This is not a peer-reviewed article.
International Symposium on Air Quality and Waste Management for Agriculture. CD-Rom Proceedings of the 16-19 September 2007 Conference (Broomfield, Colorado)
Publication date 16, September 2007
ASABE Publication Number 701P0907cd

Vegetated Treatment System Models: Modeled vs. Measured Performance

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Abstract: Vegetated treatment systems (VTS) are designed to control runoff from beef feedlots. A VTS consists of a solids settling basin followed by either a vegetated treatment area (VTA) or a vegetated infiltration basin (VIB) followed by a VTA. Two computer models were developed at Iowa State University (ISU) to simulate traditional containment, a VTS with a settling basin and a VTA, and a VTS with a settling basin, VIB, and VTA. The models predict runoff volume and nutrient mass entering and leaving the system for a given design and specific weather conditions. In this paper, the monitored performance of four feedlot VTSs in Iowa is compared to the performance predicted by each site model run. These sites are undergoing extensive monitoring to determine the mass of nutrients discharged from each system component. Weather data including maximum temperature, minimum temperature and precipitation are also continuously recorded. System component discharge data collected at each site is compared to data generated by the model using site specific weather data for model calibration purposes. Comparisons of modeled versus monitored system performance indicate that the VTS models currently under predict discharge from the VTAs at all four sites. The VTS models also under predicted the VIB performance for both of the VIB sites. While the measured and monitored flow volumes from the SSB matched relatively well, the nutrient concentration released from the SSB was much higher than the concentration predicted by the VTS models.
Keywords: Vegetated treatment system, feedlot runoff control, computer model

Introduction

A Vegetated Treatment System (VTS) is an alternative technology designed to control runoff from open beef feedlots. These systems are designed to infiltrate the runoff and utilize subsequent nutrients flowing from a feedlot into a vegetated area. A VTS can be one of two types; a solids settling basin (SSB) followed by a vegetated infiltration basin (VIB) and vegetated treatment area (VTA), or a solids settling basin followed by a stand alone VTA. Moody et al. (2006) provides a complete description of these systems.

Containment basins have traditionally been used in North America to control open feedlot runoff. Koelliker et al. (1975) developed a watershed model to estimate runoff control for a containment basin in Kansas. The modeled runoff control structure was designed to hold runoff from a 10-year, 24-hour precipitation event. Currently, there are three models being used at ISU that were developed to simulate a traditional containment system, a VTS with a settling basin and a VTA, and a VTS with a settling basin, VIB, and VTA. The traditional containment system model was based on the Koelliker et al. (1975) model. The VIB-VTA Model version 1.004 is designed for a system with a settling basin, and a VIB followed by a VTA, and the VTA Model version 1.004 is designed for a settling basin followed by a VTA. These models predict runoff volume and nutrient mass entering and leaving the system.

Five feedlots in Iowa (Table 1) have VTS systems permitted for research purposes under the National Pollution Discharge Elimination System (NPDES) by the Iowa Department of Natural Resources for controlling feedlot runoff. Monitoring at four of these sites began during the summer of 2006. Weather files for each site location containing 26 years of historical weather data (1970 to 1995) were used for the initial VIB-VTA and VTA model simulations. The systems were designed by an agricultural engineering consulting firm based on the model run results.

Table 1. Size and the VTS components of the four monitored sites

	Number of Cattle	VTS Components

	On-Site	Research Portion	On-Site	Research Portion
Northwest IA 1	1400	800	3 SSB – 5 VTA	1 SSB – 1 VTA
Northwest IA 2	4000	4000	1 SSB – 1 VIB – 1 VTA	1 SSB – 1 VIB – 1 VTA
Central IA 1	1400	1000	2 SSB – 3 VTA	1 SSB – 2 VTA
Central IA 2	2400	800	3 SSB – 5 VIB – 3 VTA	1 SSB – 1 VIB – 1 VTA

Data provided in this paper includes three months of monitoring at Northwest IA 1 and Northwest IA 2, four months of monitoring at Central IA 1, and six months of monitoring at Central IA 2. The VTS models have been run for the sites using measured rainfall collected at each site during the 2006 monitoring period for each site. This paper does not evaluate the performance of the VTS and compare it to the containment basin systems. The objective of this paper is to compare the measured discharge volumes and mass of nutrients released from the SSB, VIB, and VTA with the values predicted by the two VTS models using actual weather data.

