A Model to Predict Cattle Feedlot Runoff for Effluent Reuse Applications

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Abstract: A model for predicting the quantity and quality of runoff from beef cattle feedlots was developed and incorporated into the MEDLI (Model for Effluent Disposal using Land Irrigation) software for designing effluent reuse schemes. The feedlot runoff model is a deterministic, daily time-step, Fortran model consisting of a combination of empirical and physically based algorithms. This paper focuses on the validation of the runoff volume predictions of the model. Four data sets collected from three Australian feedlots located in southern Queensland were used to validate runoff volume predictions. The model was calibrated against one data set, then applied independently to the others. The predicted and measured runoff volumes for the four catchment sites were well-correlated, particularly for larger events. Smaller runoff events were less predictable, mainly because pad manure depth and antecedent moisture content become increasingly important for estimating infiltration and depression storage, but these parameters were not measured for the runoff experiments, and are impossible to predict with any confidence. Nevertheless, predicted overall annual yields were similar to the measured data. The model demonstrates that, for typical Australian feedlots, predicting runoff volume can be achieved by a relatively simple approach. Evaporation from the feedlot pad requires further clarification and there remains a significant knowledge gap with respect to solids removal and the processes by which nutrients and salts are dissolved in runoff, an important consideration when attempting to predict runoff quality.

Keywords: Feedlot runoff; Modelling; Effluent reuse; Runoff

1. INTRODUCTION

Sustainable effluent management is a fundamental requirement of existing and proposed beef cattle feedlot operations in Australia. Models have been developed to predict feedlot runoff in order to determine the optimal storage capacity required [Lott, 1997; Skerman, 2000], but they are not readily available in a convenient form.

To rectify this, a feedlot option has been included in the MEDLI (Model for Effluent Disposal using Land Irrigation) software [Gardner et al., 1996]. MEDLI runs on historical, daily, climatic data, and provides a versatile, user-friendly means of modelling effluent production, storage and management and exploring different design strategies for a range of effluent-generating industries. To tailor MEDLI to beef cattle feedlots, a daily time step Fortran model was developed to predict the quantity and quality of rainfall-driven runoff from the feedlot catchment. This paper describes validation and prediction of runoff volume in the feedlot model within MEDLI.

2. MODEL DESCRIPTION AND ASSUMPTIONS

2.1 Feedlot Layout and Herd Composition

The total catchment area is partitioned into three components: the pen, hard and soft areas. The pen area is the collective area occupied by production pens, handling and holding yards, and hospital pens. The pen area equals the nominated number of cattle (licensed capacity) expressed as Standard Cattle Units (SCU) times the stocking density (m^2/SCU). A SCU equates to a beast turned off at 600kg live weight [ARMCANZ, 1997]. The hard area is the collective area occupied by roads, drains, cattle lanes, manure stockpile areas, sedimentation systems, car parks, building roofs, silage and grain storage bunkers. The soft area is the collective area that is permanently grassed or otherwise vegetated.

All runoff from the catchment is channelled through a sedimentation basin into a holding pond of user-defined dimensions. Rain falling directly into the pond is accounted for in the MEDLI pond module.

Pens are stocked according to the nominated herd composition. The herd can consist of up to four classes of cattle depending on their target market e.g. Japanese, Korean, domestic. Cattle within a pen are the same class and live weight. User-defined live weights at entry and exit, and daily live weight gain for each class dictate when the cattle are turned off and the pens restocked.

2.2 Manure characteristics

A modification of the Digestibility Approximation of Manure Production (DAMP) [Barth, 1985] is used to predict the amount of Total Solids (TS) excreted. The advantage of DAMP over other approaches is that it takes into account diet composition. However, Sinclair [1997] found DAMP underestimated excreted solids by ca. 30% in feedlot cattle. Therefore, we decrease the DAMP TS estimate by 30%, then assume Volatile Solids (VS) to be 80% of this adjusted TS estimate to approximate measured data for Australian feedlots [Sinclair, 1996].

