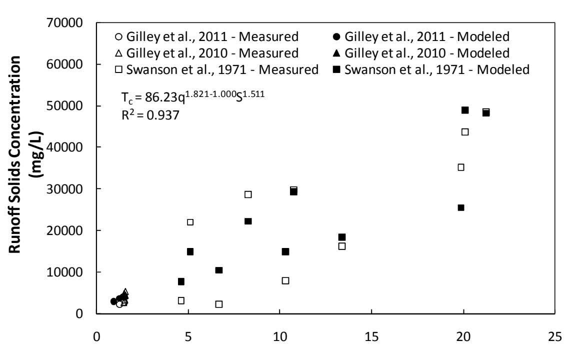
$$Q = \frac{6000\Delta t\sum_{i=1}^{n}U_i}{A} \tag{4}$$

To use the unit hydrograph approach, estimates of effective precipitation for each time step are required. Effective precipitation can be generated by using a storm hyetograph and the SCS CN method (or a feedlot surface water balance method) to estimate the amount of precipitation during each time step that would be converted to runoff. Using the SCS CN method, the amount of precipitation can be estimated by calculating cumulative precipitation and using the CN method to determine cumulative effective precipitation at a given time step. The amount of effective precipitation for the current time step is then calculated by subtracting off the cumulative effective precipitation of the previous time step. The water balance method would be performed similarly, although in this case there would be no runoff until the available soil storage capacity was exceeded, at which point all additional rainfall would be considered effective precipitation. The runoff hydrograph is then generated by convolution of the excess rainfall hyetograph and the unit hydrograph. This is done using equation 5. In this equation q_n is the flow rate of the n^{th} time increment of the runoff hydrograph in cubic meters per second, P_m is the effective precipitation, in cm, occurring during the m^{th} time increment, and U_{n-m+1} is the value of the $n\text{-}m+1$ time increment of the unit hydrograph, M is the number of increments that have excess rainfall, n is the time increment flow is being calculated for, and m is a count variable that is used to sum all effective precipitation increments that effect the flow of the current time interval.

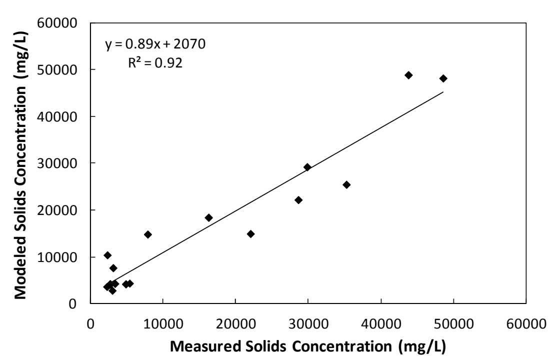
$$q_n = \sum_{m=1}^{n\leq M} P_m U_{n-m+1} \tag{5}$$

Estimation of Solids Transport

Several theories have been presented on erosion, but the prevailing sentiment among process-based erosion models is that sediment transport capacity is the fundamental concept in determining detachment and deposition processes. Building of this conceptual framework began with the work of Ellison (1944, 1947a, 1947b, and 1947c) who proposed dividing erosion into four sub-processes, (1) detachment by raindrop impact, (2) transport by rain splash, (3) detachment by surface flow, and (4) transport by surface flow. Meyer and Wischmeier (1969) proposed that sediment transport was either detachment or transport capacity limited. Since then the concept of limited sediment transport capacity of overland flow has been extensively applied in many physically based soil erosion models (Foster and Meyer, 1975; Beasley et al., 1980; Foster et al., 1995). Prosser and Rustomji (2000) focus on a simple



(a)



(b)

Figure 3. (a) Solids transport capacity as a function of runoff flow rate and feedlot slope. Open symbols represent measured data and filled symbols represent modeled data using the calibrated equation. Data used is from Swanson et al. (1971), Gilley et al. (2008), and Gilley et al. (2011). (b) Comparison of measured vs. modeled solids concentrations shown with the best-fit line. The intercept was not significantly different than 0 and the slope was not significantly different than 1 (α = 0.05) indicating adequate model fit.

