Validation of the Minnesota Feedlot Annualized Runoff Model (MinnFARM) for Use in Assessing TMDLs

Final Report

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Project Title

Validation of the Minnesota Feedlot Annualized Runoff Model (MinnFARM) for Use in Assessing TMDLs.

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Executive Summary

Feedlots can contribute to the fecal coliform and nutrient loadings of impaired streams and therefore need to be included in TMDLs (Total Maximum Daily Loads) studies. A site-specific evaluation tool, The Minnesota Feedlot Annualized Runoff Model (MinnFARM), has been developed at the University of Minnesota to make relative assessments of pollutant loading by estimating annual pollutant loads. It is widely used for planning and assessing feedlots in Minnesota. However, MinnFARM was developed as a prioritization tool and not for TMDLs loading. Additional testing of MinnFARM, and possibly revisions of its algorithms, is needed for TMDL projects. The overall goal of the project is to assess, and possibly improve, MinnFARM as tool in predicting loading from feedlots. Key steps of the project are to (1) collect and evaluate existing observed data on feedlot runoff, (2) evaluate the accuracy of the MinnFARM model for both loading at the feedlot edge and load reductions in buffer areas, and (3) modify or add algorithms in MinnFARM to improve its accuracy and usefulness.

Initial literature review and inquiries through various contacts led to the possibility of using data from seven different research projects and approximately twenty-four different feedlots. A total of 984 rainfall events was identified as possible candidates for model evaluation. A thoughtful screening process was applied to these events. Differences among the studies in sampling frequency, methods, and locations required us to make, sometimes subjective, judgment on the most suitable data for the assessment of MinnFARM. For example, a particularly challenging issue was how to use data collected as outflow from solid settling basins. After applying our screening method, the final data set for runoff water quantity analysis consisted of 179 events from 21 feedlots. A total of 292 events was selected for the water quality analysis.

Feedlot runoff volume is predicted in MinnFARM using the curve number method. Input parameters for this method are the curve number and the initial abstraction depth. Possible trends in these parameters were examined using the 179 observed events. Variability in the observed values of both parameters was substantial. There appeared to be trends in the curve numbers with season, feedlot surface (concrete or dirt) and precipitation depth. Based on these trends, we recommended changing the current curve numbers to a constant value of 98 for concrete lots and 90 for dirt lots. An area-weighted curve number is recommended for lots with a mixture of concrete and dirt. Trends in the observed initial abstraction depths were also examined. Based on these trends, we recommended the current version of MinnFARM be changed so that initial abstraction depth is also a function of precipitation depth.

Feedlot loading of pollutants is computed in MinnFARM by multiplying the runoff volume for an event by its representative concentration. In addition to values for representative concentrations, the soluble and settleable fractions are needed inputs for simulating the removal of pollutants by vegetative buffers. Annual loading for total nitrogen, total phosphorus, COD, BOD and fecal coliforms is computed in MinnFARM. Unfortunately, most of the data sets did not include measurements of COD, BOD, and fecal coliforms, and therefore these pollutants were not included in the analysis. Similar to the runoff parameters, the variability in water quality concentrations was substantial. No trends could be found concentration with respect to precipitation or other factors.

Therefore, little information was available to improve upon the current constant concentration approach. The observed average values among feedlots were in good agreement with those currently used in MinnFARM. No changes are therefore recommended in the current representative concentration (and soluble fractions) approach.

In Minnesota, vegetative buffers are the most widely used treatment for feedlot runoff. Load reductions in buffers are a function of infiltration and filtration. Filtration removes settleable solids and infiltration removes both settleable and soluble nutrients. Separate algorithms are used in MinnFARM for these two components. Several data sets were used to evaluate the accuracy of the current MinnFARM approach. Once again, variability in the observed data, and the lack of data on soluble and particulate fractions, made the assessment of the accuracy of the current MinnFARM difficult. Results are sensitive to the default soluble fraction. Possible errors in estimating soluble fractions are caused by inaccuracies in the feedlot algorithm and not the buffer algorithm. Since we have little information for improving the buffer algorithm, and the current algorithm adequately approximates observed reductions using reasonably soluble fractions, no changes are therefore recommended in the current modeling of vegetative buffers.

Biofilters have been suggested as an alternative to vegetative-buffer treatment of feedlot runoff. A biofilter algorithm was developed and tested for use in MinnFARM. The biofilter algorithm assumes a two-chamber system, where the first chamber is the settling basin that acts as pretreatment for the removal of settleable solids, and the second chamber is the biofilter for the removal of contaminants by bio-chemical filtration. Separate algorithms were developed for each of the chambers. These algorithms were based on a solution to a mass-balance equation. Evaluation of model accuracy focused on the second chamber. Observed data were obtained from an experimental site located near Melrose, MN. The observed removal efficiencies were compared to those predicted using a first-order process and using a logistic process. Predicted removal efficiencies of nitrogen for the first-order process agreed reasonably well with observed values. The first-order model also performed reasonably well in predicting the removal efficiency of phosphorus. The logistic model poorly predicted the removal efficiencies of nitrogen but adequately predicted the removal efficiencies of phosphorus.

Currently MinnFARM is computationally driven by Excel functions applied to cells located within several worksheets. This framework was too limited to incorporate the recommended changes and to include the new biofilter algorithm. An equivalent Excel Visual BASIC code has therefore been created and used to implement recommended changes and the biofilter algorithm. However, feedback from important user groups is needed before the release of the new MinnFARM version. The new version also needs additional testing to ensure that it is robust and consistent. Future improvement in MinnFARM is dependent on obtaining better data sets. This study relied on previously published data that were collected to achieve their goals and therefore often didn’t collect information necessary for model improvement and evaluation. Carefully designed collection efforts are needed to better understand complex processes on feedlots. For TMDL assessment, feedlot runoff also needs to be integrated into a broader modeling framework that considers multiple features of a comprehensive manure management plan.

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Validation of the Minnesota Feedlot Assessment Runoff Model (MinnFARM) for Use in Assessing TMDLs

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Background

As of June 2008, there were 2575 waters on the MPCA (Minnesota Pollution Control Agency) list of impaired waters and 1475 state waters requiring TMDLs (Total Maximum Daily Loads) assessment. Of these waters requiring a TMDL, 147 are for fecal coliform and another 329 are for nutrient loading. The "Fecal Coliform TMDL Assessment for 21 Impaired Streams in the Blue Earth River Basin" (Minnesota State University, 2007) suggests that 99% of the fecal coliforms generated in the watershed were from livestock. Although it is recognized that feedlots contribute to fecal coliform and nutrient loading, determining their contribution in the actual TMDL is difficult. Blanket load allocations provide limited information on what sources should be the targets of load reductions (feedlot runoff, stockpiles, manure application, wildlife, etc.).

Given the interest in feedlot runoff, a tool is clearly needed to estimate loading of nutrients and fecal coliforms from feedlots. Recently, a site-specific evaluation tool, The Minnesota Feedlot Annualized Runoff Model (MinnFARM), was developed at the University of Minnesota to make relative assessments of loading from feedlots by estimating annual loads. It is an easy-to-use Excel-based evaluation system for prioritizing state and federal cost-share funding. Throughout the state, MinnFARM is used as a planning and assessment tool to evaluate improvement from best management practices (BMPs). Based upon simple inputs, annualized loads are computed for phosphorus (P), chemical oxygen demand (COD); biological oxygen demand (BOD5); total Kjeldahl nitrogen (TKN); and fecal-coliform bacteria. MinnFARM also estimates seasonal loadings for spring (April and May), summer (June, July, and August), fall (September and October), and winter (November, December, January, February, and March). These seasonal loadings are combined to estimate annual loading.

MinnFARM also considers possible load reduction using a Vegetative Treatment Area (VTA). Reductions within VTA are computed separately for buffer infiltration and filtration. Infiltration is based on soil cover and hydrologic group, whereas filtration is based on travel time in the buffer. Other BMPs such as distance to surface waters, rerouting of 'runon water' and modifications to the size of feedlot can be assessed by the model.

Unfortunately, MinnFARM has not been validated with field monitoring data, nor were provisions made in the model to assess other runoff treatment options such as settling basin with orifice flow or biological filtration. The overall goal of the study is to assess, and possibly improve, MinnFARM as a tool for the TMDL evaluation. The specific objectives are to:

1. Collect, organize, and evaluate existing observed data on feedlot runoff,

2. Validate the MinnFARM model for both loading at the feedlot edge and reductions in buffer areas using existing field data representative of Minnesota conditions,
3. Modify MinnFARM to reflect field validation data and add algorithms into MinnFARM to include alternative runoff treatment systems such as the biofilter but not limited to specific treatments, and
4. Refine MinnFARM to improve user-friendliness and publish runoff and monitoring data in formats that can be assessed for the development or validation of other feedlot runoff models.

Activities of the project will be summarized by objectives.

Objective #1: Data Compilation

Data Overview

Initial literature review and inquiries through various contacts led to the possibility of using data from seven different research projects and approximately twenty-four different feedlots. A summary of the data sets is given in Table 1 and feedlot characteristics in Table 2 (a more detailed summary of feedlot characteristics is included in Table 24 in the Appendix). Differences among the studies in sampling frequency, methods, and locations required us to make, sometimes subjective, judgment on the most suitable data for the assessment of MinnFARM. A particularly challenging issue was how to use data collected as outflow from solid settling basins (SSB). Screening criteria for data sets used for validation included the following: 1) Data collected in using natural or mechanically produced rainfall events (actual events preferred)) and 2) Completeness of data reported in published papers or raw data files and the likelihood of accessing raw data files if needed through principal investigators or site visit.

Table 1. Data sets evaluated for use in MinnFARM validation.

Study Name	Project Description and Status of Data
Komor & Hansen	Runoff quantity and quality for two feedlots in Minnesota, which were monitored from 1995-1998 (Komor and Hansen, 2003).
Swanson	Runoff quantity and quality from simulated runoff events from four feedlots (1968), and natural runoff events from a separate feedlot (1968-1970), all in Nebraska (Swanson et al., 1971).
Kennedy	Runoff quantity for a number of runoff events (1993-1996) from four feedlots in Alberta, Canada (Kennedy et al., 1997). Water quality data is only presented by annual statistics for each feedlot.
Miller	Runoff quantity for several events Alberta, Canada (1998-2002) (Miller et al., 2004). Water quality data was only available in the form of summary statistics.
Ostrem	Runoff quantity and quality measured at four feedlots equipped with SSBs in South Dakota (2006-2009) as part of a larger USDA-NRCS CIG project in Iowa, Minnesota, and South Dakota (Ostrem et al., 2009).
Platteville	Monitored precipitation and feedlot runoff quantity and quality along with filter strip quantity and quality from 2005-2007. UMN obtained all raw data files from project.

Anderson	Feedlot runoff quantity and quality measured at six feedlots in Iowa. The monitoring effort in Iowa is part of a larger federal CIG grant in Iowa, Minnesota, and South Dakota. All feedlots in Iowa were equipped with SSBs.

Table 2. Summary of Feedlot Characteristics.

Study Name	Sample Location	Sample size	Surface	Slope	Animal Density (#/acre)
Plateville	Feedlot runoff	19 events	concrete	2%	163.7
Komor & Hansen	Feedlot runoff				
Bock	…	3 events	30% concrete	…	13.2
Sanborn	…	2 events	48% concrete	…	149.2
Anderson	settling basin runoff				
CNIA1	…	66 recorded days	dirt	…	117.9
CNIA2	…	19 recorded days	83% dirt	…	221.3
NWIA1	…	49 recorded days	dirt	…	112.7
*NWIA2**	…	58 recorded days	concrete	…	492.4
SWIA1	…	15 recorded days	dirt	…	111.9
SWIA2	…	31 recorded days	dirt	…	117.5
Swanson	Simulated runoff	31 records across 6 events	dry manure & soil	8.5% and 12.5%	N/A
Miller	feedlot runoff	only summary statistics	dirt, barely straw	2%	195.2
Kennedy	feedlot runoff	11 site-annual average data points	dirt	2.5%	100.4-226.5

Selection of Data for Water Quantity Analysis

Overview

Feedlot runoff data from the seven selected studies were assembled for use in the MinnFARM validation. A total of 984 rainfall events was identified as candidates to bed used in our analysis. A summary of events is given in Table 3. These events were thoughtfully scrutinized for inclusion in the evaluation of MinnFARM, both for water quantity and water quality analysis, based on several factors discussed below. Slightly different criteria were used for the water quantity (runoff volume) analysis than that used for water quality. This section discusses the selection criteria for water quantity.

Table 3. Summary of Rainfall/Runoff Events for Water Quantity Analysis.

			Number of Events	
Study Name	**Feedlot**	**Storm type**	**Original Data Set**	**Final Data Set**
Komor & Hansen	Bock	Rain	3	3
	Sanborn	Rain	2	2
Swanson	Nebraska 1	Simulated rain	23	2
	Nebraska 2	Simulated rain	16	2
	Nebraska 3	Simulated rain	5	2
	Nebraska 4	Simulated rain	6	2
	Natural	Rain	182	50
Kennedy	NCA1	Rain	3	3
	NCA2	Rain	14	14
	NCA3	Rain	15	15
	NCA4	Rain	3	3
Miller	Lethbridge East	Rain	10	10
	Lethbridge West	Rain	10	10
Ostrem	Haakon	Rain	19	0
	Meade	Rain	26	2
	Miner	Rain	36	0
	Roberts	Rain	2	0
Platteville	Platteville	Rain/Snow	27	10
Anderson	CNIA1	Rain	195	12
	CNIA2	Rain	41	7
	NWIA1	Rain	138	9

	NWIA2	Rain	92	14
	SWIA1	Rain	65	2
	SWIA2	Rain	51	5
		Total	**984**	**179**

All 984 runoff events were analyzed for possible use in evaluating MinnFARM. They have been included in the database given to the Minnesota Department of Agriculture (MDA) as part of the deliverables for the project. Bad data flags were used to identify the events that were removed from the data, and were assigned according to the characteristics given in Table 4. The final data set for runoff water quantity analysis consisted of 179 events from 21 feedlots. A summary of data for each of the 179 events is included in Table 25 in the Appendix.

Table 4. Data Flags Used to Identify Data For Inclusion in the Runoff Quantity MinnFARM Validation.

Bad data flag	Explanation	Count
0	Good data	150(179)*
1	Inter-storm data (where end-of-storm data was available)	40
2	Two or more events that should be treated as one	68*
3	No measured runoff	119
4	Snow/snowmelt event	8
5	Runoff > Precipitation	10
6	SSB data that involves several overlapping rainfall and runoff events, and is difficult to partition into discrete events	198
7	SSB event with no significant precipitation (<0.25 in) within 5 days prior to event	390

*The 68 events identified as a ‘2’ were combined into 29 ‘good’ events and increase the total number of ‘good’ events to 179. The ‘2’ events consisted of consecutive days with measured runoff, while the precipitation occurred only on day 1 (or days 1 and 2 for overnight storms). Combining multiple-day precipitation and runoff data into single rainfall and runoff totals more accurately represents each event.

Explanation of Data Filtering

As shown in Table 4, data were removed from the original data set for a variety of reasons. All of the original data is provided as a deliverable to MDA. A detailed description of the bad data flag is given so that other researchers can selected the criteria most useful to their feedlot studies.

The 40 inter-storm data points (bad data flag 1) from the Swanson paper were included in the original data set, but were excluded from the final data set. These points were removed because they were measures of the rainfall and runoff *before* the end of the event. Although inter-storm data were not used in the analysis, the total rainfall and runoff depths for these storms were also reported, and *are* included in the final data set.

The bad data flag 2 code was used to combine many multi-day events into a single rainfall and runoff depth for each event. Multiple day events can be caused by rainfall continuing from one day into the next, or as a result of lag time affecting runoff timing and duration.

Bad data flag 3 points were removed from the data set because the events were reported as generating no runoff. Several points (bad data flag 4) were removed from the data set because they were either snowfall-runoff events or because the measured runoff (early in the spring) appeared to be so high that it likely could only have been caused by melt water. A small number of events were also removed due to the fact that the reported runoff exceeded the measured rainfall depth (bad data flag 5).

Data with solid settling basins (SSB) created problems in determining the characteristics of feedlot runoff. SSBs treat feedlot runoff by storing it in a basin for a period of time, allowing solids in suspension to settle to the bottom of the basin. All of the SSB-equipped feedlots used in this study were instrumented to measure the outflow from the SSB, not from the feedlot itself. Because direct feedlot runoff is *not* measured, several problems arise when attempting to apply the data for use in this study including:

- Difficulty in accounting for the water storage of each of the SSB systems,
- Many SSB systems are actively managed, meaning that producers are able to control the water level in the basins, which affects storage,
- There are losses due to evaporation, which are more important over long, dry periods during the summer, and
- Many events were reported that appear to be a result of emptying the SSB, as runoff was measured when there was no rainfall.

The issues surrounding the use of SSB data in this project were addressed in two ways. The first screening tool was to allow only those events that followed other precipitation events. Only events that occurred following a 5-day cumulative rainfall of at least 0.25 inches were included in the data set. The rationale behind this approach is that the storage effect of an SSB is minimized when the SSB is full (additional feedlot runoff will be reflected perfectly in outflow from the SSB when the SSB is full), and the SSB is more likely to be full following a significant rainfall event. The events not meeting this criteria were assigned the bad data flag 7. Once again, data sets in this section are selected based on the suitability of representing runoff events.

A large number of runoff events (198) were also removed due to problems with overlapping rainfall/runoff events. A common issue was the occurrence of a large rainfall event (1 to 2 inches) followed by an event of similar magnitude 2 to 3 days later. Often, the second event would produce more runoff than the first event, and in some cases would clearly include runoff from both events. The main issue with these compound events is that discharge from the SSB was, in many cases, reported for several days following the *second* rainfall event. This led to difficulty in assigning appropriate runoff depths to each of the rainfall events and made them unsuitable for the needs of our study.

Selection of Data for Water Quality Analysis

The selection of data for water quality was not as restrictive as that used for water quantity. Some of the events excluded from the water-quantity analysis were still useful in assessing average concentrations used in MinnFARM. Currently MinnFARM predicts loading for total nitrogen, total phosphorus, COD, BOD and fecal coliforms using soluble and settleable fractions. Most data sets did not include measurements of COD, BOD, and fecal coliforms, and therefore these pollutants could not be included in the analysis. Many of the data sets included estimates of soluble (using measured dissolved values) and settleable (using measured particulate values) fractions and so when possible, these were included in the evaluation.

A total of 292 events was selected for the water quality analysis. A summary of the selected events is given in Table 5.

Table 5. Summary of Rainfall/Runoff Events for Water Quality Analysis.

Study Name	Feedlot	Storm type	Original Data Set	Final Data Set
Komor & Hansen	Bock	Rain	3	3
	Sanborn	Rain	2	2
Swanson	Nebraska 1	Simulated rain	23	15
	Nebraska 2	Simulated rain	16	15
	Nebraska 3	Simulated rain	5	0
	Nebraska 4	Simulated rain	6	0
	Natural	Rain	182	0
Kennedy	NCA1	Rain	3	11 annual site-averaged values
	NCA2	Rain	14	
	NCA3	Rain	15	
	NCA4	Rain	3	
Miller	Lethbridge East	Rain	10	Summary statistics only
	Lethbridge West	Rain	10	
Ostrem	Haakon	Rain	19	0
	Meade	Rain	26	0
	Miner	Rain	36	0
	Roberts	Rain	2	0
Platteville	Platteville	Rain/Snow	27	19
Anderson	CNIA1	Rain	195	66
	CNIA2	Rain	41	19

	NWIA1	Rain	138	49
	NWIA2	Rain	92	58
	SWIA1	Rain	65	15
	SWIA2	Rain	51	31
		Total	**984**	**292**

Objective #2: Data Analysis

Water Quantity Data Analysis

In MinnFARM, water quantity for different storm events is computed using the curve number model. In addition to precipitation, key parameters with this model are the curve number and the initial abstractions. As implemented in MinnFARM, the curve number currently varies with season. The initial abstraction depth varies with season and with slope steepness of the feedlot. An assessment of the curve number parameter is first given. Proper initial abstraction values are then examined.

Curve Number Methodology

The curve number method was employed to analyze the measured rainfall and runoff depths from the 179 events in the data set. The curve number method is used to predict runoff from a given precipitation event, as follows:

$$Z = \frac{(P-I_a)^2}{P+S-I_a} \text{ for } P > I_a \quad (1)$$

$$Z = 0 \text{ for } P \leq I_a \quad (2)$$

where Z is runoff depth, P is precipitation depth, I_a is initial abstraction depth, and S is maximum abstraction depth. According to curve number theory, precipitation must exceed the initial abstraction depth in order to produce runoff for a given event. Maximum abstraction, S, is determined from a curve number, CN, by the following relationship:

$$S = \frac{1000}{CN} - 10 \text{ for } 0 < CN \leq 100 \quad (3)$$

Areas with low curve numbers (high maximum abstraction) have lower runoff depths than areas with high curve numbers (low maximum abstraction). This study is interested in determining the curve number for feedlots.

A common assumption used with the curve number method (but not used in MinnFARM) is that

$$I_a = 0.2S \quad (4)$$

which further simplifies the curve number runoff equation to:

$$Z = \frac{(P-0.2S)^2}{P+0.8S} \quad \text{for } P > 0.2S \quad (5)$$

$$Z = 0 \quad \text{for } P \leq 0.2S \quad (6)$$

To evaluate the curve number method in MinnFARM, we first estimated the curve number assuming that $I_a = 0.2S$. From Equation 1, the value of S can be determined directly from measured precipitation (P) and runoff (Z) depths. Observed curve number can then be computed by rearranging Equation 3. Trends in these observed curve numbers were examined for the 179 selected rainfall events. Representative curve numbers for use in MinnFARM were selected from these trends. Curve numbers for individual events are given in the appendix (Table 25).

After completing the first step of the evaluation method, the representative curve number was determined for each of the 179 events. These curve numbers represent an average condition and therefore are not equal to those values computed directly from their rainfall and runoff depths. The corresponding maximum abstraction (S) for the representative curve numbers was determined using Equation 3. The necessary initial abstraction depth (I_a) to obtain the observed runoff depth (Z) from known precipitation (P) and maximum abstraction (S) can now be determined directly from Equation 1. Trends in the initial abstraction were also examined. The computed initial abstractions for individual events are also given in the appendix (Table 25).

Analysis of Curve Numbers

Average curve numbers and maximum abstraction depths obtained using observed rainfall and runoff data for each of the 21 feedlots are shown in Table 6. The range in average curve numbers (using $I_a = 0.2$ S) is large, ranging from 56 to 98. To obtain insight into trends in curve numbers, observed curve numbers were plotted as function of (1) month, (2) feedlot area, (3) feedlot type (concrete or dirt), (4) feedlot location (related to latitude), and (5) rainfall depth. As an alternative approach, observed maximum abstraction depths were divided by the average value for the lot, potentially allowing for some of the natural variability between lots to be indirectly considered. Trends in these normalized values were also examined by using the month, feedlot slope, number of animals, and rainfall depth. The results are presented in Figure 1 through Figure 8.

Table 6. Average observed initial abstraction depths, curve numbers, and maximum abstraction depths for feedlots.

