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Modeling the performance of runoff control systems on open beef feedlots in Iowa

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by

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ABSTRACT

Runoff from open feedlots has the potential to cause degradation of surface and groundwater if handled improperly. Due to this pollution potential, the United State Environmental Protection Agency (US EPA) regulates runoff control systems on concentrated animal feeding operation (CAFO) sized feedlots. For the first time, the 2003 effluent limitation guidelines allowed consideration of alternative manure treatment systems for National Pollutant Discharge Elimination System (NPDES) permitted CAFO operations. Concentrated animal feeding operations that utilize alternative manure treatment systems under an NPDES permit are required to demonstrate, through modeling, that their alternative runoff control system had an equal or lesser nutrient mass release than a conventional manure management system would. This permitting requirement renewed interest in the modeling of traditional containment systems and generated interest in modeling “alternative technology” systems. One possible “alternative technology” systems being considered are vegetative treatment systems (VTS). A VTS is defined as a runoff control system that uses a series of treatment components, at least one of which uses vegetation, to treat open lot runoff. In particular, much of the VTS research thus far has focused on vegetative treatment areas (VTA’s). A VTA is an area planted to permanent vegetation that reduces pollutant transport via sedimentation, filtration, and infiltration of the feedlot runoff. This modeling requirement led to the development of the Iowa State University (ISU) – Effluent Limitations Guidelines (ELG) model and the ISU – VTA model, which predict the performance of traditional containment systems and of vegetative treatment area systems, respectively.

This thesis reviews the accuracy of the ISU-ELG model by comparing the modeled runoff control performance of a traditional containment system to that predicted by the Soil-Plant-Air-Water (SPAW) model. Specifically, the criterion used to determine if a particular day is a “dewatering day,” i.e., suitable for land application of basin effluent, is investigated to determine its effect on basin performance, with the objective of verifying that the ISU-ELG model is providing a reasonable prediction of the runoff control provided by a containment basin in Iowa.

The ISU-ELG model is based on a model developed by Koelliker et al. (1975) to predict the performance of a holding basin at controlling feedlot runoff and uses a set of general criteria to determine if land application is acceptable, while the SPAW model uses a soil moisture criterion to determine if conditions are acceptable for land application. The results show that the ISU-ELG model over-predicts performance of traditional containment systems in comparison to the SPAW model at all five Iowa locations investigated. For wetter areas in Iowa, the number of drying days has a large affect on basin performance, whereas for the drier northwest region of Iowa this affect is limited. Possible methods of improving the ISU-ELG model predictions include adding a soil moisture accounting function to model moisture levels in the land application area or calibrating the number of drying days required before land application can commence.

In addition to modeling traditional containment systems, this thesis also examines possible methods of modeling VTA's, as previous research has shown that the ISU-VTA model greatly over-predicts VTA performance. In this study, two different approaches, both using the SPAW model, were investigated to determine their ability to predict hydraulic performance of the vegetative treatment areas (VTA's). Three of the four locations used in this study had a high water table; this water table elevation limited the space available in the soil profile to infiltrate and store water. For these locations, the performance of the VTA was limited by the storage available in the soil profile and SPAW simulations provided a realistic prediction of the monitored results. Modeling results verified that for these locations VTA performance was limited by the space available in the soil profile. Modeling statistics were calculated to determine the model's ability to predict VTA performance. For the four locations investigated, Nash-Sutcliffe efficiencies ranged from 0.45 to 0.99 while the percent bias of the model ranged from -3% to 100%. The results show that the SPAW pond module can be used to determine if VTA performance will be limited by presence of a high water table. Additionally, these methods provided insight into possible modifications to improve the performance of the ISU-VTA model.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Runoff from open lot animal feeding operations has long been recognized as a potential pollutant to receiving surface waters, as this effluent is known to contain nutrients such as nitrogen and phosphorus, as well as other potential pollutants such as organic matter, solids, and pathogens. In 1972, Congress passed the Clean Water Act, which authorized the Environmental Protection Agency (EPA) to develop regulations for the maintenance of water quality throughout the United States. This led to classification of feedlot runoff as a potential point source pollutant; as a result, feedlots were required to implement management practices to minimize the risk of the runoff effluent reaching surface waters. Specifically a set of standards, the feedlot Effluent Limitation Guidelines (ELG's), were developed. The ELG's contained specific guidelines detailing the level of runoff control required of all Concentrated Animal Feeding Operation (CAFO) sized operations. A CAFO was defined as a facility with more than 1,000 animal units (AU) for at least 45 days a year kept on areas without permanent vegetation (Federal Register, 2003). In addition, medium and small operations can also be classified as CAFO's if the facility discharges directly to a water of the United States, discharges through a manmade conveyance to a water of the United States, or if the facility is deemed a "significant pollution contributor" (Sweeten et al., 2003). The size required for an operation to be deemed a CAFO is shown in Table 1. Although non-CAFO operations are not required to meet the standards specified in the ELG's, they are required to meet any state regulations.

Table 1. CAFO sizes for different animal types from Federal Register (2003).

Animal Type	Large	Medium	Small
Cattle or Cow/Calf Pair	1,000 or more	300-999	1-299
Mature Dairy	700 or more	200-699	1-199
Veal Calves	1,000 or more	300-999	1-299
Swine (over 25 kg)	2,500 or more	750-2499	1-749
Swine (less than 25 kg)	10,000 or more	3,000-9,999	1-2,999

All facilities designated as CAFO's are required to apply for a National Pollutant Discharge Elimination System (NPDES) permit. This permit requires the producers to have no discharge from the feedlot or effluent control system except under the terms of the permit. As a minimum performance level, the NPDES permit requires all manure, wastewater, and process generated effluent be contained; in addition the runoff control facility must contain all runoff generated from the feedlot area by the 25-year, 24-hour storm (Federal Register, 2003). Traditionally, this required a holding pond be used to catch and contain all the runoff effluent. This effluent was then land applied as a final means of disposal. However, recently the ELG's were updated to allow the use of alternative runoff control options that are capable of providing performance equivalent to that provided by a traditional containment basin runoff control system. Current regulations require producers wishing to utilize an alternative waste control system to perform site-specific modeling of the performance of both a traditional containment system and the proposed alternative treatment system. This alternative treatment option has renewed interest in modeling the performance of both traditional containment systems as well as alternative treatment technologies.

Vegetative treatment systems have been identified as one possible alternative control system that could be used to treat feedlot runoff. Koelsch et al. (2006) defined a vegetative treatment system (VTS) as a combination of components, at least one of which uses vegetation, to manage and treat open lot runoff. Thus far, research has primarily focused on two different vegetative treatment components, these being vegetative treatment areas (VTA's) and vegetative infiltration basins (VIB's). A VTA is an area planted and maintained to dense vegetation for the purpose of treating runoff effluent (Moody et al., 2006). Typically, this area is flat in one dimension (width) with a slight slope (less than 5%) in the other dimension (length). The system is operated by releasing runoff effluent evenly along the top of the treatment area and allowing the effluent to flow down the length of the slope (Moody et al., 2006). The effluent is treated by both filtration as effluent flows through the vegetation and via infiltration as water enters the soil profile. Gross and Henry (2007) developed a modification to the VTA in which sprinklers are utilized to evenly apply the effluent to the treatment area.

A VIB is a flat area surrounded by berms with tile lines approximately four feet below the surface (Moody et al., 2006). Again, this area is planted to permanent vegetation. In this case, all the effluent is treated via infiltration into the soil profile. The tile lines intercept the effluent infiltrating through the soil profile; this effluent is then sent to an additional treatment component, usually a VTA.

In addition to the modeling requirement for CAFO operations wishing to utilize alternative treatment technologies, modeling also plays a key role in designing runoff control systems. Previously Wulf and Lorimor (2005) developed three models to aid producers in designing both traditional containment runoff control systems and vegetative treatment systems. These models include the Iowa State University – Effluent Limitations Guideline Model (ISU-ELG Model), the Iowa State University – Vegetative Treatment Area Model (ISU-VTA Model), and the Iowa State University – Vegetative Infiltration Basin / Vegetative Treatment Area Model (ISU-VIB/VTA Model). These models were utilized in designing and permitting VTS systems throughout the state of Iowa, specifically six VTS systems designated as “pilot systems.” These six locations have been monitored by Iowa State University for approximately two years, with a third year of monitoring currently being conducted. Moody et al. (2006) and Khanijo (2008) provide descriptions of the monitoring methodologies use to determine the performance of the vegetative treatment systems. This monitoring has provided the data necessary to validate both the ISU-VTA and the ISU-VIB/VTA models. Khanijo et al. (2007) reported that both of these models over-predicted the performance of the VTS in comparison to the performance monitored under actual field conditions. Based on these results it was determined that further review and modification of the ISU models was required to improve model performance.

Objectives

The objectives of this research focus on modeling both traditional containment systems as well as vegetative treatment system for control of open lot runoff under Iowa conditions. These models serve as both a permitting tool for runoff control systems on CAFO sized operations as well as a design tool for operations of all sizes. Thus, it is essential that these tools be further developed so that they provide realistic simulations of the waste control systems.

The objectives of this study are:

1. Evaluate the ISU-ELG Model's ability to predict the runoff control performance of a containment basin receiving open lot runoff under Iowa climatic and hydrological conditions.
2. Determine the ability of the Soil-Plant-Air-Water (SPAW) model to serve as a tool for the design and evaluation of vegetative treatment areas.
3. Based on the SPAW model results develop design and siting recommendations for vegetative treatment systems.

Thesis Organization

The research presented in this thesis is comprised of two papers, each corresponding to specific research objectives. The first paper entitled "Comparison of the Iowa State University – Effluent Limitation Guidelines Model with the Soil-Plant-Air Water Model to Describe Holding Basin Performance" has been submitted to the *Transactions of the ASABE*. The second paper, "The Use of the Soil-Plant-Air-Water Model to Predict Hydraulic Performance of a Vegetative Treatment Areas for Controlling Open Lot Runoff" will be submitted to *Transactions of the ASABE*

Literature Review

The beef industry is an important part of the state economy of Iowa, representing one of the states major economic activities (Lawrence et al., 2006). For example, in 2005, over $2.4 billion in cattle sales was reported; furthermore, it is estimated that the cattle industry contributed $5.1 billion to the Iowa economy (Iowa

Beef Industry Council, 2007) with approximately one million head of cattle on feed (Lawrence and Otto, 2006). Thus, the cattle feeding industry plays an important role in adding value to the agricultural products of Iowa.

Feedlots in Iowa typically utilize one of five designs: an earthen lot with windbreaks, an earthen lot with a shed, a concrete lot with a shed, a confinement building with a solid floor, or a confinement building with a slatted floor (Lawrence et al., 2006). Obviously, the choice of feedlot design has a large effect on the type of manure and waste management system that can best be utilized. For example, in a solid-floor confinement building, the floor is bedded and all manure is handled as a solid manure-bedding pack, where as for a slotted-floor confinement building the manure falls through the floor and into a storage pit where it is handled as manure slurry. Open feedlots must deal with waste in both solid and liquid form. The solid manure is a result of animal defecation on the feedlot surface and is collected on a periodic basis, while liquid waste is generated when rainfall that falls directly onto the feedlot surface is of sufficient size to cause a runoff event. Thus, no matter what feedlot design is selected, some form of manure management system is required. Usually, the manure is utilized as a source of nutrients for crop production.

For larger feedlot operations, this requires development of a nutrient management plan that describes the timing, rate, and method with which manure application should occur. The rate of manure application has traditionally been determined on a nitrogen basis, although recently many states have initiated a phosphorus index to determine if the amount phosphorus applied should limit the application rate. Although land disposal works well for manures with a high nutrient concentration to volume ratio, for relatively dilute nutrient sources land application is not as economical due to the cost associated with transport of the waste to land application areas. Thus, although land application of solids and manure slurry is economically justifiable, the costs associated with handling more dilute nutrient sources such feedlot runoff quickly escalates.

Event though feedlot runoff is a relatively dilute source of nutrients as compared to solid waste, it still contains nutrients such as phosphorus and nitrogen, as well as solids, organic matter, and pathogens (Blume, 2006) in sufficient quantities that it would be a source of pollution if released to surface waters. As such, producers of all sizes are facing greater pressures to be proactive in their approaches to managing feedlot runoff. For instance, CAFO sized operations are required to apply for and meet the requirements of a National Pollution Discharge Elimination System (NPDES) permit if they discharge. Specifically, this permit requires that the waste management system be designed and operated to prevent release of any manure, wastewater, or runoff effluent except from storms in excess of the 25-year, 24-hour event (Melvin, 2007). Although smaller lots are not yet facing these strict regulations, these lots are still interested in technologies that lessen their pollution potential (Blume, 2006). Murphy and Harner (2001) discuss several different types of runoff control systems for open lots of all sizes; these include containment systems and vegetative treatment systems. Examples of containment systems include lagoons, holding ponds, and evaporation ponds, while examples of vegetative systems include wetlands, infiltration areas, and grass filters. Furthermore, Hanna et al. (2007) state that as a minimum level of control all open lots are recommended to have a settling basin.

When considering what manure management system to implement, several factors need to be considered, these include state and national regulations, the number of animal units on the facility, the pollution potential of the lot (i.e. the proximity to ground and surface water), the climate of the region, and the level of management desired. In addition to these factors, the overall economics of the waste management system are of extreme importance and often become the driving factor for system selection.

Thus, although all feedlot designs and management options should be considered when planning for a particular feedlot, this thesis focuses specifically on modeling the performance of manure management systems designed to control runoff from open feedlots. The process of modeling and understanding the performance of these manure management systems can be broken down into several components. First, both the amount and quality of the feedlot runoff must be determined. These values are important as they provide information on how much effluent must be handled and as well as any limitations on how the effluent must be handled. From here, the hydrology of the runoff control system becomes of upmost importance, as the first step in modeling these systems is to determine the amount and rate at which effluent is moving through the system. After these processes have been determined, the change in pollutant content as the effluent travels through each treatment component can then be predicted. The literature review is broken down by first looking at the quality and quantity of runoff from the feedlot surface and then is followed by available information on different treatment components typically used in controlling feedlot runoff.

Feedlot Runoff Quality and Quantity

Design of runoff control systems for open feedlots requires an understanding of both the expected amount of runoff effluent and the chemical and physical properties of this effluent. An understanding of these properties provides the primary information necessary to design effective waste management systems as well as the information necessary to predict how the effluent is modified, both in volume as well as in quality, by different treatment components. Specifically, an understanding of the physical properties of the runoff effluent is required to develop sedimentation techniques for improving runoff quality, while an understanding of chemical properties is required to determine the affect different treatment options will have on the nutrient content in the runoff effluent.

Several different approaches have been used to determine the properties of runoff effluent. These include sampling effluent that was running off the feedlot surface (Gilbertson and Nienaber, 1973), sampling fresh feces to determine particle size distributions (Chang and Rible, 1975), sampling fresh feces and manure from feedlot pens to determine settling velocities of the manure particles (Lott et al., 1994), and determining the effects that different solids concentrations have on the settling velocity of manures particles (Moore et al., 1975). In addition to these studies, which focused primarily on the physical properties of the feedlot runoff, many other studies have focused on the chemical properties of the feedlot runoff

(Woodbury et al., 2003; Lorimor et al., 2005; Miner et al., 1980; Westerman and Overcash, 1980; Clark et al., 1975). A summary of the chemical properties typical of feedlot runoff is provided in Table 2. As can be seen there is a large variability in most of the properties with standard deviations being approximately half the average reported concentration. Although these data are quite variable, they still provide reasonable values that can be expected for feedlot runoff. Of note are total solids concentrations ranging from 3,000 mg/L to 17,500 mg/L and chemical oxygen demands of approximately 2,000 to 18,000 mg/L. This data set shows a correlation between the total solids concentration and COD concentration. This correlation is shown in Figure 1. This would seem to indicate approximately a one-to-one correspondence between the chemical oxygen demand and volatile solids, with the offset presumably from dissolved solids in the effluent, which do not contribute to the chemical oxygen demand.

Table 2. Summary chemical properties of feedlot runoff effluent from different facilities.

Location	Total Solids mg/L	COD mg/L	Total-N mg/L	TKN mg/L	Total-P mg/L	EC mmhos/cm
Bellville, TX[a]	9,000	4,000	85	--	85	--
Bushland, TX[a]	15,000	15,700	1,080	--	205	8
Ft. Collins, CO[a]	17,500	17,800	--	--	93	9
McKinney, TX[a]	11,430	7,210	--	--	69	7
Mead, NE[a]	15,200	3,100	--	--	300	3
Pratt, KS[a]	7,500	5,000	--	--	50	5
Sioux Falls, SD[a]	2,990	2,160	--	--	47	--
Clay Center, NE[b]	4,801	4,770	--	--	--	--
Boone, IA[c]	11,200	--	--	440	18	--
Ohio[d]	17,100	19,900	--	741	118	--
Ames, IA[e]	3,341	--	--	221	79	--
Average	10,460	8,849	583	467	106	6
Standard Deviation	5,363	6,934	704	261	85	2
Coefficient of Variation	0.51	0.78	1.21	0.56	0.84	0.35

[a] From Clark et al. (1975)
[b] From Woodbury et al. (2003)
[c] From Lorimor et al. (2005)
[d] From Edwards et al. (1986)
[e] From Lorimor et al. (2003)

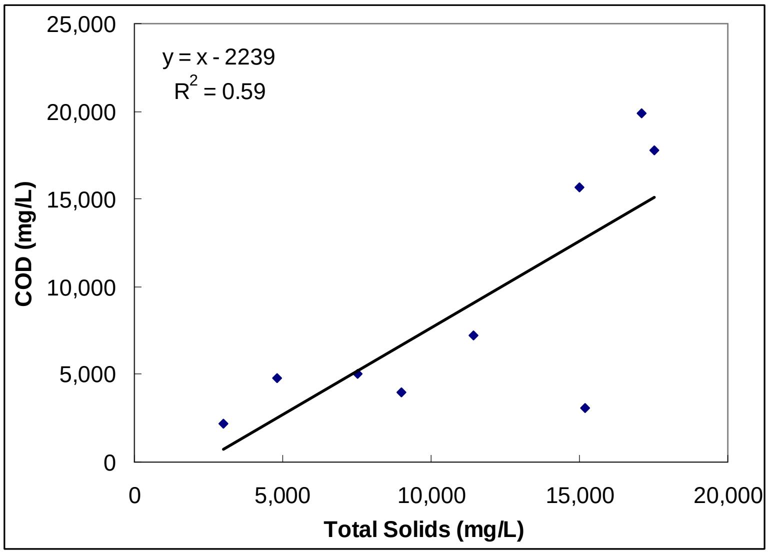

Figure 1. Correlation between the COD concentration and the total solids concentration.

In addition to the between farm variability of chemical properties of the feedlot runoff show in Table 2, the data sets of Woodbury et al. (2003) and Lorimor et al. (2005) allow the assessment of the on farm variability of feedlot runoff chemical properties. The maximum, minimum, average, and standard deviation for the data sets is displayed in Table 3. As can be seen, the chemical properties were again quite variable, more so for the Lorimor et al. (2005) data set than the Woodbury et al. (2003)set. Based on the Woodbury et al. (2003) data set, both suspended and fixed solids, as well as the chemical oxygen demand all had coefficients of variation of approximately 0.5. The Lorimor et al. (2005) data showed substantially more variation in the transport of total solids with the coefficient of variability for total solids of 0.8 and for total Kjeldahl nitrogen of 1.65. Based on this data, it would appear that the variability of chemical properties between farms is equal to or less than the variability of the chemical properties of the effluent from different runoff events on a single farm. A similar finding was reported by Sweeten (1990) for runoff effluent from Texas feedlots that was stored in holding ponds. In this study, Sweeten reported chemical concentrations in the holding ponds varied widely between feedlots as well as temporally on a given feedlot.

Table 3. Summary of variability of chemical properties of feedlot runoff from different runoff events on two different facilities.

	Woodbury et al. (2003)			Lorimor et al. (2005)			
	TSS mg/L	VS mg/L	COD mg/L	Total Solids mg/L	TKN mg/L	P mg/L	K mg/L
Minimum	1,900	370	790	3,300	74	66	378
Maximum	8,500	3,390	7,920	25,000	1,730	92	570
Average	4,689	1,415	4,770	11,200	440	79	474
Standard Deviation	2,154	761	2,463	9,000	724	18	136
Coefficient of Variation	0.46	0.54	0.52	0.80	1.65	0.23	0.29

Several authors have reported runoff quality variation as a function of feedlot hydrology (Koelliker et al., 1975; Gilbertson et al., 1975; Clark, 1975). This variation in runoff quality is reported to be due to the ration feed, the type of feedlot surface, the climate, the antecedent moisture conditions of the feedlot surface, and the storm intensity and duration. However, few correlations are available to predict quality based on these variables (Sweeten, 1990).

In addition to the chemical properties of the runoff effluent, which are important for determining the appropriate application rates for crop use, the physical properties of the effluent have also been studied. These physical properties are important for determining the effectiveness of sedimentation techniques at improving effluent quality. Gilbertson and Nienaber (1973) performed one of the earliest studies on the physical properties of runoff effluent. In these studies, automatic samplers were used to collect runoff from feedlots and from the effluent discharged from a settling basin. This allowed Gilbertson and Nienaber (1972, 1973) to directly calculate the effectiveness of the settling basin. The runoff effluent and settling basin effluent was tested for total solids, volatile solids, and settleable solids. The measured concentrations are presented in Table 4. As can be seen, approximately half of the transported solids were volatile and the other half were fixed solids. In this case, the solids transport data was less variable with coefficients of variation of approximately 0.4.

Table 4. Solids concentrations in feedlot runoff as presented by Gilbertson and Nienaber (1973).