transport capacity model, given as equation 6, which has been widely applied to hillslopes. In this equation q_s is the sediment transport capacity (g/min-meter width), q is the flowrate (L/min-meter width), S is the energy gradient (approximated as the surface gradient in%), and k, β, and γ are empirically derived constants. This equation was modified slightly for this analysis; both sides of the equation were divided by flow rate per unit width to solve the equation for runoff solids concentration (eq. 7). In this case, the concentration is in mg/L and k handles the appropriate unit conversions. For this approach to be successful it is required that solids transport is flow capacity limited, that is, there is sufficient erodible particles available on the feedlot surface to satisfy the transport capacity. According to the work of Gilley et al. (2011) this assumption is reasonable, as feedlot surfaces typically have a large supply of highly erodible material available for transport. However, in the case of a paved lot that has recently been cleaned, this may not be true and further refinement, such as tracking days since last pen cleaning to estimate manure coverage of the surface, may be necessary.

$$q_s = kq^{\beta} S^{\gamma} \tag{6}$$

$$C = kq^{\beta - 1} S^{\gamma} \tag{7}$$

The erosion model (eq. 7) was calibrated for feedlot sediment concentrations using data from Gilley et al. (2010), Gilley et al. (2011), and Swanson et al. (1971) (figure 3. These authors reported sediment transport and runoff from simulated rainfall events on feedlots of various slopes ranging from 4.8% to 13% and flow rates ranges from just above 0 to about 25 L/min/m plot width. Average solids concentrations were calculated by dividing cumulative sediment transport by total runoff. The fitted equation is noted in figure 3a; also shown (fig. 3b) is a plot of measured versus modeled concentrations. In general, this equation showed a reasonable ability to fit the measured data describing more than 93% of the total variability of the solids concentration in runoff from the feedlot. In the plot of measured versus monitored concentration data, the best-fit line's intercept was not significantly different than 0 and the slope of the line was not significantly different than 1 ($\alpha = 0.05$) indicating the model performance was adequate. Moreover, the calibrated coefficients β and γ are within the ranges recommended by Prosser and Rustomji (2000) and near their final recommendation of 1.5 for β and γ (we found $\beta = 1.821$ and $\gamma = 1.511$, respectively); however, there are several limitations to this model. Namely, the model assumes sheet flow over the feedlot surface. Although in some cases this may be true, especially on the smaller plots used in generating these data sets, on actual feedlots runoff might be more prone to channeling. This channel could change the relationship between solids concentration and flow rate. For instance, Miner et al. (1966) suggested that under channeling flow conditions runoff could be less polluted due to reduced interaction between the soil and the runoff water.

Although these controlled plot studies provide detailed information on the relationship between flow rate and total solids, they do little to illuminate how these solids were partitioned between suspended and dissolved solids. As illustrated above, solids concentrations are expected to increase with greater flow rates and steeper slopes. This is thought to be primarily due to increased suspended solid transport, as steeper slopes and greater flow rates result in greater fluid velocities, larger shear forces on the soil surface, and greater turbulence to mix the sediment into the flow. However, the opposite trend may be expected for dissolved solids. Increased velocities may lead to decreased concentrations due to less contact time between the flowing water and the feedlot surface (Miner et al., 1966). In addition to the impact of reduced contact time, larger storm events are often cited as diluting dissolved solids content in the runoff as the zone of the feedlot surface the runoff water is interacting with becomes depleted in these compounds (Malouf, 1970). To test the impact of dilution on dissolved solids concentration we regressed the percent of the total moisture the feedlot surface received due to cattle defecation (cattle defecation moisture divided by annual precipitation plus cattle defecation moisture) against average total dissolved solids concentration in the runoff (fig. 4). This correlation was tested using the data from the six sites presented in Andersen et al. (2009) and those reported by Kreis et al. (1972), Edwards et al. (1986), Yang and Lorimor (2000), Woodbury et al. (2002), and Lorimor et al. (2003). The amount of moisture added by cattle defecation was calculated based on the ASABE manure characteristics standard (*ASABE Standards*, 2005) assuming two cycles of cattle were marketed per year, except for the Edwards et al. (1986) site where the author reported that cycle had occurred. Results indicated that percent moisture added from cattle defecation and urination and average dissolved solids concentrations in the runoff were significantly correlated (r = 0.8888, $p < 0.0001$) and that this correlation was quite strong (fig. 6) as evidenced by the 201 mg/L (Standard Error ± 34) increase in dissolved solids concentration for every 1% increase in what fraction of moisture the lot received from cattle defecation. The slope of this regression line was