The moisture content of fresh manure is assumed to be 90% (wet basis) [ASAE, 1996; Sinclair, 1997].

2.3 Feedlot Pad & Volatile Solids Decay

The accumulated manure in the pens represents the modelled feedlot pad. We assume there is no leakage below the pad, that pad depth is uniform (within a pen), and that the pad has an average bulk density of 750 kg/m^3.

Measured data indicates the amount of VS in the feedlot pad at any time falls in the range of 35-85% dry basis (db) and averages about 70% db [Sinclair, 1996]. We approximate the average daily decay to 0.15% of the VS remaining in the pad, then adjust it by a temperature factor (Kt) [see Miner et al., 1980] calculated by:

$$Kt = 10^{(0.018*Tsurface - 0.38)} \quad (1)$$

where

$$Tsurface = (5*T_0+4*T_1+3*T_2+2*T_3+T_4)/15 \quad (2)$$

and Tsurface is the mean temperature (^{0}C) in the surface manure; T_0 is the mean air temperature (^{0}C) today; T_1 is the mean air temperature (^{0}C) yesterday; and T_n is the mean air temperature (^{0}C) n days ago.

2.4 Infiltration and Runoff

Infiltration and runoff from the pen area are calculated on a pen by pen basis. Relevant assumptions are: runoff can only occur in response to daily rainfall of 10 mm or more; daily infiltration of moisture to the pad equals excreted manure moisture plus rainfall less runoff; potential depression storage in pugged manure ranges from 0 to 8mm [Lott, 1997], and is a linear function of pad moisture between 100 to 190% db, and zero otherwise since the pad is either dry and compacted, or so saturated that it slumps and slurries; effective rainfall (mm) is actual rainfall (mm) minus potential depression storage, or zero, whichever is greater.

To predict runoff from the soft and hard catchment areas (non-pen areas), we use the USDA Curve Numbers (K values) adopted by Skerman [2000] as shown in Table 1. The hard catchment values were determined by calibrating the USDA Rainfall/Runoff model against research data reported by Lott [1997], for three commercial feedlots in Southern Queensland.

The soft catchment values were obtained from Horton and Jobling [1984], based on grassland in fair hydrological condition, growing on soils having medium infiltration characteristics.

Table 1. - USDA Rainfall/Runoff Model "K" values.

Catchment Area Type	K1	K2	K3	Dormant Months
Hard Area	96	96	96	Jan–Dec
Soft Area	57	75	88	May–Aug

In estimating runoff from each pen, we account for the amount and depth of manure, depression storage, and antecedent moisture condition. Essentially, the pen manure is treated as a soil and its maximum water retention (R) capability is calculated by:

$$R\ (mm) = 254*((100/CN)-1) \quad (3)$$

where CN is the USDA SCS curve number.

Using a default CN value of 95, R equals 13.4mm. The CN value of 95 is intermediate to the values of 90-91 used for estimating runoff from unpaved USA feedlots for average moisture conditions, and the values of 98-99 used for concrete lots [Westerman and Overcash, 1980]. Our slightly elevated value compensates for the fact that the runoff algorithm is based on effective rainfall rather than actual rainfall.

Should R exceed the water deficit, i.e. saturated water content less current water content, then R is set to the water deficit when calculating runoff from the affected pen.

2.5 Evaporation from Feedlot Pad

After wetting, well-managed feedlot pads initially dry out rapidly, and then at an increasingly slower rate once the surface starts to seal. Furthermore, anecdotal evidence indicates the pad dries faster when disturbed by cattle than when left undisturbed.

Lott [1997] measured feedlot manure weight loss over time and found cumulative evaporation may be up to three times the cumulative pan evaporation. However, volatile solids decay was not accounted for in Lott's study. The model uses Ritchie's [1972] two-stage soil evaporation model, but with a modification which allows pad evaporation of up to 150% of pan evaporation during periods where the moisture content exceeds 100% db. Table 2 compares the fitted Ritchie evaporation parameters, U and cona, for a feedlot pad with three soil types.