Study Name	Feedlot Name	Feedlot Number	Lot Cover	Slope (if not given, then 1.5)	Average S value	Average CN value	Average I_a value
Komor	Bock	1	30% concrete	1.5	0.57	94.79	0.11
Komor	Sanborn	2	48% concrete	1.5	6.64	68.09	1.80

Swanson	Nebraska 1	9	dirt	8.5	2.64	79.71	1.18
Swanson	Nebraska 2	10	dirt	8.5	0.32	96.87	0.00
Swanson	Nebraska 3	11	dirt	12.5	1.68	85.69	0.66
Swanson	Nebraska 4	12	dirt	13	0.58	94.55	0.00
Swanson	natural	13	dirt	6	1.44	88.05	0.34
Kennedy	NCA 1	14	dirt	2.5	7.98	55.83	2.42
Kennedy	NCA 2	15	dirt	2.5	3.50	76.06	1.47
Kennedy	NCA 3	16	dirt	2.5	4.73	74.16	1.73
Kennedy	NCA 4	17	dirt	2.5	3.13	78.50	0.79
Miller	Lethbridge East	18	dirt	2	3.31	77.21	0.77
Miller	Lethbridge West	19	dirt	2	3.13	78.18	0.75
Ostrem	Meade	21	dirt	1	2.74	78.48	0.83
Platteville	Platteville	24	concrete	2	0.17	98.36	0.04
Anderson	CNIA1	25	dirt	1	1.39	88.47	0.33
Anderson	CNIA2	26	83% Dirt	1	3.15	80.80	0.96
Anderson	NWIA1	27	dirt	1	0.33	96.82	0.01
Anderson	NWIA2	28	concrete	1	0.60	94.40	0.28
Anderson	SWIA1	29	dirt	1	0.35	96.62	0.00
Anderson	SWIA2	30	dirt	1	0.97	91.63	0.20

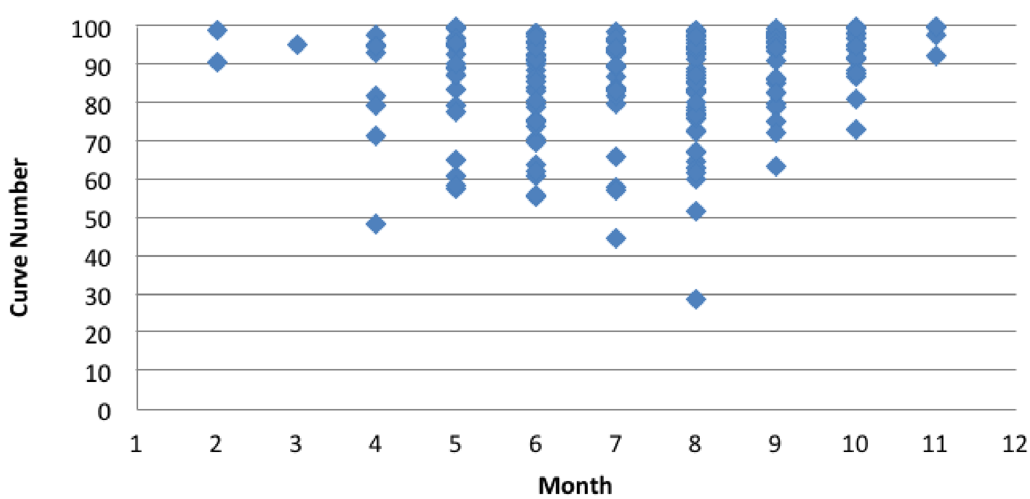

Figure 1. Observed Curve Number as Function of Month.

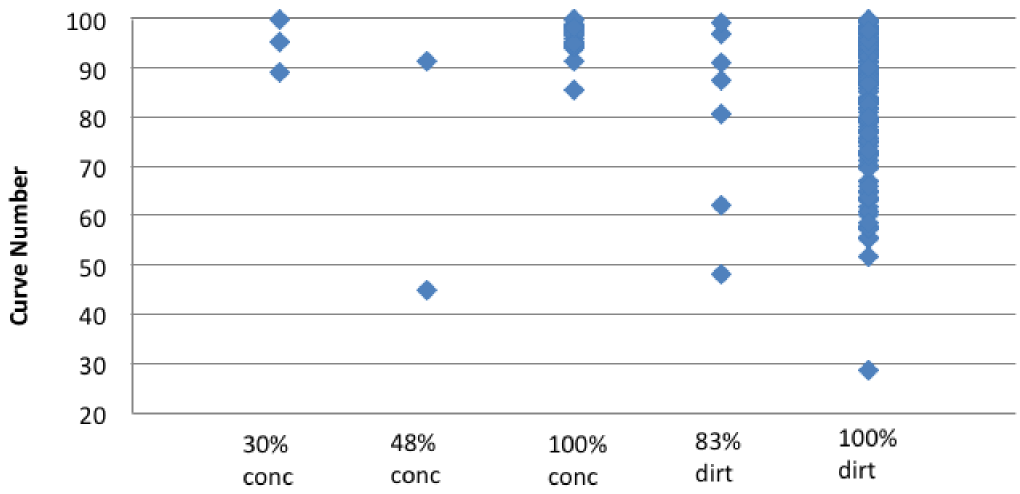

Figure 2. Variation in Curve Numbers with Feedlot Type (conc =Concrete).

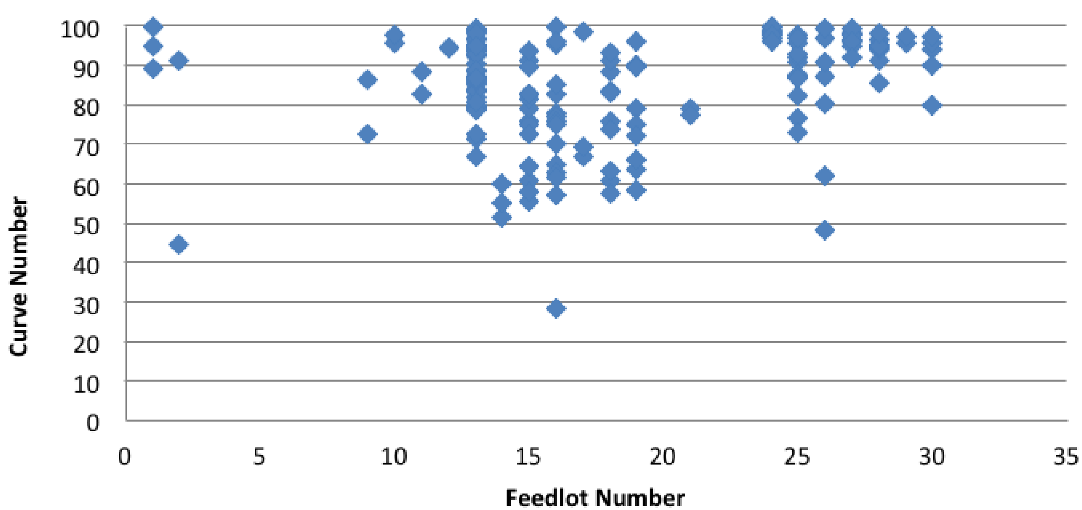

Figure 3. Variation in Curve Numbers with Feedlot Number.

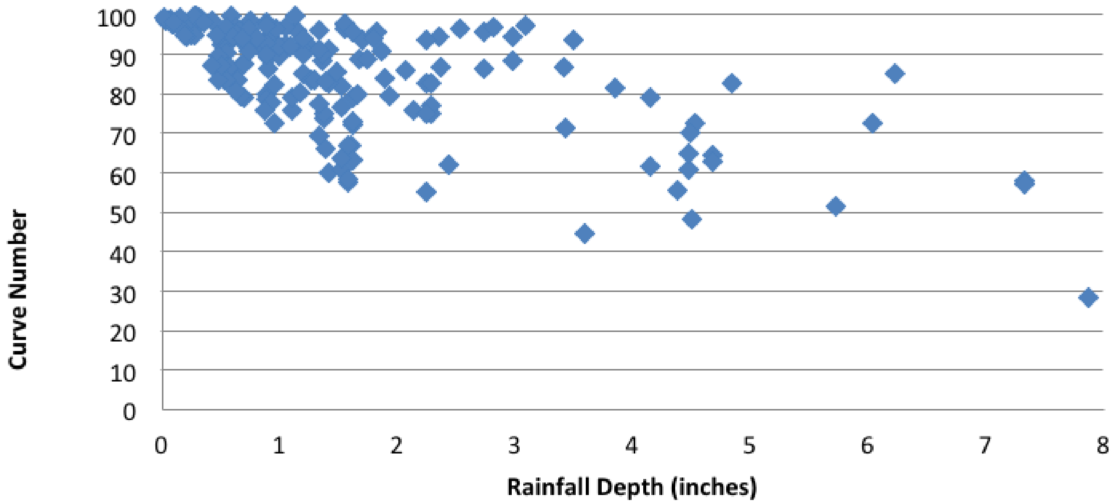

Figure 4. Variation in Curve Numbers with Rainfall Depth.

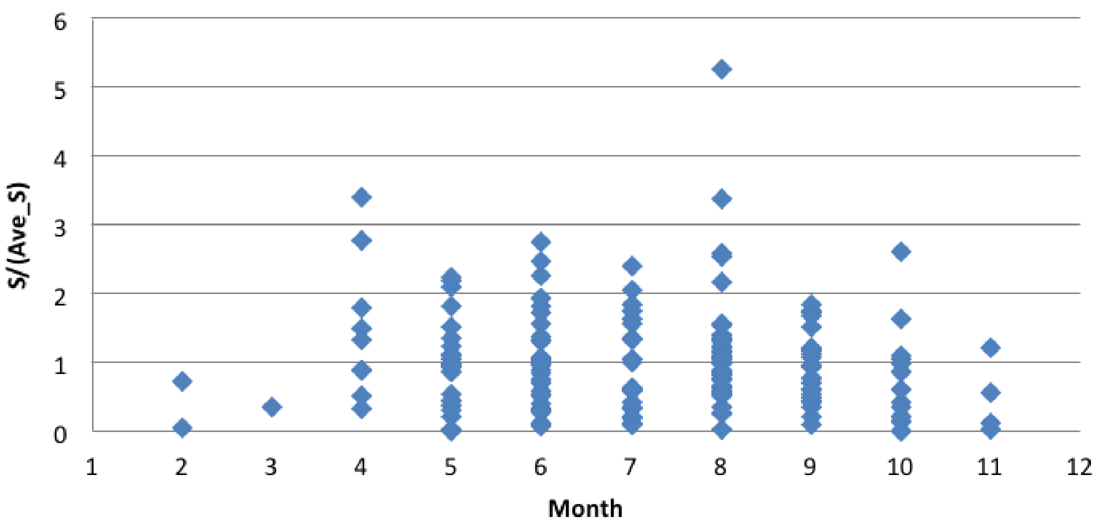

Figure 5. Variation in Normalized Maximum Abstraction with Month.

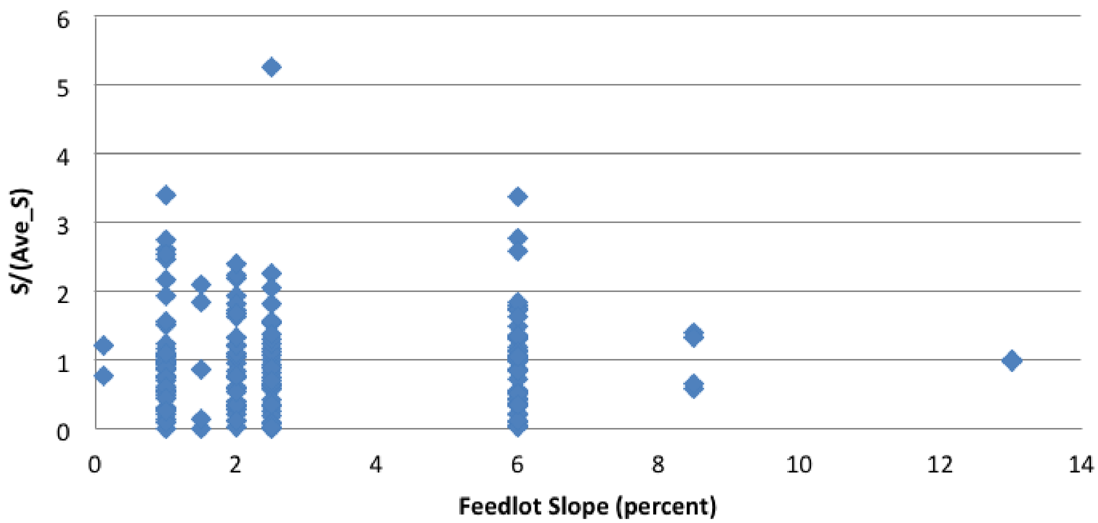

Figure 6. Variation in Normalized Maximum Abstraction with Slope.

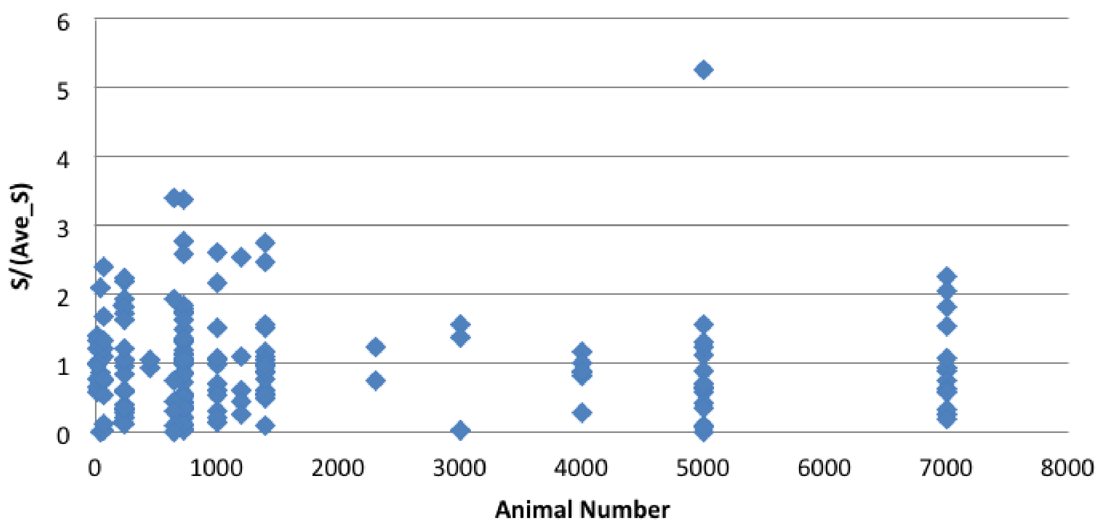

Figure 7. Variation in Normalized Maximum Abstraction with Number of Animals.

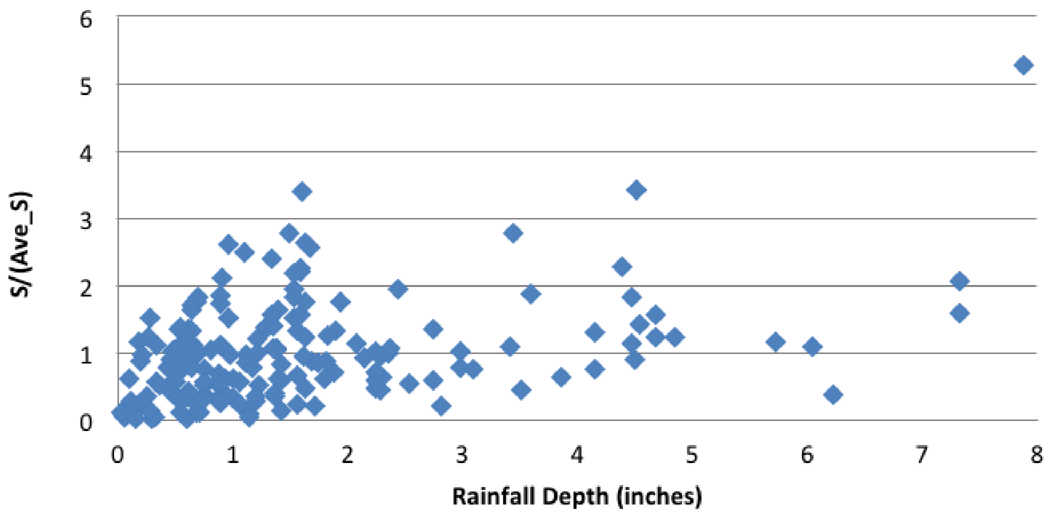

Figure 8. Variation in Normalized Maximum Abstraction with Rainfall Depth.

Little additional insight was gained by using the normalized maximum abstraction depth instead of curve numbers. Since curve numbers are more familiar to most users, we will focus our discussion on their trends. The range of observed curve numbers was generally larger for the summer months than spring or fall (Figure 1). All months had events where the curve number was near its maximum value of 100. Summer months had events where the curve numbers were less than 80. Curve numbers for 100% concrete lots were generally larger and more consistent than those obtained from dirt lots (Figure 2). As shown in Figure 3, sites with more events tend to have a larger range in observed curve numbers. From Figure 6 and Figure 7, no trends in curve number were discernable with number of animals or feedlot slope (using normalized maximum abstraction depths). The strongest observable trends in curve number (and normalized maximum abstraction) are with rainfall depth (Figure 4 and Figure 8, respectively). There is a noticeable trend of decreasing curve number with increasing rainfall depth. Similar (but not as pronounced) trends in curve numbers were observed by the lead investigator for watersheds in Oklahoma under pasture conditions.

To explore if trends by month were an indirect consequence of a possible correlation with rainfall depth, a plot of rainfall depth by month is given in Figure 9. Similar to trends shown in Figure 1, there is a larger range of rainfall depths for events during the summer months. Part of the increased range in curve numbers for the summer months is likely tied to greater variability of rainfall depths during these months.

Recommended Changes in the Curve Numbers

Based on the observed trends in curve number, we recommend changing the current curve number values to a constant curve number of 98 for concrete lots and a curve number of 90 for dirt lots. For those lots with a mixture of areas of concrete and dirt, we recommend using an area-weighted curve number. Trends in curve numbers with rainfall depth are considered in the determination of initial abstraction discussed in the next subsection.

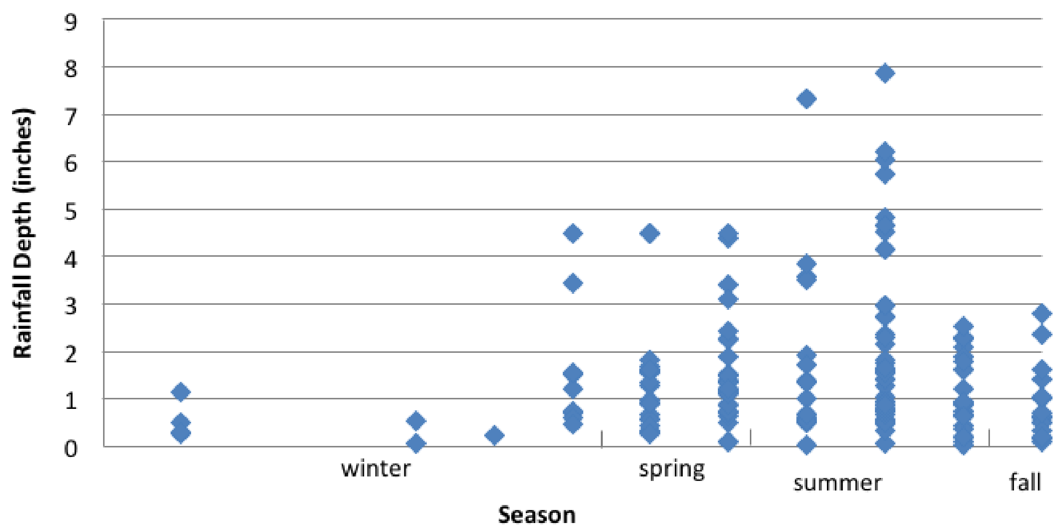

Figure 9. Rainfall Depth Trends with Seasons.

Analysis of Initial Abstraction Depth

Analysis of initial abstraction depth was done using the recommended curve numbers for concrete and dirt lots. For these curve numbers, the initial abstraction depth (I_a) can be determined from Equation 1 such that the predicted and observed runoff depths are equal. These calculations were done for all of the water-quantity events. A few of the events had negative I_a, corresponding to events where the predicted runoff depth (using our representative curve number) cannot be made to equal the observed depth with a positive I_a. Negative I_a are not physically meaningful and are set equal to zero for most of our analyses. The average values of the initial abstractions are reported in Table 6. The range in average I_a is large, varying between 0.0 and 2.4 inches.

Underlying factors that may influence the large range in observed I_a were explored by examining plots of I_a as a function of (1) month, (2) feedlot slope, (3) number of animals, and (4) rainfall depth. Similar to the previous section, the initial abstraction depths were also normalized by dividing them by the lot average value. Since the normalized depths provided little additional insight, these results are not presented. Trend results are presented in Figure 10 through Figure 13.

Not surprisingly, trends of I_a are similar to those observed for curve number. As shown by Figure 10, I_a values appear to vary with season, with summer values generally larger than those of spring and fall. Initial abstraction depth generally decreases with an increase in feedlot slope. Trends of I_a with number of animals are not apparent. Similar to the curve number, the strongest trends of I_a are with rainfall depth. These depths generally increase with rainfall depth.

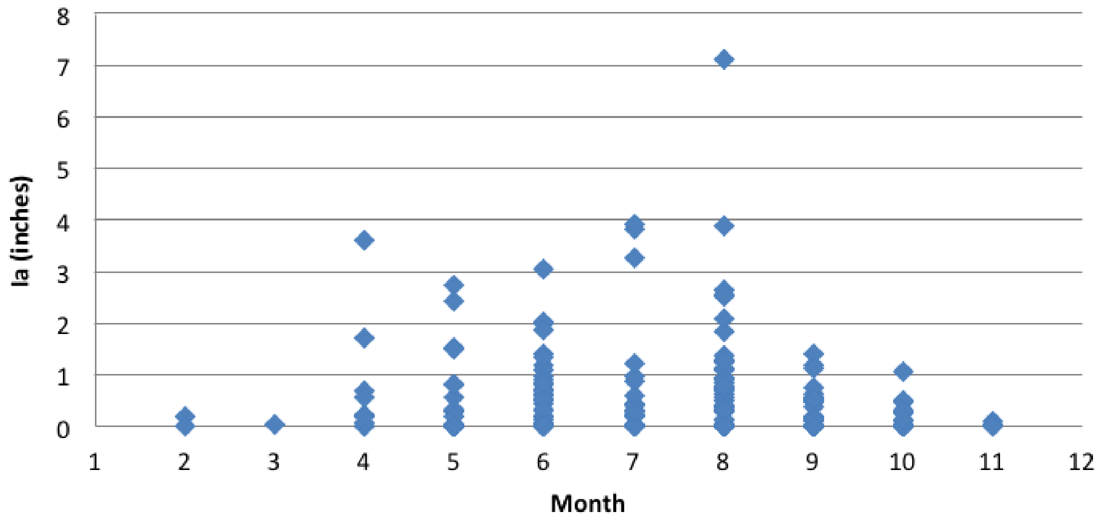

Figure 10. Trends of Initial Abstraction Depths with Months.

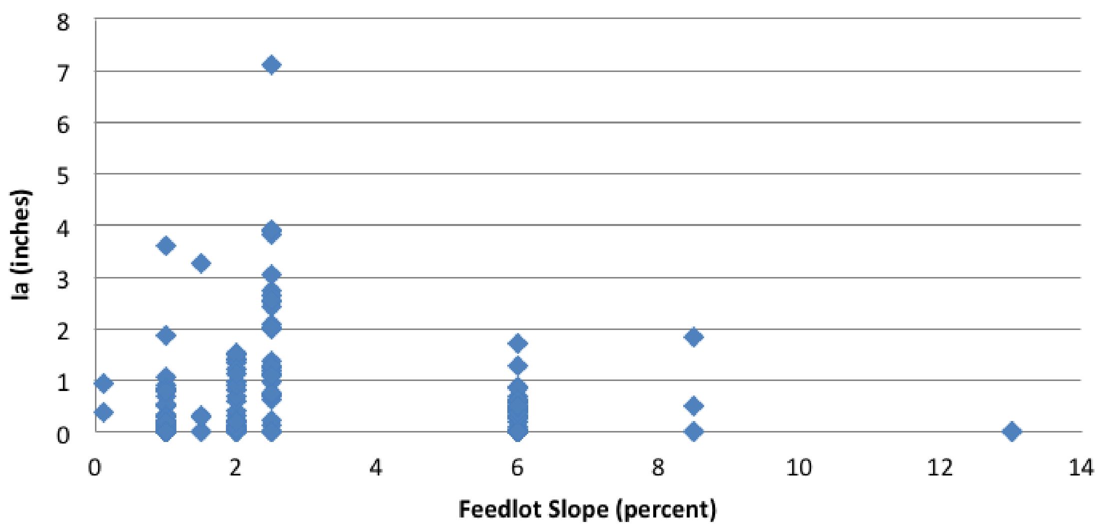

Figure 11. Trends of Initial Abstraction Depths with Slope.

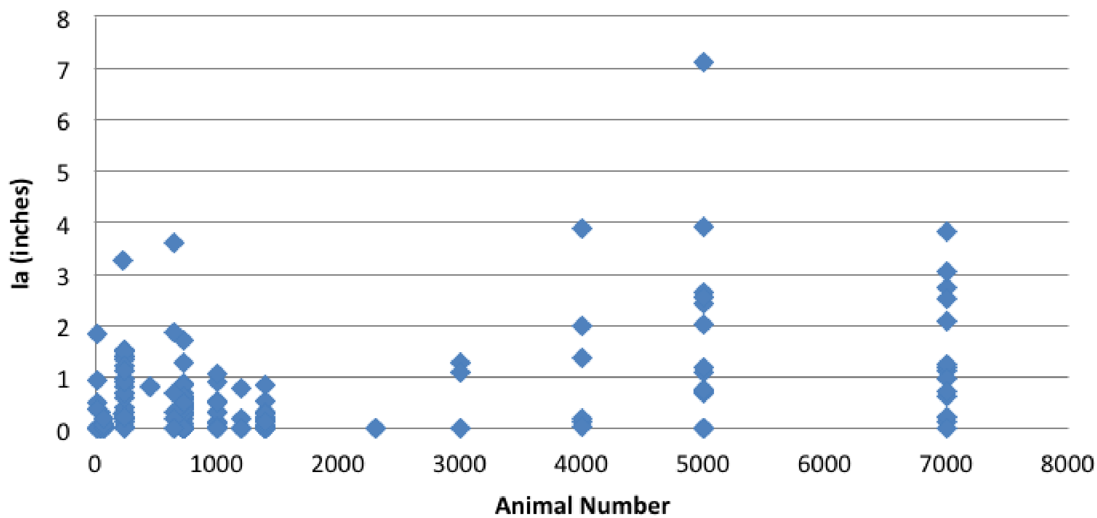

Figure 12. Trends of Initial Abstraction Depths with Number of Animals.