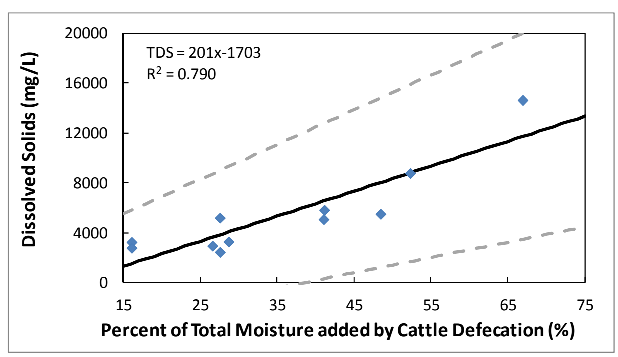


Figure 4. Regression between the average dissolved solids content of feedlot runoff and the percent of the moisture the lot receives from cattle defecation (moisture addition from defecation divided by annual rainfall plus moisture from cattle defecation). Moisture from cattle defecation calculated using ASABE manure characteristics standard. Dashed lines represent 95% confidence intervals.

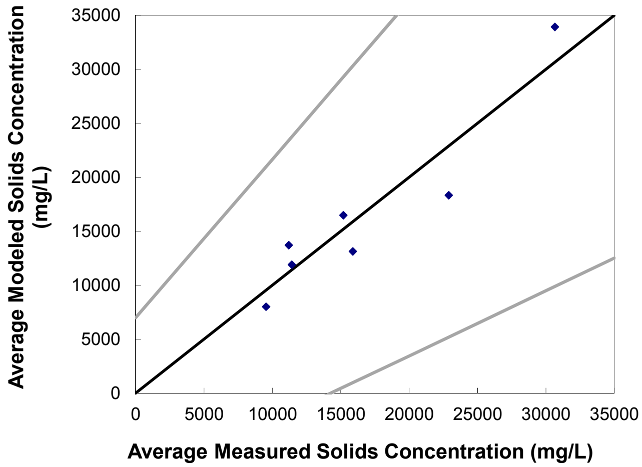


Figure 5. Comparison of average annual measured and modeled total solids concentration in feedlot runoff from seven production feedlots. Data from Kreis et al. (1972), Gilbertson and Nienaber (1973),- Lorimor et al. (1995), and Andersen (2012). The line shown represents the 1-to-1 line. The grey lines represent 95% confidence intervals on model performance.

significantly different than zero (p = 0.0003); however the intercept (-1703 mg/L) was not (p = 0.2342).