	Average (mg/L)	St. Dev. (mg/L)	Coefficient of Variation	Range
Total Solids	15,200	5,300	0.35	6,600 – 33,000
Fixed Solids	8,400	3,500	0.42	2,600 – 22,100
Volatile Solids	6,800	2,700	0.40	3,600 – 16,800

Gilbertson and Nienaber (1973) also determined the volume of settleable solids in the runoff effluent. Settleable solids were measured by putting the effluent in Imhoff cones and allowing sedimentation to occur for 1 day. The interface layer between the solids and liquids was determined; the volume of the settleable solids was then calculated as the volume of the Imhoff cone below this layer. A summary of the settleable solids in the runoff is provided in Table 5.

Table 5. Settleable solids concentration in feedlot runoff as presented by Gilbertson and Nienaber (1973).

Year	Average mL/L	St. Dev. mL/L
1970	49	19
1971	79	46
1972	60	20

Gilbertson and Nienaber (1973) performed a second study in which they determined particle densities of the solids in the feedlot runoff. In this study, Gilbertson and Nienaber (1973) collected feedlot runoff during rainfall events. The runoff effluent was then through a series of screens to separate the solids into different groups based on the particle size. A subsample from each particle size range was selected, a balance was used to measure the mass of the subsample and a pycnometer was used to determine the volume of the subsample. Knowing both the mass of the subsample and the volume of the subsample allowed calculation of particle density.

Particle density information is required to determine settling times based on Stokes Law. In their study, they found that the average particle density in the runoff effluent was 1.95 ± 0.18 g/cm^3; in addition, they performed an analysis of how particle density varied with particle size. Their findings indicate that as particle size decreases, particle density increases while the volatile solids content decreased. This would indicate that most of the organic matter transported in the feedlot runoff is attached to the larger particles, i.e., it is in an aggregated form. Table 6 displays how the particle density varied with particle size in the feedlot runoff. As can be seen, there is a notable decrease in particle density for particles larger than 250 microns, while the two particle classes below this size exhibited little variability with particle size. Furthermore, since the chemical oxygen demand is strongly correlated with organic matter these data would indicate that sedimentation can be effectively used to reduce the chemical oxygen demand of the waste by removing the larger particles. To take full advantage of this information the chemical properties of these particles also need to be known; unfortunately, Gilbertson and Nienaber did not measure nutrient contents for different particles in this study.

Table 6. Chart displaying particle densities for different particle sizes in feedlot runoff from Gilbertson and Nienaber (1973).

Particle Size (microns)	Particle Density (g/cm^3)
< 37	2.38
105 - 249	2.34
250 - 499	1.96
500 - 999	1.77

Chang and Rible (1975) presented a similar study on feces from beef cattle. In their study, they analyzed the particle sizes present in the manure, the percent of the manure in this particle size range, and the nutrient content of each particle size. In their study, Chang and Rible provided the percent nitrogen, phosphorus, and crude fiber for each particle size range. For this analysis, COD was determined by assuming all crude fiber was organic carbon and then dividing by a factor of 2.67. This conversion factor was determined by taking the ratio of COD to organic carbon from AgNPS (Young et al., 1987; Tolle, 2007). This information is displayed in Table 7 below and is important for estimating the properties of the waste after it has undergone sedimentation. In general, it can be seen that crude fiber, and therefore presumably COD, is of greater concentration on larger particles, while nitrogen and phosphorus are more prevalent on smaller particles. Thus, the crude fiber/COD data seems to correspond with that presented by Gilbertson and Nienaber (1973) that most of the volatile solids are aggregated. Furthermore, this data indicates that sedimentation can be used to effectively reduce the strength, i.e. the chemical oxygen demand, of the waste. Furthermore, sedimentation will have some effect on the nitrogen and phosphorus concentrations in the effluent; however, this effect will be limited in comparison to that of sedimentation on COD concentrations.

Table 7. Nutrient contents for different particle sizes in beef cattle feces from Chang and Rible (1975).

Particle Size (mm)	Percent of Total Manure	N (%)	P (%)	Crude Fiber (%)	COD[f] (%)
> 1.00	30.7	1.7	0.83	43.7	16.3
0.50 – 1.00	9	2.2	0.39	58.7	21.9
0.25 – 0.50	6.7	2.5	0.41	32.8	12.2
0.105 – 0.25	6.1	2.7	0.73	27.6	10.2
0.053 – 0.105	3.6	2.8	*	16.6	6.2
< 0.053	43.6	4.9	1.42	10.2	3.8

Gilbertson and Nienaber (1973) also provided data on the settling of total solids and volatile solids from the feedlot runoff. These settling characteristics were determined by placing the runoff effluent into a 1-L cylinder and then sampling the effluent at a depth of 10 cm below the liquid surface at specified time intervals. The total solids and volatile solids content of the subsample was then determined. A graphical display of the settling characteristics is shown in Figure 2. As can be seen, the initial settling rate up to a time of approximately 1-hour is very rapid; however, after this the rate of settling greatly decreases.

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[f] Determined by dividing the Crude Fiber percentage by a factor of 2.67 based on the COD to organic carbon ratio in AgNPS.

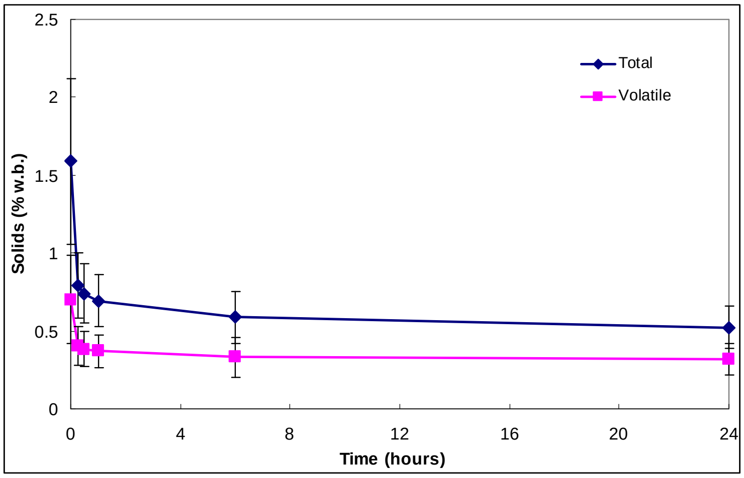

Figure 2. Settling characteristics of solids in beef feedlot runoff.

Lot et al. (1994) performed a similar study on fresh beef feces and aged feces from a feedlot surface. In their analysis, Lot et al. related settling times to the percentage of material remaining in suspension by fitting a hyperbola to the settling data. Based on this study Lot et al. concluded that a settling time of ten minutes would remove the rapidly settleable portion of solids in the feedlot runoff; furthermore, he stated that longer retention times provide very little improvement in runoff quality. To explain this phenomenon Lot et al. noted that the runoff consisted of two types of particles, a coarse material that would rapidly settle and another component, approximately 25 -55% of the solids, that settles too slowly to be retained in a settling basin. Based on this study Lot et al. (1994) suggested that this drastic change in settling rate occurs for particles that settle slower than 0.003 meters per second. Lot et al. (1994) also noted that diet had a large effect on the settling properties of the feces and that there was little difference between the settling characteristics of the fresh manure and aged feces collected from the feedlot surface.

In addition to the study of runoff quality, several efforts have been made to quantify the amount of effluent resulting from different sized precipitation events. Gilbertson et al. (1972) proposed a regression equation to determine the depth of runoff from the feedlot surface. The equation is designed for rainfall events, and does not represent snowmelt from the feedlot. This equation is shown as equation (1).

$$R = 0.28P - 0.58 \tag{1}$$

Where *P* is the depth of rainfall in inches and *R* is the depth of runoff also given in inches. Many other rainfall relationships have been proposed with regression slopes ranging from 0.36 to 0.93 per unit of precipitation with no runoff occurring until 1 cm of precipitation has fallen on the feedlot surface (Westerman and Overcash, 1980). Furthermore, Clark et al. (1975) proposed that this slope is proportional to the to the moisture deficit, with higher moisture deficits corresponding to a lower slopes of the regression line.

An alternative model, utilizing the Soil Conservation Service/ Natural Resource Conservation Service (SCS/NRCS) curve number (CN) method was utilized by Koelliker et al. (1975) to predict the quantity of runoff from feedlots. Koelliker et al. (1975) state that unpaved feedlots can be represented with a curve number of 91 for antecedent moisture conditions (AMC) II and with 97 for antecedent moisture conditions III. For paved feedlots, a curve number of 94 was recommended for AMC II, while a value of 98 was used for AMC III. The model utilized by Koelliker et al. (1975) is displayed in equation (2). In equation (2) *P* is again the depth of rainfall in inches, *R* is the depth of runoff in inches, and *S* is a soil retention factor which will also have units of inches. This soil retention factor is calculated based on the curve number, with the appropriate equation provided as equation (3). A comparison of the two models results is provided in Figure 3.

$$R = \begin{cases} 0 & if \quad P \le 0.2S \\ \dfrac{(P - 0.2S)^2}{P + 0.8S} & if \quad P > 0.2S \end{cases} \tag{2}$$

$$S = \frac{1000}{CN} - 10 \tag{3}$$

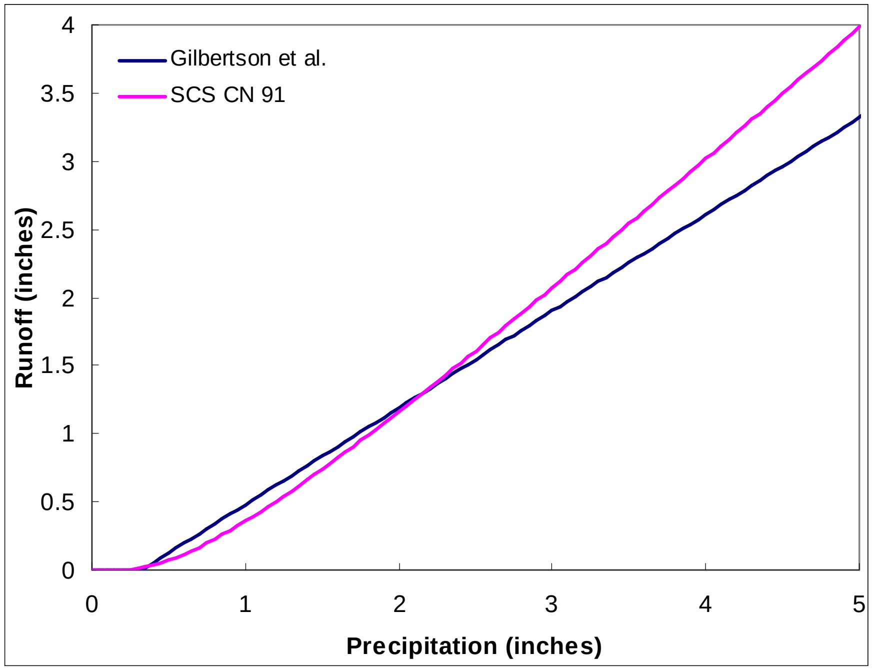

Figure 3. Comparison of feedlot runoff predictions based Gilbertson et al. model and use of the SCS/NRCS curve number prediction.

As can be seen, there is relatively little difference between the liner model proposed by Gilbertson et al. (1972) and the SCS CN model recommended and used by Koelliker et al. (1975), particularly over the range of data used by Gilbertson et al. (1972)in developing their correlation. However, for storm sizes larger than three inches the two models quickly diverge from each other. The regression equation of Gilbertson et al. (1972) substantially under predicts the amount of runoff in comparison to the SCS/NRCS model.

In addition to rainfall runoff from feedlots, in some areas snowmelt runoff also may be of concern. Unfortunately, little information was found on measurements of snowmelt runoff; however, limited data on the quality of the snowmelt runoff were available. Gilbertson et al. (1980) reported that snowmelt runoff often occurred as lava-type flow and had higher solids content, approaching values up to 218,000 mg/L. A summary of snowmelt runoff properties as reported by Gilbertson et al. (1980) can be found in Table 8.

Table 8. Summary of nutrient concentrations measured in feedlot snowmelt runoff (Gilbertson et al., 1980).

	Total Solids mg/L	Volatile Solids mg/L	Total N mg/L	Total P mg/L	pH	COD mg/L
Low	8,000	600	190	5	4.1	14,100
High	218,000	143,000	6,528	917	9.0	77,100

The final issue in dealing of concern when looking at feedlot runoff would be the expected amount of runoff effluent that must be treated on a yearly basis. This can be determined by using the SCS curve number model proposed by Koelliker et al. (1975) on a continuous basis. Table 9 shows the result of this analysis for several locations in Iowa. As can be seen the amount of feedlot runoff ranges from 3,522 cubic meters per hectare in the wettest region down to only 1,957 cubic meters per hectare of feedlot in the drier regions. The data seems to indicate that for most of Iowa the runoff volume will be approximately 3,000 cubic meters per hectare of feedlot, which is between 6.3 and 7 cubic meters per head assuming between 225 and 250 square feet of area per animal (Lawrence, 2005). Also of note, runoff is about 35% of the rainfall received in that area; however, for drier regions the percentage decreases as seen from the Waterloo and Sioux City data.

Table 9. Average runoff volumes per hectare of feedlot surface of five locations in Iowa.

		Precipitation cm	Runoff cm	Runoff as % of Rainfall	Runoff Volume m^3/ha
Ames	Average	89	32	35	3,174
	St. Dev.	23	13	6	1,250
Red Oak	Average	92	35	35	3,522
	St. Dev.	22	14	7	1,382
Sac City	Average	85	30	35	3,019
	St. Dev.	20	10	5	1,036
Sioux City	Average	67	20	29	1,957
	St. Dev.	14	7	5	667
Waterloo	Average	84	27	32	2,740
	St. Dev.	18	10	6	1,028

In addition to the overall volume of effluent that must be treated, the temporal distribution of this effluent is also important. The temporal distribution of feedlot runoff from Ames, Iowa is presented in Figure 4. Almost 80% of the entire runoff volume occurs between April and November, i.e., during the typical growing season.

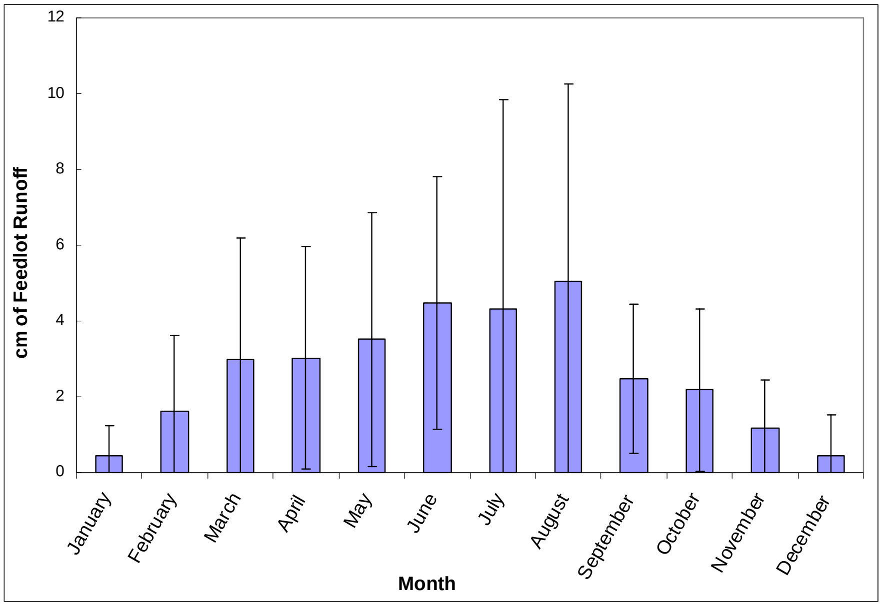

Figure 4. Temporal distribution of feedlot runoff from Ames, Iowa.

Solids Settling Systems

A settling system of some type is often the first component in a runoff control system. There are several options available for settling systems; these include settling basins, settling benches, debris basins, terrace systems, or even natural depression areas. In general, the settling system intercepts the feedlot runoff, slows the flow rate, and allows the solids to settle from the effluent. Thus, the settling system performs two important functions; it attenuates the runoff hydrograph and reduces the mass of organic material and nutrients entering the secondary treatment component. Attenuating the runoff hydrograph serves two functions, it reduces the peak inflow rate to secondary treatment components and elongates the time period over which the event occurs. Both of these functions make the runoff event easier to control. Furthermore, reduction in organic loading reduces the oxygen demand and nutrient concentration lightens the demand on the secondary treatment component. Thus, proper design and operation of the settling system is important to ensure that the entire runoff control system is successful.

Current Iowa regulations require feedlot operations of all sizes to have at a minimum, a solids settling facility. There are several possible designs for the settling facility with examples being settling basins, terraces, diversions, or natural areas; however, no mater the type of settling facility is utilized, certain design criteria must be met. Current Iowa design standards include that:

- The basins must be, at a minimum, designed to settle solids from feedlot runoff from a 1-hour, 10-year storm.
- Liquid velocity in the basin must be reduced to less than 0.5 feet per second (fps) for at least five minutes.
- At a minimum, the settling basins must have one square foot of surface area for every eight cubic feet of runoff per hour from the feedlot. The amount of runoff per hour is based on the 1-hour, 10-year storm.
- Basins must include adequate capacity to store the settled solids between cleanouts.

In addition to these design requirements, Blume (2006) made several recommendations about the use of sedimentation basins on vegetative treatment systems. These include having the capacity to store the annual sediment yield from the feedlot surface, being designed to facilitate maintenance and sediment removal, and provide controlled outflow onto the vegetative treatment area. These suggestions play a key role in the long term success of the settling system. Specifically, by including the capacity to store the annual sediment yield within the sediment basin the design will function as intended even as solids accumulate. If this volume was not considered during system design the performance of the basin could degrade as capacity, and therefore most likely retention time, is reduced. Furthermore, this issue is again highlighted by stating that the basin should designed “to facilitate” sediment removal. As mentioned, sediment accumulation in the basin reduces capacity and possibly retention time, which could be detrimental to basin performance. Furthermore, removal of settled solids from the basin ensures that the particles won’t be transported to a secondary treatment component due to resuspension. Woodbury et al. (2003) provide the additional recommendation that the settling basin should be designed to facilitate even distribution of the effluent on the vegetative infiltration area.

Several studies have been performed to quantify the performance of settling basins on different feedlots. Gilbertson and Nienaber (1972) found that the debris basin removed 71 percent, by weight, of the settleable solids being transported by the runoff. Furthermore, Gilbertson et al. (1980) report that in general a settling basin can remove 75 percent of the total solids transported in a runoff event, with an approximately 40 percent reduction in solids occurring within 30 minutes of basin retention.

More recently, interest in settling basins has focused on their use as a stand-alone runoff control system and on their use in vegetative treatment systems. Lorimor et al. (1995) monitored the performance of a settling basin on an earthen beef feedlot in Iowa. In this study, the basin used perforated, galvanized risers as the basin outlet. The drainage area into the basin consisted of a 4.1-hectare area, 2.6 of which was the feedlot surface area. Based on the data collected in this study, Lorimor et al. (1995) concluded that the settling basin had a solids removal efficiency of 64%, while removal efficiencies for nitrogen, phosphorus, and potassium was 84, 80, and 34% respectively. The mean solids concentration reported by Lorimor et al. (1995) compares favorable with the values reported by Gilbertson and Nienaber (1972). A summary of the concentrations in both the feedlot runoff and the effluent as monitored in the Lorimor et al. (2005) study is presented in Table 10. Also of note is that treatment of the runoff in the settling basin reduced the variability in total solids and total Kjeldahl nitrogen quite substantially.

Table 10. Monitoring results from a settling basin on an earthen beef feedlot in Iowa, from Lorimor et al. (2005).

	Raw Runoff				Basin Discharge Effluent			
	Total Solids mg/L	TKN mg/L	P mg/L	K mg/L	Total Solids mg/L	TKN mg/L	P mg/L	K mg/L
Max	25,000	1,730	92	570	16,000	118	57	511
Min	3,300	74	66	378	1,800	20	4	168
Mean	11,200	440	79	474	4,000	71	16	314
St. Dev.	9,000	724	18	136	1,700	34	7	129

In another recent study, Woodbury et al. (2002) reported that the TSS, VSS, and COD removal by the settling basin averaged 80%, 67%, and 59% on a cumulative mass basis over a three-year monitoring period. A summary of the average concentration of both total suspended solids and chemical oxygen demand concentrations in the feedlot runoff entering and exiting the settling basin is provided in Table 11.

Table 11. Average concentrations of feedlot runoff exiting and entering the settling basin as reported by Woodbury et al. (2003).

	Raw Runoff		Basin Discharge Effluent	
	TSS mg/L	COD mg/L	TSS mg/L	COD mg/L
Max	8,500	12,300	1,960	6,060
Min	1,900	790	200	100
Mean	4,689	5,711	849	2,311
St. Dev.	2,154	3,377	580	2,018

Moody et al. (2007) reported the concentrations of settled runoff effluent released from settling basins on four CAFO sized open feedlots in Iowa. In this study, the settled effluent was tested for a large assortment of parameters including ammonium, biological oxygen demand, chemical oxygen demand, total phosphorus, total solids, and total Kjeldahl nitrogen. Results from this sampling is shown in Table 12. As can be seen the sample result data were highly variable for all parameters and all locations. In addition to monitoring chemical concentrations in the runoff effluent, Moody et al. (2007) also attempted to correlate total solids concentrations to the rainfall intensity, rainfall depth, rainfall duration, and the number of days since the feedlot surface was last scraped. No relationship was found in this study.

Khanijo (2007) also reported the settling basin effluent from these four feedlots in both 2006 and 2007. In the study by Khanijo (2007), the settling basin outlets at Central Iowa 1 and Northwest Iowa 1 were modified after 2006 to have a valved outlet. This allowed the producer to control when effluent was released from the settling basin and increased retention time in the basin. By increasing retention time in the basin the total solids concentration in the effluent was reduced; the variability of the solids concentrations were also reduced substantially (Khanijo, 2007). A comparison of the monitored total solids concentrations for both years of monitoring at all four sites is shown in Figure 5. Khanijo (2007) also reported ammonium concentrations in the solid settling basin effluent for both years; these are shown in Figure 6. At Central Iowa 1, effluent was held for longer time periods in 2007; this may have caused the increase in ammonium concentrations in the effluent as compared to 2006 (Khanijo, 2007).