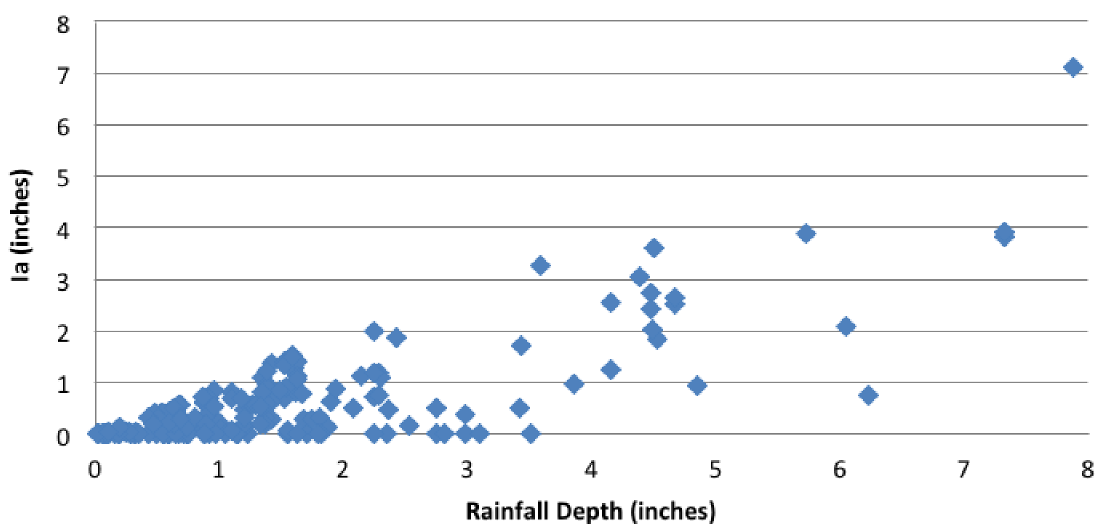

Figure 13. Trends of Initial Abstraction Depths with Rainfall Depth.

Regression analyses were used to explore the possibility of incorporating trends in initial abstraction depths with rainfall in MinnFARM. Because of heteroskedasticity of the data using simple regression analysis, the initial abstraction data were transformed using natural logarithms. Here we used the database with negative I_a. To avoid problems with negative values, the dependent variable was defined as the initial abstraction depths plus 5 inches. The regression results are shown in Figure 14. The initial abstraction depth obtained from the regression equation is:

$$I_a = \exp(0.0758P + 1.6) - 5 \tag{7}$$

where P is the precipitation depth in inches. Both I_a and "5" have units of inches.

In Figure 15, the predicted initial abstraction depths in MinnFARM are plotted as a function of those observed (using the new representative curve numbers). In comparison to observed values, the range in predicted I_a is small. The I_a values are also generally smaller than those observed.

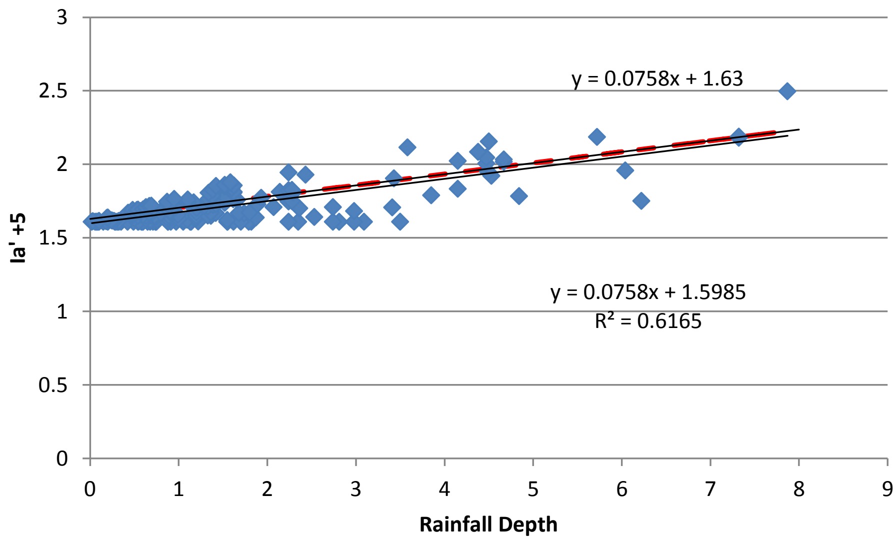

Figure 14. Regression Results for Initial Abstraction Depth with Rainfall Depth.

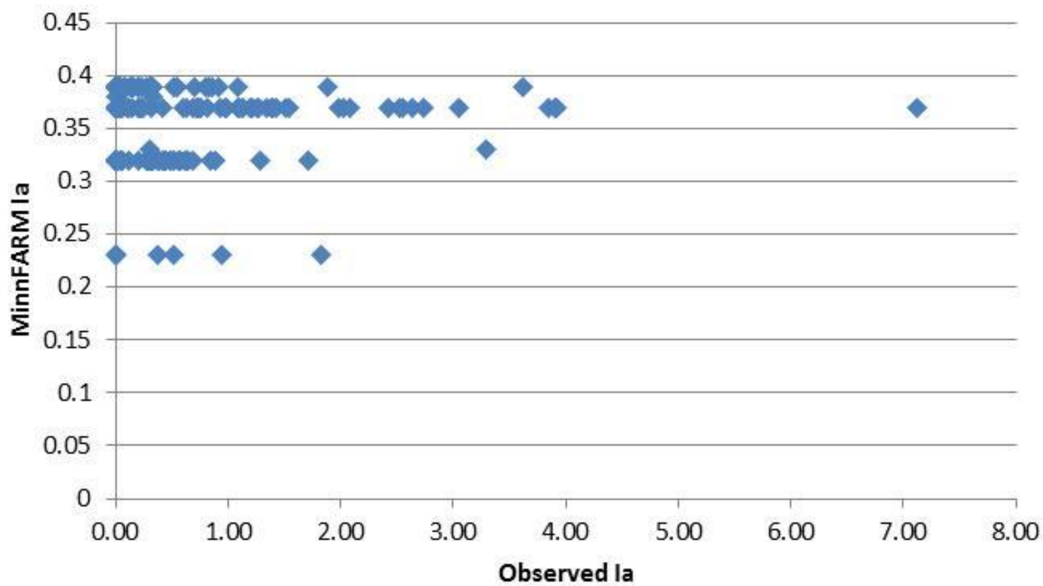

Figure 15. Current MinnFARM Predicted and Observed I_a.

Recommended Changes in Initial Abstraction Depth

Similar to the current version of MinnFARM, the initial abstraction depth should vary by season and by slope. Initial abstraction depth is predicted as

$$I_a^o = I_{a,max}\left(1 - \frac{S_f}{S_{f,max}}\right) + 0.2\,S\,\left(\frac{S_f}{S_{f,max}}\right) \quad (8)$$

where I_a^o is the initial abstraction in the current method, 0.2S is the initial abstraction obtained using the Equation 4, S_f is the slope of the feedlot, $S_{f,max}$ is a maximum feedlot slope (taken as 15%) and $I_{a,max}$ is the maximum initial abstraction (corresponding to S_f = 0). Values for $I_{a,max}$ vary by season and feedlot type. For a dirt lot, $I_{a,max}$ is 0.4 inches for spring, summer and fall seasons and 1 inch for winter. For a concrete lot, $I_{a,max}$ is 0.3 inches for spring, summer, and fall and 0.75 inches for winter.

The analysis of the previous section suggests that I_a (or the curve number) should be a function of rainfall depth. We are therefore recommending the following relationship for the initial abstraction depth:

$$I_a^n = I_a^o \mathrm{R}_I \quad (9)$$

where I_a^n is the recommended formula for MinnFARM and R_I is a rainfall factor defined as

$$R_I = 2\left(\frac{\exp(0.0758P + 1.63) - 5}{\bar{I_a}}\right) = 2\left(\frac{\exp(0.0758P + 1.63) - 5}{1.93}\right) \quad (10)$$

The numerator in the above equation is based on the regression result of the previous section. The intercept has been changed to 1.63 to avoid negative values. This new relationship is also plotted with the observed values in Figure 14. The denominator is the average initial abstraction depth obtained from the regression relationship. It has a value of approximately 1.93 inches.

The predictive accuracy of the recommended approach is shown in Figure 16 and Figure 17. Over the entire range of data, the predicted I_a values from the recommended approach are generally smaller than those observed (Figure 16). However for the more frequent and smaller rainfall depths as shown in Figure 17, the predicted and observed values are in a much better agreement. We are recommending a more conservative estimate of initial abstraction depth. More robust measurements are needed before implementing an algorithm that predicts as much as four inches of initial abstractions.

The initial abstraction estimates correspond to a form of model calibration. Hence, the original physical interpretation becomes less straightforward. Nonetheless, a possible explanation for the increase in initial abstraction depth is possible if we view the feedlot of having spatially varied initial abstraction depths. The actual initial abstraction depth for areas with very large potential initial abstraction depths is the rainfall depth. The initial abstraction depth for these areas within the feedlot obviously increases with rainfall depth.

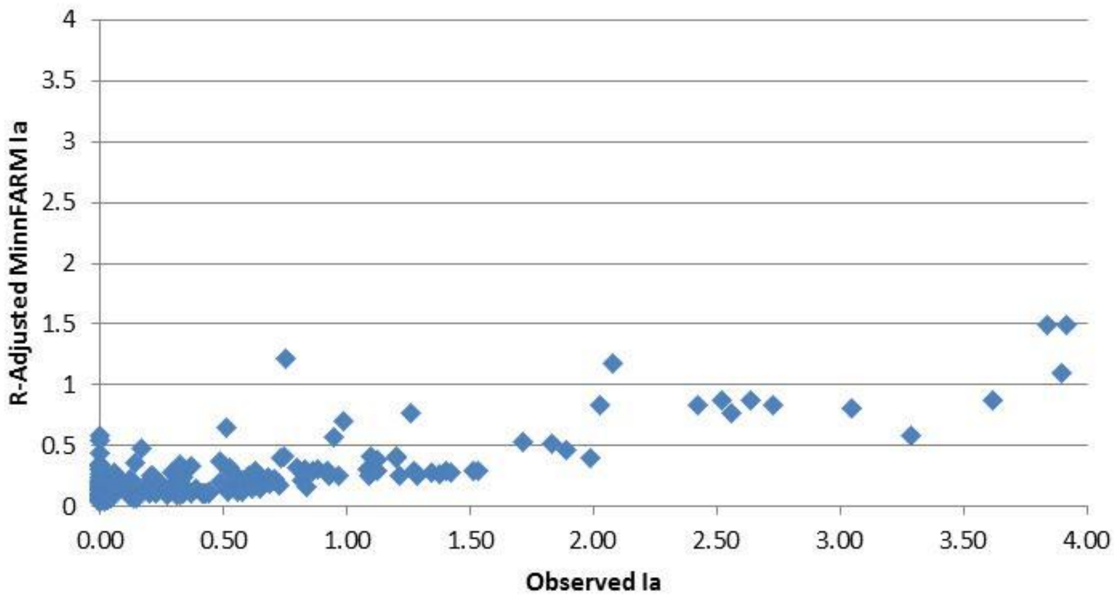

Figure 16. Recommended MinnFARM Predicted and Observed I_a for P< 4 inches.

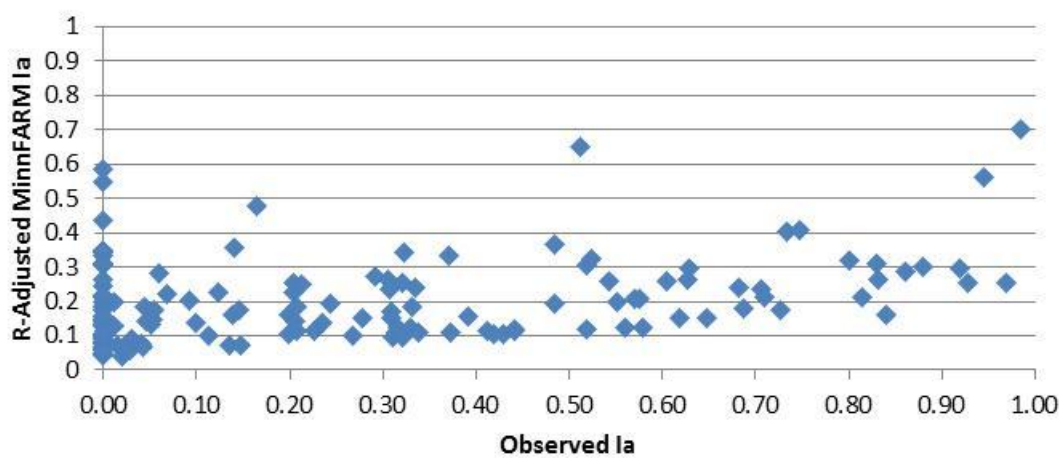

Figure 17. Recommended MinnFARM Predicted and Observed I_a for P<1 inch.

Water Quality Data Analysis

Overview

As previously discussed, 292 events were used to evaluate the water quality component of MinnFARM. The data set only had sufficient data to evaluate total nitrogen and total phosphorus. Current MinnFARM default values for total nitrogen and total phosphorus are 250 mg/L and 85 mg/L (average concentrations at the feedlot edge). MinnFARM uses 50% soluble (dissolved) and 50% settleable (particulate) fractions for all nutrients.

A summary of the statistics of the water quality data set is given in Table 7. Trends in these values will first be given for each location by using the mean value (represented by solid symbols in figures) with error bars corresponding to the standard error of the mean. We will consider trends in total nitrogen (TN), total phosphorus (TP), ratio of nitrate-nitrate (NO_3+NO_2) and total Kjeldahl nitrogen (TKN), ratio of ammonium (NH_4) and TKN, ratio of particulate N and dissolved N, and the ratio of particulate P and dissolved P. These water quality parameters will be compared using animal density and latitude in Figure 18 through Figure 29.

Table 7. Summary Statistics for the Water Quality Data.

Study Name	**TKN (mg/L)**	**TP (mg/L)**	**NO_3^--NO_2^-/TKN**	**NH_4^+–N /TKN**	**particulate N /dissolved N**	**dissolved P /total P**
Plateville	mean: 328.7 sd: 317.0	mean: 40.4 sd: 15.7	< 0.005	mean: 0.41 sd: 0.14	N/A	mean: 0.63 sd: 0.21
Komor/Hansen				N/A		mean: 0.63 sd: 0.14
Bock	mean: 204.3 sd: 142.7	mean: 60.5 sd: 36.0	<= 0.001 (0.683 outlier)	…	mean: 0.42 sd: 0.14	mean: 0.73 sd: 0.07
Sanborn	mean: 143.5 sd: 132.3	mean: 31.1 sd: 27.1	<= 0.002	…	mean: 0.82 sd: 0.06	mean: 0.5 sd: 0.07
Anderson	mean: 687.2 sd: 817.3	mean: 122.7 sd: 119.0 (OP+part P)	mean: 0.007, sd: 0.0016 (excluding one outlier)	mean: 0.40 sd: 0.15 (excluding two outliers)	N/A	mean: 0.62 sd: 0.20 for OP/TP
CNIA1	mean: 325.7 sd: 211.2	mean: 84.9 sd: 33.8	mean: 0.007 sd: 0.012	mean: 0.76 sd: 1.87	…	mean: 0.67 sd: 0.17 for OP/TP
CNIA2	mean: 323.2 sd: 275.7.2	mean: 109.2 sd: 85.3	mean: 0.006, sd: 0.007	mean: 0.31 sd: 0.11	…	mean: 0.68 sd: 0.32 for OP/TP
NWIA1	mean: 361.6 sd: 258.0	mean: 51.8 sd: 20.8	mean: 0.01 sd: 0.012	mean: 0.44 sd: 0.15	…	mean: 0.62 sd: 0.19 for OP/TP
*NWIA2**	mean: 1705 sd: 938	mean: 250.4 sd: 157	mean: 0.002 sd: 0.002	mean: 0.33 sd: 0.10	…	mean: 0.53 sd: 0.18 for OP/TP
SWIA1	mean: 145.8 sd: 53.8	mean: 51.6 sd: 11.2	mean: 0.006 sd: 0.006	mean: 0.55 sd: 0.10	…	mean: 0.73 sd: 0.21 for OP/TP
SWIA2	mean: 222.8 sd: 138.6	mean: 76.9 sd: 26.9	mean: 0.018 sd: 0.036	mean: 0.40 sd: 0.15	…	mean: 0.61 sd: 0.18 for OP/TP
Swanson	mean: 98.0 sd: 55.8 (for TN)	mean: 30.9 sd: 8.0	mean: 0.13, sd: 0.13 (for NO3-N/TN)	mean: 0.14 sd: 0.11 (NH4-N/TN ratios)	N/A	N/A

Miller	TN 19.2 min 173 max 85.7 mean	2.1 min 61.2 max 35.3 mean	mean NO3-N/mean TN 0.04 (summary data)	mean NH4-N/mean TN 0.39 (summary data)	N/A	mean OP /mean TP 0.16 (summary data)
Kennedy	mean: 238.1 sd: 80 (11 points)	mean: 54.9 sd: 19.0 (11 points)	N/A	mean: 0.30 sd: 0.11 (summary data)	N/A	N/A

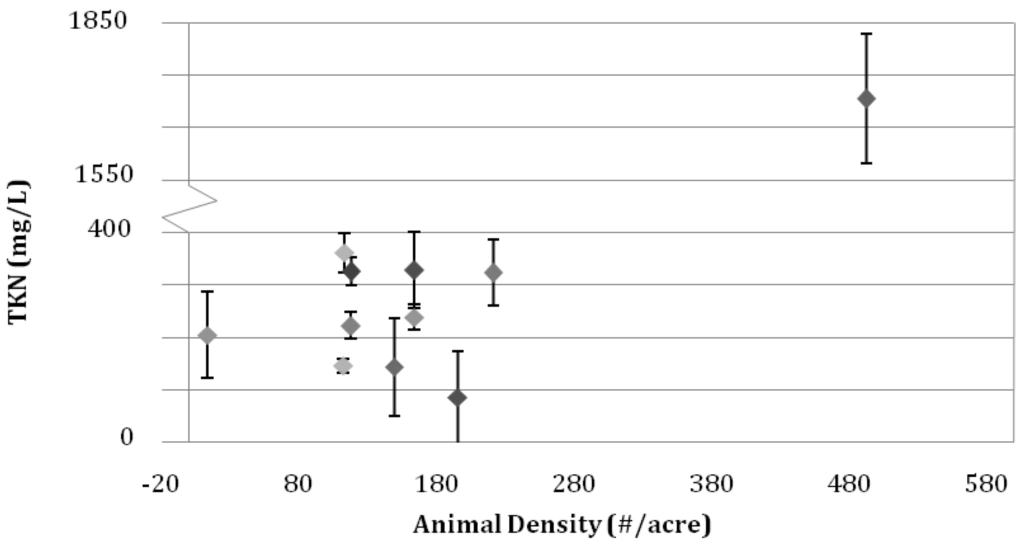

Figure 18. Observed TKN Concentrations as a Function of Animal Density.

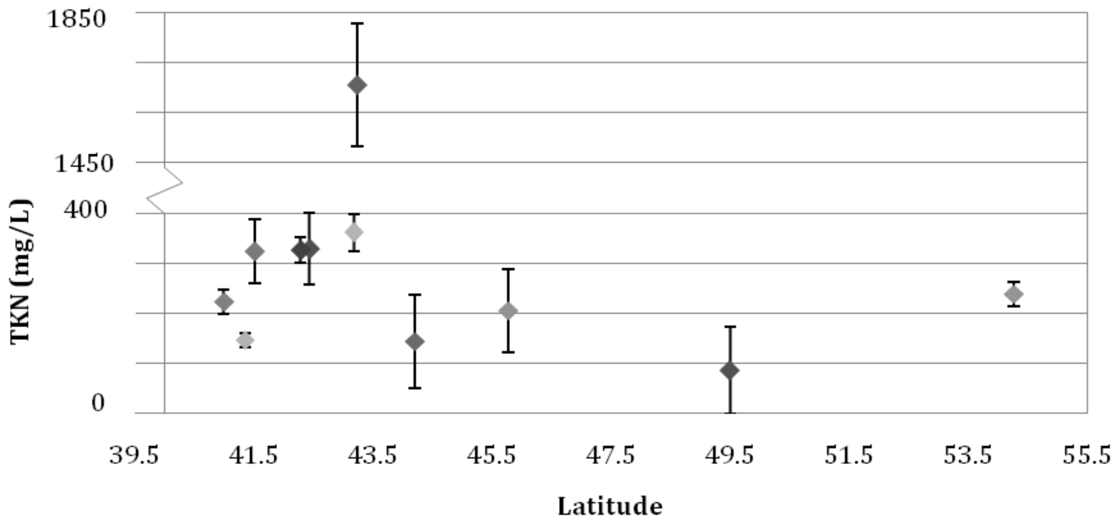

Figure 19. Observed TKN Concentrations as a Function of Location (Latitude).

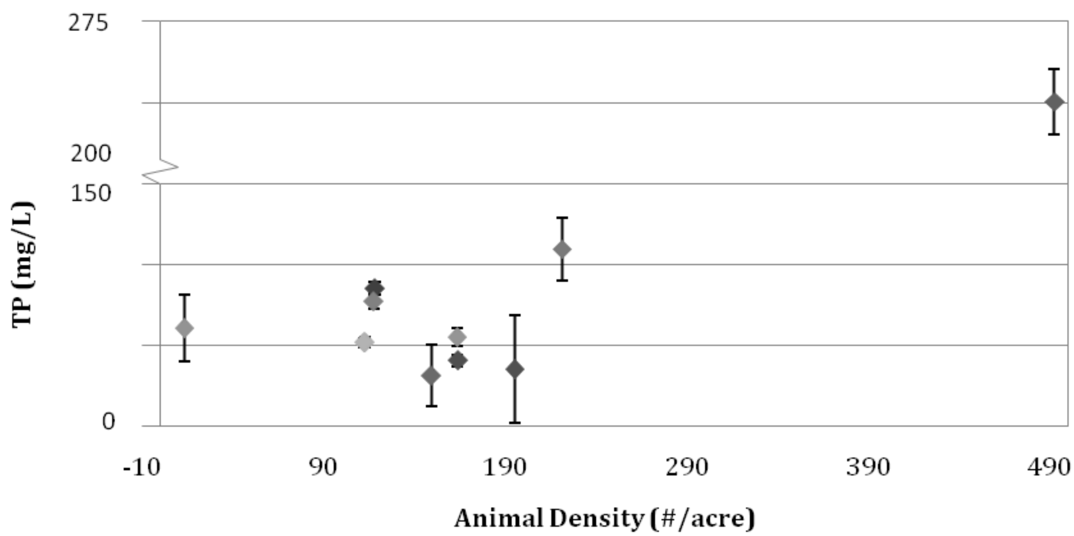

Figure 20. Observed TP Concentration as a Function of Animal Density.