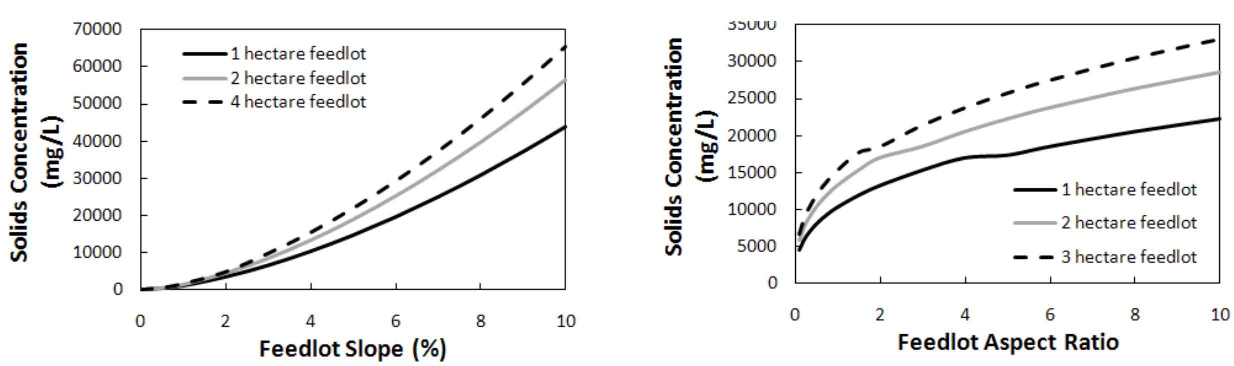
Model Validation

The runoff and erosion model described above was implemented and added to the Iowa State University-Vegetative Treatment Area model (Wulf and Lorimor, 2005) to perform validation testing. Unfortunately, no data sets where runoff rates and sediment concentrations from production feedlots were available to validate this model; however, average annual solids concentrations in runoff from feedlots have been reported on numerous lots (Kreis et al., 1972; Gilbertson and Nienaber, 1973; Lorimor et al., 1995; and Andersen, 2012). These data sets provide average solids concentrations for feedlot runoff from lots of varying sizes, slopes, and shapes under different climatic conditions. At each feedlot location (five Iowa locations, a Nebraska location, and a Texas location) we utilized our hydrology-erosion model to predict average total solids concentrations in feedlot runoff over a ten year period. The hydrology-erosion model was input with site specific data (feedlot size, aspect ratio, and slope) based on the author's description of the feedlot. Climatic data (precipitation and daily high and low temperatures) were obtained for each location for the period of 2000-2009 utilizing online sources (http://mesonet.agron.iastate.edu and http://www.wunderground.com) reported for nearby locations. The average total solids concentration for each event was calculated as the runoff event's flow-weighted average solids concentration. The minimum solids concentration for each event was set as the dissolved solids concentration calculated from the regression equation listed in figure 4. The arithmetic average total solids concentration was then calculated and compared to the average solids concentration reported in feedlot runoff from each site (fig. 5).

Model performance was evaluated by regressing the average modeled solids concentration against those measured at the site. The resulting regression line had a slope of 1.035 which was not significantly different than one ($\alpha = 0.05$) and the intercept (-783) was not significantly different than 0 ($\alpha = 0.05$). These results indicate that the model does not show a bias in predicting solids concentrations and appears to be performing well; however, at several of the sites modeled average concentrations differed from measured concentrations by up to 25%. Moreover, the slope and intercept of the regression line exhibited substantial uncertainty as 95% confidence intervals for slope were 0.603 and 1.467 while those of the intercept were -8,600 to 7,000. Despite this uncertainty, in general it appears that the model is providing a reasonable prediction of solids transport in feedlot runoff and as such may provide useful information on the impact on how different feedlot layouts affect solids transport and pollution potential.

Implications for Managing the Lot Surface

This leads to the question, given this information how should we design and manage the lot to minimize solids transport? Based on figure 3, it is clear that the flow rate of effluent across the feedlot surface should be minimized by diverting clean water around the feedlot. This need is further emphasized when one considers that the soil detachment rate is usually considered to be proportional to the difference between the sediment transport capacity and



(a) (b)

Figure 6. (a) Effects of feedlot size and slope on the solids transport from the feedlot surface on a per hectare basis. (b) Effects of feedlot aspect ratio (length-to-width) and feedlot size on the solids transport from the feedlot surface.

sediment load in the flow. Since the outside runoff water would be relatively clean, the erosion rate from the feedlot surface would be high. Along with this consideration, other measures that reduce flow rates could also be utilized. Based on equations 6 and 7 these measures would include minimizing the size of the feedlot to limit extra runoff from the contributing drainage areas, i.e., stocking cattle at the recommended density, minimizing the slope of the lot to slow the flow rate (although sufficient slope to encourage uniform drainage and maintain a well-drained feedlot need to be maintained), and adjusting feedlot shape to minimize the length-width ratio of the feedlot (shorter slope length and less contributing drainage area), or adding settling basins within the feedlot to break up longer slop lengths.

To illustrate these concepts and to better understand effects of the various design variables the developed model was utilized. The first variables investigated were feedlot size and slope. This was done by varying these two parameters while holding storm size and intensity constant. Results (fig. 6a) of this investigation are presented as total solids transported for a 2.54-cm, 1-h, uniform intensity storm. A feedlot curve number of 91 and a feedlot aspect (length-to-width) ratio of 1.0 were used. Results showed that solids concentration increased exponentially with slope, so minimizing the feedlot slope is critical. Lot size increases also increased solids concentration due to greater upslope contributing area, but in this case increases were logarithmic as doubling lot size did not double contributing flow length. Figure 6b supplements this analysis by analyzing the impact of the feedlot aspect ratio (Length to width ratio). This analysis is also presented for a 2.54-cm, 1-h storm, a feedlot curve number of 91, and a lot slope of 4%. This figure shows the logarithmic increases caused by increasing the drainage length. The slight discontinuities in this graph are caused by incremental change in the peak hydrograph time, which was required to be an increment of the 5-min time step used in the analysis.

In addition to these designer controlled properties, uncontrollable hydraulic properties also play a key role. To illustrate this effect we calculated the estimated erosion from various intensity storms. In all cases storms were modeled to last for an hour, thus each storm event was of a different magnitude. To make results comparable, flow weighted average solids concentrations are presented (fig. 7). In this case the feedlot slope was specified as 4%, the aspect ratio at 1 and the runoff curve number as 91. This plot illustrates that the larger flow rates produced by more intense rainfall events increases the transport capacity of the flow and with it projected erosion.