VIB-VTA and VTA Models Version 1.004

The models are event or routine based and simulate the performance of both VTA and VTA-VIB systems. Both models require numerous inputs such as site specific weather information, soil properties, and feedlot, settling basin, VIB and VTA design characteristics. The model outputs include volume of discharge and mass of nutrients released from each component of the system.

VTA model: The VTA model calculates daily runoff from a feedlot based on the input weather data, and accumulates the runoff in the SSB and then releases it to the VTA. In the model, the length of the VTA is divided into 100 equal lengthwise sections and the model tracks the volume of effluent and concentration of nutrients from the SSB through these 100 VTA sections. The model also accounts for infiltration into the VTA and direct precipitation onto the VTS.

VIB-VTA Model: The VIB-VTA model calculates daily runoff from the feedlot, accumulates it in the SSB, and then releases it to the VIB with subsequent discharge to the VTA. The model tracks the wetting front of the settling basin effluent down the VIB soil profile as the liquid moves through the tiles. Tile flow from the VIB is routed to the VTA and the model simulates this as inflow to the VTA. The model accounts for infiltration, evaporation and direct precipitation onto the system. The runoff front in the VTA moves to the next section until water removal exceeds input and the wetted front stops moving.

Each model has certain events, which contains code for running the models. There are 10 events in the VIB-VTA and VTA model – user input, soil properties calculation, snow events, five day rainfall, hyetograph, hydrograph, settling basin, VTA/VIB soil moisture, VTA/VIB infiltration and VTA/VIB redistribution. Most of the calculations are performed with daily execution of these events to generate final output. The soil properties event calculates porosity, field capacity and wetting front for four layers of the soil in the VIB and VTA. The snow melt event calculates the snow melt from a feedlot and adds it to the total volume discharging from a SSB. The five-day rainfall event in the model determines the antecedent moisture content of the feedlot surface. The hyetograph event generates a rainfall hyetograph from the precipitation input in the weather file. The feedlot runoff hydrograph is generated using the Soil Conservation Service (SCS) unit hydrograph method in the hydrograph event. The settling basin event tracks settling basin inputs, calculates discharge volume and nutrient concentrations, and routes the flow to VIB/VTA. The model sets the nutrient concentrations entering the system based on settling basin capacity and type of feedlot surface. Mass of nutrients leaving the settling basin is calculated as the product of outflow volume and outflow nutrient concentration. The VIB/VTA soil moisture event determines evapotranspiration of the system and plant uptake of nitrogen and phosphorus. The VTA/VIB infiltration event estimates infiltration of runoff and precipitation into the sections of the VIB/VTA. The VTA redistribution event tracks moisture in soil profile of the VIB/VTA. The detailed description of the events is given in Wulf and Lorimor, 2005.

Methods

The two year monitoring of the five sites includes recording hourly air temperature, rainfall depth, rainfall intensity and discharge runoff volume from the SSB, VIB and VTA. Samples are collected during discharge events at the outlets of the SSB, VIB and VTA. These flow-based samples are analyzed for ammonia, BOD, COD, chloride, pH, total phosphorus, total dissolved solids, total kjehldahl nitrogen (TKN), total suspended solids, nitrate–N, orthophosphate and fecal coliform concentrations. The mass of nutrients released from each component of the system is calculated as a product of the nutrient concentration and volume released. Monthly groundwater samples, annual surface water samples, annual surface soil samples and biennial deep soil samples are also collected as part of the monitoring at these sites.

The hourly temperature at each site is measured by temperature loggers, and rainfall depth and intensity is measured by ISCO 674 tipping bucket rain gauges. The runoff flowing out of the SSB is measured with ISCO 750 Area Velocity flow meter or ISCO 720 submerged probe depending upon whether a pipe or a flume is installed at the end of the SSB. The flow coming out of the tile lines in the VIB is collected in a sump and is pumped on to the VTA. Pumped volume is measured by a Neptune turbine flow meter. The discharge from the system is measured with ISCO 750 Area Velocity flow meter or ISCO 720 submerged probe depending upon weather a pipe or a flume is installed at the end of the VTA. A detailed description of the monitoring system and the instrumentation used for each site is given in Moody et al. (2006).

Northwest IA 1 and Central IA 1 sites were run with the VTA model, and Northwest IA 2 and Central IA 2 sites were run with the VIB-VTA model using collected weather data. Models were simulated for the monitored time period included here. Table 2 shows monitoring period, 25-year 24-hour design storm size, and the largest storm size recoded at each site. The weather file for each site contains weather data (precipitation and temperature) recorded during the monitoring period. Using the weather file and VTS design parameters as inputs, VIB-VTA and VTA model runs were conducted for each site.