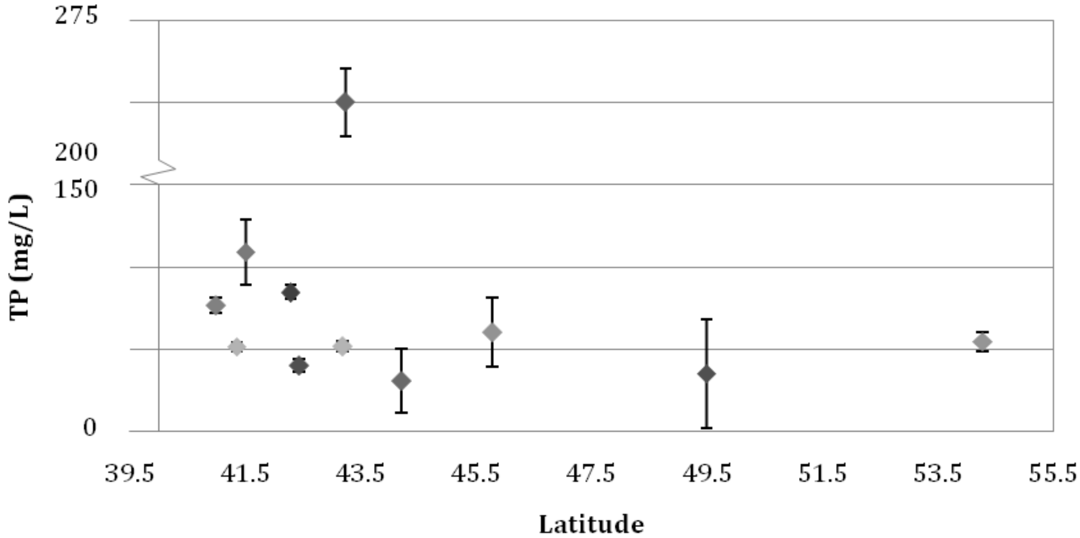

Figure 21. Observed TP Concentrations as a Function of Location (Latitude).

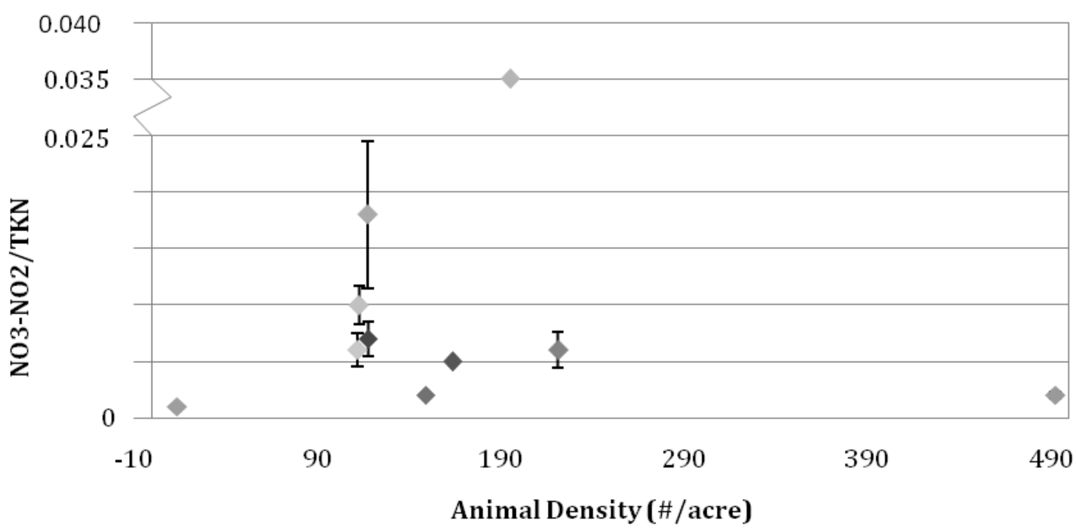

Figure 22. Observed Nitrate-Nitrite Fractions as a Function of Animal Density.

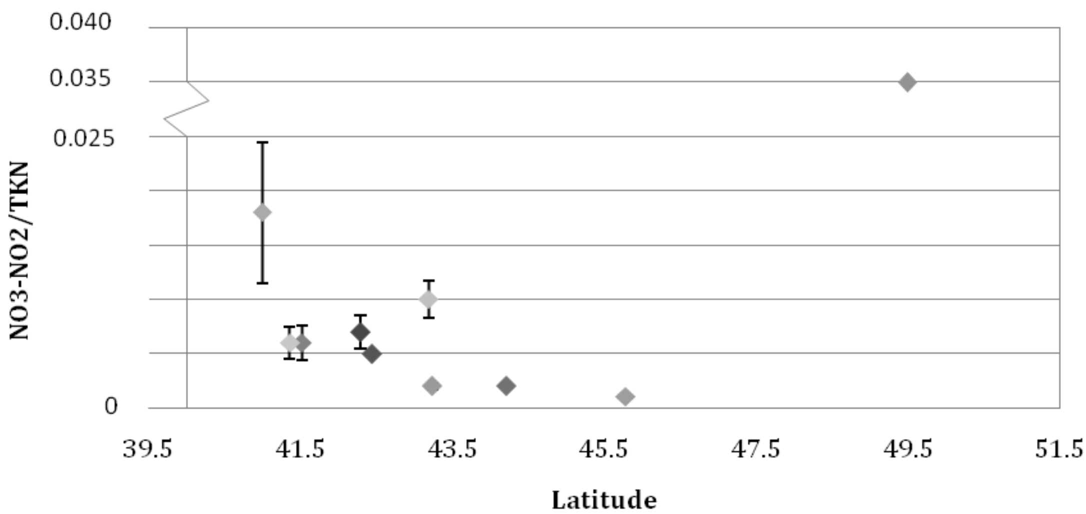

Figure 23. Observed Nitrate-Nitrite Fractions as a Function of Location (Latitude).

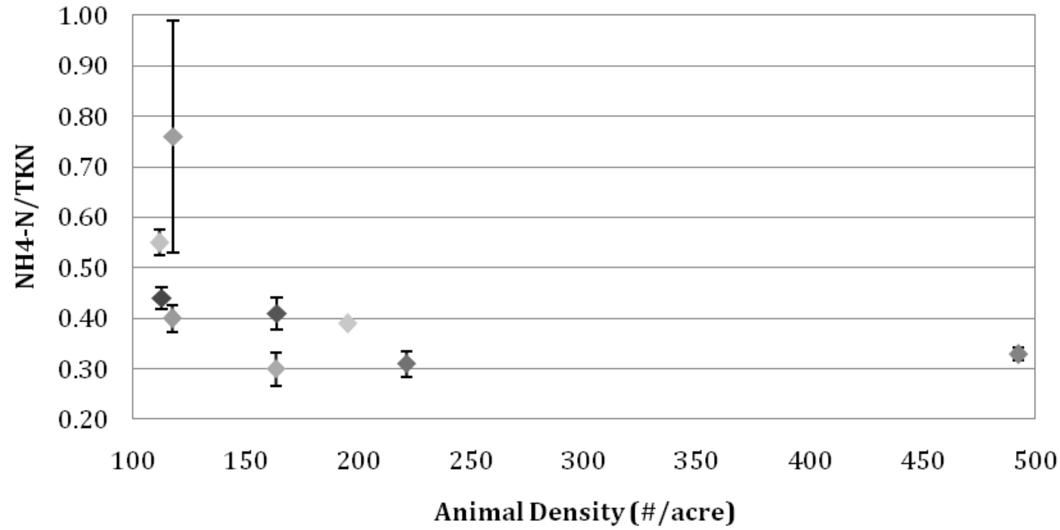

Figure 24. Observed Ammonium Fractions as a Function of Animal Density.

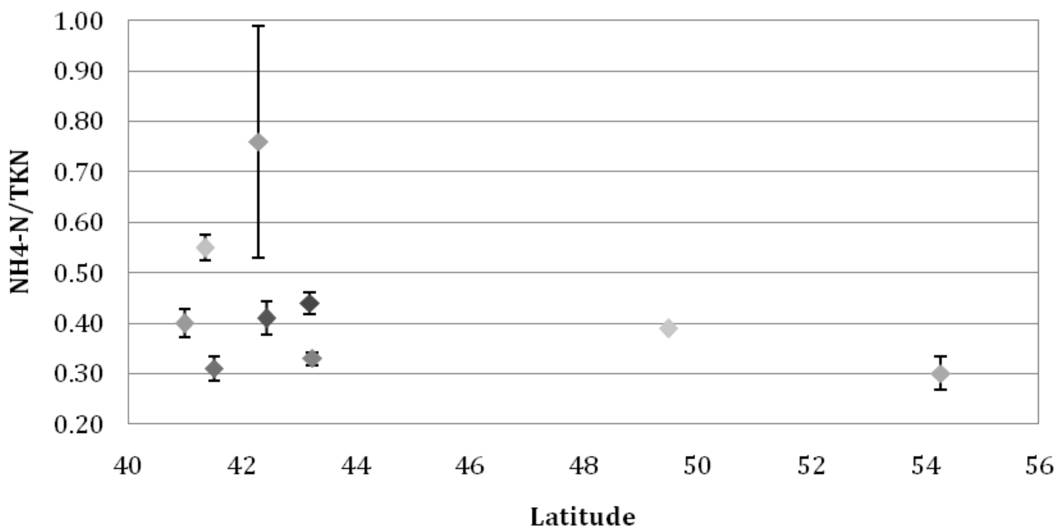

Figure 25. Observed Ammonium Fractions as a Function of Location (Latitude).

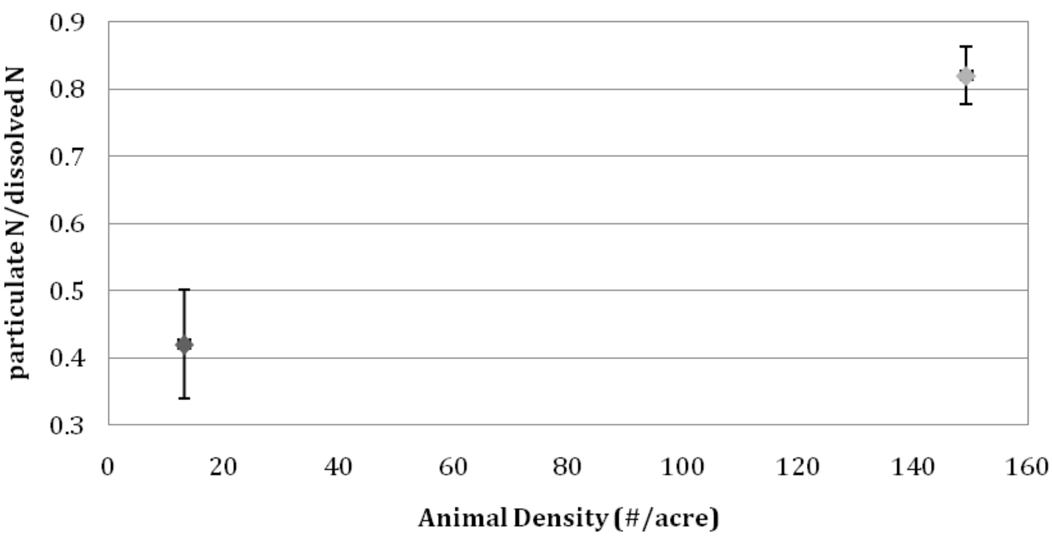

Figure 26. Observed Particulate-Dissolved N Ratios as a Function of Animal Density.

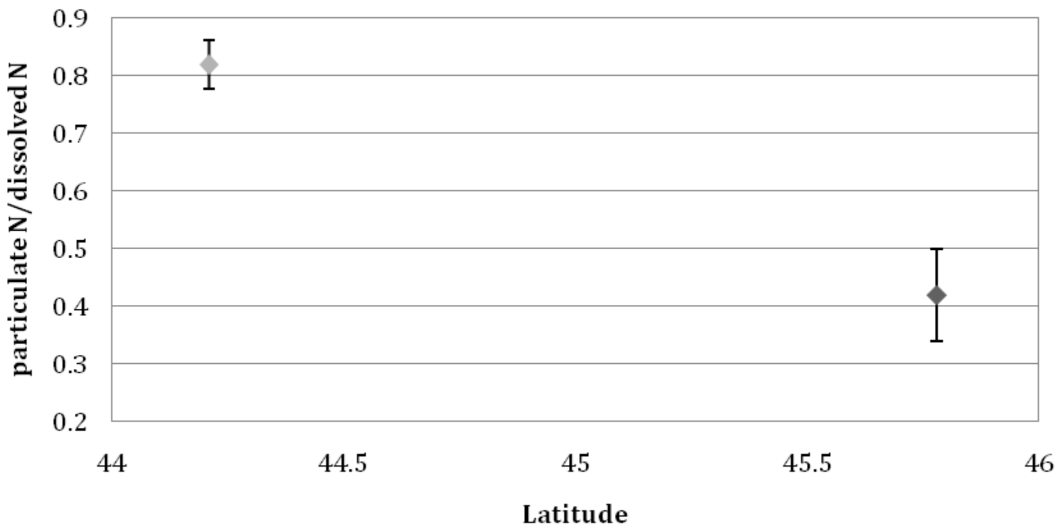

Figure 27. Observed Particulate-Dissolved N Ratio as a Function of Location (Latitude).

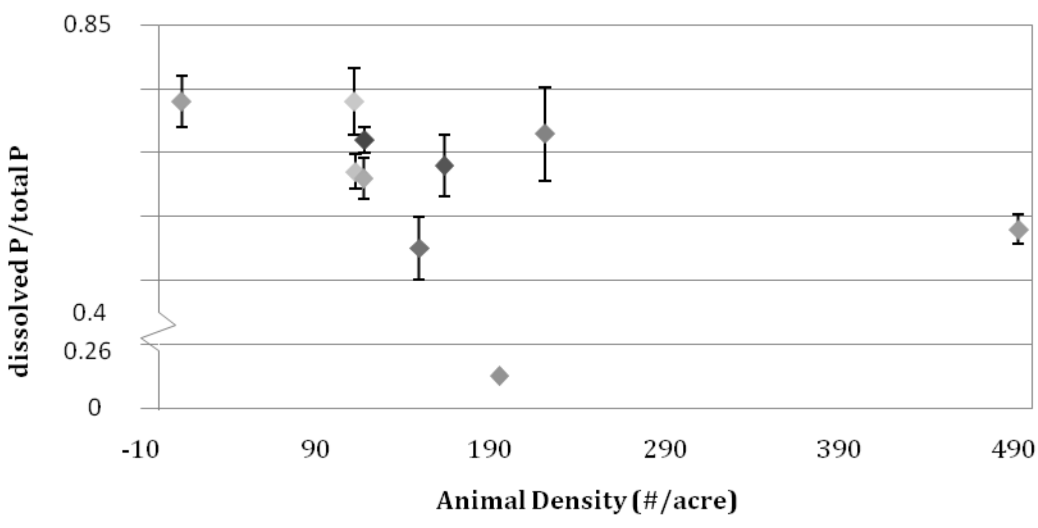

Figure 28. Observed Dissolved-Total P Ratio as a Function of Animal Density.

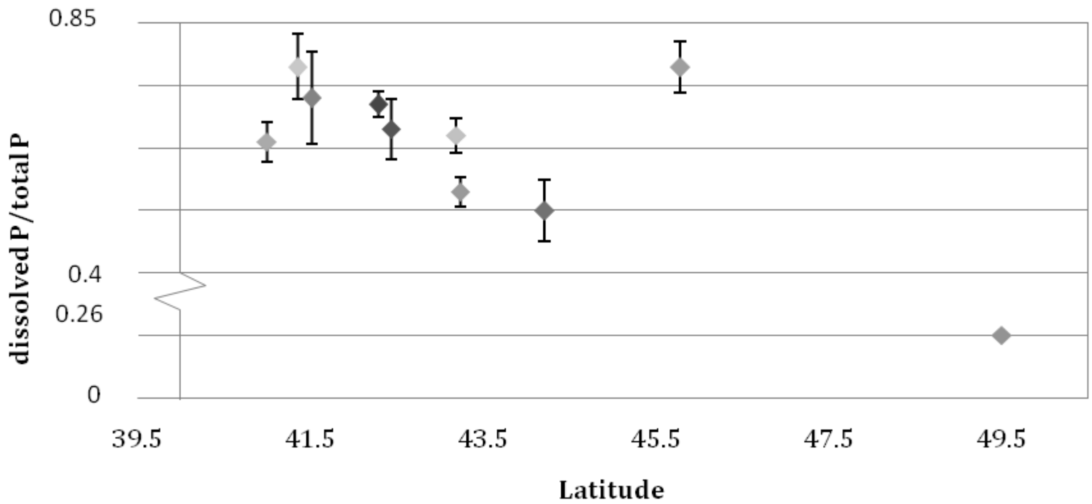

Figure 29. Observed Dissolved-Total P Ratio as a Function of Latitude.

With the exception of the Anderson NWIA2 site, most of the data values were reasonably well clustered around a common mean. In general, no apparent trends were found for the water quality variables with respect to animal density and latitude. More discussion of the observations for each location is given in the next section.

Analysis of Individual Sites

Nineteen rainfall events were analyzed for the Platteville site. The forms of nitrogen measured at this site were nitrate+nitrite and total Kjeldahl nitrogen. The fraction of nitrate-nitrite was small. The mean and standard deviation of the NH_4/TKN ratios are 0.41 and 0.14, separately. The important forms of nitrogen in the runoff are therefore NH_4 and organic N. No significant relationship was found between NO_3^--NO_2^- or TKN and precipitation, duration and feedlot runoff, using multiple regression techniques. The mean and standard deviation of dissolved P/total P ratios are 0.63 and 0.21, respectively, which implies that both dissolved and particulate forms are important. No significant regression relationship was found between dissolved P or TP and precipitation, duration and feedlot runoff.

Similar to the Plateville data, nitrogen and phosphorus measurements were taken with the Komor and Hansen data set. However, there are only five data points. Except for one data point, the NO_3-NO_2 /TKN ratios were less than 0.002. If we neglect the same data point, the particulate/dissolved ratio in terms of ammonium N and organic N ranges between 0.28 and 0.86. Mean and standard deviation of dissolved P/total P ratios are 0.63 and 0.14, respectively, which implies that both dissolved and particulate forms are important.

For the Anderson data, flow and concentrations were measured for the settling basin runoff from rainfall events spanning three years and six farms. The mean and standard deviation of the NO_3-NO_2/TKN ratios are 0.0007 and 0.0016, respectively; it implies that NO_3-NO_2 is negligible in the settling basin runoff. Except two outliers, the mean and standard deviation of NH_4/TKN ratios are 0.40 and 0.15, respectively, which are almost the same as those in the feedlot runoff at Platteville data set. Mean and standard deviation of dissolved P/total P ratios are 0.62 and 0.20, separately. These statistics are similar to those of the Platteville data set. We expected a higher ratio of dissolved P to Total P because of the influence of the settling basin on the data.

The Swanson data set is based on creating a "feedlot" by applying manure to feedlot-type soil condition and using a rainfall simulator to generator runoff. Thirty-one records (intervals) across six rainfall events were given for nutrients. Measured TKN and TP concentrations were low compared to the other data sets – likely because of the use of older manure applied to the test area. Mean and standard deviation of NO_3/TN ratios are 0.13 and 0.13; the mean and standard deviation of NH_4/TN ratios are 0.14 and 0.11; the mean and standard deviation of organic N/TN ratios are 0.72 and 0.14. Only total P was measured in this study.

The Miller data only reported average nutrient concentrations in the feedlot runoff. The mean TKN and Total P values were 85.7 mg/L and 35.3 mg/L, respectively. Mean NO_3/mean TN ratio is 0.04. Mean NH_4/mean TN ratio is 0.39. These values are also consistent with the Platteville data set. The mean OP/mean TP ratio is 0.16.

Only annual average values of N and P were available from the Kennedy study. The mean and standard deviation of the NH4/TKN ratios are 0.30 and 0.11, respectively, which are close to those of Plateville.

Recommended Changes in Water Quality Parameters

MinnFARM currently uses a constant value of 250 mg/L for total nitrogen and 85 mg/L for total phosphorus. Fifty percent of nutrients are assumed to be soluble (dissolved) and fifty percent are then settleable (particulate). Possible changes in MinnFARM include using concentrations that vary between events or using different default concentrations. Collection of feedlot concentration is expensive and must be done carefully. The available data set is too small to identify significant trends. We therefore recommend **not** changing the constant average concentrations approach in the current MinnFARM. Average concentrations across all feedlots (not averaged over all events) suggest an average TKN value of 239 mg/L and an average total P value of 60 mg/L. These average values are in reasonable agreement with those values currently used in MinnFARM. We therefore recommend **not** changing the current default concentrations.

Vegetative Buffer Validation

Framework Used in MinnFARM

In Minnesota, vegetative buffers are the most widely used treatment for feedlot runoff. Load reductions in the buffer are a function of the infiltration and filtration in the buffer area. Filtration removes settleable solids and infiltration removes both settleable nutrients and soluble nutrients. As such, validation of the buffer equations in MinnFARM requires a comparison of predicted and observed runoff volumes and predicted and observed nutrient concentrations.

Reductions in pollutant by infiltration are directly proportional to the infiltration volume. This volume is computed using the curve number method previously given by Equation 1. The percent reduction ($\%R_{inf}$) of pollutants to infiltration are calculated as

$$\%R_{\inf} = \frac{\Delta F}{V_{lotedge}} = \frac{\left(\hat{Z} - Z\right) * A_{buftotal}}{V_{lotedge}} \qquad (11)$$

where ΔF is the infiltration (acre-in) of feedlot runoff, Z is the runoff from buffer from precipitation only (inches), $\hat{Z}$ is the runoff from buffer from precipitation plus runoff, $A_{buftotal}$ is the total buffer area (acres), and $V_{lotedge}$ is the volume of runoff from lot edge (acre-in). The pollutant load at the End of Treatment (L_{EoT}) is then given by

$$L_{EoT\inf} = \left(L_{lotedge} + L_{buf}\right) * \left(1 - \%R_{\inf}\right) \qquad (12a)$$

where

$$L_{lotedge} = V_{lotedge} * C_{lotedge} \quad \text{(lbs)} \qquad (12b)$$

$$L_{buf} = P * C_{othermax} * A_{buftotal} \quad \text{(lbs)} \qquad (12c)$$

Buffers also capture pollutants through the process of filtration. However, only settleable pollutants will be removed with this process. This filtration reduction is a function of time of contact in the buffer (T_c) and also with depth of flow. Pollutant reductions due to filtration are calculated as follows.

$$\%R_{fil} = \frac{\left(-27.9 + 42.8 \log T_c\right)}{100} \qquad (13)$$

where is the $\%R_{fil}$ is the % pollutant reduction by filtration and T_c is the time of contact in the buffer (sec) defined as

$$T_c = \frac{Len_{buf}}{Vel_{buf}} * \left(\frac{D_{buf} - D_{\max}}{D_{\min} - D_{\max}}\right) \qquad (14)$$

The symbol Len_{buf} is the length of the buffer section (ft), D_{buf} is the depth of flow in the buffer (computed using velocity, flow rate, and width), D_{min} is the depth where filtration performance begins to decrease (default = 1 in) and D_{max} is the depth where there is no pollutant filtration. The flow velocity in the buffer (Vel_{buf}) (ft/s) is given by

$$\mathrm{Vel}_{\mathrm{buf}} = (0.1^{S_c})\,\mathrm{S_b}^{0.5} \qquad (15a)$$

where S_b is the buffer slope in the buffer (%) and S_c is the surface condition constant in the buffer. The value of D_{max} is computed as

$$D_{\max} = K_1 * K_2^{Sc} \qquad (15b)$$

where K_1 is a constant with default value of 2.2 and K_2 is a constant with default value of 7.

Surface condition constants (S_c) used in MinnFARM are shown in Table 8. The surface condition constants are based on Mannings equation and adjusted seasonally based on the following principles: 1) Standard S_c values provided are used for summer conditions. Summer is when the ground cover is at its maximum density and is assigned the standard S_c values found in the original manual. 2) Spring and winter have less cover and are assigned a value of 75% of standard values. 3) Fall values are the midpoint of summer and spring values. Note that higher values indicate denser vegetation and subsequently, slower runoff. These values are adjusted automatically in the model to reflect increased plant growth. As such, the cover type assigned by the user should reflect summer conditions and a typical rotation for the area being evaluated.

Table 8. Surface Condition Constants (S_c).

Ground Cover	Spring	Summer	Fall	Winter
Row Crop-Contour	0.22	0.29	0.25	0.22
Row Crop-Straight	0.04	0.05	0.04	0.04
Small Grain Contour	0.22	0.29	0.25	0.22
Small Grain Straight	0.22	0.29	0.25	0.22
Alfalfa Rotation	0.22	0.29	0.25	0.22
Fallow	0.22	0.22	0.22	0.22
Pasture/Grassland-Poor	0.05	0.05	0.05	0.05
Pasture/Grassland-Fair	0.11	0.15	0.13	0.11
Pasture/Grassland-Good	0.18	0.22	0.20	0.18
Permanent Meadow	0.53	0.59	0.56	0.53
Lawn	0.20	0.22	0.21	0.20
Driveway/Road	0.02	0.02	0.02	0.02
Farmstead mix	0.04	0.05	0.04	0.04
Woods	0.22	0.29	0.25	0.22

Observed Data for Buffer Reductions

Several researchers have investigated the effectiveness of vegetative filter strips (VFS). Similar to feedlot runoff, it is challenging to compare these studies because of the various methodologies used and monitoring parameters. For example, concentration data is taken at the beginning and end of the filter area, but they do not always consider dilution from rainfall or simulated rain falling on the VFS. Studies that assess filter performance during a sunny day where flow is taken from a storage basin may not be applicable to the performance during a rainfall event. The effectiveness of buffers is closely tied to the magnitude of the runoff event. Data on pollutant reduction also require runoff characteristics for proper interpretation.