Table 12. Solid settling basin effluent concentrations for four open beef feedlots in Iowa. From Moody et al. (2007).

	Central Iowa 1		Central Iowa 2		Northwest Iowa 1		Northwest Iowa 2	
(mg/L)	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.
NH_4	151	100	35	30	239	357	354	227
BOD_5	2,595	1,704	462	457	5,252	9,033	5,447	4,355
COD	9,045	4,397	2,221	1,817	24,378	40,483	18,541	12,473
Cl	497	114	207	120	813	203	549	209
Total P	96	41	30	23	137	152	150	70
TDS	7,704	3,026	3,089	119	9,188	6,428	8,973	4,835
TSS	2,683	1,902	1,219	1,751	13,708	14,034	7,366	3,854
TS	10,387	4,295	4,069	3,131	22,895	19,596	16,339	8,446
TKN	462	316	112	119	1,024	1,254	985	703

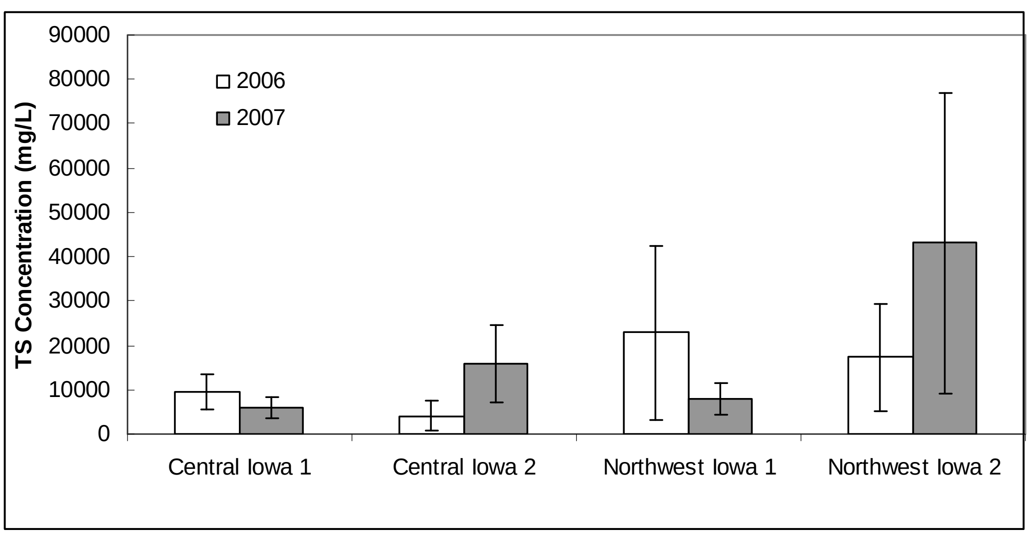

Figure 5. Total solids concentrations in effluent released from solids settling basins on four open beef feedlots in Iowa from Khanijo (2007)

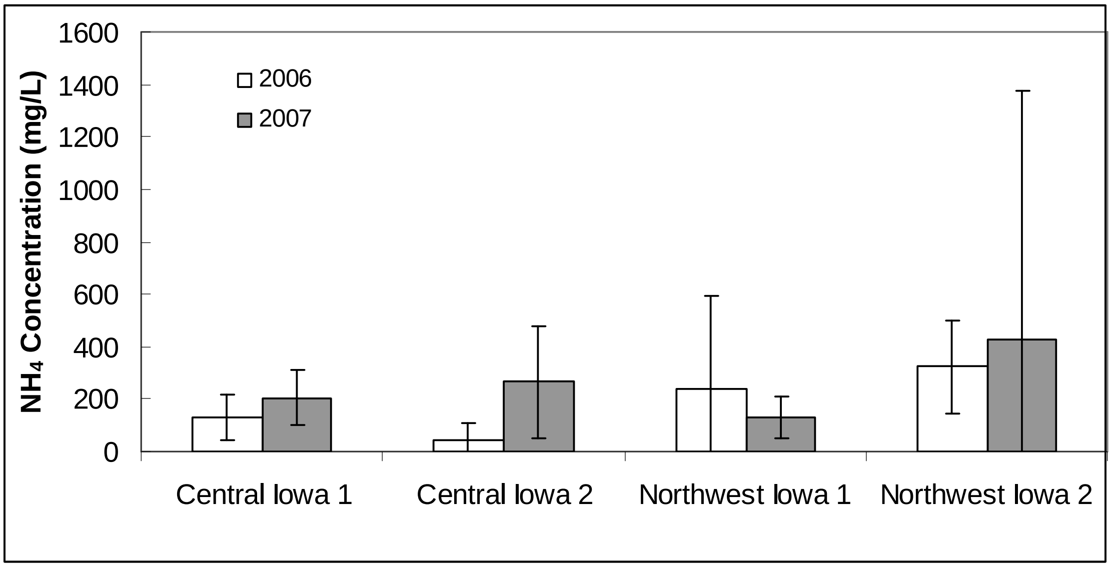

Figure 6. Ammonium concentrations in effluent released from solids settling basins on four open beef feedlots in Iowa from Khanijo (2007)

Settling basins use gravitation force to separate solids from the wastewater. The rate of sedimentation is based on the density difference between the solid particles and the liquid; often this process is modeled with the use of Stokes Law, which is displayed in equation (4).

$$v_s = \frac{(\rho_s - \rho) g d^2}{18\mu} \quad \textbf{(4)}$$

Where v_s represents the settling velocity, ρ_s the density of the solid particles, ρ the density of the liquid, g the acceleration of gravity, d the particle diameter, and μ is the dynamic viscosity of the fluid. There are several assumptions built into using Stoke's law to model sedimentation. These include that the settling velocity of the particle is reached instantaneously, that the particles are rigid, smooth spheres, and that the particles settle independently. If the settling process meets all these assumptions then the process is said to be Type 1, discrete particle settling. If the particles flocculate as the settling process occurs then the settling process is considered Type 2, which is flocculent settling. This process is the most common in waste treatment as the particles are often aggregated during the settling process. In this case Stoke's law can still be used, but usually the settling velocity will be underestimated as the particles continue to flocculate, and thus increase in size, as settling occurs. A third type of settling, hindered settling, can occur if particles adhere together and then slowly settle as a blanket; in this case settling is often slower and cannot be modeled with the use of Stoke's law. Type 3, hindered settling, usually occurs due to higher concentrations of solids in the effluent.

For most cases, the settling rate can be determined based on Stoke's law, and the particle density – particle size data presented by Gilbertson and Nienaber (1973) which were displayed in Table 6. The settling velocity for different particle sizes can be calculated, and is shown in Table 12. Combining this with the nutrient characteristic-particle size data, such as found in Chang and Rible (1975) provides insight into how settling can reduce both nutrient content and chemical oxygen demand as different particle sizes settle out of the effluent. As can be seen, larger than particles 53 microns the particle should settle more than 0.6 meters in five minutes. Therefore, if a settling basin is designed to be 0.9 m (3 feet) deep, a retention time of approximately 7.5 minutes would be required to settle these particles from the effluent. This matches well with the study of Lot et al. (1994) in which they recommended a settling time of approximately ten minutes as the rapidly settling portion of waste had been settled by this time. Furthermore, they found that after the 10 minute settling time approximately 40-50% of the manure remained in suspension, which corresponds relatively well to the 43.6% of manure particles that have a diameter between 0 and 53 microns in the Chang and Rible (1976) study. However, both the calculation of settling velocity and the experiments of Lot et al. (1994) assume ideal settling, i.e., there is no flow; therefore, a slightly longer retention time may be required to achieve the same settling efficiency in the field. Furthermore, the study by Chang and Rible (1976) looked only at the feces particles that could be transported in the feedlot runoff, not the soil particles that could also be transported in this runoff. These soil particles can substantially increase settling time as the time required for silt particles (11 microns) to settle 0.5 meters is approximately 2.3 hours, while clay particles (2 microns) would require approximately 11.5 days. Thus the addition of these particles can substantially reduce settling efficiency.

Table 13. Calculated settling data for feedlot runoff, based on the data of Gilbertson et al. (1973) and Chang and Rible (1976).

Particle Density (g/cm^3)	Settling Diameter (microns)	Percent of Total Manure	N (%)	P (%)	COD (%)	Settling Velocity (m/s)	Distance Traveled in 5 Minutes (m)
2.38	0	43.6	4.9	1.42	3.8	0.000	0
2.36[g]	53	3.6	2.8	1.08[g]	6.2	0.002	0.6
2.34	105	6.1	2.7	0.73	10.2	0.008	2
1.96	250	6.7	2.5	0.41	12.2	0.033	10
1.77	500	9	2.2	0.39	21.9	0.105	31
1.77 [g]	1000	30.7	1.7	0.83	16.3	0.418	125

Based on this data, it appears that sedimentation can be used to remove all particles larger than 53 microns in equivalent diameter. This corresponds to approximately 60% of the solid particles in the runoff. Utilizing the nutrient data from Chang and Rible (1975) and assuming 100% removal efficiency of all particles larger in diameter than 53 microns, then the estimated N, P, and COD removals would be 35%, 39%, and 84% respectively. Thus, correctly designed and functioning sedimentation basins can be an effective treatment technique, reducing nutrient and organic matter loading rates encountered by additional treatment components.

After primary treatment of runoff effluent in the settling basin, additional treatment or final disposal of the effluent is required. There are several options for both additional treatment components as well as final disposal options. For smaller feedlot operations release to a vegetated waterway can often be used as a final means of treatment and release; however, this is not allowed on CAFO operations and would be recommended only for operations were pollution potential of feedlot is relatively small. Alternative means of treatment include land application onto cropland, use of vegetative treatment systems, evaporation basins, lagoons, or

[g] Calculated based on the average of the data surrounding data points.

chemical or biological treatment to reduce nutrient concentrations to stabilize the effluent.

Evaporation Ponds

An evaporation pond is a containment system in which the final disposal method of effluent is through evaporation. A schematic of a typical evaporation system is provided in Figure 7. Like most runoff control systems, this system uses a settling basin, which in an evaporation system is followed by the evaporation basin. The primary treatment in this system is provided by the settling basin, which is designed to remove the settleable solids. Good performance of the settling basin is important, as solids entering the evaporation pond reduce the usable capacity making the basin more susceptible to overflow. Furthermore, this will increase the frequency that solids must be removed from the basin. The secondary form of treatment occurs in the evaporation pond. The runoff effluent is stored in the basin; during storage evaporation occurs which reduces the liquid content, i.e., thickens the waste. By evaporating off the liquid from the feedlot runoff effluent the waste is easier to transport and requires less volume to store. This thickening also increases the nutrient concentration of the waste, improving the economics of transporting and land applying at greater distances. However, for areas where evaporation ponds are an appropriate for of waste treatment, crops are often irrigated. Thus effluent application onto cropland is often the preferred method of effluent disposal.

In general, it is only recommended to use evaporation ponds in areas where the annual evaporation potential exceeds precipitation by more than 50 cm (Gilbertson et al., 1980), thus these systems are not appropriate for Iowa conditions. Anschutz et al. (1979) provided a more specific approach in designing evaporation ponds for feedlots. In their study, Anschutz et al. (1979) sized evaporation ponds for 20 locations around the United States such that they would not experience a basin release. At each of these locations, the ratio of the average annual precipitation to the annual lake evaporation (PE Ratio) was determined. The required surface area for the evaporation pond was then related to a PE ratio via a regression equation, shown as equation (5). In equation (5), A_{evap} represents the surface area of the evaporation pond in hectares, $A_{feedlot}$ is the area of the feedlot in hectares, and PE Ratio is the ratio of the annual volume of precipitation to the annual lake evaporation. Example calculations for thirteen locations around Iowa are displayed in Table 14; the required size is per hectare of feedlot area. Based on these data, the average feedlot in Iowa would require approximately 2.5 hectares of evaporation pond surface area per hectare of feedlot area, thus these system are not very practical in Iowa. A summary of the required evaporation pond sizes for different locations around Iowa is provided in Table 14.

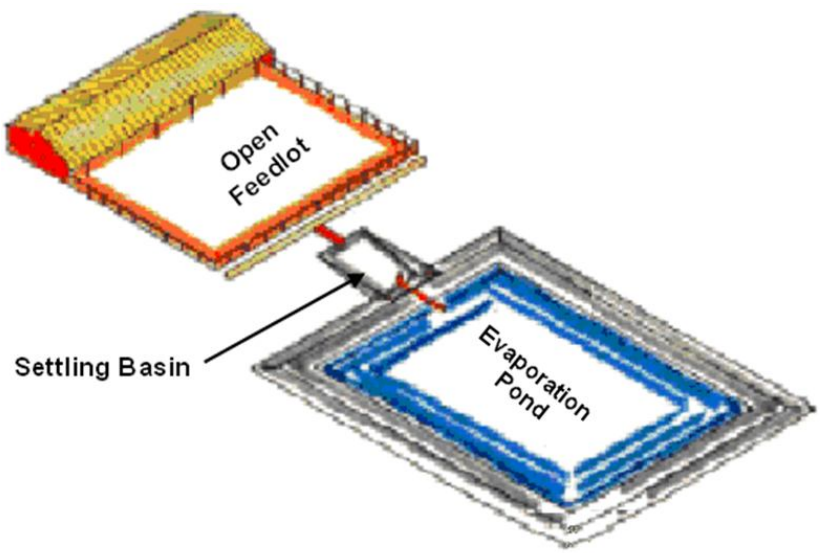

Figure 7. Schematic of a runoff control system using an evaporation pond.

$$A_{evap} = \frac{10^{2.166(PE\ Ratio)-0.302}}{16} A_{feedlot} \quad \textbf{(5)}$$

Although Anschutz et al. (1979) developed his relationship to help producers size evaporation basins appropriately for their feedlots, in some respects it has a relationship to both the land application area required for holding pond systems as well as the vegetative treatment area required for vegetative treatment systems. For instance, by idealizing the land application area or vegetative treatment system as a soil-water reservoir the approximate surface area required to evapotranspire the runoff effluent can be determined using a procedure similar to that Anschutz et al. (1979) to size the evaporation pond.

Table 14. Required evaporation pond sizes per hectare of feedlot based on evaporation basin sizing from Anschutz et al. (1979).

Location	Annual Precipitation inches	Annual Evaporation inches	PE Ratio	Evap. Pond Surface Area ha	Depth meters
Ames	35.1	40.24	0.87	2.42	1.83
Centerville	30.6	37.9	0.81	1.75	1.83
Irwin	30.9	37.8	0.82	1.84	1.83
Larrabee	28.3	37.8	0.75	1.30	1.83
Lenox	33	37.9	0.87	2.40	1.83
McGregor	30.7	35.3	0.87	2.39	1.83
Mount Pleasant	34.8	33.7	1.03	5.38	1.83
Red Oak	36.2	37.8	0.96	3.70	1.83
Sac City	33.5	37.7	0.89	2.62	1.83
Shenandoah	34.2	37.9	0.90	2.81	1.83
Sioux City	26	35.8	0.73	1.17	1.83
Saint Ansgar	29.5	36.6	0.81	1.74	1.83
Waterloo	32.9	35.3	0.93	3.26	1.83

Holding Pond

A holding pond is the traditional system used to control open feedlot runoff. Traditionally CAFO sized operations were required to construct and maintain a containment basin to prevent release of effluent. The effluent is then land applied during onto cropland as weather and soil conditions permit. An example of the layout of a traditional containment system is shown in Figure 8. As can be seen, this system consists of four basic components, the open lot area, a settling basin, a containment basin, and the land application area. In this scenario, the open feedlot is the source of runoff effluent, this effluent should then be routed through a solids settling basin to remove solids. This settling / debris basin can remove up to 75% of the total solids coming from the feedlot (Gilbertson et al., 1980). Removing these solids before storage in the containment basin minimizes build-up with in the containment basin; this maintains both the usable volume in the basin and decreases the required frequency of solids removal. Furthermore, removing these solids also makes the effluent easier to pump through an irrigation system (Gilbertson et al., 1980). The containment basin serves as a waste storage facility until application of the waste occurs. Several different methods are available for land application of the runoff effluent; these include tanker wagons, center pivot irrigation systems, overland flow irrigation, and “big gun” sprinklers.

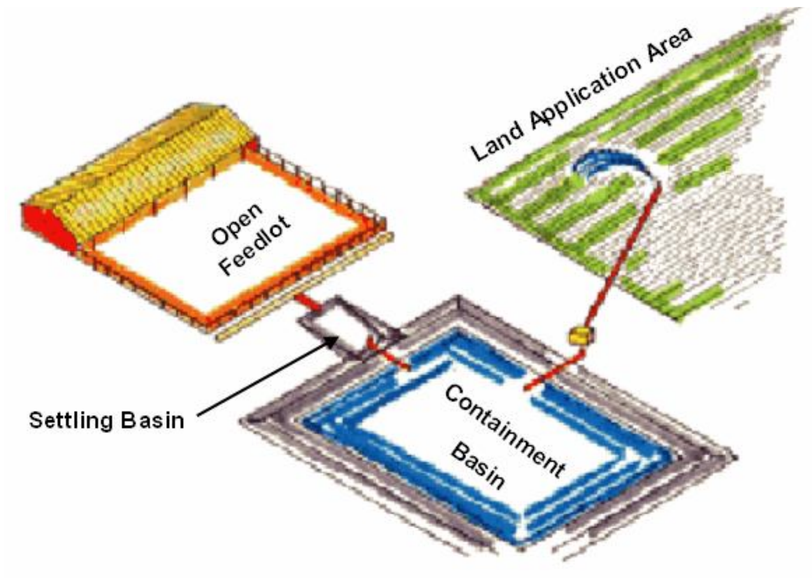

Figure 8. Example traditional containment system.

When sizing the containment basin, several factors need to be considered, these include the feedlot size, the climate of the region, the desired length of time between land application intervals, and the size both the contributing drainage area and the land application area. The maximum rate at which the basin can be dewatered also has impact on determining the size of the containment basin. Currently the Iowa AFO/CAFO guidelines list five containment basin systems that producers can choose. These options differ by the number of and timing of land application periods. The options include one effluent application period per year, July and November effluent application periods, April, July, and November application periods, application after every significant precipitation event, and April/May and October/November manure application periods.

There is a long history of both the use of these systems, as well in modeling the performance of containment basins; however, very limited data are available on their actual performance on open lot facilities. Gilbertson and Nienaber (1973) report on a case study in which a solid settling basin / containment basin system was designed for a 100 head feedlot. The system was then monitored for a one-year period; no containment basin overflow was recorded during this monitoring period.

Although there are very limited data on actual system performance, there is a long history of attempting to model the performance of these systems. Much of the modeling research can be traced back to 1975 to a feedlot runoff model developed by Koelliker et al. (1975). This model has been utilized to demonstrate that basin overflow can result not only from storms in excess of the design storm, but also because of chronic rainfall events. In addition, this model was used to establish the baseline performance that could be expected from a containment basin experiencing the site-specific weather conditions. In this model, the land application area is not explicitly modeled, but instead a general set of criteria are used to determine if land application of effluent is appropriate. The criteria include items like the soil not being frozen, the temperature being above freezing, the containment basin is more than $1/10^{th}$ full of effluent, it is not raining today, and there was less than 0.05 inches of precipitation during the three previous days. These land application criteria were selected by Koelliker et al. (1975) to represent Kansas climatic conditions, and may not be appropriate for other areas. Koelliker et al. (1975) recognized this fact during the development of their model and stated that model performance could be refined by using more disposal criteria such as the condition of the watershed in which land application would be practiced. In addition, they also state that a chemical transport model could be used to assess the total water quality impact that the feedlot, waste containment system, and land application area are having on the water quality on the watershed scale. Furthermore, Gilbertson et al. (1980) point out that the dewatering schedule used by the producer to empty the basin has a large effect on both the required size of the basin as well as the performance of the basin.

Given that actual system performance is noted to be directly related to management decisions made by the farmer, it becomes very important to define a reasonable management plan that the operator could be expected to use to manage wastewater basins. Moffitt et al. (2003) elaborated on this fact stating that application time is affected by the conditions of the field on which effluent is to be applied, the state of the crop being grown, and the application methods available. This fact has been evaluated in several modeling studies (Zovne et al., 1977; Anschutz et al., 1979; Jia et al., 2004; Moffitt et al., 2003; Moffitt and Wilson, 2004; McFarland et al., 2000). In the studies of Zovne et al. (1977), Anschutz et al. (1979), McFarland et al. (2000) , and Jia et al. (2004) the land application area was linked to the performance of a containment basin system by using soil moisture criteria to determine if land application was appropriate. However, non-point source pollution resulting from disposal of the runoff effluent on the land application area was not considered.