Table 2. Monitoring period, 25-year 24-hour design storm size and largest storm recorded at each site.

Site	Monitoring period	25 year 24 hour design storm (cm)	Largest storm (cm)
Central IA 1	153 days	12.7	1.86
Central IA 2	184 days	12.9	3.02
Northwest IA 1	123 days	12.7	1.72
Northwest IA 2	123 days	12.4	2.53

Results

The comparison of the modeled and measured results was completed in two parts: comparison of the discharge volume released from each component of the VTS and comparison of the mass of nutrients released from the VTS.

Comparison of discharge volume: Initial comparisons included plotting of modeled and actual discharge outputs from the SSB, VIB and VTA per day for the complete monitoring time period.

SSB performance: The daily modeled and measured SSB discharge volume was compared for each site. Figure 1 shows an example of such a plot for Northwest IA 2. The VIB-VTA and VTA models predicted flow from the SSB on the same dates that the measured discharges occurred at all sites. During the monitoring periods, the model for Central IA 1 predicted more than the measured discharge from the SSB for 18 out of 20 runoff events. The VIB-VTA model for Central IA 2 also predicted more SSB discharge than was measured for 35 out of 38 events during the six month monitoring period. In the case of Northwest IA 1, the modeled SSB discharge was more than the measured for seven out of 12 events. The modeled SSB discharge for Northwest IA 2 was comparable to the monitored discharge for all the runoff events.

VIB performance: The measured and modeled VIB discharge volume was plotted versus the monitored time period for the two sites with a VIB-VTA system. The modeled VIB discharge for Central IA 2 was less than the measured discharge for 14 out of 16 tile flow events. Of these 14 events, the VIB-VTA model predicted no discharge for 11 events. The VIB-VTA model predicted more than the measured discharge for four out of seven events at Northwest IA 2.

VTA performance: VTAs at all four sites had well established vegetation by the end of the monitoring period. The VTAs at all four sites discharged during the monitoring time periods. But the VIB-VTA and VTA models did not predict any discharge from the VTA for the four sites during this period. Central IA 1 and 2 recorded two and six VTA discharge events, respectively. Northwest IA 1 and 2 recorded two and four VTA discharge events, respectively.

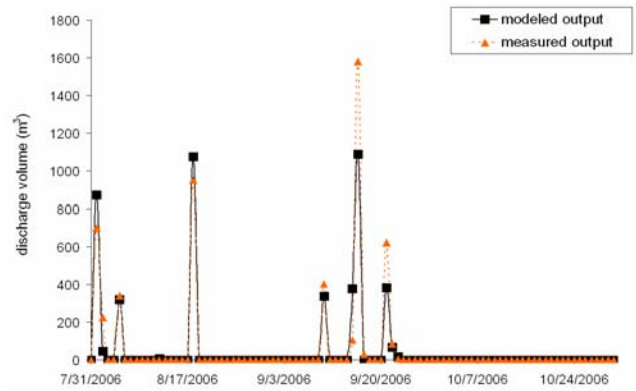

Figure 1. Daily solid settling basin discharge for the monitoring period at Northwest IA 2.

Next, the measured and modeled outputs volumes were compared. The daily discharge data was summed per event and days with no discharge were omitted from the data set. The difference between modeled and measured discharge from the SSB, VIB and VTA were calculated for each discharge event. Table 3 shows the average difference between modeled and measured values per site for each component of the system over the monitoring period.

Table 3. Average difference between modeled and measured event outputs for each site

Site	Average difference between modeled and measured discharge (m^3)	Monitoring period (days)	Modeled component performance
Solid settling basin			
Central IA 1	4.4	153	Model under predicted SSB performance
Central IA 2	24.7	184	Model under predicted SSB performance
Northwest IA 1	-153.41	123	Model over estimated SSB performance
Northwest IA 2	-57.17	123	Model over estimated SSB performance
Vegetated infiltration basin			
Central IA 2	-38.46	184	Model over estimated VIB performance
Northwest IA 2	-21.37	123	Model over estimated VIB performance
Vegetated treatment area			
Central IA 1	-187.06	153	Model over estimated VTA performance
Central IA 2	-32.57	184	Model over estimated VTA performance
Northwest IA 1	-166.77	123	Model over estimated VTA performance
Northwest IA 2	-48.47	123	Model over estimated VTA performance

During the monitoring period, rainfall resulted in VTA discharges at all four sites. Neither the VIB-VTA or VTA model predicted discharge from the VTAs however; hence, the models overestimated the VTA performance at all four sites. However, on average, the VIB-VTA model better predicted discharge from the VIB than the VTA during the monitoring periods for Central and Northwest IA 2 (Table 1).The VTS models have shown a mixed trend in modeling SSB performance. The VTS models under predicted the SSB performance for Central IA 1 and 2 and over predicted the SSB performance for Northwest IA 1 and 2.