Conclusions

Design of open lot runoff control systems to meet environmental guidelines while minimizing construction and operation costs requires accurate estimation of the runoff volumes. When containment basins are used the estimated volumes most relevant are at the time scale of the application schedule; however, other treatment options, such as sediment basins and vegetative treatment systems,

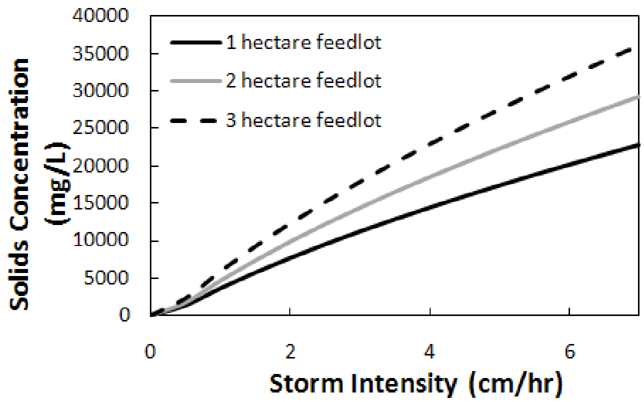


Figure 7. Total solids concentrations in feedlot runoff from a 1-, 2-, and 3-ha feedlot as a function of storm intensity for a 1-h, uniform intensity storm. Results are for a feedlot with slope of 4%, an aspect ratio of 1, and a curve number of 91.

respond to runoff at an event-by-event basis increasing the importance of accurately estimating runoff from individual events. Available literature on estimating feedlot runoff volumes was reviewed; the results indicated that while a curve number of 91 seemed appropriate for earthen lots and a value of 93 for concrete lots. However, substantial variation about this value existed with reported values ranging from 55 to 100 for individual storm events. Although this variation appears to be related to feedlot manure pack moisture dynamics, insufficient data exists to validate these claims. Future work assessing temporal moisture patterns in response to weather and cattle stocking density that assist in modeling the impact of manure pack moisture on runoff curve number would be a valuable step forward in feedlot modeling. A simple transport capacity model was then calibrated to erosion data available from rainfall simulator studies of feedlot erosion. The transport capacity model was linked to a feedlot runoff-flow routing model to predict solids concentrations in feedlot runoff events. Modeled sediment concentrations were compared to those measured at several production feedlots to validate the model, with results generally indicating good agreement between measured and modeled average solids concentrations (best fit line had a slope of 1.035 and an intercept of -783, which was not statistically different than 1 and 0 respectively), though considerable uncertainty in model performance remains as only seven sites could be modeled (95% confidence interval on slope was 0.603 to 1.467). The developed model was then used to assess the impact of various feedlot design characteristics, including feedlot area, aspect ratio, and slope, on solids transport from the feedlot surface. Overall the results indicated that minimizing feedlots slope (~2-3%) was important for limiting the erosive potential of feedlot runoff. Moreover, limiting pen-to-pen drainage paths and instead routing runoff water to conveyance structures will reduce flow rates and limit the loss of sediment from the feedlot surface. Finally, better understanding of the manure pack characteristics and their hydraulic characteristics can be used to evaluate different scraping strategies for managing the lot. In particular, it might be feasible that less frequent scrapping of concrete lots could reduce runoff volumes by providing a "sponge" (the manure pack) to soak up some of the added moisture, reducing runoff rates and potentially solids transport. However, if the manure pack is already wet from previous rainfall events, or the storm is large enough to minimize the impact of the sponge effect, scrapping to reduce available solids for transport may be advisable.

REFERENCE

Andersen, D.S. (2012). Evaluating solids, phosphorus, and nitrogen cylcing and transport in vegetative treatment systems used for runoff control on beef feedlots. Iowa State University, Ames Iowa.

Andersen, D.S., Burns, R.T., Moody, L.B., & Helmers, M.J. (2011). Using total solids concentration to estimate nutrient content of feedlot runoff effluent from solid setting basins, vegetative infiltraiton basisns, and vegetative treatment areas. *Applied Eng. in Agric.* 27: 813-820.

Anschutz, J. A., Koelliker, J. K., Zovne, J. J., Bean, T. A., & Peterson, M. J. (1979). Sizing components on open feedlot runoff-control systems. *Trans. ASAE, 22*(4), 803-808. http://dx.doi.org/10.13031/2013.35105

ASABE Standards. (2005). D384.2: Manure production and characteristics. St. Joseph, Mich.: ASABE.

Ayers, Q. C. (1936). Soil erosion and its control. New York, N.Y.: McGraw-Hill Book Co., Inc.