The model developed by Zovne et al. (1977) used a simple water balance in the disposal area to predict soil moisture in the land application area, with land application of effluent being delayed if soil moisture was greater than 90% the available moisture content in the soil profile. Anschutz et al. (1979) then used this model to determine the required basin sizes base for different locations. In this study, Anschutz et al. (1979) developed a regression equation, shown in equation (6) below, to select the required basin size based on the moisture deficit of the climate, with moisture deficit being defined as the mean annual lake evaporation minus the mean annual precipitation.

$$Vol = \frac{A_{feedlot}}{16} 10^{4.91-5.92*10^{-4}(MD)} \quad \textbf{(6)}$$

Where MD is the moisture deficit in mm, $A_{feedlot}$ is the area of the feedlot in hectares, and Vol is the required volume of the containment basin in cubic meters. This regression equation was developed to provide 100% runoff control. Furthermore, “standard conditions” were assumed in the land application area; these included having subsoil that had an intake rate that was moderate (an intake family 0.5), growing corn in the land application area, and a land application to feedlot area ratio of one-to-one. An assortment of modification factors was then created to modify the system for non-standard conditions; these are shown in equation 7. In equation (7), *S* is the soil type factor, *C* is a crop factor, *D* is the ratio of feedlot area to land application area, *R* is the disposal rate factor which is based on the depth of effluent applied per day, *H* is a factor representing the depth of the retention pond, *M* is a factor based on the moisture deficit in the area, and *PRC* is the is a factor based on the percent of runoff to be controlled. Elaborating on the soil type factor, *S*, it is related to the soil intake family and represents the water infiltration capability of a soil (USDA NRCS, 1997). The soil intake factor is related to both soil type and irrigation method. Guidance for estimating a soil intake factor is available in the USDA NRCS Irrigation Guide (1997) and is shown in Table 15.

Table 15. Soil intake factors for different textures and application methods from the USDA NRCS Irrigation Guide (1997).

	Soil Intake Characteristics		
Soil Texture	Sprinkler	Furrow	Border & Basin
Clay, Silty clay	0.1 - 0.2	0.1 - 0.5	0.1 - 0.3
Sandy clay, Silty clay loam	0.1 - 0.4	0.2 - 0.8	0.25 - 0.75
Clay loam, Sandy clay loam	0.1 - 0.5	0.2 - 1.0	0.3 - 1.0
Silt loam, Loam	0.5 - 0.7	0.3 - 1.2	0.5 - 1.5
Very fine sandy loam, Fine sandy loam	0.3 - 1.0	0.4 - 1.9	1.0 - 3.0
Sandy loam, Loamy very fine sand	0.3 - 1.25	0.5 - 2.4	1.5 - 4.0
Loamy fine sand, Loamy sand	0.4 - 1.5	0.6 - 3.0	2.0 - 4.0
Fine sand, Sand	0.5 +	1.0 +	3.0 +
Coarse sand	1.0 +	4.0 +	4.0 +

$$Act\_Vol = Vol \times S \times C \times D \times R \times H \times M \times PRC \qquad \textbf{(7)}$$

The sizing requirement for a containment basin of one-hectare feedlot based on equation (7) is shown in Table 16. For thirteen locations in Iowa, the size requirement for storage ranged from 3,600 cubic meters to 5,300 cubic meters, with an average size of 4,300 cubic meters of storage per hectare of feedlot surface area.

Table 16. Containment basis sizes required per hectare of feedlot area for 13 Iowa locations. Based on sizing requirements presented by Anschutz et al. (1979).

Location	Annual Precipitation inches	Annual Evaporation inches	MD mm	Containment Pond Size m^3
Ames	35.1	40.2	131	4,252
Centerville	30.6	37.9	185	3,946
Irwin	30.9	37.8	175	4,001
Larrabee	28.3	37.8	241	3,656
Lenox	33.0	37.9	124	4,287
McGregor	30.7	35.3	117	4,332
Mount Pleasant	34.8	33.7	-28	5,277
Red Oak	36.2	37.8	41	4,806
Sac City	33.5	37.7	107	4,393
Shenandoah	34.2	37.9	94	4,469
Sioux City	26.0	35.8	249	3,618
Saint Ansgar	29.5	36.6	180	3,973
Waterloo	32.9	35.3	61	4,675

Current Iowa standards are based for containment basin sizing are based on the 25-year, 24-hour storm size. This is roughly 5.1 inches for most of Iowa, which results in a required basin size of 1,036 cubic meters for a one-hectare feedlot. Thus current Iowa design requirements for containment basins are roughly ¼ the size recommendations of Anschutz et al. (1979).

The study of McFarland et al. (2000) assessed the impact of chronic rainfall events on lagoons receiving runoff from dairy loafing lots. In this study, McFarland et al. (2000) used an antecedent precipitation index (API) to schedule or delay irrigation of lagoon effluent. Although the API is an artificial concept used to represent the soil water redistribution process, it is still a first step at representing soil-moisture in the land application area. This study also provided an important first step in defining chronic rainfall, which McFarland et al. defined as precipitation on consecutive days. Jia et al. (2004) extended on this analysis with the use of DRAINMOD. Rather than using the API, Jia et al. (2004) used DRAINMOD to simulate the hydrology of the land application area. In this simulation, land application was modeled to occur when the water-free pore space was larger then the amount of effluent to be land applied. In addition to this soil moisture constraint additional constraints of wastewater availability in the lagoon and the crop nitrogen limit were also used. Based on this research, Jia et al. (2004) concluded that prolonged wet periods cause high soil moisture conditions that prohibit irrigation of effluent. This in turn caused high stage levels in the modeled lagoon.

Moffitt and Wilson (2004) utilized the Soil-Plant-Air-Water model (SPAW) to predict the level in holding ponds that received runoff from dairy lots. In this study, the results from SPAW closely followed the monitored levels in four waste storage facilities located in Oregon. It was therefore concluded that SPAW provided a useful design and evaluation tool for simulating waste storage structures.

As mentioned, management of a containment basin is a very important aspect of basin performance. There are several options available for dewatering a basin; selection of the appropriate dewatering technique should be based on the dewatering schedule, the size of the basin, the availability of labor, the characteristics of the waste, and economics. Options for dewatering include a stationary gun, a traveling gun, center pivot irrigation, hand-moveable sprinkler systems, overland flow irrigation, furrow irrigation, and a pump-and-haul irrigation system. Gilbertson et al. (1980) recommended the use of an irrigation system to dewater the basin, rather than pump-and-haul systems due to the larger labor requirement of using a pump and haul system. Gilbertson et al. (1980) also provided a few points to consider when planning and designing a land application system. Specifically, when sizing the land application area requirements, consider both the nutrient and water needs of the crop, the water holding capacity of the soil, the application rate, the characteristics of the runoff, and state laws and regulations.

In addition to the overflow events predicted in these models there are other aspects of a traditional containment system that could cause potential pollution. These include seepage from the basin as well as non-point source pollution from the land application area. Both items have received attention from field-scale, lab-scale, and modeling studies, but in general, these items have never been linked with a containment basin model to predict when the overall impact of a containment basin – land application system.

Seepage from runoff holding ponds is a concern since it could result in contamination of groundwater by nutrients and pathogens in the effluent stored in the basin. This has resulted in states setting hydraulic conductivity and/or flux standards to limit the seepage of waste from lagoons. Several studies field and lab studies have been performed to try to quantify seepage rates from existing lagoons. Much of the field-scale research has focused on determining seepage rates for lagoons under different environmental and climatic conditions. From these studies, it has been determined that initial seepage rates from lagoons can be relatively high, but a “sealing process” reduces the infiltration rate (Rowsell et al., 1985). This sealing process can reduce infiltration rates by several orders of magnitude and occurs from both physical and biological processes that reduce the hydraulic conductivity of the soil (Barrington et al., 1987). Several modeling attempts have been performed to try to quantify both the amount of seepage occurring from these structures and the environmental impacts. Typically, the amount of seepage occurring from these structures by assuming saturated conditions in the liner and then using Darcy’s law to calculate the flux rate. This is shown in equation (8).

$$q = K_L \frac{L_W + L_L}{L_L} \quad \textbf{(8)}$$

Where q is the flux rate through the liner, K_L is the hydraulic conductivity of the liner, L_W is the depth of waste in the basin, and L_L is the thickness of the linear.

The third mechanism by which containment-land application systems could transport nutrients is from non-point source pollution originating from the land application area. Currently Iowa NPDES permits do not include non-point source pollution from this area in determining the mass of nutrients released from an animal feeding facility as long as best management practices with regards to timing and application rate of the effluent are followed. However, the Federal Register (2003) states that waste control systems should be evaluated “holistically”. Therefore, future studies on both modeling and monitoring the containment-land application systems should focus on addressing all mechanism by which the waste management systems cause environmental concern. Specifically, adding non-point source pollution originating from land-application areas.

Vegetative Treatment Areas

A vegetative treatment area (VTA) is designed to manage runoff from open livestock facilities and is typically planted to a perennial grass or forage crop (Koelsch et al., 2006). This area typically has a slope of less than 5% and should be designed to encourage uniform sheet flow through the length of the VTA. Ikenberry and Mankin (2000) propose that VTA's treat the runoff effluent by sedimentation, filtration, infiltration, and evapotraspiration. Koelsch et al. (2006) elaborate on these treatment mechanisms stating that the two primary mechanisms of treatment in the VTA are sedimentation, which usually occurs in the first few meters of the VTA, and infiltration of the runoff effluent. After being infiltrated into the soil, several processes occur which can improve the effluent quality; these include filtration of bacteria and solids, immobilization of nutrients such as ammonia and phosphorus, which are adsorbed to the soil surface, and the subsequent uptake of these nutrients by plants. Furthermore, it is possible that the VTA will cycle between aerobic and anaerobic conditions as effluent saturates the upper soil profile and then subsequently drains away or is evapotranspired; these fluctuations could promote the breakdown of organic compounds during aerobic conditions and possibly denitrification during anaerobic conditions. As mentioned previously, maintenance of sheet flow is important for maximizing performance of the VTA. By ensuring sheet flow on the VTA surface flow velocity is reduced, therefore increasing contact time between the VTA and the effluent, increasing the opportunity for infiltration of the effluent, and reducing the transport mechanism (i.e. the carrying capacity) of nutrients. Many VTA's use overland flow via gravity to distribute the effluent down the length of the treatment area; however, recently Gross and Henry (2007) proposed and developed a sprinkler system that could be utilized to more evenly distribute the effluent over the VTA. This option provides the advantage of more even application of effluent; however, this system also reduces the opportunity for filtration of the effluent as it flows through the vegetation.

VTA's have been utilized as a form of waste treatment for many years; however, it was only recently that engineers began to formalize a design process and to quantify the results these treatment systems were having on the quality and quantity of effluent released from an animal feeding facility. Thus far, two general procedures have been purposed for sizing vegetative treatment areas. These procedures are based on the either the hydraulic loading rate or the nutrient loading rate expected. When sizing a VTA based on the hydraulic, or water balance method, the risk of runoff from the VTA should be minimized, thus nutrient transport from the facility will be reduced. By sizing on a nutrient mass balance, usually nitrogen, the risk of nitrate leaching will also be reduced since the effluent is applied at an agronomic rate (Woodbury et al., 2004).

A general procedure for sizing a VTA using the water balance method is to determine the volume of effluent resulting from a design storm. First, determine the saturated soil infiltration rate for the treatment area. Saturated soil infiltration rate is often determined with the use of a soil survey data; however, *in situ* measurements provide a more thorough analysis and will provide a design that better matches actual field conditions. The second step is to determine the drain time of the settling basin; typical drain times are between 30 and 72 hours (Woodbury et al., 2003). The required VTA size is then determined by dividing the entire effluent volume by the saturated infiltration rate. This solution assumed even hydraulic loading of the entire VTA area, so a term amounting to a safety factor is added to account for any channelization that may occur.

Sizing the VTA by the nutrient mass balance is performed in a slightly different manner than the hydraulic balance, rather than looking at the system on a design storm basis, the system is analyzed on a yearly basis. This requires determination of the average annual runoff volume from the feedlot surface. This value is then multiplied a concentration that is representative of the effluent flowing onto the vegetative treatment area. The estimated uptake of nitrogen and phosphorus from the vegetation then should be determined. This is done by taking typical vegetation uptake rates and multiplying by the expected harvest rate. The required VTA size is then determined by matching the expected annual nutrient harvest to the average annual nutrient load transported from the feedlot.

Along with understanding the design process of vegetative treatment areas, it is important to understand, at least conceptually, how the entire system will operate in order to effectively model the performance. Blume (2006) provides a framework for considering how the vegetative treatment system operates and how this relates to the design of the system.

1. Rainfall begins on the feedlot and the vegetative treatment system.
2. Runoff begins from the feedlot after the initial abstraction has been satisfied. The vegetative treatment continues to infiltrate most of the rainfall.
3. Runoff from the feedlot enters a settling basin. The outlet on the settling basin can be operated either passively or actively, but in either case outflow from the settling basin should be substantially limited during the rainfall event.
4. Release of effluent onto the VTA can now commence; application rates of effluent onto the VTA should be matched to the infiltration rate of the soil.
5. Soil moisture in the VTA will then be depleted by evapotranspiration until the next rainfall event. This resets the system for step 1.

Along with the available design guidance there is substantial research that has been performed on VTA's at the field and plot scale. Koelsch et al. (2006) completed a literature review of field and plot trials from over 40 studies. These studies in general showed reductions of total solids of 70-90%, with the majority of this reduction occurring in the first few meters. Total phosphorous reductions were typically around 70%, with performance often being similar to that of total solids. Similar results have been seen for most nutrients with the exception of nitrate (Koelsch et al., 2006). In a study by Paterson et al. (1980) nitrate concentrations increased while passing through the treatment system. Moreover, in their literature review Koelsch et al. (2006) reported several studies in which nitrate concentrations increased, but even with the increase in nitrate concentrations the total mass of nitrate transported still decreased. Overcash et al. (1981) proposed a design equation to account for nutrient reductions as the effluent passed through the VTA. This is shown in equation (9).

$$C_x = C_B + (C_O - C_B)\exp\left(\left(\frac{1}{1-D}\right)\ln\left(\frac{1}{1+K}\right)\right) \quad \textbf{(9)}$$

In equation (9) C_x is the concentration at the outlet of the treatment area, C_B is the background concentration (i.e., the concentration regardless of whether or not waste has been applied), C_O is the influent concentration, D is the ratio of infiltration to runoff, and K is the ratio of VTA length to the waste generation area length. This equation can be used for most contaminants and was originally developed to predict the pollutant reduction occurring in buffer zones located next to land application area. This is a first order decay equation that basically state that given sufficient flow distance the treatment strip will reduce the effluent concentrations to the levels in rainfall runoff from the filter area.

Woodbury et al. (2002, 2003) performed a more recent study on the effects of a full-scale VTS on an open feedlot near Clay Center, Nebraska. In this study a flat-bottomed debris basin and a vegetative treatment area where used to control the runoff. In this study, the feedlot drainage area was 2.4 hectares with and additional 1.2 hectares of grassland contributing runoff to the settling basin. The VTA in this study is 6.0 hectares, giving a VTA to a feedlot ratio of 1.67. During this study, no effluent was monitored exiting the VTA; furthermore, the vegetation removed from the treatment area accounted for more nitrogen removal then was added from the effluent runoff from the feedlot. Thus, it was concluded that the system was effective at controlling runoff from the open feedlot.

Vegetative Infiltration Basins

A vegetative infiltration basin (VIB) is a possible vegetative treatment component that relies on the soil to filter nutrients and contaminants from the feedlot runoff effluent (NRCS, 2006). Moody et al. (2006) provides a description of typical VIB design and operation, stating that a VIB is a flat area surrounded by berms and planted to permanent vegetation, thus there is no direct surface discharge from the

VIB. Tile lines installed at depths between four to six feet are placed under the VIB; these tile lines enhance infiltration into the soil so that water remains ponded in the VIB for only short time periods. VIB's perform several important functions; they significantly reduce both the concentration and mass of most nutrients transported in the runoff. VIB's also delay and extend the period of release from the hydrograph, which reduces the risk of an effluent discharge by providing a more controlled release to any additional treatment components.

Edwards et al. (1986) report the performance of a VIB system used on a 56-head concrete feedlot located in Ohio during a three-year period. In this case the treatment system consisted of two components, a settling basin and a vegetative infiltration basin. For this site the feedlot had an area of 243 m^2, the settling basin capacity was 6.3 m^3, and the VIB area was 165 m^2, giving a VIB to Feedlot area ratio of 0.68. The VIB was isolated from the surrounding area by installing metal borders (0.9 meters deep) and a perimeter tile around the VIB. Tile lines under the VIB were also installed at 0.9 meters of depth.

The hydraulic performance of the system as monitored by Edwards et al. (1986) is provided in Table 17. As can be seen, a reduction in the volume of water exiting each component was reduced in comparison to the total volume of effluent and rainfall added to that component. However, if the volume of effluent exiting the infiltration bed is compared to the volume of runoff exiting the feedlot a reduction in effluent quantity was only obtained during the first year of the study (7% reduction). For the remaining years, the volume of effluent actually increased, by 40% and 20%, respectively, for years two and three. This was due to rainfall directly on the infiltration bed increasing the hydraulic loading rate. Based on this study it seems logical to conclude that use of a vegetative infiltration basin does not reduce the overall quantity of feedlot runoff effluent. This fact coincides with the recommendations in the recommendation presented in the NRCS VTS design guidelines, which state that a VIB will not significantly reduce the volume of water moving to a VTA. Although both the data by Edwards et al. (1986) and the design guidelines presented by the NRCS suggest this to be the case, it is important to understand the theoretical basis behind this.

Table 17. Hydraulic performance of VIB system given by Edwards et al. (1986).

	Feedlot				Settling Basin				Infiltration Bed			
Year	1	2	3	Total	1	2	3	Total	1	2	3	Total
Precipitation (m^3)	227	167	202	596	34	25	30	89	156	115	139	410
Run on (m^3)	0	0	0	0	158	92	132	382	158	99	122	379
Total Inflow (m^3)	227	167	202	596	192	117	162	471	314	214	261	789
Total Outflow (m^3)	158	92	132	382	158	99	122	379	147	129	158	434
% Reduction	30	45	35	36	18	15	25	20	53	40	39	45

To understand why this is the case, it is important to understand how a VIB is constructed and what are the hydraulic conditions it will encounter. As mentioned previously, a VIB is a relatively flat area surrounded by berms to prevent a surface release. Tile lines will underlie the VIB and serve to increase infiltration through the soil profile and collect the infiltrating effluent; this effluent is then transferred to additional treatment components. In order to function properly a VIB should be located in an area with impervious subsurface soils, as this will create a perched water table allowing the tile lines to function properly. Furthermore, this impervious subsoil layer limits seepage from the system. Based on these conditions, a simple water balance model can be used to asses how effluent will move through the VIB. This water balance model is shown in equation (10).

$$\Delta S = P + R - ET - TD - DD \quad \textbf{(10)}$$

In this equation P represents the volume of precipitation falling onto the VIB, R the volume of runoff inflow into the VIB, and ET the volume lost to evapotranspiration. TD and DD both represent volumes lost due to drainage, where TD is the volume of tile drainage and DD is the volume lost to deep drainage, i.e., the volume lost due to seepage below the tile lines. The final term, ΔS represents the change of water content in the soil profile as well as the change in volume water stored on the surface of the VIB. If located properly, very little effluent will be lost to deep drainage. Furthermore, if functioning properly the VIB will only have standing water on the surface for a couple of days, thus looking over the course of an event there would be no change in surface storage in the VIB. Finally, looking at the change in storage of soil water content in the soil profile there should be little to no change in soil water content, as the soil profile should be approximately at equilibrium water content at the start of the event and drains to equilibrium at the end of the event.

As seen in Table 18, Edwards et al. (1986) report that the concentration of most nutrients is substantially reduced in both the settling basin and the vegetative infiltration basin. For instance, in the settling basin both total solids and chemical oxygen demand are decreased by approximately 50%, while soluble nutrients such as ammonium and potassium see little reduction in concentration. As the effluent is filtered by the soil profile concentrations of the soluble nutrients such as ammonium and potassium are reduced. The concentration of nitrate increases during the filtration through the infiltration basin (Edwards et al., 1986). This increase in nitrate concentrations may have been the result of aerobic conversion of ammonium to nitrate by *Nitrosomonas* and *Nitrobacter* (Prantner et al., 2001). In addition to the concentrations reductions, the overall mass of nutrients transported in the feedlot runoff was also substantially reduced (Table 19). Throughout the runoff control system the total solids, chemical oxygen demand, ammonium, total phosphorus and soluble phosphorus concentrations were reduced by 70-80%. Again, nitrate was the only nutrient in which the mass exported exceeded the mass imported, which again suggests that nitrate was being created from the ammonia and organic nitrogen loading in the infiltration basin.

Table 18. Nutrient concentrations at each point of the treatment system from Edwards et al. (1986).

	TS	COD	NO_3-N	NH_4-N	Organic N	Total P	Soluble P	K
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Feedlot	17,100	19,900	0.7	209	532	118	73	701
Settling Basin	8,800	9,800	0.5	208	346	93	63	645
Infiltration Basin	3,000	3,000	5.2	50	104	24	13	259

Table 19. Total masses of nutrients exiting each stage of the treatment system from Edwards et al. (1986).

	TS	COD	NO_3-N	NH_4-N	Organic N	Total P	Soluble P	K
	kg	kg	kg	kg	kg	kg	kg	kg
Feedlot	2181	2534	0.09	26.7	67.9	15	9.3	89
Settling Basin	1114	1243	0.06	26.3	43.7	11.8	8	82
Infiltration Basin	431	437	0.75	7.3	15	3.5	1.9	38

Yang and Lorimor (2000) reported on the use of a soil infiltration-wetland treatment system used on a 380 head beef cattle feedlot near Ames, Iowa. In this study the cattle were housed on 22,720 m^2 (5.5 acre) concrete lot. Concrete aprons around the pens served as solid settling basins. After passing through the solid settling basins runoff effluent was routed into a 3,976 m^2 infiltration area The infiltration area, surrounded by earthen berms, was drained with three 0.1 m (4 inch) tile lines. These tile lines collected and transported the infiltrating runoff effluent to a wetland area for final treatment.

In this study, Lorimor et al. (2003) reported 80% reductions in total Kjeldahl nitrogen concentrations and 81% reduction in ammonium concentration during treatment in the VIB. Furthermore, total solids and total phosphorus concentrations were reduced by 65% and 77%, respectively. In this study, as in the Edwards et al. (1986) study, nitrate concentrations increased during treatment in the infiltration basin. Lorimor et al. (2003) reported settling basin outflow concentrations of 0.98 mg/L and 1.7 mg/L after treatment in the VIB.