All measured discharges from the SSB, VIB and VTA were compared to the predicted model discharges for the four sites (figure 2, 3 and 4). In figure 2, the points lying above the 1:1 line (theoretically where modeled equals measured) show that the model is predicting more discharge than the monitored results from the SSB. Points below the 1:1 line show that model under estimated the SSB's discharge volume.

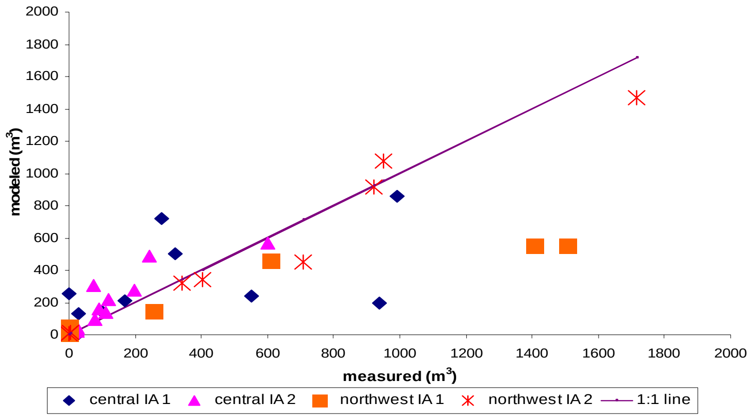

Figure 2. Measured versus modeled solid settling basin outputs.

Figure 3 shows the measured and modeled discharges from the VIB for the two sites. The model over estimated the VIB performance for central IA 2 for 14 of the 16 events and 3 of the 7 events for Northwest IA 2. As can be seen in the graph, the magnitude of the over/under prediction varies by event. Figure 4 shows over estimation of the VTA's performance for the four sites. The VTA models predicted no discharge from the VTA at the four sites but the VTAs at all four sites discharged at least twice during the monitoring periods. The number of discharge events at the VTA recorded at each site is as follows: Central IA 1 – two events, Central IA 2 – six events, Northwest IA 1 – two events and Northwest IA 2 – four events.

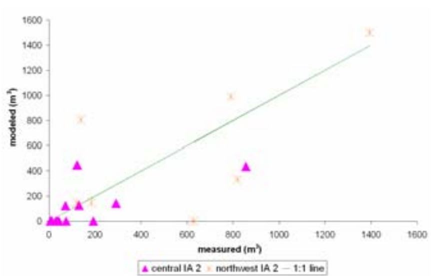

Figure 3. Measured versus modeled vegetated infiltration basin outputs.

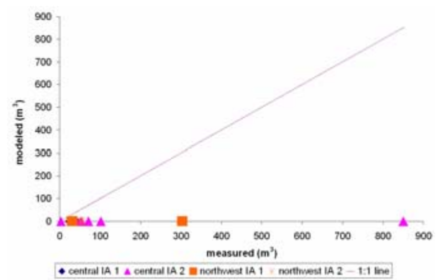

Figure 4. Measured versus modeled vegetated treatment area outputs.

The performance of the VTS models was tested using linear regression. Linear models were fit for the SSB and VIB modeled versus measured discharges as shown in Figures 5 and 6. Coefficient of determination R^2 for each linear fit line was calculated using MS Excel and the slope of the linear fit line was tested to be significantly different from one at the 0.05 significance level using t-test. The model is considered to be an accurate prediction of the system if the R_2 value is high and the slope of the linear fit is close to one (the 1:1 theoretical line where the modeled value equals the measured value).

The R^2 values calculated by fitting linear models to the SSB performance were: Central IA 1 – 0.93, Central IA 2- 0.83, Northwest IA 1 – 0.92 and Northwest IA 2 – 0.95. The slope of the linear fit line was not significantly different from one for three of the four sites. At Northwest IA 1, while the R^2 value was high, the slope of the line was determined to be significantly different from one, signifying that the model is consistently predicting less than the measured values. Analysis of SSB flow data from Central IA 1, Central IA 2 and Northwest IA 2 have high R^2 values and slopes of the regression lines that are not significantly different from one, implying that the modeled and measure discharge volumes compare reasonably.