It is also important to clarify reductions of concentrations and mass loading in respect to the soluble or settleable fractions. Often, the study monitors effluent coming from a settling or catch basin rather than directly off the feedlot. These reported soluble/settleable fractions of nutrients will likely be different than those from a feedlot since it is assumed that most of the settleable nutrients would be removed in the settling basin. Relative reductions in the VFS may be a function of these fractions and therefore may or may not be applicable to runoff coming directly from a feedlot.

Vegetative Buffers and Feedlot Runoff

Komor and Hansen (2003) reported attenuation values from two well monitored field sites. Both of these sites had small settling basins with picket dams designed to remove solids and meter the effluent onto the filter strip. Most storm events during the monitoring period did not produce runoff from the VFS (most effluent infiltrated). Table 9 summarizes some of the results related to percent mass reduction. Additional reductions are given in Table 10 using calculated values obtained from other measurements. The VFS at the Sanborn site had a length of 59 meters and slope of 0.5%. The VFS for the Bock site was 79 meters long with a 1.2% slope. The Sanborn site produced runoff from the VFS during 3 rainfall events (S1, S2, S3), while there was only one event of value at the Bock site (B1). Events S1 and S2 produced similar runoff from the filter strip and similar volume retained in the VFS. This is surprising since S1 was a 52-hour storm with 9.1 cm of rainfall whereas S2 was a 6.5-hour storm with only 3.6 cm of rainfall. The similar response was due to depth of rainfall detained on the feedlot. As shown by Table 9, high reductions in loading were the result of good infiltration whereas concentration changes were unpredictable – most likely due to sampling and measurement error. However even for large infiltration, the loading reduction can still be small. For example, S1 had significant reduction in runoff volume by infiltration but some of the nutrients actually showed increases in load and concentration through the VFS.

Table 9. Summary of reductions from Komor and Hansen (2003).

Event	Rainfall (inches)	[1]Volume % red	[2]Dilution %	[3]COD % load change	COD % conc. change	Dissolved nitrate and nitrite % load change	Dissolved nitrate and nitrite % conc. change	Dis. NH4 % load change	Dis. NH4 % conc. change
S1	3.6	85	90	19	46	-1844	-1200	-716	-446
S2	1.4	83	32	77	10	74	0	82	29
S3	0.2	98	5	98	10	99	67	99	36
B1	0.9	47	41	-	-	55	50	61	57

[1]*Volume off of VFS divided by volume off feedlot plus rain on VFS.*
[2]*% dilution is Rainfall on VFS divided by Rainfall VFS & Feedlot runoff volume*
[3]*% reduction in loading is a calculated value by authors of this paper.*
Calculated by load off of feedlot divided by load off of filter strip. %red =1- $(C_{lot} x V_{lot})/C_{vfs} x V_{vfs})$

Table 10. Summary of change in VFS from Komor and Hansen (2003).

Event	Sus. ammonia and org N % load	Sus. ammonia and org N % conc.	Dis. org N % load change	Dis. org N % conc. change	Dis. P % load change	Dis. P % conc. change	Sus. P % load change	Sus. P % conc. change	Fecal Cfu % load change	Fecal cfu/100 ml % conc. change

	change	change								
S1	5	36	-22	19	-54	-3	39	59	-31	13
S2	71	-12	83	33	74	-2	72	-10	63	-46
S3	97	-17	97	-52	98	-8	97	-28	97	-30
B1	84	83	55	50	60	56	81	80	69	66

% reduction in loading is a calculated value by authors of this paper.

Calculated by load off of feedlot divided by load off of filter strip. %red =1- ($C_{lo\ t}$x V_{lot})/C_{vfs} x V_{vfs})

Dickey and Vanderholm (1981) measured reductions in concentrations of 73%, 85%, 78%, 80% and 86% for TS, COD, P, TKN, and NH4 respectively over a 91 meter VFS with a 0.5% slope. Effluent was from a settling basin collecting runoff from a concrete dairy lot that was scraped daily. Mass reductions were all above 95% but this was primarily due to infiltration with over 83% of the effluent infiltrating in the VFS. Concentrations were measured at various flow distance and the average reductions for the seven measured events were plotted. The linear regression for this data is

$$TKN = 160*(0.983)^D \quad r^2=0.983 \quad (16a)$$

$$NH4\text{-}N=63.4*(0.974)^D \quad r^2=0.971 \quad (16b)$$

$$TS=2680*(0.985)^D \quad r^2=0.982 \quad (16c)$$

$$COD\text{-}2420*(0.984)^D \quad r^2=0.962 \quad (16d)$$

where D is the travel distance in VFS (meters).

Mankin et al. (2006) monitored concentration reductions in NRCS-designed VFS from four feedlots and 22 runoff events (sedimentation area with controlled outlet). Filter lengths and widths along with reductions are reported in Table 11. It is interesting to note that of the 22 feedlot runoff events recorded (of the 135 total rainfall events) only three events of less than 20 mm (0.78 inches) produced feedlot runoff. Of the 36 rainfall events above 20 mm, 19 produced feedlot runoff and 12 produced runoff from the VFS. In this study, higher concentrations reductions for fecal coliforms than for nutrients may suggest the difference in VFS performance as a function of settleable and soluble nature of the pollutants. In evaluating the significant variables in VFS performance it was determined that the rainfall depth and ratio of VFS area to feedlot area were the most significant parameters, but even these parameters had very little predictive power (r^2 of 0.22 to 0.42).

Observed and MinnFARM predicted reductions in concentrations of total nitrogen and total phosphorus for the Mankin et al. (2006) study are given in Table 12. The observed reductions for total nitrogen and total phosphorus are very similar. They range from 52% to 84% for nitrogen and from 51% to 91% for phosphorus. In MinnFARM, both nitrogen and phosphorus are modeled the same way (for equal soluble and settleable fractions), and therefore only one value for nutrients is reported in Table 12. Two sets of predicted values are given in Table 12. The first set uses the default percentages of soluble and settleable nutrients of 50%. The concentration reductions with these parameter values give good prediction for Sites B and D and somewhat overpredicts concentration reductions for Sites A and C. The second set of MinnFARM values were obtained by assuming 100% soluble. The results are sensitive to the assumption of soluble fractions. Good predictions are obtained for Sites A and C using 100% soluble. Unfortunately, the fraction of soluble and settleable nutrients was not measured in this study.

Table 11. Site summary reported by Mankin et al. (2006).

Site	Area ratio VFA/Feedlot	VFS length (m)	VFS width (m)	Slope %
A	0.23	137	15	1.0
		75	9	0.5
B	0.97	375	29	1.4
C	0.36	210	46	2.0
D	0.59	137	37	0.6

Table 12. Observed and Predicted Concentration Reductions of Mankin et al. Data

Reported % concentration reductions average for all events (Mankin et al. 2006)				
	Site A	Site B	Site C	Site D
TN	52	88	56	84.3
TP	51	85.6	54.4	91.3
MinnFARM concentration reductions using 50% soluble nutrients				
All nutrients	71	87	79	84
% soluble	*100*	*100*	*100*	*100*
All nutrients	*55*	*74*	*61*	*68*

The comparison between predicted and observed *concentration* reduction, as given in Table 12, may be misleading. The goal of MinnFARM is to compute *load* reduction. Load reduction is not only a function of concentration reduction but also *volume* reduction. Table 13 includes information on load reduction. Many of the rainfall events had complete infiltration losses in the buffer, which corresponds to MinnFARM predicted values.

Table 13. Comparison of Mankin 2006 data with MinnFARM results.

Observed					**MinnFARM**		
	Precip.	#	**Number of Runoff Events**		**Runoff**		**Total**
Site	**Range (in)**	events	***FeedLot***	**VFS**	**Feedlot**	**Buffer**	**Load**
					(in)	**(in)**	**% red**
A	0-0.04	10	0	0	0	0	100
	0.04-0.19	8	0	0	0	0	100
	0.19-0.39	5	0	0	0	0	100
	0.39-0.78	7	0	0	0.11	0	100
	0.78-1.96	3	2	1	0.95	0.25	94
	1.96-3.94	2	2	2	2.77	1.8	72
B	0-0.04	8	0	0	0	0	100

	0.04-0.19	15	0	0	0	0	100
	0.19-0.39	9	0	0	0	0	100
	0.39-0.78	5	0	0	0.12	0	100
	0.78-1.96	7	3	2	0.97	0	100
	1.96-3.94	4	2	0	2.79	0.79	87
C	0-0.04	12	0	0	0	0	100
	0.04-0.19	10	1	0	0	0	100
	0.19-0.39	6	1	0	0	0	100
	0.39-0.78	3	0	0	0.11	0	100
	0.78-1.96	5	3	2	0.95	0.05	97
	1.96-3.94	5	5	3	2.77	1.12	80
D	0-0.04	8	0	0	0	0	100
	0.04-0.19	7	0	0	0	0	100
	0.19-0.39	9	0	0	0	0	100
	0.39-0.78	10	1	0	0.11	0	100
	0.78-1.96	11	2	2	0.95	0.01	99
	1.96-3.94	0	0	0	2.77	0.88	84

Lim et al (1998) reported concentration and mass reductions of pollutants at 20 foot increments in a 20 x 60 foot buffer. Rainfall was simulated at 100 mm/hr and runoff collected at 2, 4, 8, 18, 30, 45, and 60 minutes at each 20 foot segment of the buffer area. Mass and concentrations shown in Table 14 are based on their reported values. Comparisons were made at the 60 meters between the reported data and MinnFARM with soluble nutrient concentrations of 0, 50, and 100%, cover types of good and soil hydrologic groups B and C (Table 15). Once again, a large range of predicted values can be obtained depending on the fractions of soluble nutrients. Since these values are unknown for the Lim et al.'s study, it is possible that the MinnFARM model adequately represents these field values.

Table 14. Mass and concentration reductions reported by Lim et al.

	TKN	**PO4-P**	**TP**	**TSS**	**TS**
Mass[2]	96%	94%	94%	97%	69%
Conc[3]	90%	82%	84%	92%	25%

Table 15. MinnFARM data showing concentration and mass reductions with soils and cover types.

				Soluble	**Soluble**	**Soluble**
Measured			**Volume**	**0%**	**100%**	**50%**
			Reduction*	**Conc Red.**	**Conc. Red.**	**Mass Red.**
Soil Hydro Group	**Cover Type**	**CN**	**%**	**%**	**%**	
B	Pasture Good	40	97	54	0	98
B	Perm Meadow	37	99	66	0	99
C	Pasture Good	54	61	54	0	79
C	Perm Meadow	51	73	66	0	86

*Measured Volume reduction of 63%.

Unpublished data from University of Wisconsin Pioneer Farm in Platteville Wisconsin allowed some additional data comparisons. The study site consisted of a 0.35 acre concrete lot with runoff flowing to a 30 x 90 foot (0.06 acre) vegetative buffer area (2%

slope) that was heavily vegetated. Rainfall and runoff from the feedlot and buffer were measured in 2006 and 2007. This data set contained 19 events across different seasons. We have already discussed the runoff and water quality characteristics discharged from the feedlot. We are interested here in the buffer response.

MinnFARM requires an estimate of the curve number for the buffer. This curve number can be investigated using the Platteville data. Figure 30 shows the relationships between curve number and season, and Figure 31 and Figure 32 explore trends between curve number and precipitation – both rainfall and effective precipitation. Effective precipitation is the sum of the inches of rainfall on the buffer plus the volume of runoff from the feedlot divided by the buffer area (in inches). Average CN value for the entire data set was 85. Curve numbers used in MinnFARM are reported in Table 16. The data showed a slight reduction in CN with increasing rainfall depths (similar to that obtained for the feedlot given by Figure 4) and a slight increase in CN in the fall season compared to spring and summer. Both of these trends are counterintuitive and may be caused by the small area ratio of buffer to feedlot (0.16). Most area ratios are larger and, as such, the authors are uncertain as to the usefulness of the data set.

Figure 33 through Figure 42 examine percent reductions in (1) total solids, (2) total suspended solids, (3) ammonium, (4) total Kjeldahl nitrogen, and (5) total phosphorus through the Platteville's vegetative buffer. Trends are considered with respect to season and precipitation depth. There are no strong trends in any of the water quality parameter values with season or precipitation. Percent reduction in total solids and total phosphorus might be increasing from spring to fall, possibly corresponding to the increased vegetation in the buffer. The removal of chemicals by vegetative buffers is a complex process that involves many factors. It is unlikely that a statistical analysis by itself will be able to capture the observed trends.

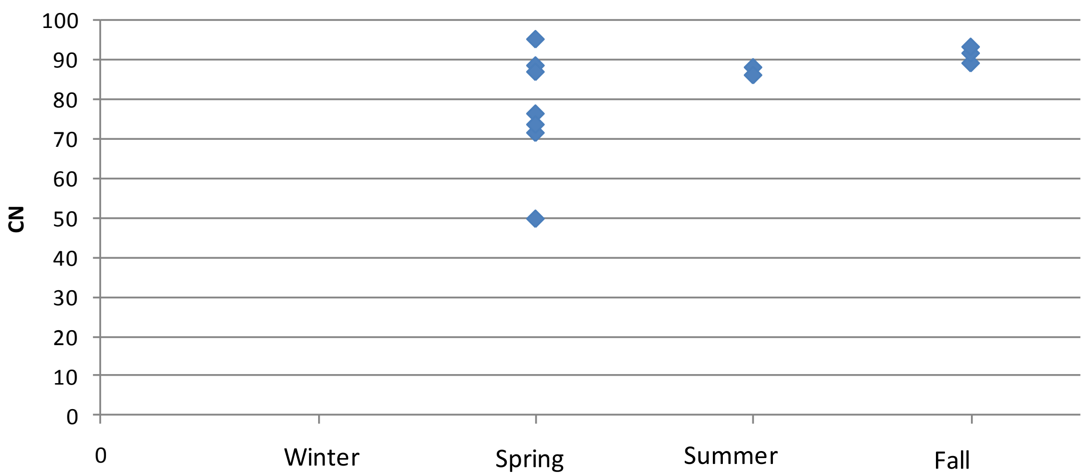

Figure 30. Platteville Buffer: Curve Number as a function of Season.

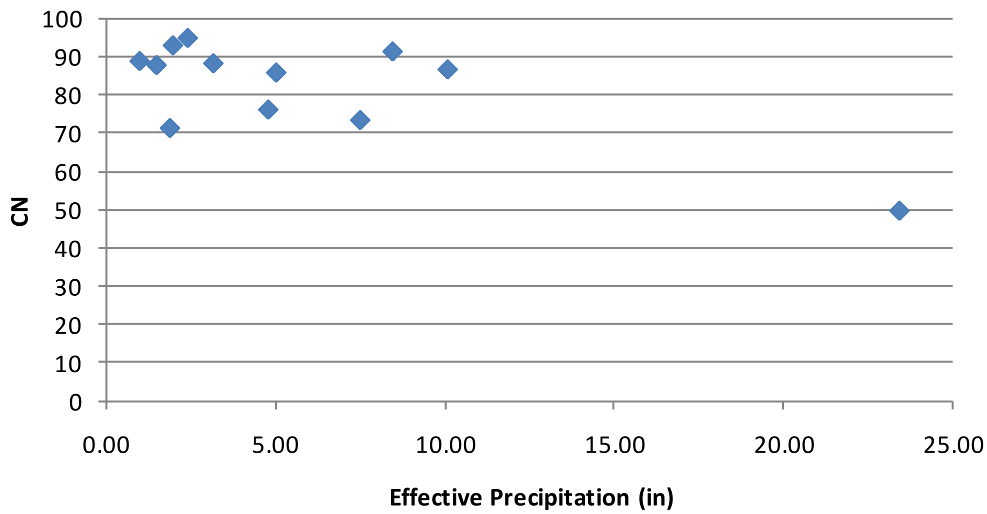

Figure 31. Platteville Buffer: Curve Number as a function of Effective Precipitation.

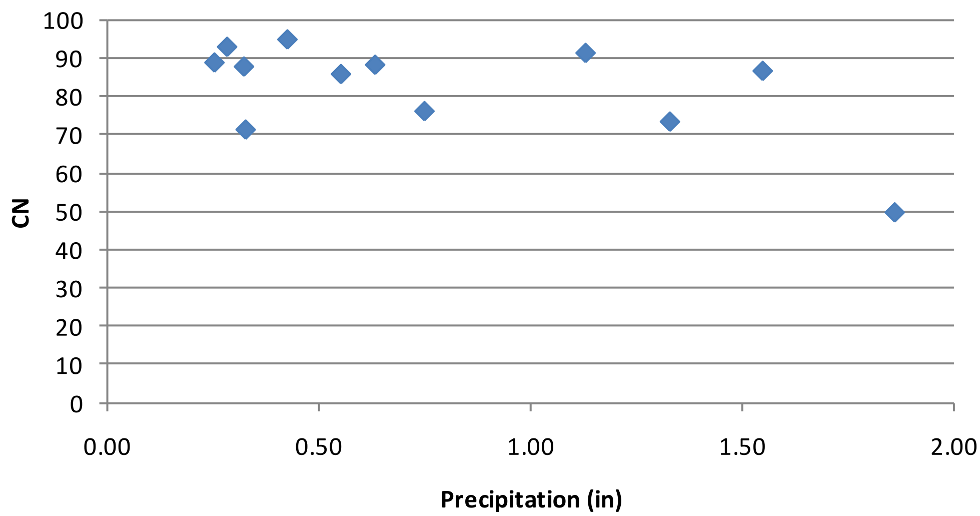

Figure 32. Platteville Buffer: Curve Number as a function of Precipitation.

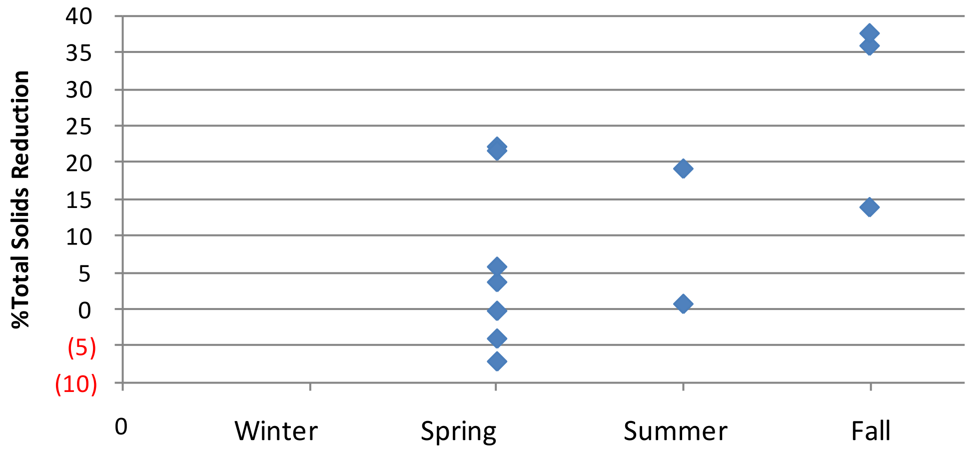

Figure 33. Platteville Buffer: Reduction in Total Solids Concentration as a function of season

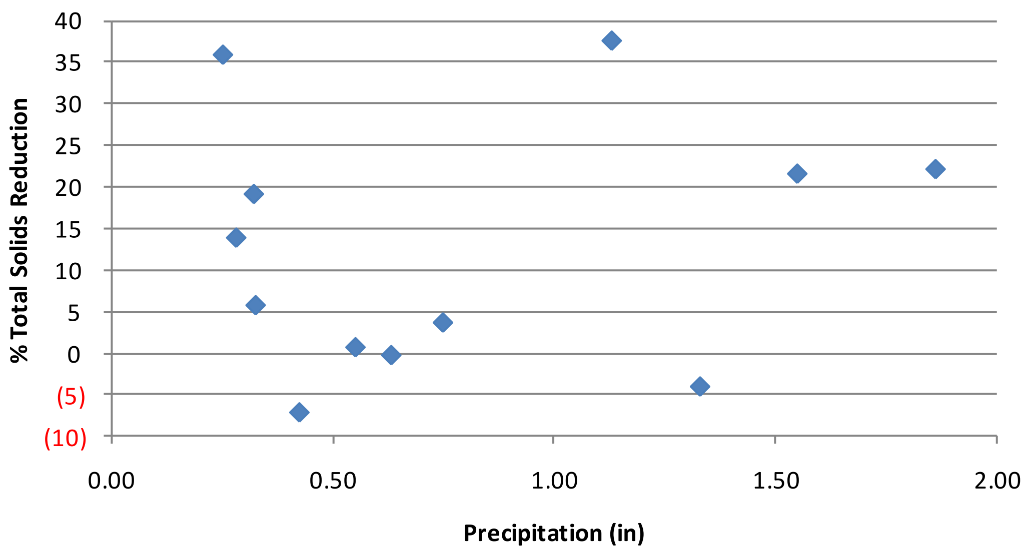

Figure 34. Platteville Buffer: Reduction in Total Solids Concentration as a function of Precipitation.

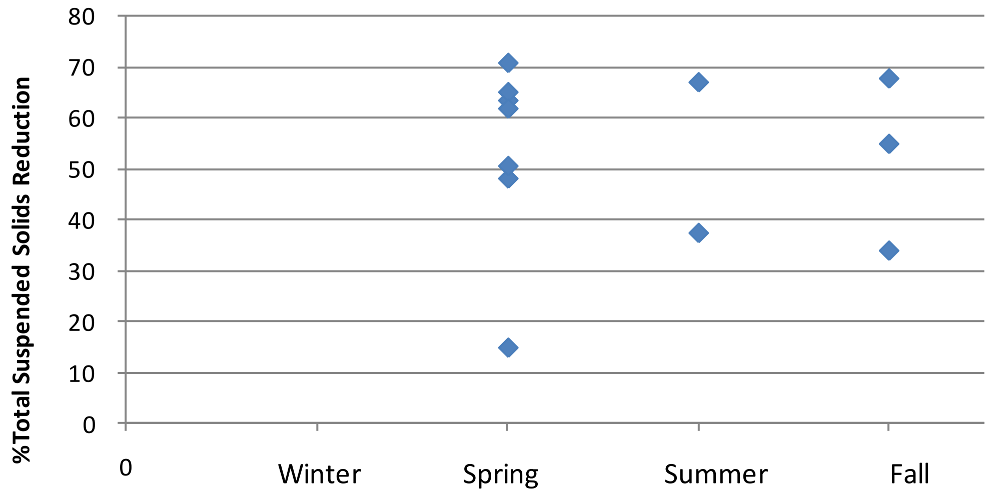

Figure 35. Platteville Buffer: Reduction in Total Suspended Solids Concentration as a function of Season.

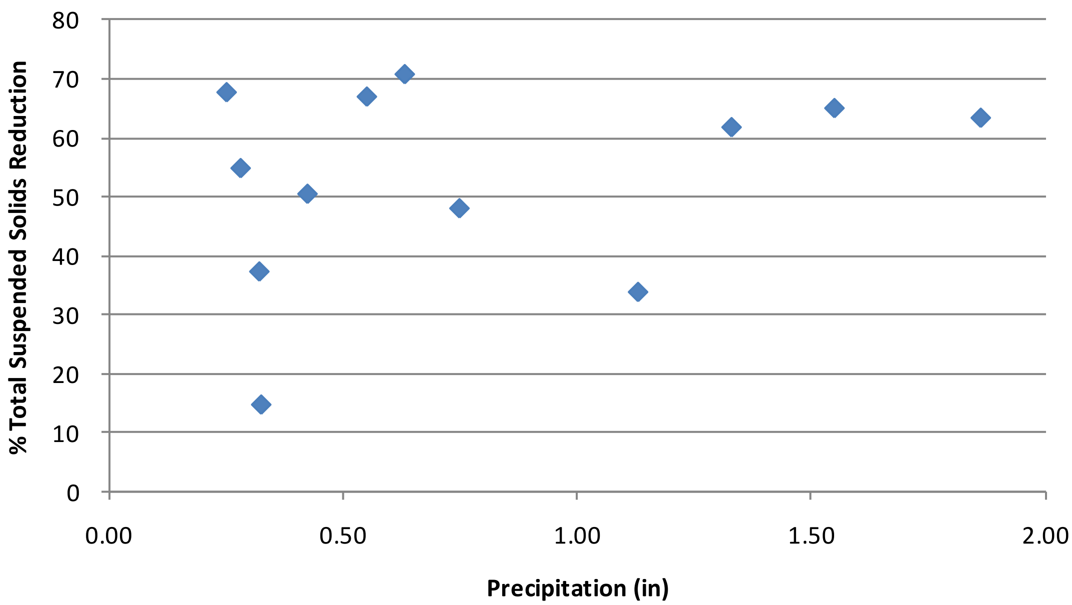

Figure 36. Platteville Buffer: Reduction in Total suspended Solids Concentration as a function of Precipitation.