Lorimor et al. (2003) also assessed total mass transport reduction occurring during thee flow events. These events occurred on June 8 - 13, July 4 - 10, and Aug 5 -13. Overall mass reductions for TKN, ammonium, nitrate, total phosphorus, and total solids were 88%, 86%, 57%, 80%, and 79% respectively (Lorimor et al., 2003). Thus, even though nitrate concentrations increased, there was still an overall reduction in nitrate transport during these three periods. This is in contrast to the Edwards et al. (1986) study, which showed an overall increase in nitrate mass transport along with the concentration increase.

Monitoring of VTSs in Iowa

Iowa State University has been monitoring the performance of VTS located on six CAFOs located throughout the state of Iowa. At four of these locations, monitoring began in 2006. Monitoring data from those four locations is available from Khanijo (2007). A summary of the sites used in the study are provided in Table 20 and pictures of these sites are provided in Figure 9. For this study two of the sites, Central Iowa 1 and Central Iowa 2, were designed as stand-alone VTA systems. These sites had VTA to feedlot area ratios of 0.50:1 and 0.58:1 respectively. The remaining two systems, Central Iowa 2 and Northwest Iowa 2 are VIB-VTA systems. For these systems the ratio of VTS (VIB and VTA areas) to feedlot area are 0.52:1 and 0.55 respectively.

Table 20. VTS configurations and system component sizes for monitored VTSs in Iowa from Khanijo (2007).

	VTS Configuration	Feedlot Area (ha)	SSB Volume (m^3)	VIB Area (ha)	VTA Area (ha)
Central Iowa 1	1 SSB - 2 VTAs	3.08	4,276	-	1.53
Central Iowa 2	1 SSB - 1 VIB - 1 VTA	1.07	561	0.32	0.24
Northwest Iowa 1	1 SSB - 1 VTA	2.92	3,710	-	1.68
Northwest Iowa 2	1 SSB - 1 VIB - 1 VTA	2.95	1,104	1.01	0.60

The pilot portion of the Central Iowa 1 VTS consists of a solid settling basin that drains into two VTAs. The settling basin at this site is designed to contain all feedlot runoff and direct precipitation from a 25-year, 24-hour storm event. This settling basin uses a slotted picket fence outlet design to filter solids from the runoff effluent. During the spring of 2007, a gated V-notch weir was added to the basin outlet to improve solid settling and to allow the operator more control over when effluent would be applied to the VTAs. Pictures of the original picket fence outlet and the gated V-notch weir outlet are shown in Figure 10a and b. From the solid settling basin, the effluent is applied via gravity drainage onto two VTAs.

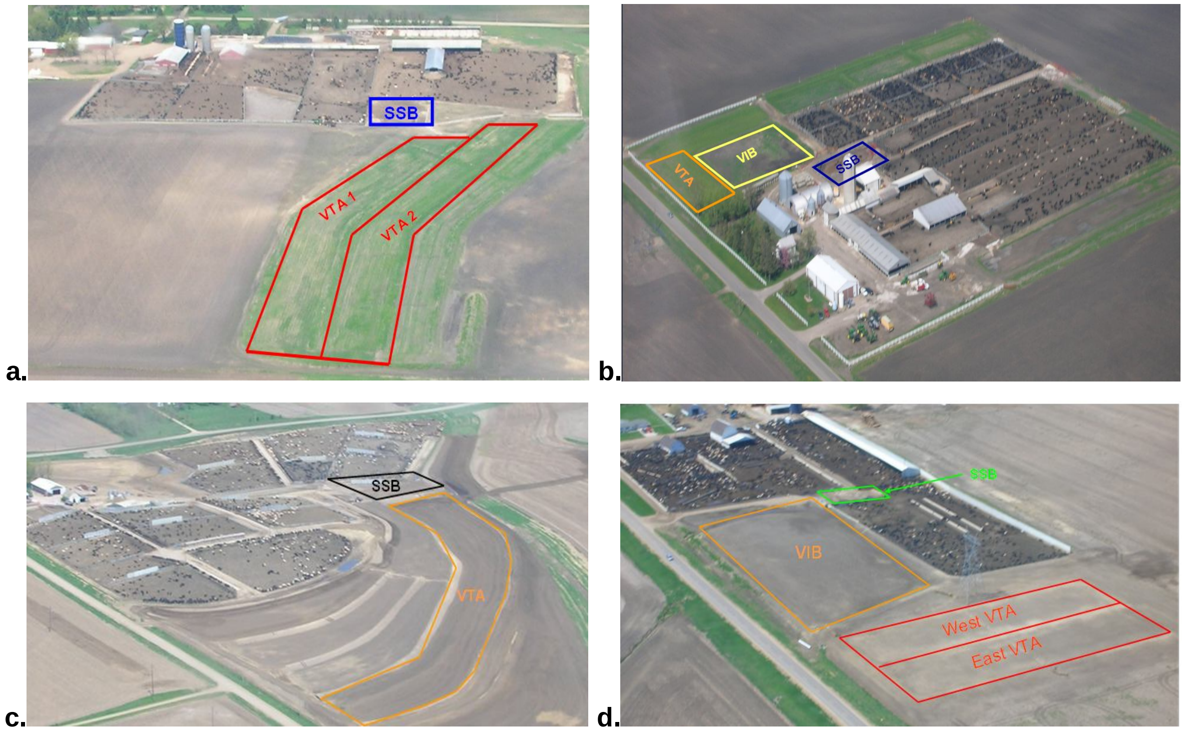

Figure 9. Pictures of the VTSs monitored by Iowa State University from Khanijo (2007). a.) Central Iowa 1 b.) Central Iowa 2 c.) Northwest Iowa 2 d.) and Northwest Iowa 1

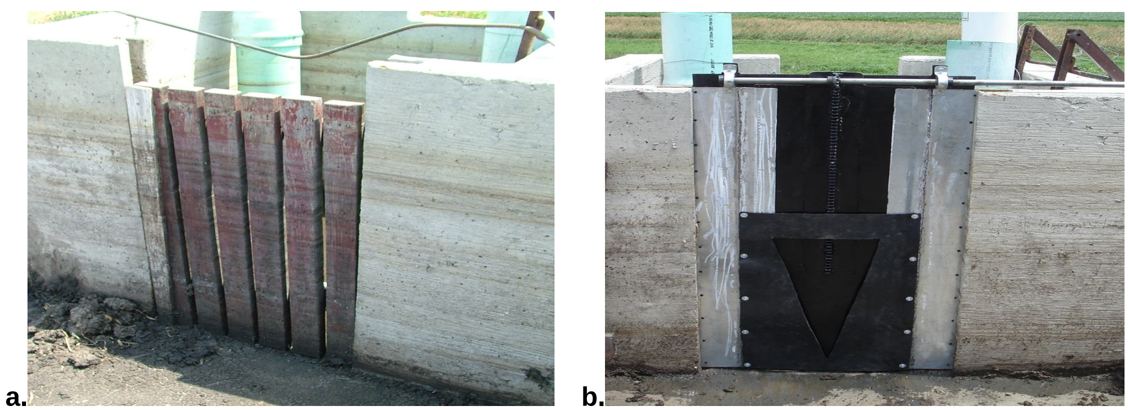

Figure 10. Photo a.) shows the original picket fence outlet structure and photo b.) shows the outlet structure after installation of the gated V-notch weir.

Central Iowa 2 is a VIB-VTA system. In this the runoff effluent drains into a concrete settling basin. The settling basin uses again a picket fence outlet structure. Effluent from the settling basin is released into the VIB through a PVC pipe; a gate valve on the pipe inlet controls when effluent is released. The VIB has four-inch perforated tile installed at a four foot depth below the VIB surface. The drainage tiles were installed with a 20 foot spacing. The tile collects and transports effluent infiltrating through the soil profile. This effluent is then applied to a VTA for additional treatment

Northwest Iowa 1 was very similar in design to Central Iowa 1. The system was a stand-alone VTA system with storage for a 25-year, 24-hour storm event in the settling basin. The settling basin used a picket fence outlet structure and had a valve to control when effluent was released. The VTA was planted primarily to brome grass and had geotextile flow spreaders located every 200 feet down its length to encourage even flow distribution.

Northwest Iowa 2 used a VIB-VTA system. This was the only concrete surfaced feedlot in the study. As with Central Iowa 1, the runoff effluent drained from the settling basin into the VIB. Tile lines were installed under the VIB to enhance drainage. Effluent collected in these tile lines was pumped to the top of the VIB and applied the VTAs. Effluent reaching the bottom of the VTAs was collected and routed back into the VIB.

The performance of these systems, on a nutrient mass release basis from these systems is given in Tables 21 and 22. In 2006, all system performed well with nutrient mass reductions ranging from 67% to 99%. For 2007, the performance of several systems was less than in 2006, most noticeably at Central Iowa 1, where the percentage reduction in nutrient mass transport ranged from 35-53%. The large volumes of release from the VTA were the primary cause of the reduced system performance, as the release volume from the VTA was larger than the volume of runoff from the feedlots. Northwest Iowa 2 consistently was the best performing system reducing the nutrient mass transport by over 99% for all nutrients in both years.

Table 21. Percentage reduction in nutrient mass transport reported in 2006 for four VTSs from Khanijo (2007).

2006	NH_4	TKN	Total P	COD	TS
Central IA 1	97%	97%	97%	97%	97%
Central IA 2	83%	78%	72%	74%	67%
Northwest IA 1	94%	97%	96%	97%	97%
Northwest IA 2	99%	99%	99%	99%	99%

Table 22. Percentage reduction in nutrient mass transport reported in 2007 for four VTSs from Khanijo (2007).

2007	NH_4	TKN	Total P	COD	TS
Central IA 1	53%	44%	41%	44%	35%
Central IA 2	94%	95%	92%	95%	89%
Northwest IA 1	80%	82%	76%	82%	84%
Northwest IA 2	99%	99%	99%	99%	99%

Khanijo (2007) also provided the arithmetic average concentrations of the effluent released from each component of the VTS; these are shown in Table 23. In general, concentration reductions occurred during each phase of the treatment process at the sites. On average, concentration reductions of 67, 62, 57, 69, and 66% were reported for NH4, TKN, Total P, Total Solids, and COD respectively. Thus although though these systems are not providing complete runoff control they due seem to provide a high level of both nutrient mass transport reduction and nutrient concentration reduction.

Table 23. Average concentrations in effluent released from each VTS component.

	NH_4		TKN		Total-P		Total Solids		COD	
System Component	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
2006										
Central Iowa 1 - SSB	128	87	429	238	88	38	9,539	3,978	7,903	3,931
Central Iowa 1 - VTA	73		366		82		870		6,330	
2007										
Central Iowa 1 - SSB	205	107	349	188	102	34	5,983	2,266	5,872	3,189
Central Iowa 1 - VTA	59	34	124	80	46	21	2,342	1,405	1,848	1,326
2006										
Central Iowa 2 - SSB	43	62	141	160	30	25	4,120	3,312	2,371	2,366
Central Iowa 2 - VIB	12	10	100	107	13	9	2,680	1,324	1,177	739
Central Iowa 2 - VTA	8	12	37	40	10	9	1,829	1,331	688	715
2007										
Central Iowa 2 - SSB	265	211	780	587	215	139	15,890	8,564	14,076	8,274
Central Iowa 2 - VIB	71	59	119	127	38	42	3,631	2,754	2,161	2,417
Central Iowa 2 - VTA	15	30	35	62	7	6	1,240	1,158	506	884
2006										
Northwest Iowa 1 - SSB	239	357	1,024	1,254	137	152	22,895	18,596	24,378	40,483
Northwest Iowa 1 - VTA	41	11	171	26	37	2	5,046	467	2,427	105
2007										
Northwest Iowa 1 - SSB	132	83	317	220	48	23	7,865	3,843	5,070	2,581
Northwest Iowa 1 - VTA	83	70	185	126	40	24	4,860	3,255	2,924	2,151
2006										
Northwest Iowa 2 - SSB	325	177	1,145	777	152	87	17,294	12,158	16,895	10,939
Northwest Iowa 2 - VIB	132	105	697	949	60	47	8,248	5,348	7,023	4,352
Northwest Iowa 2 - VTA	166	106	541	345	60	34	7,697	4,029	7,509	4,383
2007										
Northwest Iowa 2 - SSB	425	200	1,539	950	263	170	43,169	33,899	41,931	38,679
Northwest Iowa 2 - VIB	66	44	250	179	37	27	5,596	2,606	5,111	3,611
Northwest Iowa 2 - VTA	96		432		60		9,030		8,220	

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CHAPTER 2. COMPARISON OF THE IOWA STATE UNIVESITY – EFFLUENT LIMITATION GUIDELINES MODEL WITH THE SOIL-PLANT-AIR-WATER MODEL TO DESCRIBE HOLDING BASIN PERFORMANCE

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Abstract

In Iowa, all open beef feedlot operations over 1,000 head are required to have runoff control systems. Currently, Iowa regulations allow the use of vegetative treatment systems (VTS) on open beef feedlots that meet regulatory siting requirements. For a National Pollutant Discharge Elimination System (NPDES) permit, the runoff control performance of VTS's must meet or exceed the performance of traditional runoff containment basins as predicted by the Iowa State University-Effluent Limitations Guideline (ISU-ELG) model. The ISU-ELG model was based on a model developed by Koelliker et al. (1975) to predict the performance of a holding basin at controlling feedlot runoff. In this paper, the criterion used to determine if a particular day is a "dewatering day," i.e., suitable for land application of basin effluent, was investigated to determine its effect on basin performance, with the objective of verifying that the ISU-ELG model was providing a reasonable prediction of the runoff control provided by a containment basin. This paper compares results from the ISU-ELG model to results obtained using the Soil-Plant-Air-Water (SPAW) model to simulate traditional feedlot runoff containment basin performance. The SPAW model uses a soil moisture criterion to determine if conditions are acceptable for land application of basin effluent. The results show that the ISU-ELG model over-predicts performance of traditional containment systems in comparison to the SPAW model at all five locations investigated. For wetter areas in Iowa, the number of drying days has a large effect on basin performance, whereas for the drier northwest region of Iowa this effect is limited. Possible methods of improving the ISU-ELG model predictions include adding a soil moisture accounting

function to model moisture levels in the land application area or calibrating the number of drying days required before land application can commence.

Keywords. feedlot runoff control, Effluent Limitation Guidelines Model, SPAW, containment basin performance

Introduction

Water pollution associated with runoff from open beef cattle feedlots has been a concern for many years. The passage of the Federal Water Pollution Control Act Amendments in 1972 placed the Environmental Protection Agency (EPA) in charge of developing runoff control guidelines (Anschutz et al., 1979). As a result, the EPA released the Effluent Limitation Guidelines, which described the design and operating criteria for concentrated animal feeding operation (CAFO) waste treatment systems (Sweeten et al., 2003). These effluent limitation guidelines historically required collection, storage, and land application of feedlot runoff. In Iowa, the current guideline for CAFO beef feedlot runoff control was written to require removal of all settleable solids and no effluent discharge resulting from precipitation events less than or equal to the 25-year, 24-hour precipitation event (Iowa Department of Natural Resources, 2006).

The Iowa regulations for feedlot runoff control facilities on CAFO operations was recently modified to allow the use of alternative treatment systems when performance is equivalent to or exceeds that of a traditional system (Federal Register, 2003). Permitting alternative treatment technologies requires a comparison of the median annual overflow over a 25-year period between a traditional containment system and the proposed alternative treatment system. This comparison is made by performing site-specific modeling of both a theoretical traditional system and the proposed alternative treatment system. In addition to playing a key role in the initial permitting of these alternative treatment systems, modeling of the traditional containment system is required to ensure that the installed alternative treatment system is achieving a level of control equaling or exceeding that of the traditional containment system. This comparison is made on a yearly pollutant mass load exiting the runoff control system (EPA, 2008). In Iowa, site specific traditional containment system performance is predicted using the Iowa State University-Effluent Limitations Guideline Model (ISU-ELG Model) implemented according to the guidelines described in Appendix A of the Iowa AFO/CAFO Regulation (Iowa Department of Natural Resources, 2006). One traditional containment option available to producers is a basin sized to contain all runoff from the 25-year, 24-hour precipitation event from all contributing drainage areas. For this option, land application of the collected effluent must begin on the first day that conditions are suitable (Iowa Department of Natural Resources, 2006). Modification of the feedlot runoff control regulations to allow use of alternative treatment systems has renewed interest in predicting control provided by runoff control systems, as evidenced by the development of models to determine the runoff control achieved by vegetative treatment systems. Examples of these models include the Iowa State University-Vegetative Treatment Area Model (ISU-VTA Model), the Iowa State University-Vegetated Infiltration Basin / Vegetative Treatment Area Model (ISU-VIB/VTA Model) (Wulf et al., 2005), and runoff control system models developed for Kansas (Tolle et al., 2007). Accuracy of the ISU-ELG model to predict traditional containment basin performance is key to alternative treatment system design and installed system evaluation. However, thus far little research has been done to determine if the ISU-ELG Model is providing reasonable prediction of the performance a traditional containment system would achieve, especially under Iowa conditions.

Objective

This paper compares the modeled overflow volumes obtained using the ISU-ELG and SPAW models to simulate the performance of a containment basin controlling feedlot runoff. This analysis was performed to determine if the ISU-ELG model provides a reasonable prediction of containment structure performance under Iowa climatic conditions. The analysis was performed for five locations throughout

Iowa. At each location, actual site-specific historical weather data were used in modeling system performance.

Background

There is a long history of modeling the performance of traditional containment systems on open beef feedlots. This modeling effort can be traced back to the EPA's release of effluent limitation guidelines in 1972. Shortly after the creation of the effluent limitation guidelines, Koelliker et al. (1975) developed a model to predict runoff control achieved by a traditional containment system following the effluent limitation guidelines. This model was written as a continuous watershed model operating on a daily time step to estimate the runoff control provided by the containment system. The model was developed to use the SCS curve number method to determine runoff volume from the feedlot surface; runoff volume was then routed into a holding pond. The holding pond volume was simulated using a water balance with inflows of runoff from the feedlot and direct precipitation onto the holding pond and outflows of evaporation, overflow, and land application of effluent. In this model, Koelliker et al. (1975) did not specifically consider the disposal area, but instead created a set of guidelines to determine when land application was appropriate. They considered land application appropriate if: daily precipitation for each of the three previous days was less than 0.05 inches, the average daily temperature was above freezing, there was no snow on the ground, the soil was not frozen, and more than 10% of the basin's total volume was filled with effluent. Using this model, Koelliker et al. (1975) demonstrated that a period of chronic rainfall could cause basin overflow. Furthermore, they suggested that by including more detailed disposal criteria the ELG Model could be refined. Wensink and Miner (1975) performed a similar modeling effort to evaluate the effect of chronic rainfall on total containment systems for Oregon locations. They recognized that runoff events in Kansas represented mainly catastrophic rainfall events whereas in western Oregon chronic rainfalls characterized the climate. In their investigation, Wensink and Miner (1975) noted the amount of overflow, the date, and the precipitation that caused this overflow. Based on this data the legality of the overflow was determined, i.e., was it caused by a storm event of equal or greater magnitude to the 25-year, 24-hour event. This allowed them to determine that many of the overflows were caused by events of lesser magnitude than the 25-year, 24-hour event. Based on the results of the study, they designed a second model that used what they termed the "Sufficient Design Technique" to help size containment structures to prevent discharge from events of lesser magnitude than the 25-year, 24-hour storm.

Based on these earlier modeling attempts, Zovne et al. (1977) developed a model that took into account the soil moisture in the disposal area. They considered the disposal area to be a soil-water reservoir that was recharged by both precipitation and land application, and depleted by evaporation and deep drainage. There were three components in this model: the feedlot surface which generated the runoff effluent, the effluent wastewater storage facility which modeled the holding pond level, and the disposal area which performed a soil moisture accounting procedure and enabled the modeling of soil conditions in the disposal area. Based on the soil conditions in the disposal area, a decision was made about the appropriateness of land application. In this analysis, a percentage of available moisture in the root zone above 90% was the threshold value for delaying land application. Anschutz et al. (1979) used the Zovne et al. (1977) model to study important variables in designing runoff control systems. For irrigation disposal systems, they found that moisture deficit was the most important factor. Moisture deficit was defined as the difference between the mean evaporation from a lake and the annual precipitation.

More recent interest in modeling holding pond performance has been provided by Wulf and Lorimor (2003), who created the ISU-ELG model to determine the performance of a traditional containment system under Iowa conditions. The ISU-ELG model was developed as a modified version of the Koelliker et al. (1975) model. The ISU-ELG model was written to operate on a daily time step with runoff volumes from the contributing drainage area calculated using the NRCS/SCS curve number method. This flow was then routed into a containment basin. The flow entering the basin has the concentrations shown in Table 24. These concentrations are used to calculate the mass of specific parameters entering the basin. The concentrations of the parameters in the basin were then adjusted to account for both water loss due to evaporation and water addition from rainfall directly onto the containment basin surface. The adjusted concentration was used to determine the mass of specific parameters removed from the basin due to either land application or basin overflow. In this model, Wulf and Lorimor (2005) used the same guidelines as Koelliker et al. (1975) for determining when land application was appropriate. These guidelines were deemed appropriate for Kansas climatic conditions, but no effort was made to verify these assumptions for Iowa climate conditions.

Table 24. Concentrations of specific parameters in the containment basin used in the ISU-ELG Model.