Figure 6 shows the accuracy of the VIB-VTA model to predict VIB performance at two sites. The R^2 value for Central IA 2 is 0.51 and the slope is significantly different from one at the 0.05 significance level; this indicates that modeled and measured values are not comparable and the model is predicting less than the measured for most of the events. In the case of Northwest IA 2, the slope of the regression line is not significantly different from one, but the R^2 is only 0.42 implying inconsistent performance of the model compared to the measured values. Initial lack of well established vegetation on the VIBs may be a factor in the model's overestimation of the VIB performance.

There is no relationship between the measured and modeled VTA discharge outputs because the model did not predict discharge events for the four sites during the monitoring period.

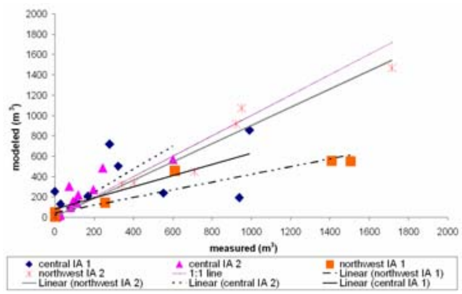

Figure 5. Linear models fit to modeled versus measured solid settling basin discharge outputs per site.

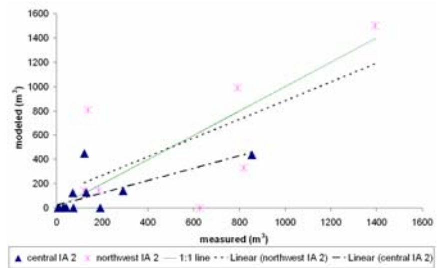

Figure 6. Linear models fit to modeled versus measured vegetated infiltration basin discharge outputs.

Comparison of mass of nutrients: The VTS models determine the concentration of nutrients leaving the SSB depending upon the settling basin capacity and type of feedlot surface. The SSB's for the four sites are designed to store a 12 cm rainfall. All the sites have earthen feedlots except Northwest IA 2 which has a concrete feedlot. Table 4 compares the nutrient concentration assumed by the VTS models to the average nutrient concentration released per event during the monitoring period.

Table 4. Comparison of the modeled and measured nutrient concentration released from the solid settling basin

Modeled nutrient concentration assumed from SSB (mg/L)			Average measured nutrient concentration released from SSB (mg/L)			
Nutrients	Earthen feedlot	Concrete feedlot	Central IA 1 (earthen)	Central IA 2 (earthen)	Northwest IA 1 (earthen)	Northwest IA2 (concrete)
TKN	135	200	462	112	1024	985
Ammonia	100	150	151	35	239	354
Total Phosphorous	60	90	96	30	137	150
Total Solids	4000	6000	10387	4069	22895	16339
COD	5300	7950	9045	2221	24378	18541

The nutrient concentrations assumed by the VTS models are typically lower than the nutrient concentration released from the SSB at the four sites. The nutrient concentrations released from the SSB of Northwest IA 2, Central IA 1 and Northwest IA 1 are much greater than the concentration assumed by the model for concrete and earthen feedlots. The nutrient concentrations released from the SSB of Central IA 2 are relatively close to the concentration assumed by the model when compared to the other sites. This effect is likely due to the placement of round bales around the settling basin outlet by the producer to slow down the flow and reduce the solids leaving the basin. This design modification is not accounted for by the model. For a more detailed description of settling basin performance, see Moody et al., 2007, a companion paper to this document.

Total nutrient mass discharged from the VTA at each site during the monitoring period is compared against the nutrient mass discharge predicted by the VTS models (figure 7). The VTS models predicted no release of nutrients from the VTS because the model did not predict any VTA discharge events during the monitoring period. Total mass of nutrients released from the VTS at Central IA 2 is higher compared to the other sites because more discharge events occurred at this site. The release of nutrients from the system is dependent on the discharge event from the VTS.