Barrington, S. G., Jutras, P. J., & Broughton, R. S. (1987). The sealing of soils by manure: I. Preliminary investigations. *Canadian Agric. Eng., 29*, 99-103.

Beasley, D. B., Huggins, L. F., & Monke, E. J. (1980). ANSWERS: A model for watershed planning. *Trans. ASAE, 23*(4), 938-944. http://dx.doi.org/10.13031/2013.34692

Clark, R. N., Gilbertson, C. B., & Duke, H. R. (1975a). Quantity and quality of beef feedyard runoff in the Great Plains. *Managing Livestock Wastes, Proc. 3rd Intl. Symp. Livestock Wastes* (pp. 429-431). St. Joseph, Mich.: ASAE.

Clark, R. N., Schneider, A. D., & Stewart, B. A. (1975b). Analysis of runoff from southern Great Plains feedlots. *Trans. ASAE, 18*(2), 830-835. http://dx.doi.org/10.13031/2013.36579

Cole, N. A., Mason, A. M., Todd, R. W., Rhoades, M. B., & Parker, D. B. (2009). Chemical composition of pen surface layers of beef cattle feedlots. *Prof. Animal Scientist, 25*(5), 541-552.

Dickey, E. C., & Vanderholm, D. H. (1977). Feedlot runoff holding ponds. Nutrient level and related management aspects. *J. Envir. Qual., 6*(3), 307-312. http://dx.doi.org/10.2134/jeq1977.00472425000600030016x

Ellison, W. D. (1944). Studies of raindrop erosion. *Agric. Eng., 25*, 131-136, 181-182.

Ellison, W. D. (1947a). Soil erosion studies - Part I. *Agric. Eng., 28*, 145-146.

Ellison, W. D. (1947b). Soil erosion studies - Part II: Soil detachment hazard by raindrop splash. *Agric. Eng., 28*, 197-201.

Ellison, W. D. (1947c). Soil erosion studies - Part V: Soil transportation in the splash process. *Agric. Eng., 28*, 402-408.

Euken, R., Dorn, B., Clark, C., Shouse, S., Ellis, S., Loy, D., & Schulz, L. (2012). Beef feedlot systems manual. Ames, Iowa.: Iowa Beef Center, Iowa State University Ext. Outreach.

Foster, G. R., & Meyer, L. D. (1975). Mathematical simulation of upland erosion by fundamental erosion mechanics. Present and prospective technology for predicting sediment yields and sources. 45-59. USDA, Science Education Administration, Agric. Reviews Manuals, ARM-W-10.

Foster, G. R., Flanagan, D. C., Nearing, M. A., Lane, L. J., Risse, L. M., & Finkner, S. C. (1995). Hillslope erosion component. *USDA - Water Erosion Prediction Project: Hillslope profile and watershed model documentation*, 11.1-11.2. West Lafayette, Ind: Natl. Soil Erosion Res. Laboratory.

Gilbertson, C. B., Clark, R. N., Nye, J. C., & Swanson, N. P. (1980). Runoff control for feedlots-State of the art. *Trans. ASAE, 23*(5), 1207-1212. http://dx.doi.org/10.13031/2013.34748

Gilbertson, C.B. & Nienaber, J.A. 1973. Beef cattle feedlot runoff-physical properties. *Trans. ASAE 16*(5)(: 997-1001.

Gilley, J. E., Berry, E. D., Eigenberg, R. A., Marx, D. B., & Woodbury, B. L. (2008). Spatial variations in nutrient and microbial transport from feedlot surfaces. *Trans. ASABE, 51*(2), 675-684. http://dx.doi.org/10.13031/2013.24380

Gilley, J. E., Vogel, J. R., Eigenberg, R. A., Marx, D. B., & Woodbury, B. L. (2010). Nutrient transport in runoff from feedlots as affected by wet distillers grain diet. *Trans. ASABE, 53*(2), 545-552. http://dx.doi.org/10.13031/2013.29569

Gilley, J. E., Vogel, J. R., Eigenberg, R. A., Marx, D. B., & Woodbury, B. L. (2011). Runoff, erosion, and size distribution of sediment from beef cattle feedlots. *Trans. ASABE, 54*(2), 435-440. http://dx.doi.org/10.13031/2013.36446

Haan, C. T., Barfield, B. J., & & Hayes, J. C. (1994). Chapter 3. Design hydrology and sedimentology for small catchments. San Diego, Calif.: Academic Press.