Contaminant	Earthen Lot (mg/L)	Concrete Lot (mg/L)
Total Kjeldahl Nitrogen	65	97.5
Ammonium Nitrogen	60	75
Total Phosphorus	20	30
Total Solids	2000	3000
Chemical Oxygen Demand	2650	3975

The Soil-Plant-Air-Water (SPAW) Model has been used to simulate the performance of waste containment structures. Moffitt et al. (2003) performed a comparison of Soil-Plant-Air-Water (SPAW) and the National Resources Conservation Services (NRCS) Animal Waste Management (AWM) program to test the temporary storage component of AWM. In this analysis, AWM was used to size the temporary storage component of the basin. They then used SPAW to examine the basin performance on a daily time step (Moffitt et al., 2003). In a separate study, Moffitt and Wilson (2004) utilized SPAW to model the pond levels in four wastewater storage ponds located on dairies in Oregon. These dairies had lot areas ranging from 232 to 11,655 m^2 (0.06 to 2.88 acres) which contributed runoff to the holding ponds. In this study, Moffitt and Wilson (2004) demonstrated good general agreement between the SPAW modeled levels and the experimentally determined levels, with deviations between the results possibly caused by issues such as operators deviating from their waste management plans, inaccuracies in containment structure level measurement, or differences in actual and modeled manure and wastewater inputs. This study showed that SPAW provided a model that could predict the performance of a waste storage pond if the system was operated according to the nutrient management plan. Specifically Moffitt and Wilson (2004) stated that a model is only as good as the operators' ability to follow their operating/nutrient management plans. They also pointed out that there were several factors that effect application time; these were the field conditions on which the containment structures contents were to be applied and the application time in relation to the crops nutrient demand.

Given that actual system performance was noted to be directly related to management decisions made by the farmer, it has become very important to define a reasonable management plan that the operator could be expected to use to manage wastewater basins. The Nebraska Department of Environmental Quality has released two guidance documents providing information on suggested containment basin operation. In the guidance document on holding pond operation, they specified that land application must occur on all dewatering days until the available holding pond capacity was able to contain all runoff from a 25-year, 24-hour event (Nebraska Department of Environmental Quality, 2005). A dewatering day was defined as a day with weather and soil conditions suitable for land application of livestock wastes (Nebraska Department of Environmental Quality, 2003). Proper soil conditions were defined such that the amount of liquid applied should not exceed the capacity of the soil to store the moisture in the root zone of the crop. The amount of liquid the soil can hold is determined by taking the current moisture level of the soil and subtracting this value from the field capacity (Nebraska Department of Environmental Quality, 2003). This idea of manure application timing based on soil moisture was also recommended to producers in the Wisconsin Agriculturist (Hanson, 2007) and Hoard's Dairyman (Weisenberger and Madison, 2007). Hanson (2007) discussed the effect of soil texture on the moisture holding capacity of soil and recommended keeping a moisture budget to determine if effluent application is acceptable. Weisenberger and Madison (2007) extended the analysis stating that no application of manure should occur when the moisture content in the top four inches exceeded 35% due to the risk of runoff.

As stated previously, Moffitt and Wilson (2004) reported the use of SPAW in modeling the depth of effluent in a containment basin. In their investigation, Moffitt and Wilson (2004) assumed that during the scheduled application period field conditions would be acceptable for land application. This made it easier to model the performance of the containment basin. More recently, Saxton and Willey (2004) reported an update to the SPAW model that allows the user to perform an irrigation budget for a field. The use of the irrigation budgeting could be used to determine when effluent application onto the application area would be appropriate from a soil moisture standpoint.

Methodology

The first item investigated was the sensitivity of the ISU-ELG Model to the number of dry days required after a precipitation event before land application could proceed. In the ISU-ELG model, this variable was determined to be equivalent to setting the soil moisture at which land application is considered appropriate. In the ISU-ELG model to date, a value of three days has been used; this followed the guidelines suggested by Koelliker et al. (1975) for their original containment basin model used in Kansas. The sensitivity of the model to this assumption was investigated for five hypothetical feedlots across the state of Iowa; these feedlots were located in Ames, Red Oak, Sac City, Sioux City, and Waterloo (Figure 11). Each of the simulations was performed for a 26-year period using actual site-specific historical weather data. The model was run ten times at each location varying the number of dry days required before land application could begin. Land application was then modeled to proceed at a rate of one-tenth of the total containment basin volume per day until either rainfall occurred or less than one-tenth of the basin volume was filled with effluent. The amount of discharge was then normalized at each site as average annual quantity of discharge per hectare of feedlot area. The size of the 25-year, 24-hour event at each of the locations is shown in the Table 24. This storm size was used to determine the size of a containment basin required to hold all feedlot runoff and direct precipitation onto the containment structure.

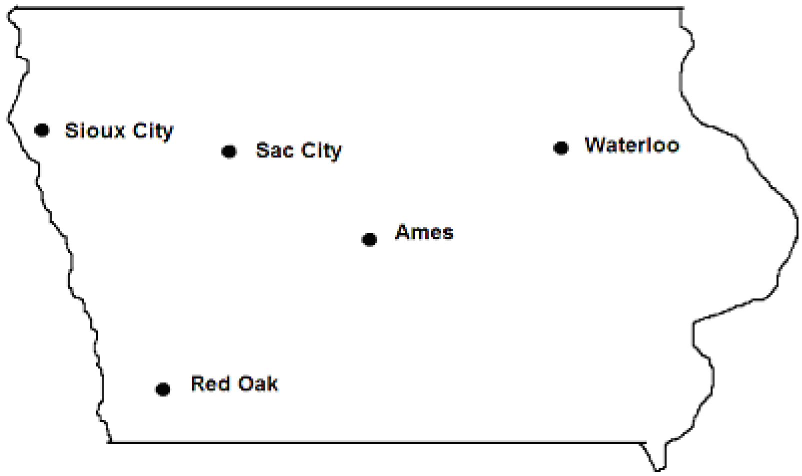

Figure 11. Locations of the five hypothetical feedlots used in the simulation.

Each of these simulations was also performed using the SPAW model. The SPAW model was used to simulate all parts of the feedlot hydrology including runoff from the feedlot, storage in a containment basin, and land application. SPAW, like the ISU-ELG Model, was developed to use the NRCS/SCS curve number method to determine the runoff volume from the feedlot. The curve numbers entered into the SPAW model were the same as the values programmed into the ISU-ELG Model, which are 91 and 94 for earthen and concrete surfaced feedlots respectively, under normal antecedent moisture conditions (AMC II), and 97 and 98 for earthen and concrete feedlots, under wet antecedent moisture conditions (AMC III), respectively. Stage-storage dimensions were entered in the SPAW model so that it replicated basin geometry used in the ISU-ELG Model. Finally, the land application area was modeled in SPAW such that land application would occur whenever the moisture level in the root zone reached 95% of the field capacity. The amount of irrigation supplied would replenish the moisture content of the root zone up to field capacity. Modeling the land application area required several additional input variables; these included the soil texture in the land application area, size of the application area, and rooting depth of the crop. For this analysis, the rooting depth was assumed to be four feet at all locations. By supplying soil texture SPAW then calculates additional hydraulic soil properties such as the soil-water retention curve, the hydraulic conductivity, and the bulk density of the soil. For this analysis, a representative soil for each of the five locations was determined by use of a USDA web soil survey applet. The soil texture present in that land application area at each of the five locations is also shown in Table 25. This soil texture information, along with thicknesses of the soil layers, was entered into the SPAW model; SPAW then calculated required soil properties such as hydraulic conductivity, the soil-water retention curve, and porosity based on this data.

Again, each of the simulations was run for a 26-year period using site-specific historical weather data. The model was run repeatedly at each location with varying land application area dimensions. The average annual overflow from the containment basin was again normalized by determining the average annual overflow on a per hectare of feedlot area basis.

Table 25. 25-Year, 24-Hour Storm Size and Soil Texture for Five Locations in Iowa

Location	25-year, 24-hour Storm Size mm (inches)	Soil Texture in Land Application Area
Ames	129.5 (5.1)	Loam
Red Oak	129.5 (5.1)	Silty Loam
Sac City	129.5 (5.1)	Loam
Sioux City	124.5 (4.9)	Silty Loam
Waterloo	127.0 (5.0)	Loam

The results of both modeling efforts were compared to determine if the original hypothesis of beginning land application three days after a precipitation event was a reasonable management plan based on the soil moisture in the application area. The number of dry days required before land application could begin was then adjusted to calibrate the ISU-ELG model so that the average annual discharge per hectare of feedlot predicted by the ISU-ELG Model and the SPAW model were approximately equal.

Results and Discussion

Figure 12 shows how the performance of a traditional containment basin varied, as predicted by the ISU-ELG Model, when the number of dry days required before land application could begin was adjusted. This analysis was conducted for five locations to represent the weather conditions expected throughout Iowa. The locations of Ames, Red Oak, Sac City, and Waterloo, showed the same general trend of increasing discharge when more time was required before land application could begin. Sioux City also showed this trend, but to a much lesser extent. As can be seen in Figure 12, the assumption about the amount of time required for the land application area to dry before effluent application could begin had a pronounced effect on performance for the majority of Iowa. The model's sensitivity to this variable made it important to accurately choose the number of dry days required before land application began.

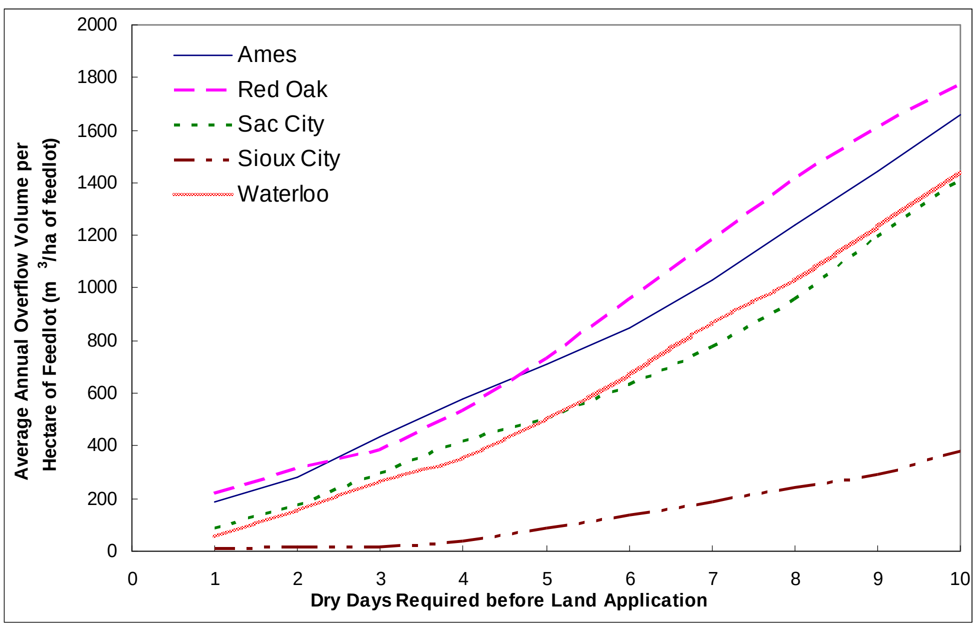

Figure 12. Sensitivity of the ISU-ELG Model to the number of dry days required before land application could begin for five locations in Iowa.

A regression analysis was used to quantify how system performance changed with the number of dry days required before land application could begin. Examples of this regression analysis for the feedlot at Ames and Sac City are shown in Figure

13. In this figure, the two dashed lines represent a 90% confidence interval for the average annual basin overflow volume per hectare of feedlot surface. The average annual overflow volume per hectare of feedlot for each dry day requirement is marked in the figure. A regression line was fit to the average data; the best-fit line was used to assess the ISU-ELG Model's sensitivity to the dry day requirement. For the Ames location, the analysis showed that for every day of drying required before land application commenced, on average an extra 163 cubic meters of basin overflow per year per hectare of feedlot would occur. Whereas for Sac City, on average an extra 143 cubic meters of basin overflow per year per hectare of feedlot would occur. Similar results were obtained for Red Oak and Waterloo.

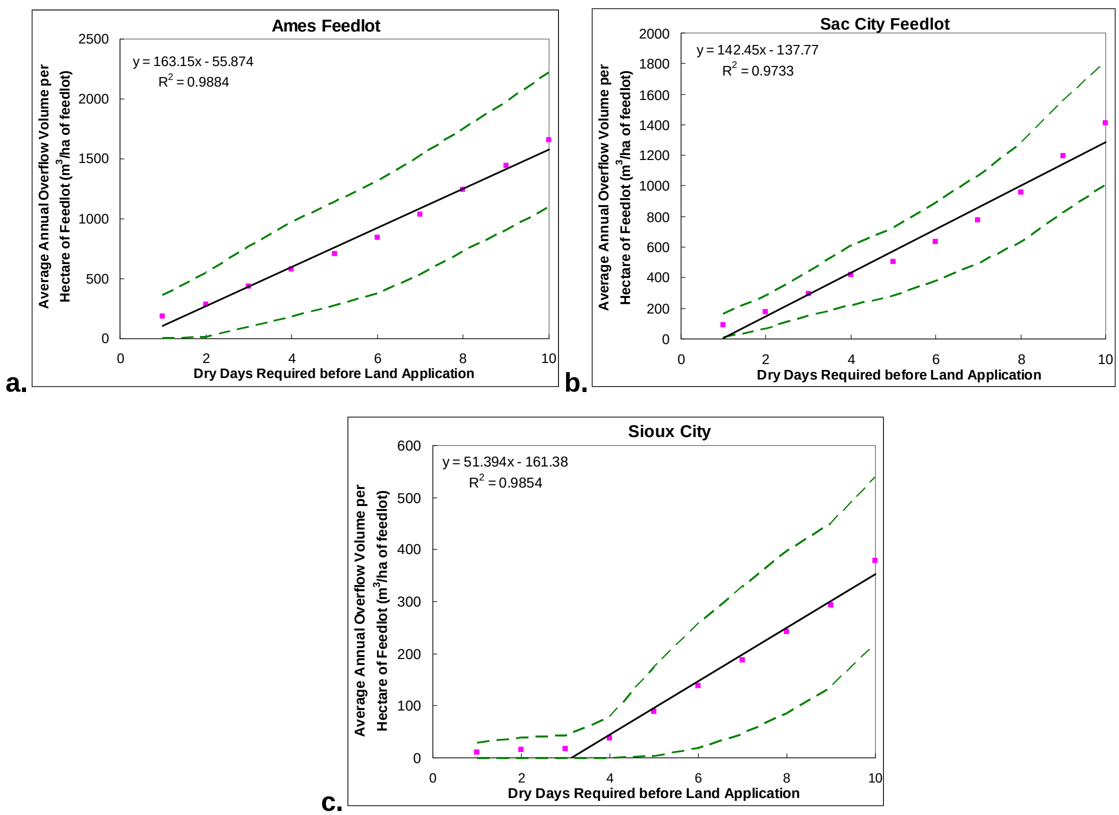

Figure 13. Regression analysis to determine the sensitivity of the ISU-ELG Model to the number of dry days required before land application could begin. Dashed lines represent 90% confidence intervals on the average annual overflow volume per hectare of feedlot. The data points with the solid regression line represent the average annual overflow volume per hectare of feedlot. a.) Ames b.) Sac City c.) Sioux City

The results from the regression analysis of Sioux City were quite different from the other locations, and are also shown in Figure 13. In modeling the Sioux City feedlot, changing the dry day requirement from one to three days had very little effect on the overall performance of the runoff control structure; thus, in this case the regression was only performed on dry days three through ten. At the Sioux City location, the temporal pattern of rainfall consisted of larger storms with a longer interlude between the storms in comparison to the other sites. Table 26 shows sensitivities to the dry day requirement for each of the five locations.

Table 26. Sensitivity coefficient for the ISU-ELG Model to the number of dry days required before land application could begin.

Location	m^3 overflow per hectare of feedlot per year per dry day required before land application (ft^3 overflow per acre of feedlot per year per dry day required before land application)
Ames	163 (2,332)
Red Oak	184 (2,632)
Sac City	143 (2,036)
Sioux City[h]	51 (734)
Waterloo	155 (2,211)

The result of the SPAW analysis is shown in Figure 13. In this case, the performance of the runoff control system was a function of the land available for application of the feedlot runoff, since a larger area would allow application of more effluent every time the disposal criteria was reached. For all five locations, it was assumed that the land application area would be planted to corn and irrigation could occur regardless of the crop size, i.e., irrigation was only limited by the soil moisture criteria. In this case, the basin could be completely emptied, i.e., there was no minimum treatment volume required to remain in the containment structure. As can be seen in Figure 14, Ames, Red Oak, Sac City, and Waterloo again showed a similar trend in response to the land application area available. For the Sioux City feedlot, a smaller disposal area was required and the system achieved a greater level of control than at the other locations. Figure 14 also illustrates that increasing

[h] Note that only days three through ten are considered in calculating the sensitivity coefficient for Sioux City.

the application area only has an effect on the performance of the containment system up to a ratio of five hectares of land application per hectare of feedlot surface, after this point there was a relatively small increase in system performance for increasing the application area. This was because at a certain point in each case the performance of the system was no longer limited by the size of the application area, but was instead limited by the temporal pattern of soil moisture in the land application area. Due to the drier climate in northwestern Iowa, a smaller application area was required per hectare of feedlot surface than in the areas that received more rainfall, and therefore naturally maintain a wetter soil profile. The soil moisture status was a function of several variables; among these were the volume and time distribution of rainfall, the soil texture, amount and time distribution of evapotranspiration, and soil properties in the land application area.

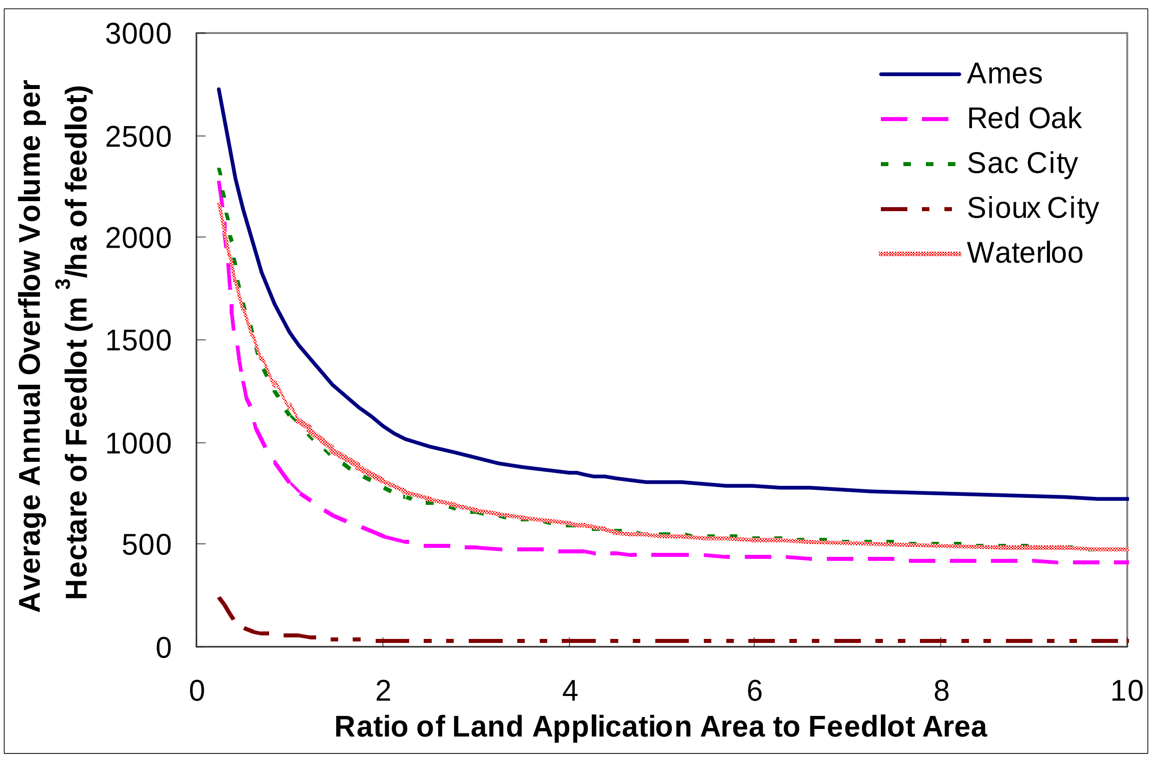

Figure 14. Sensitivity analysis of a containment basin, as predicted by the SPAW model, to the ratio of land application area to feedlot area for five locations in Iowa.

As mentioned previously, the ISU-ELG model was originally developed based on the model Koelliker et al. (1975) developed for predicting containment basin performance in Kansas. In this model, they assumed that land application would be possible three days after a rainfall event based on Kansas conditions. The ISU-ELG model had never been calibrated and no adjustments have been made for Iowa conditions. A comparison between the performances predicted by the SPAW model and the ISU-ELG Model has provided some insight into how well the assumption of three days before land application commences fits Iowa conditions. Based on these results and using the SPAW results as the measure of comparison, it was possible to calibrate the ISU-ELG model by adjusting the number of dry days required after a rainfall event to obtain the same performance as predicted by the SPAW model, which based land application timing on the modeled soil moisture. This calibration is shown for Ames, Red Oak, Sac City, Sioux City, and Waterloo in Figure 15. The calibrations were made on the average annual discharge volume per hectare of feedlot. For Ames, waiting approximately five days after the rainfall before land application made average annual discharge equivalent. For Sac City, between four and five days made the modeling procedures equivalent, with a similar result for Waterloo. Sioux City and Red Oak both had relatively good agreement when the release day criterion was left at three dry days before land application. This was caused by the substantially drier climate around Sioux City; the annual precipitation at this location was 66 cm (26 inches), this was similar to the 72.6 cm (28.6 inches) of precipitation averaged in Kansas. In addition, the similarity between the SPAW and ELG model results for Red Oak resulted from higher evaporation rates in this location. The results of the calibrated number of dry days required to obtain similar results to the SPAW model is shown in Table 27.