Table 2. Ritchie [1972] constants for various soil types, and fitted values for feedlot pad manure.

Soil type	Stage I U (mm)	Stage II cona (mm day$^{-1/2}$)
Clay loam	12	5.1
Loam	9	4.0
Black clay	6	3.5
Feedlot pad	9	3.0

2.6 Solids Transport

Reddell and Wise [1972] proposed a predictive method based on depth of runoff. We adopted a similar approach but found that a 3-fold increase in predicted TS runoff concentration was necessary to achieve holding pond concentrations published in the literature, and in unpublished DPI data.

Limited data suggest the proportion of VS to TS in runoff varies little and is around 50% of total solids [Madden and Dornbush, 1971]. We assume, that unless VS is limiting, the TS:VS ratio in runoff is 2:1. Thus, VS in runoff is calculated as:

$$VS\ (kg/m^2) = TS\ (kg/m^2)*0.5 \qquad (4)$$

where

$$TS\ (kg/m^2) = 0.045*runoff\ (mm)*area\ (m^2) \qquad (5)$$

2.7 Manure Harvesting

The user defines the harvesting regime by entering the cleaning cycle and manure depth limits. The amount of manure that can be removed per day is determined by the capacity of the feedlot and an operational limit that ensures it is practically possible to harvest the expected annual manure DM (about one tonne DM per head) over a realistic minimum number of pen-cleaning days.

2.8 Sedimentation Basin

The sedimentation basin is modelled simply as a screening process that removes preset fractions of solids (and nutrients) in the runoff before it enters the holding pond. We assume the sedimentation basin removes 64% of TS in runoff [Lorimor et al., 1995].

3. METHOD

Runoff validation was conducted with measured data from the three southern Queensland feedlots monitored by Lott [1997]. The data relates to four different catchments within three different rainfall climates. Only measured runoff (no estimated) data were used. The feedlot areas, herd composition, pen manure management and stocking density details for each catchment were entered into MEDLI as separate scenarios. All other feedlot parameters were identical.

The feedlots used for the validation shall be referred to as A, B and C. Two sets of pens at A were monitored and are referred to as the Upper and Lower sites. Table 3 lists relevant details for the four catchments.

The measured runoff data from A Upper catchment was used to calibrate the MEDLI runoff prediction for three reasons: there were more data points collected at A; there were higher rainfall events at A; there was a higher frequency of higher rainfall events at A.

The runoff was fitted to the measured (A Upper) data by varying the curve number (CN). The predictions were then compared with the independent data sets for the other three feedlot catchments, and analysed using statistics listed in Table 4.

Table 3. Feedlot catchment design parameters.

Feedlot	A – Upper	A- Lower	B	C
Standard Cattle Units (SCU)	920	2180	3020	1730
Stocking density (m^2/SCU)	11.1	11.1	11.6	12.0
Total Pen area (ha)	1.021	2.420	3.497	2.074
Soft Area (ha)	0.0	0.0	0.0	0.0
Hard Area (ha)	0.965	0.842	0.408	1.085
Total Area (ha)	1.986	3.262	3.905	3.159
Total Pen Area (% total area)	51	74	90	66
Mean Annual Rainfall (mm)	936	936	613	625

Climate data for the period 1957-1996 were obtained for Gatton, Condamine and Oakey (all in southeast Queensland). These climate data consisted of minimum and maximum temperatures, rainfall, pan evaporation and radiation data. (Radiation is not used in the feedlot model, but is required for MEDLI).