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

Kizil, U., & Lindley, J. A. (2002). Determination of runoff curve number for a bison feedlot. Conf. Proc. 2002 ASAE/CSAE North-Central Intersectional Meeting. Paper No. MBSK 02-302. St. Joseph, Mich.: ASAE.

Kreis, R. D., Scalf, M. R., & McNabb, J. F. (1972). Characteristics of rainfall runoff from a beef cattle feedlot. USEPA Publ. #EPA-R2-72-061. Washington, D.C.: USEPA.

Lorimor, J. C., Melvin, S. W., & Adam, K. M. (1995). Settling basin performance from two outdoor feedlots. *Proc. 7th Intl. Symp. Animal, Agric. Food Process. Wastes* (pp. 17-23). St. Joseph, Mich.: ASAE.

Lorimor, J. C., Wulf, L., & Jaranilla, P. 2003. An infiltraiton-wetland system for treating open feedlot runoff. In *Proc. of the 9th Internatinal Systemposition, Animal, Agricutral, and Food Processing Wastes:* 405-410. St. Joseph, Mich.: ASAE.

Lott, S. C., McKay, M. E., & Horwood, W. (1990). Kinematic modeling of feedlot runoff. *Proc. Inst. Eng. Australia Conf. Agric. Eng.*, (pp. 428-431).

Malouf, J. B. (1970). Water pollution from cattle feedlots. MS thesis. Lubbock, Tex.: Texas Tech University, Civil Engineering Department.

Maule, C. P., & Fonstad, T. A. (2000). Impacts of cattle penning on groundwater quality beneath feedlots. *Canadian Agric. Eng., 42*(2), 87-93.

Maule, C. P., & Fonstad, T. A. (2002). Solute and moisture flux beneath cattle feedlot pens. *Trans. ASAE, 45*(1), 73-81. http://dx.doi.org/10.13031/2013.7876.

Maule, C., & Chi, D. (2006). Development of an evaporative-runoff model from cattle feedlot pens. ASABE Paper No. 064066. St. Joseph, Mich.: ASABE.

McConkey, B. G., Reimer, C. D., & Nicholaichuk, W. (1990). Sealing earthen hydraulic structures with enhanced gleization and sodium carbonate: I. Laboratory study of the effect of freeze-thaw cycle and drying interval. *Canadian Agric. Eng., 32*, 163-170.

McCullough, M. C., Parker, D. B., Robinson, C. A., & Avermann, B. W. (2001). Hydraulic conductivity, bulk density, moisture content, and electrical conductivity of a new sand loam feedlot surface. *Appl. Eng. Agric., 17*(4), 539-544. http://dx.doi.org/10.13031/2013.6471

Meyer, L. D., & Wischmeier, W. H. (1969). Mathematical simulation of the process of soil erosion by water. *Trans. ASAE, 12*(6), 754-758, 762. http://dx.doi.org/10.13031/2013.38945

Mielke, L. N., & Mazurak, A. P. (1976). Infiltration of water on a cattle feedlot. *Trans. ASAE, 19*(2), 341. http://dx.doi.org/10.13031/2013.36024

Mielke, L. N., Swanson, N. P., & McCalla, T. M. (1974). Soil profile conditions of cattle feedlots. *J. Envir. Qual., 3*(1), 14-17. http://dx.doi.org/10.2134/jeq1974.00472425000300010004x

Miller, D. N., & Berry, E. D. (2005). Cattle feedlot soil moisture and manure content: I. Impacts on greenhouse gases, odor compounds, nitrogen losses, and dust. *J. Envir. Qual., 34*(2), 644-655. http://dx.doi.org/10.2134/jeq2005.0644

Miller, J. J., Beasley, B. W., Yanke, L. J., Larney, F. J., McAllister, T. A., Olson, B. M., Selinger, L. B., Chanasyk, D. S., & Hasselback, P. (2003). Bedding and seasonal effects on chemical and bacterial properties of feedlot cattle manure. *J. Envir. Qual., 32*(5), 1887-1894. http://dx.doi.org/10.2134/jeq2003.1887

Miller, J. J., Curtis, T., Larney, F. J., McAllister, T. A., & Olson, B. M. (2008). Physical and chemical properties of feedlot pen surfaces located on moderately course- and moderately fine-textured soils in southern Alberta. *J. Envir. Qual., 37*(4), 1589-1598. http://dx.doi.org/10.2134/jeq2007.0422

Miller, J. J., Handerek, B. P., Beasley, B. W., Olson, E. C. S., Yanke, L. J., Larney, F. J., McAllister, T. A., Olson, B. M., Selinger, L. B., Chanasyk, D. S. & Hasselback, P. (2004). Quantity and quality of runoff from a beef cattle feedlot in southern Alberta. *J. Envir. Qual., 33*(3), 1088-1097. http://dx.doi.org/10.2134/jeq2004.1088

Miller, M. H., Robinson, J. B., & Gillham, R. W. (1985). Self-sealing of liquid manure storage ponds: I. A case study. *J. Envir. Qual., 14*, 533-538.