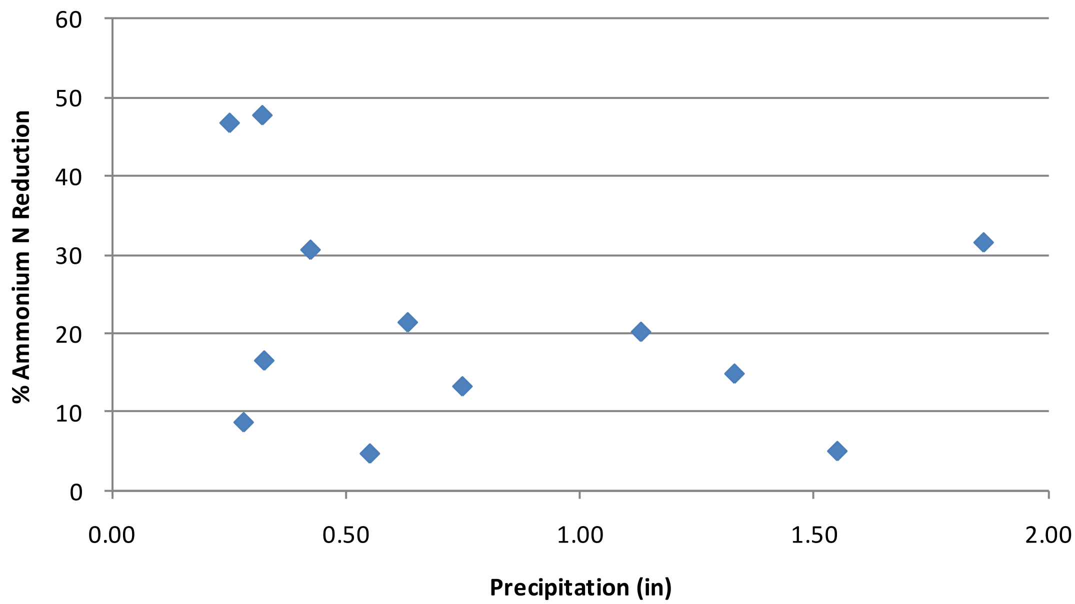

Figure 37. Platteville Buffer: Reduction of Ammonium-N as a function of Precipitation

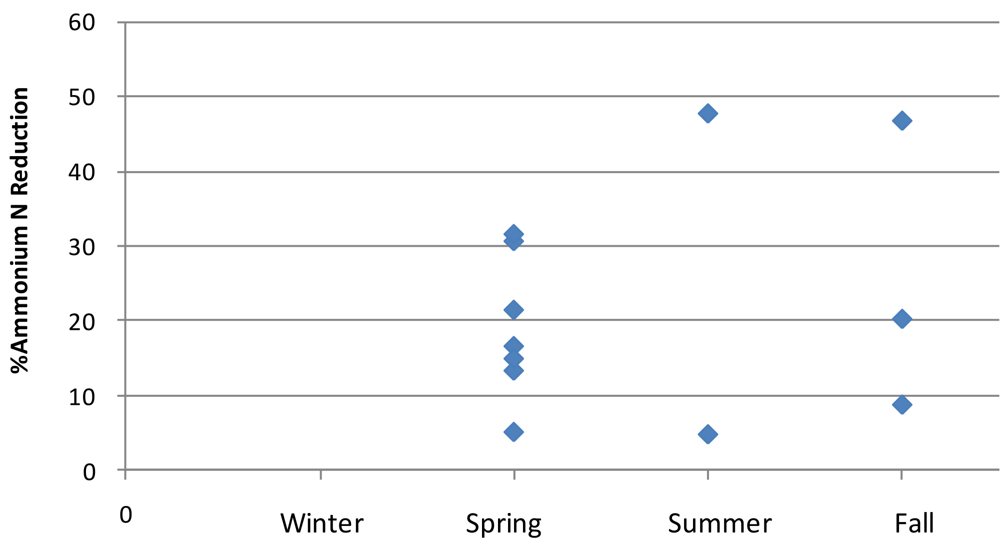

Figure 38. Platteville Buffer: Reduction of Ammonium-N as a function of Season

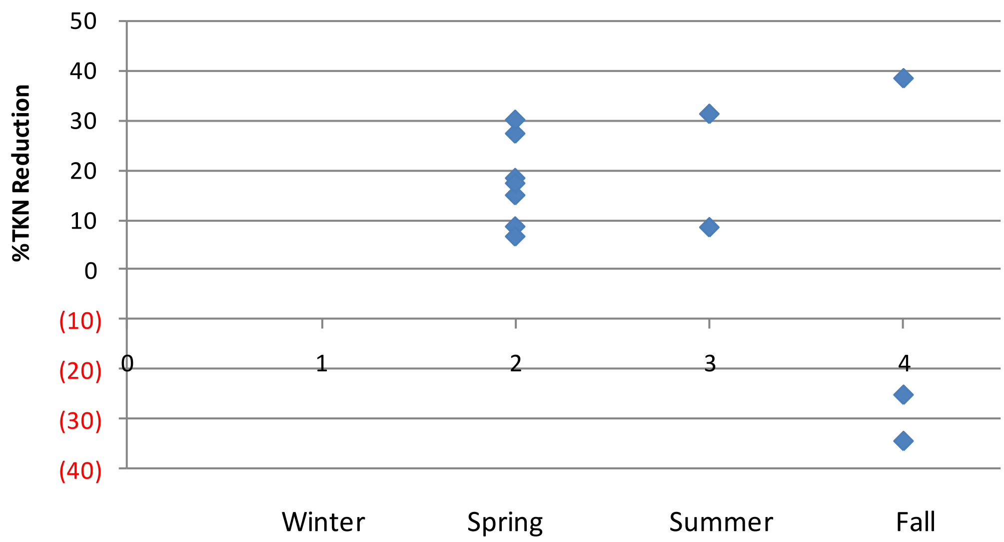

Figure 39. Platteville Buffer: Reduction of Ammonium-N as a function of Season

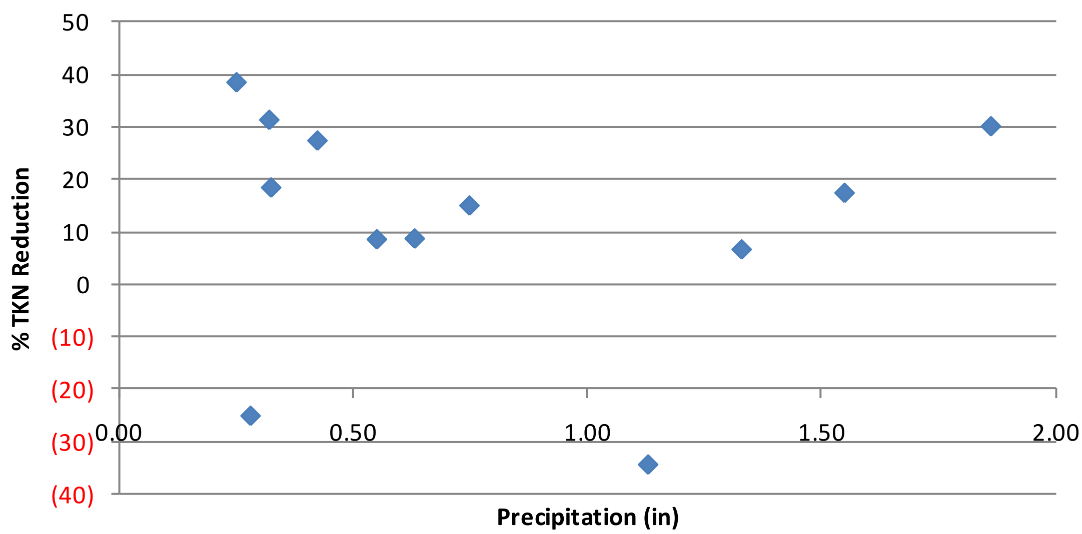

Figure 40. Platteville Buffer: Reduction of TKN as a function of precipitation.

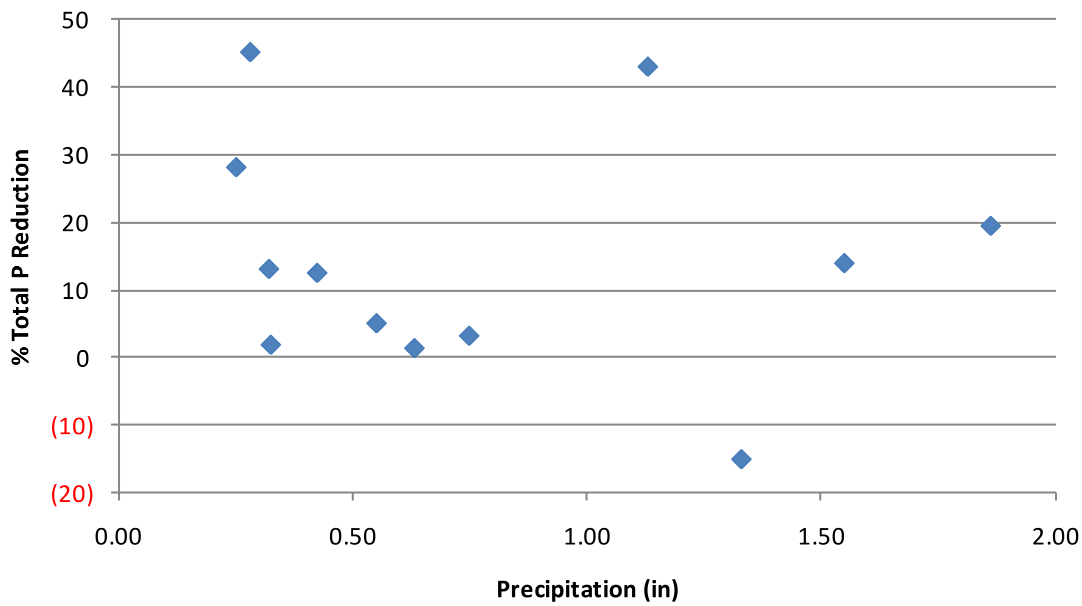

Figure 41. Platteville Buffer: Reduction of Total P as a function of precipitation.

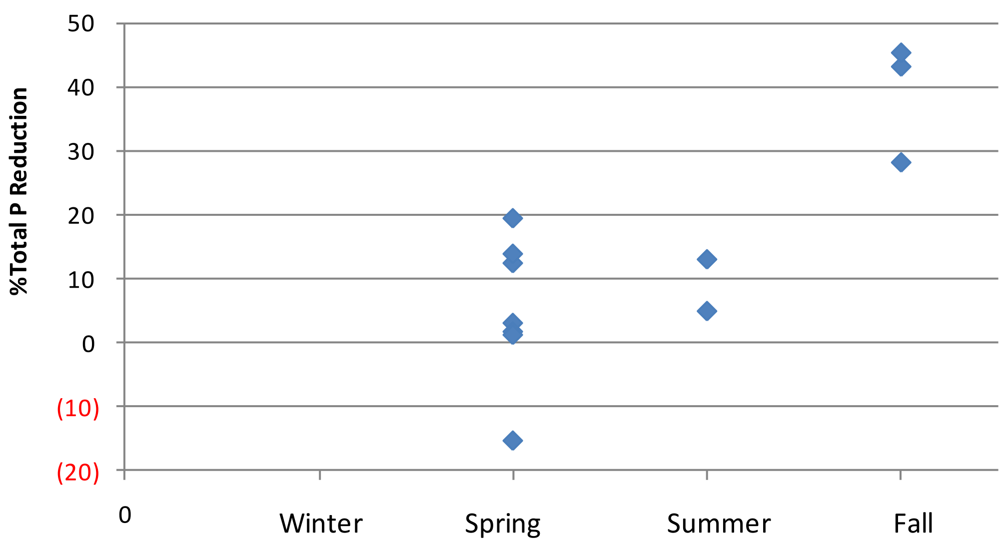

Figure 42. Platteville Buffer: Reduction of Total P as a function of season

Table 16. MinnFARM Default Curve Number values based on different soil and cover types.

Hydro Group	Cover	Spring	Summer	all
C	Perm Meadow	71	51	1
C	Good Pasture	74	54	4
D	Perm Meadow	78	60	9
D	Good Pasture	80	63	1

Mankin and Okoren (2003) monitored a VFS that was treating runoff from a beef feedlot with a sedimentation/controlled outlet system. They found on average 85% of the effluent infiltrated over the first 30 m of filter area. In this same 30 m, 93% of the Total Suspended solids and 74% of the Total Dissolved Solids were removed along with 77% of the nitrogen and 84% of the Phosphorus. No additional reductions were measured along the length of the filter (150 m).

Similarly, Schellinger and Clausen (1992) monitored filter strip performance for dairy feedlot runoff passing through a sedimentation pond. The filter was constructed on silty clay loam (permeability <0.15 cm/hr) which may have contributed to poorer overall performance than other filter strip studies. Performance of the filter, both subsurface and surface flow, was evaluated seasonally (snowmelt, growing season, and spring/fall) for nutrient and fecal concentrations, flow, and mass reductions. The filter was 22.9 meters long and 7.6 meters wide with a 2% slope. Average concentration reductions shown in Table 17 indicate that the filter performance was much worse than reported in other literature. Mass reduction also was quite variable by season and much less than reported in other literature. Mass reductions for Total Phosphorus ranged from 60% to an increase of 30%. A similar trend was reported for Total Kjeldahl Nitrogen (TKN) and Total Suspended Solids. Study authors contribute the ineffectiveness of the filter on hydraulic loading however this ratio of VFS to feedlot area is similar to other studies (0.27). It is likely that the low permeability soils significantly limited infiltration which may account for the poor performance.

Table 17. Concentration reductions in filter strip as reported by Schellinger and Clausen (1992).

Parameter	Spring/fall	Growing	Winter	Snowmelt
TSS	16	10	-113	-110
Total P	-5.1	31.1	-63.8	5.6
Total Dissolved P	-19.5	26.9	-67.8	-5.8
TKN	47	47.5	-24.0	5.0
Ammonium–N	-1.3	52	55.1	8.2
Fecal Coliform	45.6	47.6	-	21.1

Young et al. (1980) monitored filter strip reductions from direct feedlot runoff on filters (4% slope, 27.43 meters long) with four different cover types: corn, orchardgrass, sorghum-sudangrass, and oats. Runoff was generated by a rainfall simulator with a total of 7.5 cm of water applied in 71 minutes. Rainfall was applied twice on the plots in a two day period thus comparisons could be made between dry and wet conditions on the feedlot and filter area. A summary of the resulting load reductions are reported in Table 18. Load reductions are quite variable and, in the case of nitrate, loading increases in the filter. In general, reductions are better during the first rainfall event when conditions are dryer and more effluent infiltrates into the filter area.

Table 18. Load reductions (%) in filter strip from Young et al. (1980).

Vegetation	Runoff	Sediment	TKN	Ammonia	Nitrate	TP	OP
Corn (1)	98	93	98	98	95	98	98
Oats (1)	81	66	69	65	8	76	77
Sorghum (1)	61	82	50	47	-81	48	42
Corn (2)	66	74	79	78	-341	74	41
Oats (2)	41	75	45	33	-1653	50	-3

Vegetative filter strips and land applied manure

Chaubey et al (1995) and Chaubey et al (1994) used simulated rainfall to study the effects of VFS length on quality of runoff. Three plots 1.5 by 24.4 m were constructed with a 3% slope. Poultry or swine manure was applied on the top 3.1 meters and simulated rainfall was applied two days later at 5 cm/hr. Rainfall lasted 1 hour after the beginning of runoff from the VFS. Samples were collected at 0, 3.1, 6.2, 9.3, 15.2 and 21.4 meters from the manured section of the plot. Concentrations and mass reductions for the several of the measured parameters were determined at these distances (see Table 19) but significant differences in reductions were not found after 9.3 meters for most constituents. Mass reductions of COD, TSS, and FC were not significantly different from 3.1 to 21.4 meters for the swine site (61, 50, and 58% respectively). Mass reductions of TSS and COD for poultry manure were not significantly different with distances between 3.1 and 21.4 meters (34.5% and 50.7% respectively). Mass reductions were caused by settling, trapping, or infiltration. Concentration reductions were a function of settling, trapping, infiltration and dilution.

Table 19. VFS reductions reported by Chaubey et al. (1994) and Chaubey et al. (1995).

	Poultry (% mass reduction)					Swine (% mass reduction)				
Constituent	3.1 m	6.1 m	9.2 m	15.2 m	21.4 m	3.1 m	6.1 m	9.2 m	15.2 m	21.4 m
TKN	39.2	53.5	66.6	75.7	80.5	64.9	69.1	88.7	86.2	87.3
NH4-N	46.6	69.8	77.6	94.1	98.0	70.9	82.9	96.4	98.8	99.2
TP	39.6	58.4	74.0	86.8	91.2	67.0	70.9	87.2	91.1	92.4
PO_4-P	38.8	55.1	70.5	84.9	89.5	65.4	71.3	88.7	92.9	94.3

Srivastava et al. (1996) reported on poultry litter runoff reductions with different VFS lengths using a similar experimental design as Chaubey (1994, 1995). Pollutant concentrations followed a first order exponential decline over VFS distance but this was primarily attributable to dilution. Concentrations did not decrease after 6 meters of VFS. This was likely due to the variability in measured values which may have masked the actual pollutant removal effectiveness. Mass removal did not increase with VFS length ($P<0.05$) but this was likely due to the variability in concentration measurements. However, mass removal effectiveness (efficiency) in the VFS generally decreased with increasing loading suggesting that mass removal was largely a function of infiltration.

Dillaha et al (1988) studied VFS effectiveness in reducing sediment, N, and P runoff from a bare field and a field where dairy manure was applied. The 9.2 and 4.6 meter VFS removed 91 and 81% of the sediment as measured by TSS. The VFS removed only 69 and 58% of the P and 74 and 64% of the N. This reduction in removal efficiency was due to the high soluble fraction of N and P in the VFS influent. Soluble N and P were often higher in the VFS effluent than influent. Deep channel filters such as waterways were much less effective at TSS, N, and P removal with efficiencies of 40-60%, 70-95% and 61-70%, respectively, lower than with sheet flow filters.

Recommended Changes in Vegetative Buffer Algorithm

Similar to trends with feedlot runoff and concentrations, the variability among observed percent reduction makes the assessment of the accuracy of the current MinnFARM difficult. Results are sensitive to soluble fractions. However, errors in estimating these fractions are related to the feedlot algorithm and not the buffer algorithm itself. The accuracy of the buffer algorithm cannot be assessed without observed soluble and particulate fractions. We have little information for improving the buffer algorithm, and the current algorithm can adequately approximate observed reduction for reasonable adjustment in the soluble fraction. We therefore recommend **not** changing the current modeling approach in MinnFARM for vegetative buffers.

Objective #3: Modifications to MinnFARM

Feedlots and Buffers

Currently MinnFARM is computationally driven by Excel function applied to cells located within several worksheets. Increasing the complexity of the MinnFARM within this framework has proved to be tedious and likely too limited for the additional algorithm developed for this project, as well as other possible improvements in future work. We have therefore decided to convert the cell-based calculations into Excel BASIC code (VBA). VBA will provide us the flexibility of adding substantially more rigorous routines while maintaining a similar user interface for data input and output. To ensure that the VBA code was working properly, the predicted response was compared to that obtained with the original Excel-based MinnFARM. An example of the results at the feedlot edge and end of a buffer is shown in Figure 43. The VBA code produced the same results as the Excel-based MinnFARM.

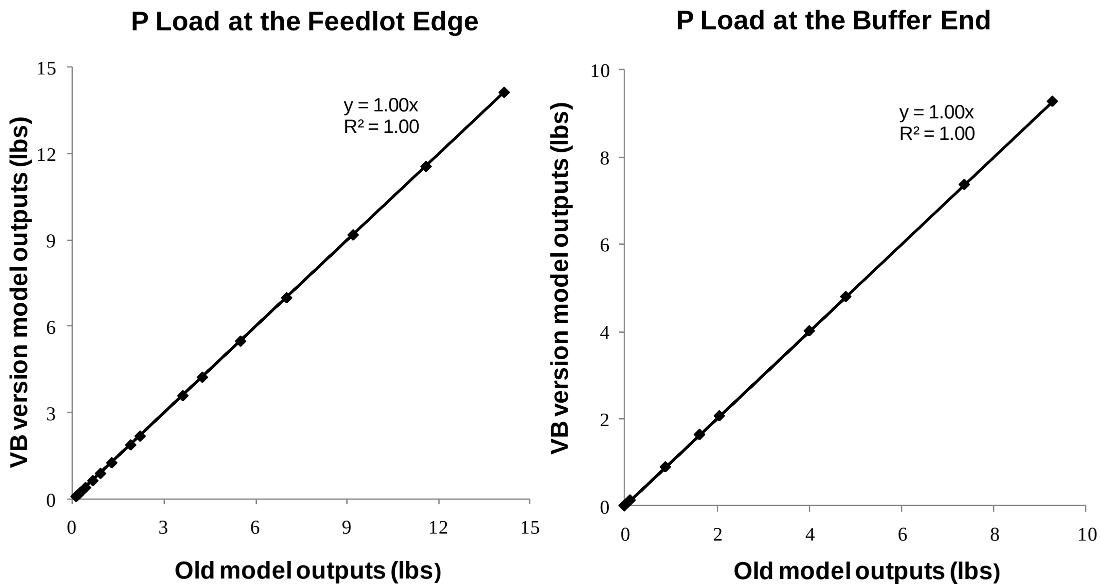

Figure 43. Comparison of Results Using Excel-based and VBA Platforms.

After the VBA code was verified to represent the original Excel-based MinnFARM, the recommended changes in MinnFARM given under Objective 2 were incorporated into the VBA version. Once again, the major changes are the curve numbers for concrete and dirt lot and the trend in initial abstraction as given Equation 9. As previously discussed, no changes are recommended for the default concentrations of water quality parameters and for the algorithms used to predict the removal of potential contaminants from buffers.

Biofilter Algorithm

One of the goals of the project was to develop another treatment option that could be used instead of vegetative buffers. Biofilters have been suggested as possible treatment option, especially for those feedlots where it is difficult to use a vegetative buffer. A biofilter algorithm was therefore developed and tested for MinnFARM.

Biochemical reactions within biofilters are complex and dependent on the inflow rate and influent concentrations from the feedlot. Given the dynamic process on the feedlot itself, there will also be uncertainties in the predicted values of these inputs. A balance in the modeling approach is therefore needed. The model needs to have sufficient rigor to capture key components of biofiltration but simple enough to represent processes by a reasonable number of parameters and at commensurate level with the accuracy of inflow values.

A schematic of our biofiltration system is shown in Figure 44. A two-chamber system is used, where the first chamber is the settling basin that acts as pretreatment for the removal of setteable solids, and the second chamber is the biofilter for the removal of contaminants by bio-chemical filtration. The first chamber also acts to dampen the flow rate so that it is reasonable to assume that the flow rate is approximately constant for the biofilter. Separate algorithms are used and discussed for each of the chambers; however, the primary focus of this study is the validity of the bio-chemical filtration of the second chamber.

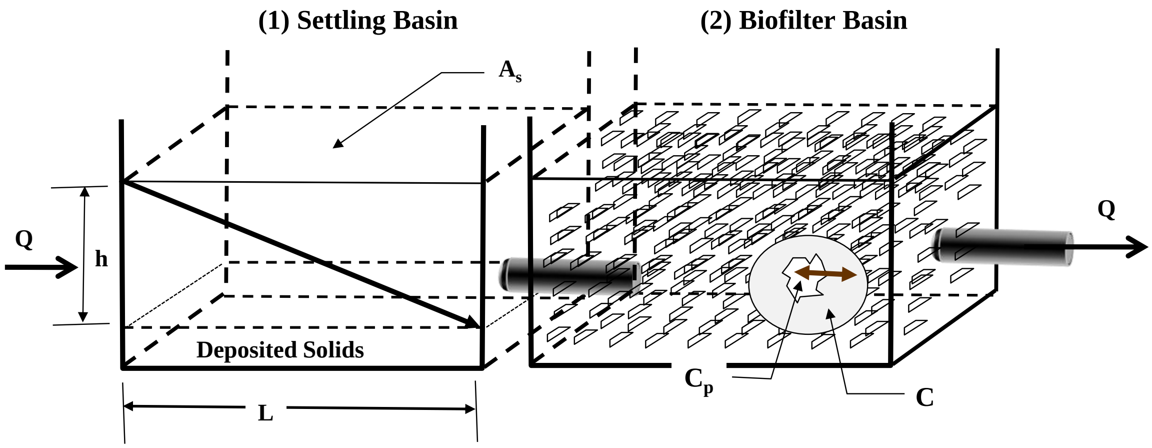

Figure 44. Schematic of the biofiltration system.