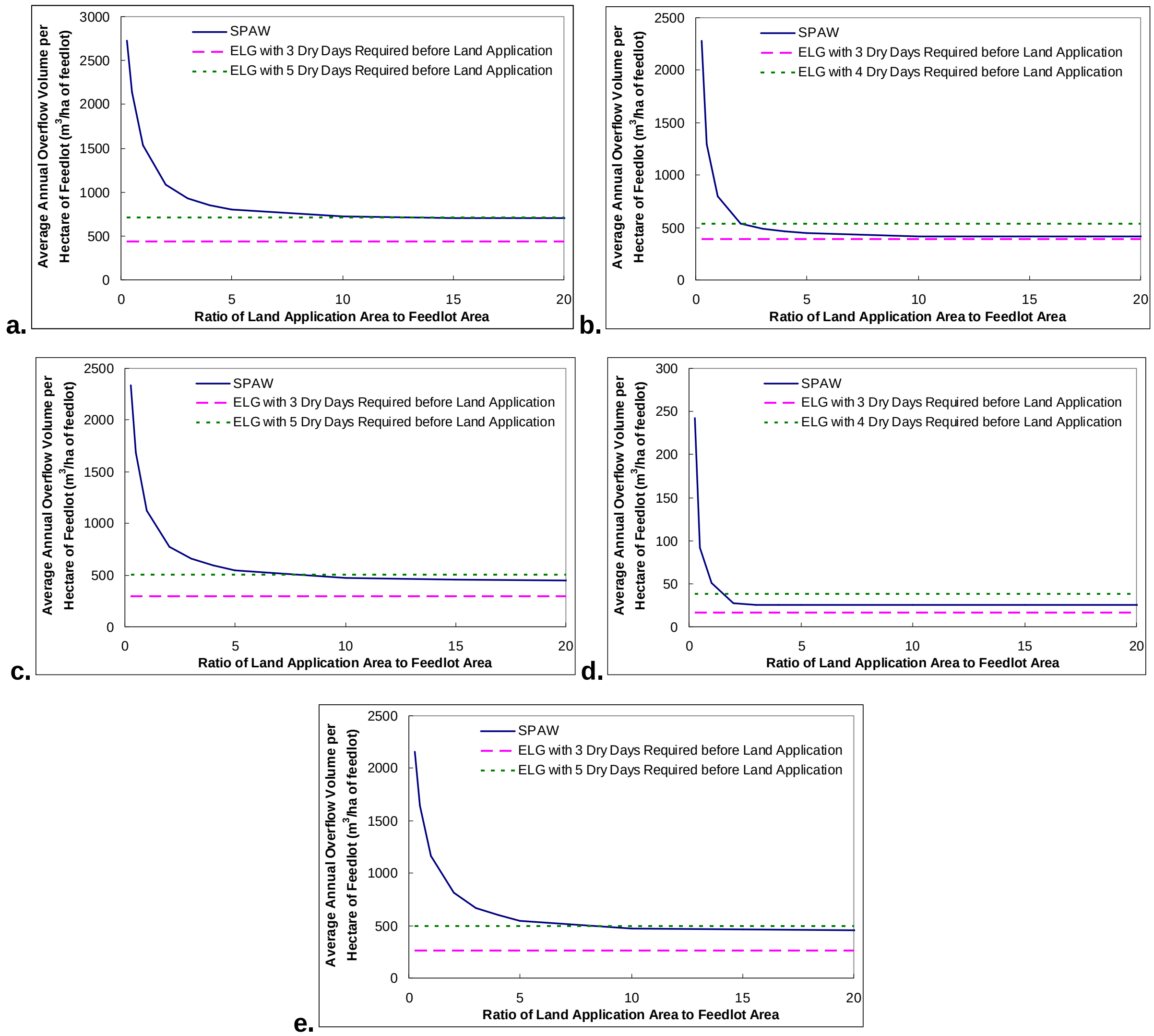

Figure 15. Calibration of the ISU-ELG Model dry day requirement to match SPAW predicted performance. a.)Ames b.) Red Oak c.) Sac City d.)Sioux City e.)Waterloo

Table 27. Calibrated number of dry days required to match ISU-ELG and SPAW model predictions of effluent release.

Location	Calibrated Number of Dry Days before Land Application
Ames	5
Red Oak	3
Sac City	5
Sioux City	3
Waterloo	5

A second way to conceptualize these results was to compare the predicted average annual yearly overflow volumes for both the SPAW and ISU-ELG models (Table 28). For most of Iowa, the SPAW model predicted 1.5 times the effluent discharge volume predicted by the ISU-ELG model when the three drying day criteria was used. The exception to this statement was Red Oak, where SPAW only predicted 1.1 times as much annual overflow as the ISU-ELG model. It should also be noted that the ratio of the two predictions for Sioux City was 1.5. In this case, the overflow volumes predicted by both models were very small. This large ratio was a result of the small overflow volumes predicted for this location. This can be verified by examining Table 29, which displays the percent runoff control predicted at each location. There was almost no change in the percent of runoff controlled at both Red Oak and Sioux City, whereas for Ames, Sac City, and Waterloo, a sizeable decrease in the predicted control was seen in the SPAW model predictions as compared to the ISU-ELG model.

A second method of modifying the ISU-ELG model that could be used would be to utilize the ratio between the two predictions as a multiplication factor to correct the ISU-ELG model annual predicted overflow volume to be equal to that of the SPAW model. Applying this correction factor would maintain the current definition of chronic rainfall (precipitation events within three days of each other). Applying this correction factor would make the average annual release volume predicted by the ISU-ELG model equal to the average annual release volume simulated by SPAW.

Table 28. Comparison of the average annual overflows predicted by the ISU-ELG and the SPAW Models. The third column displays the ratio of the SPAW prediction to the ISU-ELG prediction.

Location	Average Annual Yearly Overflow Predicted by ISU-ELG Model m^3/ha of feedlot	Average Annual Yearly Overflow Predicted by SPAW Model m^3/ha of feedlot	Ratio of SPAW Prediction to ISU-ELG Prediction
Ames	436	704	1.6
Red Oak	388	416	1.1
Sac City	29	445	1.5
Sioux City	16	25	1.5
Waterloo	264	455	1.7

Table 29. The percent runoff control as predicted by the ISU-ELG and the SPAW model for each of the five locations.

Location	ELG Model	SPAW
Ames	86%	78%
Red Oak	89%	88%
Sac City	90%	85%
Sioux City	99%	99%
Waterloo	90%	83%

Figures 16, 17, and 18, show a comparison between the ISU-ELG model results and the SPAW on a year-by-year basis. Both the original ISU-ELG model, with the three dry-day criterion before land application, and the dry day calibrated ISU-ELG model are shown in the site comparisons. As can be seen even the calibrated ISU-ELG model did not follow the same temporal pattern as SPAW in predicting when basin discharges would occur. Only a slight improvement in the temporal distribution of when the runoff occurred was realized from calibration of the ISU-ELG model to the SPAW model. Figure 16 shows a year-by-year comparison of the cumulative yearly overflow volumes on a per hectare of feedlot basis for Sac City. In this case, the uncalibrated ISU-ELG model predicted basin overflow for 13 out of the 26 years, after calibration basin discharge was predicted in 15 of the 26 years. The SPAW model also projected basin discharge in 15 of the 26 years modeled. For Sioux City, the ISU-ELG modeled predicted two years with discharges, while the SPAW model projected three years with discharge, according to both models most of the projected discharge occurred in 1972. In 1979, SPAW projected almost 148 m^3 of basin overflow, while the ISU-ELG model predicted no overflow. This resulted from a wet September, which kept modeled soil moisture levels elevated in the SPAW model, limiting land application opportunities. The ISU-ELG model did not predict an overflow during this period because the precipitation events occurred more than three days apart, which allowed dewatering the containment basin. The year-by-year simulations results for Sioux City are shown in Figure 17. For Waterloo, shown in Figure 18, 1993 accounted for a large portion of the discharge volume in all three modeling scenarios. For Waterloo, the original ISU-

ELG model projected 8 years with a discharge, after calibration 14 of the years had a discharge. The SPAW model projected 19 years with discharge for this site.

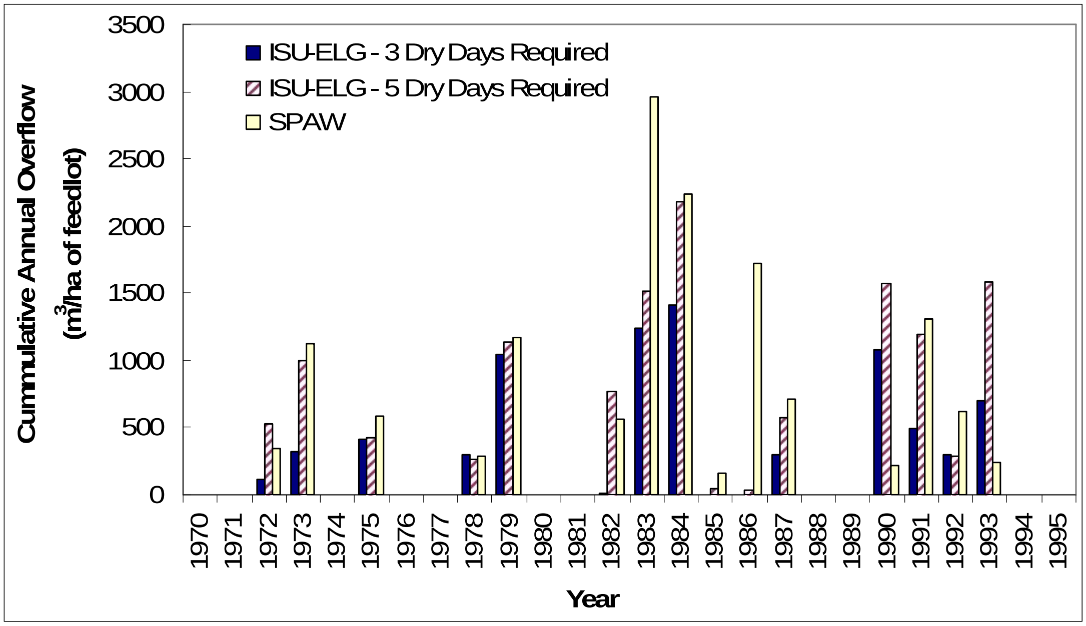

Figure 16. Temporal distribution of basin overflow volumes on a per hectare of feedlot basis for Sac City, Iowa.

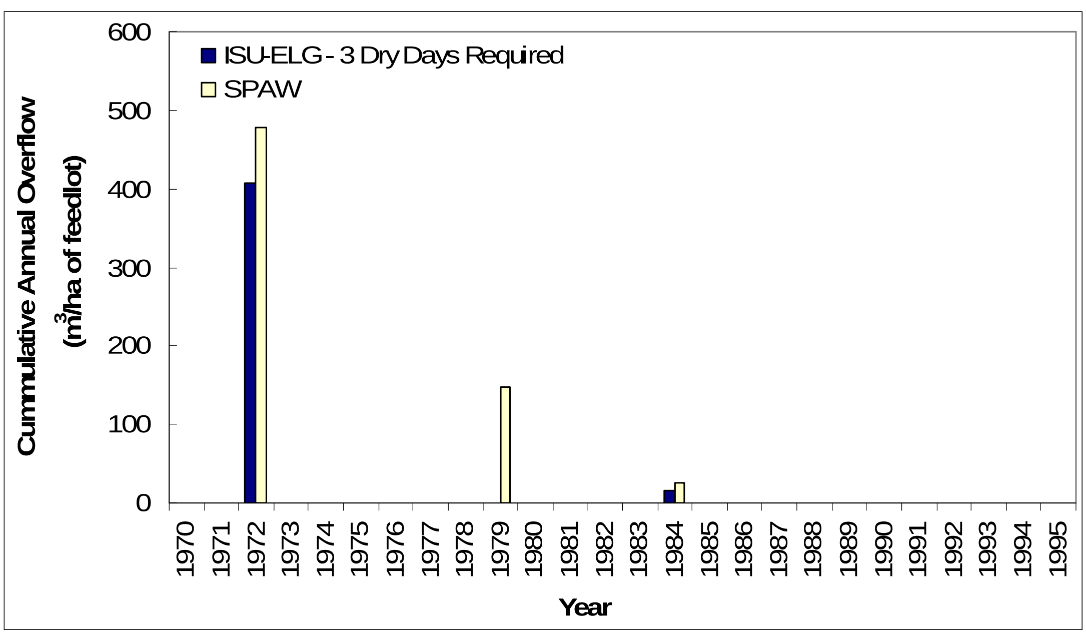

Figure 17. Temporal distribution of basin overflow volumes on a per hectare of feedlot basis for Sioux City, Iowa.

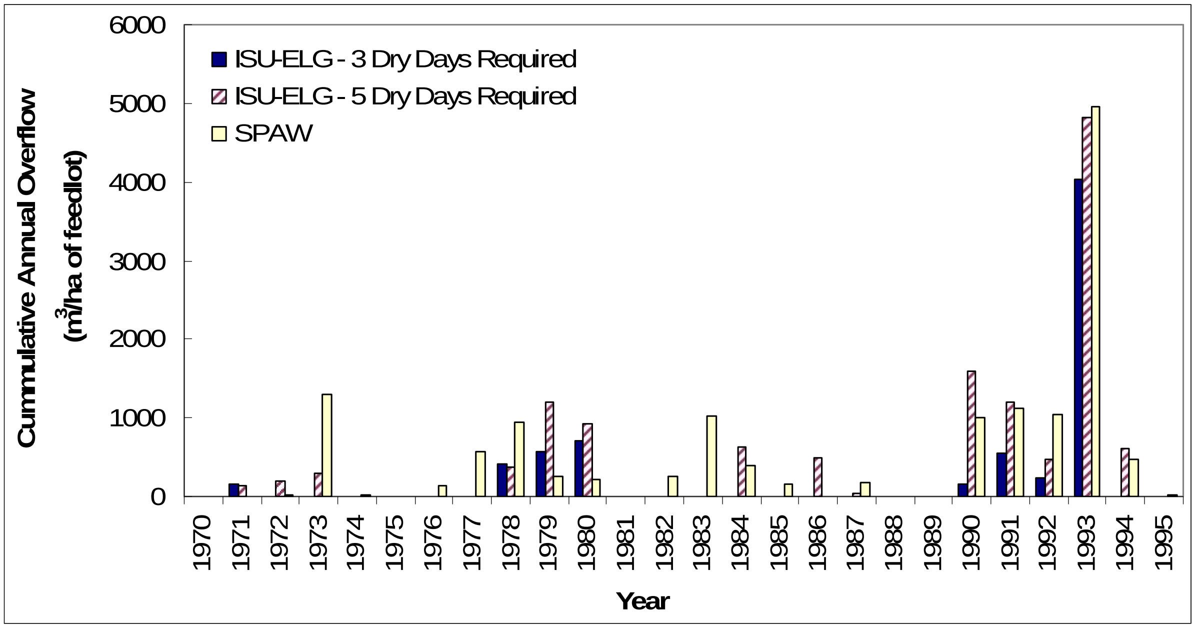

Figure 18. Temporal distribution of basin overflow volumes on a per hectare of feedlot basis for Waterloo, Iowa.

As recommended by Moriasi et al. (2007), three modeling statistics, along with a graphical comparison, were used to assess the agreement between the two models. The modeling statistics used were the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of the SPAW model results (RSR). These statistics were determined for the ISU-ELG model in both calibrated and un-calibrated form. Data comparisons where made on an annual basis. The NSE was used to indicate how well a plot of the observed data versus the modeled fits the one-to-one line (Moriasi et al., 2007); the NSE was developed to have a value between negative infinity and one. A NSE of one means that the models showed a perfect match; any value less than zero would indicate that the use of the mean value of the SPAW model was a better predictor of performance than use of the ISU-ELG model results. The PBIAS measured the average tendency of the ISU-ELG simulated data as compared to the SPAW simulated data. In this case, a value of zero indicates the two models predict similarly, a positive value would indicate that the ISU-ELG model would underestimate the volume of overflow and a negative value would indicate the ISU-

ELG model overestimates the volume of overflow in comparison to SPAW. The third statistic used was the RSR; the RSR was calculated as the ratio of the root mean square error between the ISU-ELG simulation and the SPAW simulation divided by the standard deviation of the SPAW simulated data (Moriasi et al., 2007). This statistic was developed to have a range of zero to positive infinity, with the optimum value being zero. Moriasi et al. (2007) also provided guidelines for when these statistics indicate satisfactory model performance; for flow modeling these were, a NSE > 0.50, a RSR < 0.70, and PBIAS of less than plus or minus 25%.

The statistics for both the calibrated and un-calibrated ISU-ELG model in comparison to the SPAW simulation are shown in Table 30. Each of these modeling statistics provided an important piece of information about the comparison of these two models. It was important that the models had very little percent bias, as this value provided information on the tendency of the model to either under- or over-predict the amount of basin overflow. In all cases, both calibrated and un-calibrated, the ISU-ELG model predicted less basin overflow than the SPAW model. The NSE provided information on temporal variation between the two models. Values close to one indicate that the models predict similar amounts of release during the same years. Thus, the statistic provided information about whether both models predicted the system was stressed by the same weather patterns. Thus for Sioux City, which has a high NSE, the assumption of commencing land application three days after a precipitation event seemed to cause a similar temporal pattern of when basin overflow would occur as that predicted by the soil moisture criterion calculated by SPAW; however, the percent bias indicated that the ISU-ELG model constantly under-predicts the release volume. After calibration, the ISU-ELG model provided satisfactory performance in comparison to SPAW at three locations; at the Sioux City location, the PBIAS was larger than the accepted value. At the Sac City location, the NSE was slightly lower than the suggested value while the RSR was slightly higher; however, this site showed good agreement in the average annual overflow volume. Overall these results imply that after calibration the ISU-ELG model provides good agreement between the average volumes of overflow, but without the desired temporal agreement between the ISU-ELG and SPAW models.

Table 30. Nash-Sutcliffe modeling efficiency, percent bias, and the root mean square error – standard deviation ratio of the ISU-ELG model in comparison to the SPAW model. These statistics are shown for both the calibrated and uncalibrated ISU-ELG models.

	ISU- ELG Model – Un-calibrated			ISU-ELG Model - Calibrated		
Location	NSE	PBIAS	RSR	NSE	PBIAS	RSR
Ames	0.58	46	0.65	0.59	12	0.64
Red Oak	0.75	13	0.50	0.75	13	0.50
Sac City	0.37	46	0.79	0.42	8	0.76
Sioux City	0.89	35	0.34	0.89	35	0.34
Waterloo	0.73	51	0.52	0.79	8	0.46

Conclusions

The current ISU-ELG model under-predicted the amount of discharge that occurred from a traditional containment structure when compared to the SPAW model for all five locations investigated. At Red Oak and Sioux City, the differences in discharge volumes were relatively minor, while the Ames, Sac City, and Waterloo locations showed large discrepancies. It is believed that the drier climate in Sioux City contributed to soil moisture conditions that made the three dry days before land application assumption appropriate. Over the 26-year simulation period used in modeling runoff containment facility at Sioux City the average yearly rainfall was 66 cm (26 inches), which was very similar to the 72.6 cm (28.6 inches) average for Kansas. This would suggest that the assumptions Koelliker et al. (1975) made for when land application was appropriate were for the Kansas climatic conditions for which the model was developed. Even at the Sioux City location, the ISU-ELG model showed a large percent bias, although there was no difference in the percent control reported by the ISU-ELG model and the SPAW model. Red Oak, Iowa, although located in a wetter climate region, had higher evaporation rates and a soil texture in the disposal area that contributed to improved drainage and drying of the soil profile. This increased drying of the soil and made the three-day assumption more appropriate than for the other locations around Iowa. For the remaining three locations, it was determined that the sites required approximately five days before beginning land application to calibrate the average annual discharges to match the SPAW model.

The sensitivity of the ISU-ELG Model to the criterion of number of dry days required before land application could begin was tested. For most locations it was determined that on average approximately 150 cubic meters of discharge per hectare would be generated for every day that it takes for the application area to dry to a moisture content that would be suitable for land application. The Sioux City simulation showed a much lower sensitivity to the dry day criterion. The Nash-Sutcliffe modeling efficiency was used to compare the ELG model and SPAW model results on yearly annual discharge. The uncalibrated ELG model was found to have a modeling efficiency ranging from 0.37 to 0.89. After calibration, the modeling efficiency was increased to range from 0.42 to 0.89. Therefore, even after calibration, the two models still displayed different temporal patterns of when discharge would occur. In its uncalibrated form the PBIAS statistic ranged from 13-51%, after calibration, this value was improved to 8-35%.

To increase the similarity between the ISU-ELG and SPAW model's predictions; modification of the ISU-ELG model is required. There are several options available to perform these modifications. One option would be to perform a calibration of the ISU-ELG model to determine the number of dry days required in the ISU-ELG model to make the average annual overflow volume per hectare of feedlot equal to that predicted by the SPAW model. In this manner, the ISU-ELG model could be modified to more accurately represent soil moisture conditions. A second alternative would be to develop a scaling factor to adjust the ISU-ELG model average discharge to be equal to the volume predicted by the SPAW model. The advantage of using this method is that it would keep the temporal pattern of basin overflow the same, i.e., the definition of chronic rainfall is not changed from the modification. A third option available would be the use of the SPAW model to determine the amount of basin overflow that would occur. One difficulty in simulating the hydrology of the feedlot waste management system with SPAW is that three simulations must be performed, one for the feedlot surface, one for the land application area, and one for the liquid level in the containment basin. The fourth option available would be to add a soil moisture modeling component to the ISU-ELG model. Making this addition to the ISU-ELG model would allow the entire system to be simulated by a single model run, simplifying the simulation procedure.