Table 4. Runoff Validation Statistics

Site	Modelling Efficiency [a]	Mean Absolute Error (mm) [b]	Root Mean Square Error (mm) [c]
A Upper	0.95	1.0	2.9
A Lower	0.95	0.9	2.9
B	0.62	1.0	3.0
C	0.89	0.8	2.1

[a] Modelling Efficiency is a dimensionless statistic relating model predictions to observed data [Mayer and Butler, 1993]. This value parallels the regression coefficient R^2 fitted about the line $y = y_{predicted}$.
The modelling efficiency (EF), is defined as $EF = 1 - \Sigma(y_{measured} - y_{predicted})^2 / \Sigma(y_{measured} - y_{average})^2$
EF is an overall indication of goodness of fit. A model with a negative EF is unsuitable, while an EF close to one indicates a 'near-perfect' model.

[b] Mean Absolute Error (MAE) = $(\Sigma \text{ ABS}(y_{measured} - y_{predicted}))$/number of points
According to Mayer and Butler [1993] MAE is a valid summary measure of the relative degree of deviations.

[c] Root Mean Square Error (RMSE) = $((\Sigma(y_{measured} - y_{predicted})^2) / \text{number of points})^{1/2}$

The relevant rainfall and pan evaporation data corresponding with the monitored period (1990-1994) were substituted with the corresponding daily data measured at each site. The correlation between the data was very good at all sites except for 3 months of evaporation data from A. In this case, Gatton evaporation data for the Jan-Mar 1994 period were used instead of the measured values.

For A, complete daily data for 978 out of 1386 days was collected. For B, 899 days out of 1361 days was obtained, and for C, 38 complete months out of 44 months were available.

Pen slopes in A are typically 5-6% and pens are well managed and would usually not accumulate more than 100 mm of dry manure before being harvested. Unusually high catchment yields (runoff as a % of rainfall) of 52 % and 50% were recorded for the Upper and Lower catchments respectively. B had pen slopes of 2-3% and a catchment yield of 21% over a three-year period. The catchment yield at C was 39% over a three-year period [Lott, 1997].

4. RESULTS

4.1 Feedlot Pad Composition

The predicted average dry matter (%wb) of the feedlot pads for A Upper, A Lower, B and C were 57, 57, 80 and 69, respectively.

4.2 Runoff Quantity

Figure 1 is the comparison of measured versus predicted runoff for A Upper, showing the scatter of points relative to the unity line, y=x. This data was used for the calibration of the model.

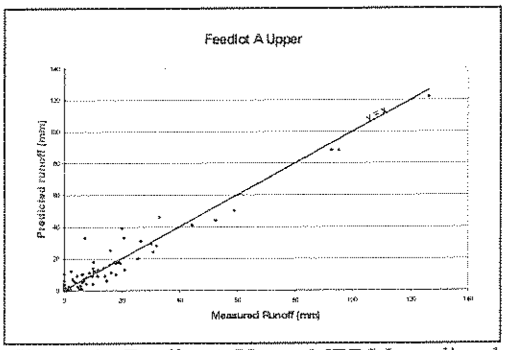

Figure 1. Feedlot A Upper MEDLI-predicted runoff vs measured runoff (calibration data).

Predicted runoff was good for feedlots A and C, and this is also reflected statistically in Table 4. The model has demonstrated its ability to predict particularly high runoff events, a useful feature for design purposes.

The best modelling efficiency, 0.95, was achieved at A, the highest rainfall feedlot, while the lowest rainfall feedlot (C) also indicated a good modelling efficiency of 0.89. B generally had lower runoff measured than predicted for lower rainfall events. However, a good modelling efficiency obtained for C suggests that the model does not have a bias associated with rainfall climate.

The mean absolute difference between measured and predicted values was 1mm or less for all feedlots. For runoff events greater than 20mm (the larger runoff events) this represents an error of 5%.

Figure 2 is a plot of runoff versus rainfall for every measured runoff event at A-Upper, the calibration site. The scatter of points is greater for lower rainfall events because pen management has a greater impact on the amount of runoff. The plot shows low runoff when rainfall is approximately < 15mm, and a linear relationship between rainfall and runoff at rainfall events higher than 20mm.