Models for both chambers are based on the conservation of mass. The conservation of mass can be written as (Wilson and Barfield, 1984)

$$\frac{\partial C}{\partial t}+\frac{\partial[U\,C\,]}{\partial\,x}+\frac{\partial[V\,C\,]}{\partial\,y}+\frac{\partial[\,(W-\omega_s)C\,]}{\partial\,z}=r+\frac{\partial}{\partial x}(\varepsilon_x\,\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\,\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(\varepsilon_z\,\frac{\partial C}{\partial z}) \qquad (17)$$

where C is the contaminant concentration, U, V, and W are the velocities and the corresponding ε_x, ε_y, and ε_z are the turbulent diffusion coefficients in the x, y, and z direction, respectively, ω_s is the settling velocity of the contaminant (considered independent of time and space), and r is the source/sink term corresponding to possible interaction with potential biofilter media. To simplify, one-dimensional flow will be assumed and therefore V = W = 0. The mass balance will be applied for a control volume moving at an average velocity defined as the volumetric flow rate divided by the flow cross-sectional area and is assumed to be constant for all flows. There is then no net advection of contaminants into the control volume. The diffusion of sediment along the flow path will also be neglected, which when combined with the other assumptions results in a plug-flow representation of the system. The mass balance under these conditions can be simplified as

$$\frac{\partial C}{\partial t}+\omega_s\,\frac{\partial\,C}{\partial\,z}=r+\frac{\partial}{\partial z}(\varepsilon_z\,\frac{\partial C}{\partial z}) \qquad (18)$$

Chamber 1: Settling Basin

Since there is no biofilter media in the detention pool, the sink term in the mass balance of Equation 18 can be neglected. An analytical solution for the resulting relationship was developed by Dobbins (1944) and Camp (1945) using separation-of-variables techniques. This solution requires a constant turbulent diffusion coefficient, no bed scour, and uniform vertical concentration gradient at the inlet. By integrating over the flow depth for a rectangular shaped chamber and by integrating over the duration of time within the filter, the removal efficiency (F) is obtained as (Camp, 1945)

$$F_1 = \frac{QC_i - QC_o}{QC_i} = 1 - 8\,N_p^2\ \exp(N_p) \sum_{i=1}^{\infty} \frac{J_i \exp[-N_h(\beta_i^2 + N_p^2)/(2N_p)]}{\beta_i^2 + N_p^2} \qquad (19)$$

where Q is the volumetric flow rate, C_i is the influent concentration and C_o is the outflow concentration after traveling time equal to the detention time (t_d), N_p is the dimensionless sedimentation Peclet number defined as

$$N_p = \frac{\omega_s h}{2\varepsilon_z} \qquad (20a)$$

where h is the flow depth in the chamber. The Peclet number is a measure of the importance of the turbulence flux relative to that of settling. In Equation 19, N_h is the dimensionless Hazen number defined as

$$N_h = \frac{\omega_s}{h/t_d} = \frac{\omega_s}{\omega_c} \qquad (20b)$$

and is a measure of the settling velocity of a particle of interest relative to that of a particle that, under quiescent settling, would fall the entire flow depth within the detention time. This latter velocity is called the critical fall velocity (ω_c). The terms J_i and β_i in Equation 19 can be obtained from known values of the Peclet and Hazen numbers (Camp 1946).

Solutions of Equation 19 for three different Peclet numbers are shown in Figure 45. Clearly the removal efficiency decreases with larger turbulence fluxes (smaller Peclet numbers) and with smaller particles (smaller Hazen numbers). Cordola-Molina et al. (1978) obtained the following approximation to Equation 19 for a Peclet number of zero (infinite turbulent diffusion coefficient).

$$F_1 = 1 - \exp(-\frac{\omega_s}{\omega_c}) = 1 - \exp(-\frac{\omega_s A}{Q}) \qquad (21)$$

where last term assumes a rectangular chamber of constant depth and of surface area of A. The solution of Equation 21 is also shown in Figure 45. It is an excellent approximation to the solution obtained for $N_p = 0.1$.

For the feedlot model, the removal efficiency of settleable solids is computed directly from Equation 21. This equation assumes plug flow, no gradient in turbulent diffusion coefficient with depth, a rectangular-shaped basin of constant depth, no scour from the bottom, uniform gradient of concentration at the inlet, and highly turbulent flows in the chamber. In application, the surface area is defined directly from the chamber geometry. The average influent concentration is defined using the mass of contaminants divided by the runoff volume from the feedlot, as determined by the MinnFARM predictions. The effluent concentration is obtained by the influent concentration multiplied by 1 - F_1.

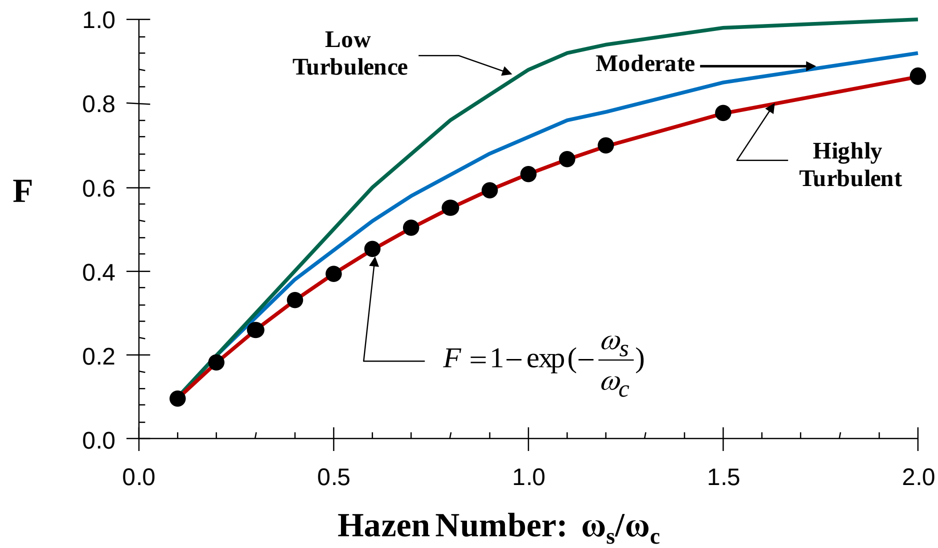

Figure 45. General Solution for Removal Efficiency in Settling Chamber

(after Trimble and Wilson, 2011).

The settling velocity in Equation 21 is estimated using Stokes equation developed for spherical particles with negligible inertia forces during settling. Stokes equation can be written as (Haan et al, 1994)

$$\omega_s = (\frac{g}{18\,\nu})(\rho_s - \rho_w)\, d^2 \qquad (22)$$

where g is the acceleration of gravity, υ is the kinematic viscosity, ρ_s is the density of manure particles, ρ_w is the density of water and d is the effective diameter of manure particles. Within MinnFARM, we applied four kinematic viscosities separately for spring, summer, fall and winter (at average seasonal temperatures 53°C, 71°C, 41°C, and 21°C). Densities of manure particles were taken from Hafez et al. (1974) for beef (five breeds) cattle, dairy cattle, chicken, horses, and swine. In addition to densities, the fractions of manure particles for effective diameters of 2000, 488 and 25 μm were also estimated from this source.

Chamber 2: Biofilter Basin

The mass balance of Equation 18 is applied to the second chamber as well. For this chamber, the settling of contaminants and turbulent flux are neglected. The mass balance equation can then be simplified as

$$\frac{dC}{dt} = r \qquad (23)$$

where r is the average removal rate of concentration during the detention time within the biofilter. This equation is used to determine the concentration of the constituent after it has moved through the biofilter. From this final concentration, the removal efficiency for the biofilter (F_2) is determined as

$$F_2 = \frac{QC_o - QC_f}{QC_o} = 1 - \frac{C_f}{C_o} \qquad (24)$$

where C_o is the influent concentration (corresponding to the effluent from chamber 1) and C_f is the concentration after a detention time exposure (T_d) to the biofilter.

Two different methods were explored to predict the removal rate. The simplest method assumes first-order processes (Shuler and Kargi 1992). For this method, r is defined as

$$r = -\kappa C \qquad (25)$$

where κ is rate coefficient [units 1/T]. Concentration is then defined directly by using Equation 26 and integrating Equation 24 between t = 0; C = C_o and t = T_d; C = C_f , that is,

$$\frac{C_f}{C_o} = \exp(-\kappa\ T_d) \qquad (26)$$

By substituting this result into Equation 25, we obtain the removal efficiency as simply

$$F_2 = 1 - \exp(-\kappa\ T_d) \qquad (27)$$

The other removal model is the logistic model. Here the rate of change in concentration is a function of the overall capacity for reduction. The logistic model can be written as (Shuler and Kargi 1992)

$$r = -\kappa_l\, C\,(C - C_m) = \lambda\, C\,(1 - \frac{C}{C_m}) \qquad (28)$$

where C_m is a minimum concentration at which the rate of removal is zero and λ is a rate coefficient [units 1/T] defined as κ_l C_m. Conceptually, C_m is the concentration in the solution at which there is no potential gradient between the media and the solution.

The final concentration can be obtained for the logistic model by using Equation 29 for r in Equation 24. This relationship can be integrated using partial fraction between t = 0; C = C_o and t = T_d; C = C_f as (Shuler and Kargi 1992)

$$\frac{C_f}{C_o} = \frac{\exp(\lambda\, T_d)}{1 - \frac{C_o}{C_m}[1 - \exp(\lambda T_d)]} = \frac{\exp(\kappa_l C_m T_d)}{1 - \frac{C_o}{C_m}[1 - \exp(\kappa_l C_m T_d)]} \qquad (29)$$

and therefore the corresponding removal efficiency is defined as

$$F_2 = 1 - \frac{\exp(\lambda\, T_d)}{1 - \frac{C_o}{C_m}[1 - \exp(\lambda T_d)]} = 1 - \frac{\exp(\kappa_l C_m T_d)}{1 - \frac{C_o}{C_m}[1 - \exp(\kappa_l C_m T_d)]} \qquad (30)$$

Hydraulic Variables

To simplify the analysis, steady flow for both chambers is assumed. This flow rate is defined using discharge through the outlet pipe for each of the chambers. A single, representative hydraulic head is used for each runoff event. For pipe flow, the flow rate can be defined as (Haan et al., 1994)

$$Q = A\sqrt{\frac{2g(H+H')}{K_e + K_b + K_c L + 1}} \qquad (31)$$

where Q is the pipe flow through the system; A is the cross-section area of pipe, g is the acceleration of gravity; H is head above the crest of the pipe's inlet, H' is the additional elevation corresponding to the difference between the inlet pipe crest and the outlet for no tailwater or an elevation for the adjustment of tailwater depth. The symbol L is the pipe length, K_e is the entrance-loss coefficient, and K_b is the bend-loss coefficient, and K_c is the friction-loss coefficient computed that can be computed from a known pipe diameter and Manning's roughness coefficient (Haan et al., 1994). In Equation 31, the entrance and bend losses have been set to a total value of 1.5.

Detention time is computed for plug-flow conditions as (Haan et al., 1994)

$$T_d = \frac{L}{U} = \frac{V}{Q} \qquad (32)$$

where V is the volume of water in the respective chamber for each rainfall event, U is the average velocity, and Q_p is the discharge of outlet pipe as previously given by Equation 32. Volume is computed as

$$V = L \cdot W \cdot h \cdot \phi \qquad (33)$$

where L, W, and h are the representative length, width, and depth of the chambers and ϕ is the porosity of the biofilter. If the chamber is not rectangular, then the representative dimensions are selected so that the volume matches that of the actual chambers.

Evaluation of Biofilter Algorithm

Description of Observed Data

Since the general use of plug-flow model for computing deposition by settling has been evaluated elsewhere (Wilson and Barfield, 1985), model evaluation is focused on the removal within the biofilter. An important component of this evaluation is the assessment of model accuracy. Unfortunately, the observed data of biofilters from feedlot runoff are quite limited and insufficient observations to independently evaluate parameters and model accuracy.

The experimental site for the observed data is located near Melrose, MN. The data were collected by Bob Guthrie as part of grant activities supported by Minnesota Department of Agriculture. Runoff was obtained from a feedlot with a surface area of approximately 0.4 ha. The feedlot was used by approximately 130 dairy cows. Runoff from the feedlot was directed into a settling basin. The outflow from the settling basin was then diverted into a biofilter. Data were only collected in the biofilter itself. The evaluation of the model for the settling basin was therefore not possible with this data set. The biofilter chamber has a length of 20.4 m and a width of 5.4 m. Wood chips were used as the material for the biofilter. The porosity is estimated at 0.6. Its outlet pipe has length of 1.8 m, diameter of 0.1 m, and Manning's n of approximately 0.024.

Observed data were available for seven runoff events. Key characteristics of these events are summarized in Table 20. Water depths were sampled at several locations during the treatment within the biofilter. Total nitrogen (N) and orthophosphate (P) were measured at different locations. Final concentrations, C_f, were either taken as those measured at the outlet or adjusted proportionally by distance from observations at the middle point. Initial concentrations, C_o, were measured at the biofilter inlet. .

Detention time is an important hydraulic characteristic of the biofilter and is also reported in Table 20. It was estimated directly from Equation 32 for all of the observed events. The biofilter volume was determined using the surface area and the 24-h average depth at the midpoint of the biofilter. Constant outflow rate was computed using the pipe flow relationship given by Equation 31. The 24-h average depth at the midpoint was used to determine H. The sum of K_e and K_b was set at 1.5 to account for energy losses at the pipe's inlet (Haan et al., 1994). The friction loss coefficient, K_c, was calculated as 12.68 m^{-1} from Manning's n (see Haan et al., 1994). The value of H' was set as 0.35 of the diameter.

Estimation of Bio-Chemical Parameters

The decay-rate rate coefficient for the first-order model can be computed directly from Equation 26 using measured influent (C_o) and effluent (C_f) concentrations and estimated detention time. The decay-rate coefficients for nitrogen and phosphorus are given in Table 21. The mean and standard deviation of κ are 0.33 h^{-1} and 0.18 h^{-1}, respectively, for nitrogen and are 0.21 h^{-1} and 0.06 h^{-1}, respectively, for phosphorus.

Relationships between κ and possible independent variables of C_o, precipitation, average flow depths and detention time were investigated using multiple regression techniques. The best predictor variable was found to be C_0. Trends with this variable are shown in Figure 46 and Figure 47. The regression results are summarized in Table 22. No non-standard trends were discernible in the analysis of residuals. The regression relationships represent a marginal improvement over the mean in representing κ. The coefficient of determination is 0.52 for N and 0.32 for P.

The effective decay rate coefficient, λ, for the logistic model can be evaluated using the same approach as that used for the first-order model for a specified minimum concentration (C_m). A value of 1 mg L^{-1} was selected for both nitrogen and phosphorus to investigate possible trends in λ. This value was smaller than all of the observed concentrations in the biofilter. For C_m=1 mg L^{-1} and for the detention times given in Table 20, the effective decay coefficient can be computed directly from measured influent and effluent concentrations using Equation 29. The results for N and P are also given in Table 21. The mean and standard deviation of λ are 0.0153 h^{-1} and 0.0365 h^{-1}, respectively, for nitrogen and are 0.0193 h^{-1} and 0.0163 h^{-1}, respectively, for phosphorus. The variability in this parameter relative to the mean is greater than that obtained for the first-order decay coefficient κ. The deviations for nitrogen are particularly large for the first and last storm in the data set. The influent concentrations were small (< 200 mg L^{-1}) for these two storms.

Trends in λ as a function of independent variables of C_o, precipitation depth, average flow depths and detention time were also explored using multiple regression technique. Once again, the best predictor variable was C_0. Trends with this variable are shown in Figure 48 and Figure 49. The regression results are summarized in Table 22. The regression relationships represent a marginal improvement over the mean in representing λ. The coefficient of determination is 0.50 for N and 0.48 for P.

Table 20. Summary of Events for Biofilter evaluation.

Sample Date	D (ft)	C_0 for N (mg/L)	C_0 for P (mg/L)	T_d
9/15/2008	1.01	188	33.3	4.3
3/6/2009	1.67	705	10.7	5.5
3/14/2009	1.58	637	11.7	5.4
3/16/2009	1.28	454	15.4	4.8
4/3/2009	0.99	525	45.5	4.2
6/19/2009	0.8	367	59.4	3.8
9/10/2009	0.96	54.5	21.66	4.2

Table 21. Estimated parameters for biofilter algorithm.

	First Order Coefficient κ		Logistic Rate Coefficient λ	
Sample Date	N	P	N	P
9/15/2008	0.42	0.14	0.0051	0.0055
3/6/2009	0.23	0.21	0.0007	0.0483
3/14/2009	0.34	0.18	0.0009	0.0218
3/16/2009	0.07	0.24	0.0002	0.0337
4/3/2009	0.22	0.28	0.0006	0.0099
6/19/2009	0.39	0.29	0.0017	0.0073
9/10/2009	0.62	0.14	0.0980	0.0087

Table 22. k and λ relationships with C_0.

Parameter	Chemical	C_0 Range	Relationship
κ	N	50-700	$k = -0.0005C_0 + 0.5534$
	P	10-60	$k = 0.0019C_0 + 0.1585$
λ	N	50-700	$\lambda = -0.0001C_0 + 0.0615$
	P	10-60	$\lambda = -0.0006C_0 + 0.0365$

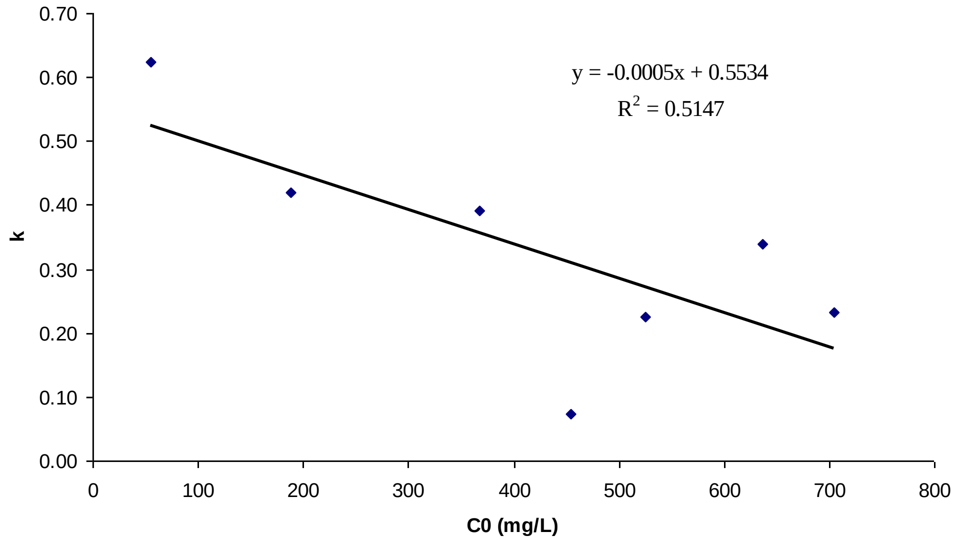

Figure 46. k vs. C0 for the first-order model of N.

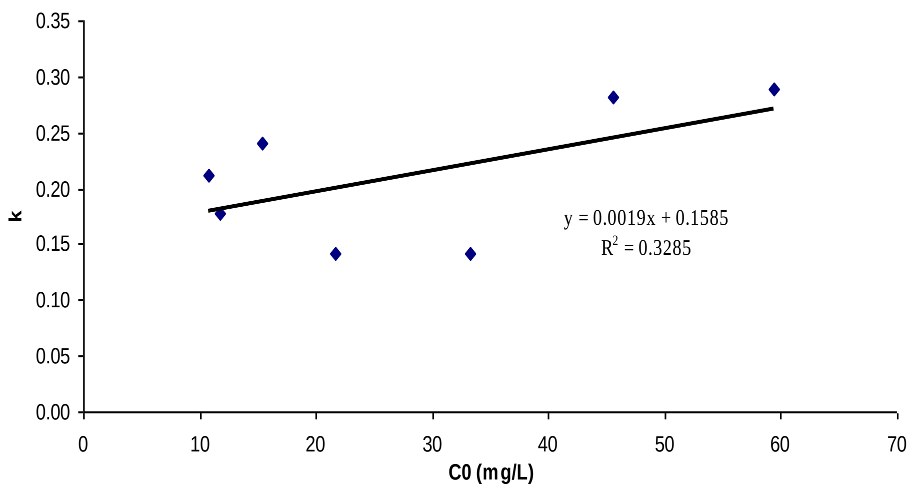

Figure 47. k vs. C0 for the first- model of P

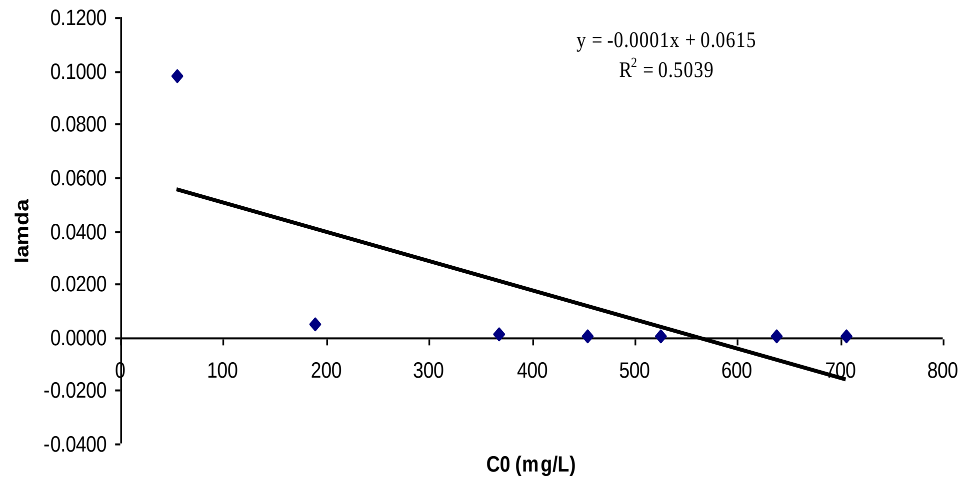

Figure 48. λ vs. C_0 for the logistic model of N

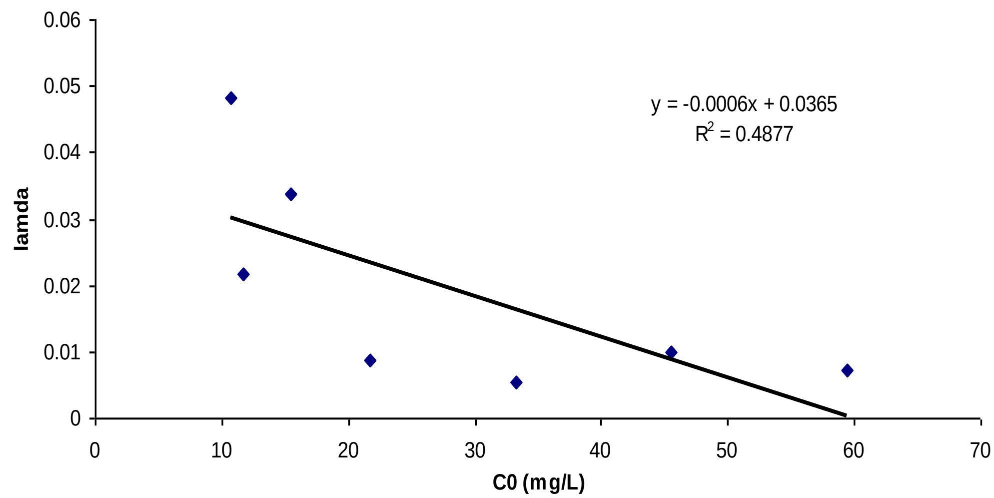

Figure 49. λ vs. C0 for the logistic model of P

Evaluation of Model Accuracy

Model accuracy was assessed by comparing the predicted and observed removal efficiencies. The observed removal efficiencies were computed directly from the observed data. The predicted removal efficiency for the first-order model was computed using Equation 27 and Equation 30 for the logistic model. Detention times and initial concentrations given in Table 20 were used in both predictive models. For the first-order model, the decay-rate coefficients were computed using the regression relationships given in Table 22.