Miner, J. R., Lipper, R. I., Fina, L. R., & Funk, J. W. (1966). Cattle feedlot runoff - Its nature and variation. *J. (Water Pollution Control Federation), 38*(10), 1582-1591.

NOAA. (2015). Climate of Iowa. Retrieved from http://www.crh.noaa.gov/Image/dvn/downloads/Clim_IA_01.pdf.

Olson, E. C. S., Chanayk, D. S., & Miller, J. J. (2006). Effects of bedding type and within-pen location on feedlot runoff. *Trans. ASABE, 49*(4), 905-914. http://dx.doi.org/10.13031/2013.21736

Prosser, I. P., & Rustomji, P. (2000). Sediment transport capacity relations for overland flow. *Progress Physical Geography, 24*(4), 179-193. http://dx.doi.org/10.1177/030913330002400202

Rowsell, J. G., Miller, M. H., & Groenevelt, P. H. (1985). Self-sealing of earthen manure storage ponds II. Rate and mechanism of sealing. *J. Envir. Qual., 14*(4), 539-543. http://dx.doi.org/10.2134/jeq1985.00472425001400040014x.

Schuman, G. E., & McCall, T. M. (1975). Chemical characteristic of a feedlot soil profile. *Soil Sci., 119*(2), 113-118. http://dx.doi.org/10.1097/00010694-197502000-00001.

Soil Conservation Service. (1975). Urban hydrology for small watershed, Tech. Release No. 55. Washington, D. C. : Soil Conservation Service, USDA.

Southcott, P. H., & Lott, S. C. (1996). Preliminary results on soil permeability and physical characteristics of feedlot pends. *7th Australia New Zealand Conf. Geomechanics, Geomechanics Changing World* (pp. 844-849). Australia: Inst. Eng.

Swanson, N. P., & Mielke, L. N. (1973). Solids trap for beef cattle feedlot runoff. *Trans. ASAE, 16*(4), 743-745. http://dx.doi.org/10.13031/2013.37615

Swanson, N. P., Mielke, L. N., Lorimor, J. C., McCalla, T. M., & Ellis, J. R. (1971). Transport of pollutants from sloping cattle feedlots as affected by rainfall intensity, duration, and recurrence. *Proc. Intl. Symp. Livestock Wastes* (pp. 51-55). St. Joseph, Mich.: ASAE.

Sweeten, J., Miner, R., & Tengman, C. (2003). A brief history and background of the EPA CAFO rule. *Manure Matters, 10*(1). Retrieved from www.p2pays.org/ref/15/14479.pdf

Vanderholm, D. H., Dickey, E. C., Jackobs, J. A., Elmore, R. W., & Spahr, S. L. (1979). Livestock feedlot runoff control by vegetative filters. EPA Grant R8043401-01-1. Ada, Okla.: R.S. Kerr Envir. Res. Lab.

Vanderholm, D. H., & Dickey, E. C. (1980). Design of vegetative filters for feedlot runoff treatment in humid areas. *Trans. ASAE, 23*(3), 681-684, 687. http://dx.doi.org/10.13031/2013.34646

Woodbury, B.L., Nienaber, J.A., & Eigenberg, R.A. (2002). Operational evaluation of a passive beef cattle feedlot runoff control and treatment system. *Applied Eng. Agric. 18*(5), 541-545.

Wulf, L., & Lorimor, J. (2005). Alternative technology and ELG models for open cattle feedlot runoff control: Model descriptions and user's guide. Ames, Iowa: Iowa State Univ.

Yang, P. & Lorimor, J. (2000). Physical and chemical analysis of beef cattle feedlot runoff before and after soil infiltraitonand wetland treatment. *Presented at the Eight International Symposium on Ag. and Food Processing Wastes*. Oct. 9-11, 2000, Des Moines, Iowa.

Zing, A. W. (1940). Degree and length of landslope as it affects soil loss in runoff. *Agric. Eng., 21*, 59-64.