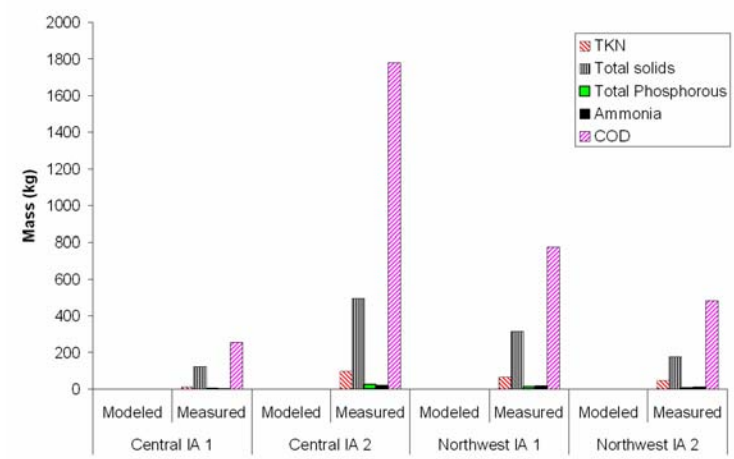

Figure 7. Comparison of measured and modeled pollutant mass discharge from the system for each site

Discussion

The measured pollutant concentrations leaving the SSB are greater than predicted by the model. This has resulted in higher pollutant concentrations in the subsequent components of the system. The increased mass discharge from the VTA (figure 7) could be a result of either high nutrient concentration in the discharge or high flows exiting the VTA. The potential sources for the difference between the measured and modeled flow volumes from the VTA at each site are: SSB performance for each site (either low attenuation of flow or low solids retention), poor infiltration within the VTA during both dry and saturated conditions (creating higher than predicted flows off the VTA system), channeled flow in the VTAs, inability of the model to simulate flow under saturated conditions due to a large rainfall event or successive small rainfall events, and sensitivity of the VTS models to the soil hydraulic properties. In other words, the difference in the modeled and measured results can be due to the inability of the VTS models to simulate the flow in the system at the four sites or due to physical components in the systems that control the runoff. Further evaluation of additional data is underway to identify and address these issues. Moreover, long term monitoring of the sites may produce more consistent results.

Conclusion

The measured data collected from initial monitoring of the four sites was compared to the data predicted by the vegetated treatment system (VTS) models. The comparison was done in two parts: comparison of the discharge volume released from each component of the VTS and comparison of the mass of nutrients released from the VTS. The comparisons were completed to evaluate the performance of the VTS models. The ISU VTS models over estimated the performance of vegetated treatment areas (VTAs) at all four sites. The VTS models also over estimated the vegetated infiltration basin (VIB) performance for the two sites with VIBs. Linear models fit to the modeled versus measured VIB outputs resulted in $R^2 = 0.51$ for Central IA 2 and 0.42 for Northwest IA 2. Scattering of points around the regression lines indicates a weak linear relationship between the measured and modeled VIB outputs. R^2 of 0.92 and the slope of the regression line being significantly different than one indicate that the model is consistently over estimating the solid settling basin (SSB) performance for Northwest IA 1. The R^2 values of 0.93, 0.83 and 0.95 for Central IA 1, Central IA 2 and Northwest IA 2 and slope not being significantly different from one show that measured and modeled SSB discharge volumes for these two sites compare reasonably well. Therefore, a mixed trend was observed in the model's performance for predicting flow from the SSB. The concentration nutrients released from the SSB is much higher than the concentration predicted by the VTS models. The total mass of nutrients released from the system at four sites could not be compared to the modeled values, as model did not predict discharge from the VTA for the four sites during the monitoring period.

References

Koelliker, J.P., P.H. Magnes, R.I. Lipper. 1975. Modeling the performance of feedlot-runoff control facilities. Trans of ASAE. 18(6):1118-1121.

Moody, L. B., C. Pederson, R.T. Burns, I.K. Khanijo. 2006. Vegetative Treatment Systems for Open Feedlot Runoff: Project Design and Monitoring Methods for Five Commercial Beef Feedlots. ASABE. Paper Number: 064145. St Joseph, MI : ASABE

Moody, L., N. Heitoff, R. Burns, C. Pederson, I. Khanijo. 2007. Settling basin design and performance for runoff control from beef feedlots. International Symposium on Air Quality and Waste Management for Agriculture. ASABE, St. Joseph, MI

Wulf, L.W. and J.C. Lorimor. 2005. Alternative Technology and ELG Models for Open Cattle Feedlot Runoff Control: Model Descriptions and User Guidelines. Iowa State University.

Wulf, L.W., J.C. Lorimor, S.W. Melvin. 2003. Modifications to feedlot runoff containment systems in Iowa. Animal, Agricultural and Food Processing Wastes IX. Proc. of the Ninth International Symposium, 387-396. St. Joseph, MI: ASAE.