The predicted and observed removal efficiencies are shown in Table 23. With the exception of the event of 3/16/2009, predicted removal efficiencies of nitrogen for the first-order process agreed reasonably well with observed values. The first-order model also performed reasonably well in predicting the removal efficiency of phosphorus. The logistic model poorly predicted the removal efficiencies of nitrogen. The predictive accuracy of the logistic model for phosphorus was better than that obtained for nitrogen but still poorer than the first-order model.

Table 23. Predicted and observed removal efficiency of the biofilter.

Sample Date	Observed Removal Efficiency for N	Removed Efficiency by first-order model for N	Removed Efficiency by logistic model for N	Observed Removal Efficiency for P	Removed Efficiency by first-order model for P	Removed Efficiency by logistic model for P
9/15/2008	0.84	0.88	0.97	0.39	0.64	0.7
3/6/2009	0.72	0.66	1.17	0.68	0.63	0.58
3/14/2009 (mid)	0.59	0.46	1.37	0.38	0.38	0.45
3/16/2009	0.29	0.79	0.97	0.68	0.59	0.64
4/3/2009	0.54	0.69	0.95	0.4	0.63	0.62
6/19/2009	0.63	0.69	0.96	0.59	0.54	0.13
9/10/2009	0.97	0.90	0.92	0.42	0.58	0.67

Objective 4: User friendliness and Observed Data.

It was decided that MinnFARM user friendliness was adequate and no additional changes were made to the user interface. The observed data have been organized in easy to use format and have been given to Minnesota Department of Agriculture as part of the deliverables. Additional details of the data set are given in the appendix.

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Appendix: Site Descriptions and Summary of 179 Rainfall/Runoff Events in Final Validation Data Set

Table 24. Site Descriptions for 24 Feedlots Used in MinnFARM Validation.

Study Name	Feedlot Name	Feedlot Number	Lot Cover	Feedlot Area (square feet)	Slope (if not given, then 1.5)	Other Area	Animal Number (in feedlot contributing runoff - if not given, then = area/50)	Animal Weight (901 pounds if not listed)
Komor	Bock	1	30% concrete	101990	1.5	2367	35	901
Komor	Sanborn	2	48% concrete	58095	1.5	1097	225	901
Swanson	Nebraska 1	9	Dirt	420	8.5	0	8.4	901
Swanson	Nebraska 2	10	Dirt	420	8.5	0	8.4	901
Swanson	Nebraska 3	11	Dirt	420	12.5	0	8.4	901
Swanson	Nebraska 4	12	Dirt	420	13	0	8.4	911
Swanson	natural	13	Dirt	36000	6	0	720	901
Kennedy	NCA 1	14	Dirt	940650	2.5	0	4000	1000
Kennedy	NCA 2	15	Dirt	1734684	2.5	0	7000	1000
Kennedy	NCA 3	16	Dirt	1141466	2.5	0	5000	1000
Kennedy	NCA 4	17	Dirt	769226	2.5	0	3000	1000
Miller	Lethbridge East	18	Dirt	48198	2	5594	240	901
Miller	Lethbridge West	19	Dirt	48198	2	5594	240	901
Ostrem	Haakon	20	Dirt	422310	5	0	665	901
Ostrem	Meade	21	Dirt	779328	1	0	450	901
Ostrem	Miner	22	Dirt	544224	4	0	675	901
Ostrem	Roberts	23	Dirt	132350	4	0	200	901
Platteville	Platteville	24	Concrete	20255	2	2341	72	800
AndersonD	CNIA1	25	100% dirt	221564	1	0	1000	900
AndersonD	CNIA2	26	83% Dirt	115084	1	0	650	900
AndersonD	NWIA1	28	100% dirt	312987	1	0	1400	900
AndersonD	NWIA2	28	concrete	318364	1	0	1400	900
AndersonD	SWIA1	29	100% dirt	805591	1	0	2300	900

AndersonD	SWIA2	30	100% dirt	400107	1	0	1200	900

Table 25. Water Quantity Summary – Final 179-event Data Set

										Assume I_a = 0.2*S to calculate CN		Assume a CN value to calculate I_a	
New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	S (inches)	CN	Assumed CN value	I_a
1	1	1	10	10/23/95	1	rain		0.5906	0.578	0.01	99.89	92.40	-0.45
2	2	1	5	5/5/96	2	rain		0.5512	0.214	0.50	95.23	92.40	0.01
3	3	1	5	5/14/96	3	rain		0.9055	0.236	1.20	89.25	92.40	0.33
4	4	2	7	7/27/96	1	rain		3.5827	0.092	12.34	44.76	93.84	3.29
5	5	2	10	10/17/96	2	rain		1.4173	0.697	0.94	91.42	93.84	0.31
6	46	9	8		1	simulated rain	1	2.7400	1.48	1.56	86.53	90.00	0.52
7		9	8		**2+3**	simulated rain	2	4.5300	1.91	3.72	72.89	90.00	1.83
8	49	10	8		1	simulated rain	1	2.7400	2.28	0.43	95.84	90.00	-0.36
9	50	10	8		2	simulated rain	1	1.5510	1.32	0.21	97.90	90.00	-0.49
10	51	11	8		1	simulated rain	1	2.9800	1.83	1.32	88.37	90.00	0.37
11		11	8		**2+3**	simulated rain	2	4.8400	3.03	2.05	83.00	90.00	0.95
12	54	12	8		1	simulated rain	1	2.9800	2.38	0.58	94.50	90.00	-0.23
13	55	12	8		2	simulated rain	1	2.3480	1.78	0.57	94.61	90.00	-0.21
14	57	13	7	21	2	rain	1	3.5000	2.84	0.63	94.04	90.00	-0.19
15	60	13	7	31	5	rain	1	0.0309	0.00	0.14	98.66	90.00	0.02
16	62	13	8	8	7	rain	1	1.6000	0.07	4.89	67.14	90.00	1.28
17	63	13	8	10	8	rain	1	0.7500	0.27	0.74	93.11	90.00	0.05
18	64	13	8	16	9	rain	1	0.5700	0.03	1.66	85.78	90.00	0.37
19	65	13	8	27	10	rain	1	1.0500	0.47	0.80	92.62	90.00	0.06
20	67	13	9	3	12	rain	1	1.2000	0.28	1.74	85.18	90.00	0.48
21	69	13	9	16	14	rain	1	2.2400	1.60	0.67	93.75	90.00	-0.11

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume I_a = 0.2*S to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
22	70	13	9	17	15	rain	1	0.2000	0.04	0.32	96.87	90.00	-0.03
23	71	13	9	18	16	rain	1	0.7400	0.35	0.52	95.06	90.00	-0.08
24	75	13	10	9	20	rain	1	0.6000	0.21	0.61	94.25	90.00	0.00
25	76	13	10	18	21	rain	1	2.8100	2.47	0.31	97.00	90.00	-0.49
26	79	13	11	14	24	rain	1	0.5000	0.10	0.81	92.53	90.00	0.11
27	99	13	2	27	44	rain	1	0.5400	0.08	1.04	90.56	90.00	0.20
28	100	13	2	28	45	rain	1	0.0700	0.02	0.09	99.14	90.00	-0.09
29	109	13	4	4	54	rain	1	1.5200	0.36	2.18	82.10	90.00	0.68
30		13	4	15-17	**55**	rain	3	3.4300	1.04	4.01	71.37	90.00	1.72
31	115	13	4	26	55	rain	1	0.6900	0.01	2.62	79.26	90.00	0.58
32	118	13	5	2	55	rain	1	0.9100	0.47	0.56	94.72	90.00	-0.08
33		13	5	4-5	**55**	rain	2	0.3100	0.27	0.04	99.64	90.00	-0.39
34	122	13	5	7	55	rain	1	1.2700	0.27	1.97	83.56	90.00	0.57
35	124	13	5	16	55	rain	1	0.6700	0.08	1.44	87.41	90.00	0.33
36	126	13	5	21	55	rain	1	1.5500	1.22	0.32	96.87	90.00	-0.37
37		13	6	11-12	**55**	rain	2	1.8900	0.67	1.90	84.06	90.00	0.63
38	132	13	6	22	55	rain	1	0.4800	0.02	1.49	87.06	90.00	0.32
39	135	13	7	6	55	rain	1	0.6000	0.02	1.96	83.62	90.00	0.44
40		13	7	17-18	**55**	rain	2	1.9300	0.51	2.54	79.74	90.00	0.88
41	146	13	8	20	55	rain	1	0.4700	0.02	1.45	87.35	90.00	0.31
42	148	13	8	31	55	rain	1	1.2900	0.28	1.97	83.54	90.00	0.57
43	151	13	9	10	55	rain	1	0.6700	0.01	2.53	79.81	90.00	0.56

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume I_a = 0.2*S to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
44	155	13	10	19	55	rain	1	0.5000	0.04	1.27	88.74	90.00	0.27
45		13	3	19-20	**55**	rain	2	0.2400	0.03	0.51	95.19	90.00	0.04
46	180	13	4	11	55	rain	1	0.7400	0.37	0.48	95.44	90.00	-0.11
47		13	4	18-19	**55**	rain	2	1.2200	0.63	0.75	93.04	90.00	0.01
48		13	5	11-12	**55**	rain	2	1.6800	0.76	1.26	88.83	90.00	0.31
49	196	13	6	10	55	rain	1	0.6400	0.03	1.92	83.88	90.00	0.44
50	197	13	6	12	55	rain	1	0.8600	0.34	0.76	92.90	90.00	0.05
51		13	6	15-17	**55**	rain	3	0.8800	0.05	2.50	79.99	90.00	0.62
52	202	13	6	19	55	rain	1	0.0800	0.01	0.17	98.34	90.00	-0.03
53	209	13	7	26	55	rain	1	0.5700	0.04	1.52	86.84	90.00	0.34
54	211	13	7	28	55	rain	1	0.5300	0.01	1.93	83.82	90.00	0.42
55	212	13	8	2	55	rain	1	1.7400	0.82	1.23	89.06	90.00	0.29
56	213	13	8	17	55	rain	1	0.9500	0.01	3.76	72.70	90.00	0.84
57	214	13	8	21	55	rain	1	0.5400	0.01	1.97	83.53	90.00	0.43
58	215	13	9	2	55	rain	1	0.8800	0.04	2.66	78.96	90.00	0.65
59		13	9	14-15	**55**	rain	2	2.0700	0.900	1.63	85.96	90.00	0.52
60	221	13	9	23	55	rain	1	0.9000	0.16	1.57	86.46	90.00	0.39
61		13	10	7-9	**55**	rain	3	2.3619	1.180	1.53	86.75	90.00	0.48
62	226	13	10	23	55	rain	1	0.6300	0.01	2.36	80.93	90.00	0.52
63	227	13	10	26	55	rain	1	0.4900	0.17	0.50	95.21	90.00	-0.04
64	238	14	8	08/07/95-08/09/95	1	rain	1	5.7205	1.130	9.31	51.78	90.00	3.90
65	239	14	8	8/26/95	2	rain	1	1.4213	0.002	6.60	60.24	90.00	1.38

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
66	240	14	6	06/17/1996-06/19/1996	3	rain	1	2.2402	0.046	8.03	55.46	90.00	1.99
67	241	15	8	08/24/1993-08/26/1993	1	rain	1	2.1402	0.485	3.17	75.93	90.00	1.12
68	242	15	9	09/11/1993-09/12/1993	2	rain	1	2.2799	0.531	3.31	75.12	90.00	1.20
69	243	15	5	05/31/1994-06/02/1994	3	rain	1	4.4701	1.061	6.40	60.98	90.00	2.73
70	244	15	6	6/11/1994-06/14/1994	4	rain	1	4.3799	0.728	7.93	55.78	90.00	3.05
71	245	15	7	07/01/1994-07/06/1994	5	rain	1	7.3201	2.636	7.22	58.06	90.00	3.84
72	246	15	8	08/05/1994-08/07/1994	6	rain	1	4.6701	1.420	5.45	64.73	90.00	2.52
73	247	15	8	08/07/1994-08/09/1994	7	rain	1	0.8701	0.286	0.94	91.38	90.00	0.15
74	248	15	8	08/16/1994-08/17/1994	8	rain	1	4.1500	2.090	2.65	79.05	90.00	1.26
75	249	15	7	07/25/1995-08/02/1995	9	rain	1	3.8504	2.065	2.22	81.86	90.00	0.99
76	250	15	8	08/07/1995-08/12/1995	10	rain	1	6.0394	3.094	3.75	72.72	90.00	2.08
77	251	15	8	08/26/1995-08/27/1995	11	rain	1	1.4213	0.331	2.06	82.89	90.00	0.63
78	252	15	6	06/17/1996-06/19/1996	12	rain	1	2.2402	0.867	2.04	83.06	90.00	0.73
79	253	15	7	07/01/1996-07/02/1996	13	rain	1	0.9921	0.301	1.16	89.60	90.00	0.24
80	254	15	7	07/10/1996-07/11/1996	14	rain	1	1.7008	1.094	0.68	93.67	90.00	-0.08
81	255	16	8	8/14/93	1	rain	1	0.9201	0.040	2.82	78.02	90.00	0.69
82	256	16	8	08/23/1993-08/26/1993	2	rain	1	2.2902	0.617	2.97	77.10	90.00	1.10
83	257	16	9	09/11/1993-09/13/1993	3	rain	1	2.2799	0.888	2.06	82.92	90.00	0.75
84	258	16	5	05/29/1994-05/31/1994	4	rain	1	0.2902	0.276	0.01	99.88	90.00	-0.42
85	259	16	5	05/31/1994-06/02/1994	5	rain	1	4.4701	1.326	5.33	65.22	90.00	2.42
86	260	16	6	06/11/1994-06/17/1994	6	rain	1	4.4898	1.696	4.20	70.41	90.00	2.03
87	261	16	6	06/18/1994-06/29/1994	7	rain	1	0.7098	0.353	0.46	95.58	90.00	-0.12

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
88	262	16	7	07/01/1994-07/06/1994	8	rain	1	7.3201	2.566	7.43	57.37	90.00	3.92
89	263	16	8	08/05/1994-08/06/1994	9	rain	1	4.6701	1.312	5.84	63.12	90.00	2.64
90	264	16	8	08/07/1994-08/09/1994	10	rain	1	0.8701	0.016	3.17	75.92	90.00	0.73
91	265	16	8	08/16/1994-08/18/1994	11	rain	1	4.1500	0.938	6.16	61.88	90.00	2.56
92	266	16	8	08/07/1995-08/09/1995	12	rain	1	6.2205	4.543	1.72	85.29	90.00	0.75
93	267	16	6	06/17/1996-06/19/1996	13	rain	1	2.2402	0.505	3.33	75.00	90.00	1.20
94	268	16	6	06/30/1996-07/02/1996	14	rain	1	1.1417	0.769	0.40	96.13	90.00	-0.24
95	269	16	8	08/13/1996-08/18/1996	15	rain	1	7.8701	0.298	24.96	28.60	90.00	7.13
96	270	17	8	8/26/96	1	rain	1	1.5787	0.066	4.88	67.19	90.00	1.27
97	271	17	8	08/31/1996-09/02/1996	2	rain	1	0.0551	0.005	0.13	98.68	90.00	-0.02
98	272	17	6	6/17/96	3	rain	1	1.3386	0.045	4.36	69.64	90.00	1.09
99	273	18	6		1	rain	1	1.1024	0.059	3.19	75.82	90.00	0.81
100	274	18	6		2	rain	1	1.3622	0.504	1.31	88.46	90.00	0.32
101	275	18	6		3	rain	1	1.5197	0.008	6.45	60.78	90.00	1.42
102	276	18	6		4	rain	1	1.1969	0.528	0.93	91.51	90.00	0.12
103	277	18	7		5	rain	1	0.6772	0.228	0.72	93.33	90.00	0.05
104	278	18	7		6	rain	1	0.4803	0.004	1.95	83.66	90.00	0.41
105	279	18	5		7	rain	1	1.5827	0.002	7.31	57.77	90.00	1.53
106	280	18	6		8	rain	1	1.3780	0.110	3.50	74.09	90.00	0.97
107	281	18	7		9	rain	1	1.3858	0.323	2.01	83.25	90.00	0.60
108	282	18	9		10	rain	1	1.6220	0.035	5.76	63.45	90.00	1.41
109	283	19	6		1	rain	1	1.1024	0.102	2.64	79.10	90.00	0.71

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
110	284	19	6		2	rain	1	1.3622	0.591	1.08	90.26	90.00	0.20
111	285	19	6		3	rain	1	1.5197	0.024	5.70	63.68	90.00	1.35
112	286	19	6		4	rain	1	1.1969	0.469	1.08	90.29	90.00	0.20
113	287	19	7		5	rain	1	0.6772	0.374	0.37	96.43	90.00	-0.18
114	288	19	7		6	rain	1	0.4803	0.047	1.12	89.89	90.00	0.23
115	289	19	5		7	rain	1	1.5827	0.004	7.07	58.58	90.00	1.51
116	290	19	6		8	rain	1	1.3780	0.130	3.28	75.28	90.00	0.93
117	291	19	7		9	rain	1	1.3858	0.024	5.13	66.10	90.00	1.21
118	292	19	9		10	rain	1	1.6220	0.154	3.86	72.16	90.00	1.13
119	325	21	5	5/24/08	14	rain	2	1.6142	0.324	2.60	79.38	90.00	0.83
120	326	21	5	5/27/08	15	rain	2	1.3386	0.159	2.89	77.59	90.00	0.83
121	383	24	8	8/6/06	8	rain	1	0.7480	0.616	0.13	98.76	98.00	-0.03
122	384	24	8	8/13/06	9	rain	1	0.3240	0.234	0.09	99.08	98.00	-0.04
123	385	24	9	9/3/06	10	rain	1	0.6310	0.384	0.28	97.24	98.00	0.10
124	386	24	9	9/4/06	11	rain	1	0.4230	0.299	0.13	98.72	98.00	-0.02
125	388	24	10	10/17/06	13	rain	1	0.3240	0.17	0.19	98.17	98.00	0.03
126	390	24	11	11/26/06	15	rain	1	0.2520	0.11	0.20	98.00	98.00	0.04
127	391	24	11	11/27/06	16	rain	1	1.1300	1.12	0.01	99.94	98.00	-0.17
128	392	24	11	11/29/06	17	rain	1	0.2790	0.25	0.02	99.78	98.00	-0.11
129	393	24	4	4/24/07	18	rain	1	1.5480	1.31	0.22	97.81	98.00	0.06
130	394	24	7	7/3/07	19	rain	1	1.3300	0.94	0.40	96.13	98.00	0.21
131	408	25	8	8/6/06	6	rain	*	0.50	0.026	1.46	87.30	90.00	0.32

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
132	409	25	8	8/10/06	7	rain	*	1.53	0.217	3.02	76.79	90.00	0.92
133		25	9	9/16/06-9/17/06		rain	2	1.87	1.05	0.98	91.03	90.00	0.14
134	474	25	9	9/24/07	73	rain	*	0.95	0.105	2.11	82.55	90.00	0.55
135		25	10	10/10/07-10/12/07		rain	3	1.00	0.408	0.86	92.12	90.00	0.09
136	482	25	10	10/13/07	81	rain	*	0.10	0.014	0.20	98.04	90.00	-0.03
137	483	25	10	10/15/07	82	rain	*	1.62	0.175	3.64	73.30	90.00	1.08
138	484	25	10	10/19/07	83	rain	*	0.69	0.097	1.37	87.95	90.00	0.31
139	503	25	5	5/10/08	103	rain	*	0.58	0.257	0.45	95.73	90.00	-0.10
140	511	25	5	5/26/08	111	rain	*	0.89	0.366	0.75	92.99	90.00	0.04
141		25	6	6/7/08-6/8/08	114	rain	*	3.41	2.095	1.50	86.92	90.00	0.51
142		25	10	9/29/08-10/3/08		rain	5	1.05	0.75	0.32	96.94	90.00	-0.31
143		26	4	4/24/07-4/25/07		rain	2	4.50	0.423	10.73	48.23	91.36	3.62
144	607	26	5	5/27/08	33	rain	*	0.43	0.013	1.44	87.41	91.36	0.31
145	609	26	6	6/8/08	35	rain	*	1.17	0.153	2.41	80.58	91.36	0.71
146	610	26	6	6/12/08	36	rain	*	2.43	0.198	6.13	62.01	91.36	1.89
147	625	26	6	6/23/09 - 6/26/09	51	rain	*	0.73	0.191	0.97	91.15	91.36	0.20
148	627	26	7	7/13/09 - 7/17/09	53	rain	*	0.54	0.286	0.32	96.92	91.36	-0.14
149	632	26	10	10/6/09 - 10/12/09	58	rain	*	0.15	0.092	0.07	99.34	91.36	-0.19
150		27	5	5/5/07-5/8/07		rain	4	0.97	0.67	0.32	96.86	90.00	-0.29
151		27	6	6/21/07-6/22/07		rain	2	0.88	0.69	0.18	98.21	90.00	-0.41
152	674	27	8	8/30/07	55	rain	*	0.65	0.352	0.37	96.45	90.00	-0.18
153		27	9	9/12/07-9/13/07		rain	2	0.35	0.21	0.17	98.35	90.00	-0.24

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
154	703	27	5	5/12/08	90	rain	*	0.27	0.043	0.50	95.21	90.00	0.03
155	730	27	9	9/5/08	126	rain	*	0.09	0.010	0.20	98.03	90.00	-0.02
156	731	27	9	9/6/08	127	rain	*	0.02	0.004	0.03	99.66	90.00	-0.05
157	734	27	9	9/13/08	130	rain	*	0.18	0.021	0.39	96.27	90.00	0.01
158		27	6	6/16/09-6/17/09		rain	2	1.095	0.493	0.83	92.37	90.00	0.07
159	781	28	8	8/5/06	5	rain	*	0.74	0.448	0.34	96.74	98.00	0.14
160		28	9	9/15/06-9/16/06		rain	2	2.53	2.18	0.33	96.85	98.00	0.16
161	803	28	8	8/18/07	27	rain	*	0.80	0.347	0.63	94.05	98.00	0.31
162	804	28	8	8/20/07	28	rain	*	1.80	1.299	0.52	95.06	98.00	0.32
163		28	9	9/2/07-9/3/2007		rain	*	0.63	0.29	0.47	95.54	98.00	0.21
164	824	28	4	4/26/08	48	rain	*	0.60	0.234	0.54	94.85	98.00	0.24
165		28	6	6/3/08-6/4/08		rain	2	1.33	0.62	0.94	91.37	98.00	0.54
166		28	6	6/5/08-6/6/08		rain	2	1.48	0.47	1.67	85.68	98.00	0.86
167		28	6	6/28/08-6/29/08		rain	2	1.20	0.70	0.59	94.43	98.00	0.33
168	847	28	7	7/24/08	71	rain	*	0.68	0.267	0.61	94.27	98.00	0.28
169	851	28	9	9/29/08	75	rain	*	0.20	0.010	0.58	94.50	98.00	0.15
170	855	28	10	10/17/08	79	rain	*	0.19	0.012	0.53	94.98	98.00	0.14
171	861	28	4	4/30/09	85	rain	*	0.46	0.140	0.54	94.91	98.00	0.21
172	868	28	6	6/24/09	92	rain	*	0.10	0.018	0.17	98.33	98.00	0.03
173	884	29	5	5/30/2008*	22	rain	*	1.82	1.381	0.44	95.79	90.00	-0.29
174		29	6	6/11/08-6/13/08		rain	3	3.09	2.797	0.26	97.46	90.00	-0.56
175	942	30	8	8/24/07	9	rain	*	1.66	0.375	2.46	80.23	90.00	0.80

New Event ID	Original Event ID	Feedlot Number	Month	Day or Date		Storm Type	Event Duration (days)	Precipitation (inches)	Measured Runoff (inches)	Assume $I_a = 0.2*S$ to calculate CN		Assume a CN value to calculate I_a	
										S (inches)	CN	Assumed CN value	I_a
176		30	9	9/16/08 - 9/20/08		rain	5	1.79	1.230	0.60	94.36	90.00	-0.15
177	971	30	5	5/12/2009 - 5/14/2009	40	rain	*	0.89	0.259	1.08	90.26	90.00	0.21
178		30	5	5/15/09-5/20/09		rain	6	1.62	1.189	0.44	95.77	90.00	-0.27
179	979	30	8	8/19/2009 - 8/20/2009	48	rain	*	0.88	0.636	0.25	97.54	90.00	-0.34