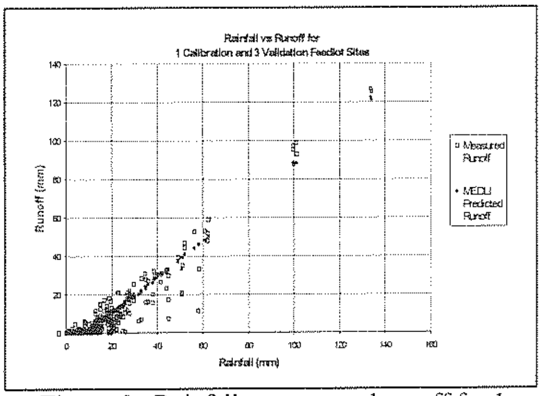

Figure 2. Rainfall vs measured runoff for 1 calibration and 3 validation sites.

Table 5 compares the predicted and measured annual yields (runoff as a percentage of rainfall) for the data sites. Lott [1997] reported the yields using composite data, which consisted of some measured and some estimated runoff values. The 'Measured' values use only measured runoff data, with some rainfall data obtained from the local climate stations when feedlot rainfall data records were incomplete. At all sites, MEDLI predicted only marginally higher yields than were measured, except at B. The measured annual yields varied considerably at each site.

Much lower yields were measured at B than for the other sites, which may be explained by the pad management practices at that site. While MEDLI can model a sequence of manure harvesting based on the suitability of the pad condition and the time between harvests for all of the pens, it is difficult to try to replicate the actual management at a particular feedlot without collecting that information. During the data collection period, pen manure at B was not harvested as often as at the other sites. The yields measured at A and C are probably more indicative of the yields which could be expected from a well-managed feedlot catchment.

Table 5. Overall MEDLI-predicted % runoff yields compared with measured yields [Lott, 1997] for the three validation sites.

Feedlot	MEDLI (Annual range) %	Lott [1997] Measured (Annual range) %
A Upper	51 (41-59)	51 (39-61)
A Lower	49 (39-51)	44 (45-52)
B	33 (18-46)	20 (2-33)
C	38 (34-54)	30 (20-52)

The annual ranges shown below the overall yields in Table 5 refer to yields for 1992, 1993 and four months in 1994 for C, and include 1991 data for A and B. Data was not collected for every rainfall event during these years, and MEDLI yields have been calculated only for the dates when data were collected. Annual yield ranges predicted by MEDLI generally reflect those measured by Lott [1997].

5. CONCLUSIONS

The model is best suited to feedlots that meet the guidelines for Queensland feedlots [Skerman, 2000]. It can be applied with reasonable confidence to other cattle feedlots in Australia, but may need further calibration for different climatic zones. The model predicts similar runoff volumes to those measured by Lott [1997], particularly for high rainfall events. Although smaller events are far less predictable, the overall annual yields compare favourably with the measured data.

Despite efforts to model realistic manure harvesting, the correlation of the actual and predicted runoff was not significantly improved. Refining the validation, particularly for smaller runoff events, would require measurement of pad depth, antecedent pad moisture, and rainfall intensity data. Knowledge of the pad depth would necessitate knowing the manure harvesting schedule. Rainfall intensity would necessitate a smaller time step. As the main use of the feedlot model is to size ponds capable of handling the major runoff events, there is little merit in trying to improve prediction of smaller events, especially given the vagaries of feedlot operations. It was more important that the overall annual harvesting rates and average pad composition agreed with the measured data and this has largely been achieved.

The rate of pad evaporation, particularly after wetting, warrants further experimentation. The modelling supports the evidence that pen evaporation exceeds pan evaporation, even in periods of low evaporation. Applying a pan factor of around 1.5 during the first stage of evaporation following rainfall produces credible average pad moisture levels.

The amount of solids in pad runoff needs to be measured in order to predict feedlot runoff quality with any degree of confidence.

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