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CHAPTER 3. THE USE OF THE SOIL-PLANT-AIR-WATER MODEL TO PREDICT THE HYDRAULIC PERFORMANCE OF VEGETATIVE TREATMENT AREAS FOR CONTROLLING OPEN LOT RUNOFF

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Abstract

Several Iowa beef feedlots have interim, National Pollution Discharge Elimination System (NPDES) permits for vegetative treatment systems (VTS) to control and treat feedlot runoff. Monitoring of these sites has provided data to validate performance modeling of these systems. In this study, two approaches using the field module and the pond module of the SPAW model were investigated to determine their ability to predict hydraulic performance of vegetative treatment areas (VTAs). Three of the four locations used in this study had a high water table; this water table elevation limits the space available in the soil profile to infiltrate and store water. For these locations, the performance of the VTA was limited by the storage available in the soil profile, and SPAW simulations provided a realistic prediction of the monitored results. Modeling results verified that for these locations VTA performance was limited by the space available in the soil profile. Modeling statistics were calculated to determine the models ability to predict VTA performance. For the four locations investigated, Nash-Sutcliffe efficiencies ranged from 0.45 to 0.99 while the percent bias of the model ranged from -3% to 100%. The results showed that the SPAW pond module could be used to predict hydraulic performance of VTAs, specifically under high water table conditions.

Keywords. Feedlot runoff control, SPAW, Vegetative Treatment Areas, hydraulic modeling

Introduction

Pollution associated with runoff from open beef cattle feedlots has been a concern for many years. The passage of the Federal Water Pollution Control Act

Amendments in 1972 placed the Environmental Protection Agency (EPA) in charge of developing runoff control guidelines (Anschutz, 1979). As a result, the EPA released the Effluent Limitation Guidelines which described the design and operating criteria of the waste treatment system for concentrated animal feeding operations (CAFOs) (Sweeten, 2003). These effluent limitation guidelines historically required collection, storage, and land application of the feedlot runoff; however, recent modifications allow the use of alternative treatment systems when their performance is equivalent to or exceeds that of a traditional containment system (Federal Register, 2003). As part of permitting alternative treatment technologies on CAFO operations, a comparison of the median annual release volume over a 25-year period between a traditional containment system and the proposed alternative treatment system is required. EPA states that one possible method of making this comparison is to use simulation models, along with site-specific climate data and wastewater characterization data, to determine the pollutant discharge level (Federal Register, 2003).

One possible alternative treatment technology that has been proposed is a vegetative treatment system (VTS). A VTS is a combination of treatment components, of which at least one component utilizes a form of vegetative treatment to manage runoff from open lots (Moody, 2006). Vegetative treatment areas (VTAs) and vegetative infiltration basins (VIBs) are two proposed vegetative treatment components for VTSs. A VTA is an area that is level in one dimension and has a slight slope along the other, planted and managed to maintain a dense stand of vegetation (Moody, 2006). Operation of a gravity flow VTA consists of applying feedlot effluent evenly across the top of the vegetated area and allowing the effluent to flow down the length of the treatment area (Moody, 2006). Gross and Henry (2007) proposed a modification to VTAs, called a “sprinkler VTA,” which uses a sprinkler system to apply the effluent more evenly over the VTA. Ikenbery and Mankin (2000) identified several methods in which effluent was treated by VTAs, these included settling solids, infiltrating runoff, and filtering the effluent as it flowed through the vegetated area. A VIB is a flat area surrounded by berms and planted to permanent vegetation (Moody et al., 2006). These areas have drainage tiles located approximately 1.2 meters (4 feet) below the soil surface to encourage infiltration of effluent through the soil profile. The tile lines collect the infiltrating effluent, which then receives secondary treatment, often from a VTA. Pollutant removal in the VIB relies on filtration of the effluent as it flows through the soil, uptake of nutrients by plants, and pollution degradation (Moody et al., 2006).

Currently, Iowa State University (ISU) is monitoring the performance of six vegetative treatments systems located around the state of Iowa. At four of these locations, a complete year of monitoring data was collected in 2007. At these sites, the vegetative treatment system was divided into both pilot and non-pilot systems. The pilot systems were monitored by Iowa State University and will be the focus of this modeling study; where as the non-pilot portions of the system are monitored by the producers. Moody et al. (2006) provided a description of the monitoring techniques Iowa State has been using to determine system performance at these locations. The data being collected includes daily temperature and precipitation values, as well as effluent volume and nutrient mass exiting each component of the treatment system.

Table 31 shows the size of the feedlots and the vegetative treatment area of the pilot system at each of the four locations. In addition, the configuration of the VTS system is specified. On these sites there were two different VTS configurations, a solid settling basin (SSB) followed by a stand-alone VTA, or a SSB followed by a VIB which was then followed by a VTA. Schematics of both types of systems are shown in Figure 19. Figure 19a shows a stand-alone VTA system; in this system, runoff is generated from the beef feedlot and contained in a solid settling basin designed to provide sufficient detention time to settle solids from the effluent. The effluent from the solid settling basin is then released onto the VTA as permitted by soil and weather conditions. These VTAs utilize gravity flow to spread the effluent down the length of the VTA. Figure 19b shows a VIB-VTA system; it also utilizes a solid settling basin, but in this case the effluent is first released to a VIB. Tile lines collect the effluent draining from the VIB. This tile drainage is then pumped onto the VTA for further treatment.

Table 31. Description of the four pilot systems monitored by ISU during 2007. Displayed in the table are the site name, the system configuration (solid settling basin (SSB), vegetative treatment area (VTA), and vegetative infiltration basin (VIB)), and the areas of both the feedlot and the VTA.

Site Name	System Configuration	Feedlot Area (ha)	VTA Size (ha)
Central IA 1	1 SSB - 2 VTA	3.08	1.53
Central IA 2	1 SSB - 1 VIB - 1 VTA	1.07	0.24
Northwest IA 1	1 SSB - 1 VTA	2.92	1.68
Northwest IA 2	1 SSB - 1 VIB - 1 VTA	2.95	0.60

a. b.

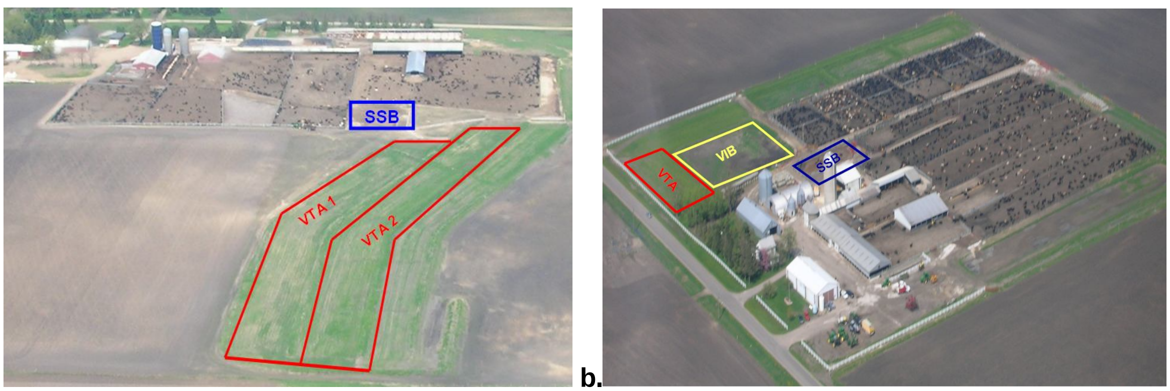

Figure 19. Schematics of a SSB-VTA systems (a) and a SSB-VIB-VTA system (b).

Data in the literature review performed by Koelsch et al. (2006) suggested that VTSs may be effective in a variety of situations. Modeling the performance of these systems plays a key role in determining where these systems would perform as desired, as well as in determining the optimum design of a VTS. There is a recent history of modeling VTS performance. For example, Tolle et al. (2007) developed a series of models that have been used to simulate VTS performance throughout Kansas; Wulf and Lormior (2005) developed a series of models for VTSs in Iowa, referred to here as the ISU models. Smith et al. (2007) performed a sensitivity analysis of the ISU models to determine what variables have an important influence on VTS system performance. Khanijo et al. (2007) compared the ability of the ISU-

VTA and ISU-VIB/VTA model to predict discharge volumes as well as nutrient mass released from four VTSs. Khanijo et al. (2007) found that the ISU models over-predicted VTS performance on all Iowa sites, specifically over-predicting both VIB and VTA hydraulic performance; these models are currently undergoing revisions to improve the models predictive power. Along with improving the performance of these models, ISU has been looking at the use of other available models that could be utilized to aid in both the design of VTSs as well to quantify the expected system performance. As suggested by Gross and Henry (2007), the Soil-Plant-Air-Water (SPAW) model may by useful for designing VTAs.

The SPAW model was developed to perform a one-dimensional water budget on agricultural fields using a daily time step. SPAW performs this water budget in the vertical dimension and focuses the simulation on major components in the water balance such as runoff, infiltration, evapotranspiration, percolation, and the water content of the soil profile (Saxton and Willey, 2004). By assessing the available room for water storage in the soil profile, the VTA size required to infiltrate and hold the volume of effluent generated from the design storm size can be determined. Gross and Henry (2007) reported the use of SPAW in design of their VTA systems on small feedlots in Nebraska.

There are several reasons that make SPAW a logical choice for modeling the hydraulic performance of vegetative treatment areas. One of the key reasons is the wide acceptance of the SPAW model. It is a publicly available model and has a history of being used to model the performance of wastewater storage systems (Moffitt and Wilson, 2004; Moffitt et al., 2003). In these studies, Moffitt and Wilson (2004) and Moffitt (2003) used SPAW to evaluate the temporary storage design proposed by the NRCS's Animal Waste Management software on a daily basin (Moffitt et al., 2003) and then showed that SPAW could be used to simulate the level in wastewater containment structures on dairy operations (Moffitt and Wilson, 2004). In addition to Moffitt and Wilson (2004) and Moffitt et al.'s (2003) use of SPAW to model effluent level in waste containment structures, Saxton (1983) used SPAW to simulate soil moisture in a variety of situations. In these simulations, Saxton showed that SPAW could be used to simulate the temporal soil moisture patterns as a function of soil texture, vegetation type, and hydrological inputs with reasonable accuracy. Thus, SPAW could be used to quickly assess the expected hydrological response of a vegetative treatment area to the hydrological inputs it receives. Based on the modeled hydraulic response, the overall performance of the VTS could then be determined.

Objective

The objective of this investigation was to test the ability of the SPAW model to simulate the hydrological performance of the vegetative treatment area (VTA) component of a vegetative treatment system (VTS). This study focused only on the hydrology of the VTA; nutrient transport into and through the system was not considered. The predicted VTA performance was compared to the monitored VTA performance at four sites throughout Iowa. Hydraulic performance of the VTA was modeled with two different methods. The first method utilized the field module of the SPAW model, while the second method utilized the pond module of the SPAW model. The results of the modeling options were compared to determine which option was most effective in predicting VTA hydraulic performance and the relevance to using SPAW to design VTAs is discussed.

Materials and Methods

Iowa State University has been monitoring the performance of four VTSs since 2006. The data collected included daily temperature and precipitation values, effluent volume released from each component of the VTS, and the nutrient concentrations of this effluent. For complete descriptions of the monitoring methodologies used by Iowa State refer to Moody et al. (2006) and Khanijo (2007); however, a brief description is provided here. Temperature measurements were collected on an hourly basis using Hobo temperature loggers (Onset, Bourne, MA). Precipitation depths were measured with the use of an ISCO 674 tipping bucket rain gauge (Teledyne ISCO, Lincoln, NE) with a passive rain gauge installed on site as a back-up.

Monitoring method at the settling basin outlet was dependent on the settling basin outlet. For settling basins with round pipe outlets an ISCO 750 low-profile area-velocity sensor was used (Teledyne ISCO, Lincoln, NE). For all other settling basins an ISCO 720 submerged probe (Teledyne ISCO, Lincoln, NE) in conjunction with a 1.5 foot H-flume was used to monitor settling basin outflow. A flow measurement was taken every two minutes. Flow based samples were collected using an ISCO 6712 automated sampler (Teledyne ISCO, Lincoln, NE).

For sites with a VIB, the effluent captured in the tile lines was collected in a sump and then pumped onto the VTA. At these sites the pumped volume was measured using a Neptune two-inch turbine flow meter (Neptune, Tallassee, AL). Flow based samples were again collected using ISCO 6712 automated samplers. The ISCO sampler was interfaced to the turbine meter with the use of an ISCO 780 smart 4-20 Analog Interface Module (Teledyne ISCO, Lincoln, NE), which allowed the ISCO 6712 automated sampler to collect flow weighted samples from the beginning to the end of the VIB release.

Flow monitoring at the VTA outlet was similar to monitoring at the settling basin outlet, with an ISCO 750 low profile area-velocity sensor (Teledyne ISCO, Lincoln, NE) used on sites where the VTA had a pipe outlet while an ISCO 720 submerged probe (Teledyne ISCO, Lincoln, NE) in conjunction with a 1.5 foot H-flume was used on the other VTAs. Monitoring data was again collected at a two-minute interval. An ISCO 6712 automated sampler (Teledyne ISCO, Lincoln, NE) was used to collect flow paced samples.

The flow paced samples collected at the settling basin, the VIB, and the VTA were all analyzed for chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), total phosphorus (Total P), five day biochemical oxygen demand (BOD_5), nitrate-nitrogen (NO_3-N), dissolved reactive phosphorus (PO_4), chloride (Cl^-) pH, fecal coliform, total suspended solids (TSS), and total dissolved solids (TDS). Based on the flow paced samples and the monitored flow volumes the mass of above parameters released from each component was calculated.

In addition to monitoring the parameters discussed above, the depth to groundwater was tracked in a well in or near the VTA using the Global Water WL16 Level Logger (Global Water, Gold River, CA). The level logger was lowered to the bottom of the monitoring well; the logger then recorded the depth above the sensing element on the logger. The depth of water above the sensing element was subtracted from the distance of the sensing element below the VTA surface to determine groundwater depth.

Methodology

SPAW Field Module

The field module of the SPAW model was used to perform a water balance on four Iowa VTAs. The hydraulic processes performed by the VTA and included in this water balance were infiltration, runoff, evapotranspiration, percolation, and storage of water in the soil profile. In this model, runoff was simulated with the NRCS/SCS curve number method. Runoff predictions are sensitive to curve number selection, thus accurate knowledge of the curve number was important in order to accurately predict the amount of expected runoff. The hydraulic soil group was determined using a soil survey map (Web Soil Survey, USDA NRCS, 2008), which along with knowledge on the land cover type can be used to predict the curve number. Additional, the water table depth below the VTA was measured with the use of a WL16 level logger (Global Water, Gold River, CA).

There are several limitations in using the SPAW field module to predict VTA performance. First, the curve number method was a relatively simple method of predicting runoff volume and has several limitations; however, this method was developed from years of empirical data and provided a quick method to determine runoff volumes. In SPAW, the curve number used to simulate runoff depth was adjusted based on soil moisture; if the soil profile reached 90% of the saturated water content extra runoff was predicted from the event.

Additionally, the SPAW field module assumption that effluent application is level and uniform over the VTA. For VTA gravity flow systems, this was not the case; in fact effluent application would rarely be expected to be uniform as more effluent is applied to the upper end of the VTA (near the settling basin outlet) then the lower end of the VTA. Furthermore, there was a potential for channeling to develop throughout the VTA, which would again reduce the evenness of effluent application. Additionally, for smaller runoff events, the effluent may not cover the entire treatment area, but instead could be infiltrated in the front sections of the VTA.

For these simulations, the equivalent depth of effluent applied to the VTA was added to the precipitation depth on a daily basis. This was done because many of the events that occurred had small equivalent depths that were at, or below, the irrigation depths SPAW was capable of simulating. Adding the effluent application depth to the precipitation should provide similar results to modeling the process as irrigation, as both functions were handled similarly in the SPAW model.

SPAW model runs utilizing the field module were performed for each of the four sites. These model runs utilized the value of the curve number determined from soil survey data information. Additionally, the measured water table depth was included in the model as a constant-boundary condition for the VTA area.

SPAW Pond Module

The second method used to model the hydraulic performance of the Iowa VTA's utilized the SPAW pond module. In this scenario, the soil-water system was considered as a reservoir. When the reservoir was completely filled, overflow (i.e. runoff) will occur. In this analogy, there are several methods in which water is added to the reservoir; these include rainfall, effluent application from the settling basin, or effluent application for a vegetative infiltration basin. Furthermore, there is no need to make the assumption of uniform effluent application, just that it occupies a certain portion of the space available in the storage reservoir, i.e. in the soil profile. Two mechanisms for effluent removal from the storage reservoir where also included in the model, these include evapotranspiration and seepage losses. For this modeling scenario, seepage losses represent the amount of water lost due to a decline in water table elevation. Appropriate numbers for several values must be determined in order to model VTA's. These include the storage capacity of the soil profile, the amount of water originally in the soil profile, and as previously mentioned the seepage/percolation rate of water from the soil water reservoir.

In this perspective of modeling VTA performance, only saturation overland flow is modeled, i.e., the volume of effluent predicted to be released from the VTA results by completely saturating the soil profile from the bottom up, as opposed to Hortonian, infiltration rate limited, overland flow (Chow, 1971). Thus for high water table locations where the soil profile may be prone to saturation this assumption may prove useful. For instance, Nachabe et al. (2004) used a similar approach to model both the amount of moisture stored in the soil profile as well as the movement of a shallow water table with success.

However, that this modeling method only considers one of the mechanisms that can cause VTA releases can be severely limiting. However, this modeling perspective would provide insight into if VTA performance would be limited by the space available in the soil profile to infiltrate moisture. Furthermore, for locations in which saturation overland flow is the dominant mechanism by which VTA release occurs the modeling method could provide valuable insight into the performance a VTA could be expected to obtain.

In using this methodology, it is important to understand the limitations of assuming that all releases will be caused by saturation overland flow. For instance, since VTA releases from Hortonian overland flow is not included we would expect the model to over predict VTA performance, as only one of the mechanisms that can generate runoff is accounted for. Moreover, it is also important to understand when VTA performance would be limited by infiltration rate and when it is limited by complete soil saturation. For instance, for locations with either a deep water table or with low hydraulic conductivities, we would expect performance to be primarily limited by the infiltration rate of the soil, as complete saturation of the soil profile would be rare. However, for the opposite case, i.e., for shallow water table locations with higher water tables it is more likely that complete saturation of the soil profile would occur. In actuality, most sights that experience saturation overland flow would also experience Hortonian overland flow. However, there are several actions that would help minimize the risk of a Hortonian overland flow release. For instance, by encouraging thick vegetation in the VTA the rate of flow will be reduced, providing and increased contact time between the VTA and the effluent/rainwater. This increases the time available for infiltration to occur, reducing the likelihood and volume of any Hortonian overland flow release. Moreover, VTA's have small slopes (0 – 5%) which again increase the contact time between the VTA and the effluent, reducing the likelihood of Hortonian overland flow again. Furthermore, the rate of outflow from the settling basin can be controlled by the producer; by applying effluent at a rate equal to or lesser than the infiltration rate of the soil, Hortonian overland flow can again be avoided. Thus, if the settling basin is actively managed Hortonian overland flow can be reduced to times when the rainfall rate exceeds the soil's infiltration rate. The number of times per year that this occurs is dependent on both the soil infiltration rate and the typical storm intensity characteristic of the climate. Thus for a complete understanding of VTA performance, Hortonian overland flow must also be considered; however, use of the saturation overland flow concept can be utilized to determine if available storage capacity in the soil profile will be a limiting factor of VTA performance.

The storage capacity of the soil water reservoir was approximated as the pore space in the soil profile to a depth of 2.44 meters (8 feet). The calculation used to determine this volume is shown in equation (11). In equation (11) *d* represents the depth of the water table, η represents the porosity of the soil, and $Area_{VTA}$ is the area of the VTA. The soil porosity was determined by taking three soil cores from each VTA to determine the bulk density of the soil. Bulk density was determined by drying the soil in an oven for 24 hours and then measuring the mass of the soil. Soil cores were collected in 7.6 cm (three-inch) diameter rings and had a length of 7.6 cm (three inches). A subsample of the dried soil was used to measure particle density; a pycnometer was used to make this measurement. Knowing both the bulk density of the soil and the particle density allowed the porosity of the soil to be calculated.

$$Storage = d\eta Area_{VTA} \quad \textbf{(11)}$$

The initial amount of water in the reservoir was determined by assuming the soil profile at equilibrium conditions with a specified water table depth. The formula used to determine this volume is shown in equation (12). In equation (12), *d* represents the depth of the water table, θ_v is the volumetric soil water content (which is a function of soil water potential), and $Area_{VTA}$ which is the area of the VTA. The value of *d* used was determined based on a site-specific measurement of the water table depth using the WL16 (Global Water, Gold River, CA)

$$Initial\_Volume = Area_{VTA}\int_0^d \theta_v dz \quad \textbf{(12)}$$

A soil moisture-tension model (Saxton and Rawls, 2006) was used to determine the relationship between the soil water matric potential and the soil water content. This was a three-part model, it assumed complete saturation for all potentials above the air entry pressure, a linear model from the air entry pressure to the field capacity, and a power law relationship between field capacity and the permanent wilting point. This model is shown in Equation (13). In equation (13) θ_v is the volumetric water content, θ_s is the volumetric water content at soil saturation (assumed to be the soil porosity), θ_{33} the volumetric water content at field capacity, h_a the air entry pressure in kPa, and λ is the pore size distribution index, and *h* is the soil water potential. Values for the water content at field capacity, the air entry pressure, and the pore size distribution index were determined using the regression equations provided by Saxton and Rawls (2006) and measurements of soil texture. Figure 20 shows the general representation between soil water potential and the soil moisture.

$$\theta_v = \begin{cases} \theta_s, & h \le h_a \\ \left(\dfrac{33kPa - h}{33kPa - h_a}\right)(\theta_s - \theta_{33}) + \theta_{33}, & h_a < h < 33kPa \\ \left(\dfrac{h}{h_a}\right)^{-\lambda}, & h \ge 33kPa \end{cases} \tag{13}$$

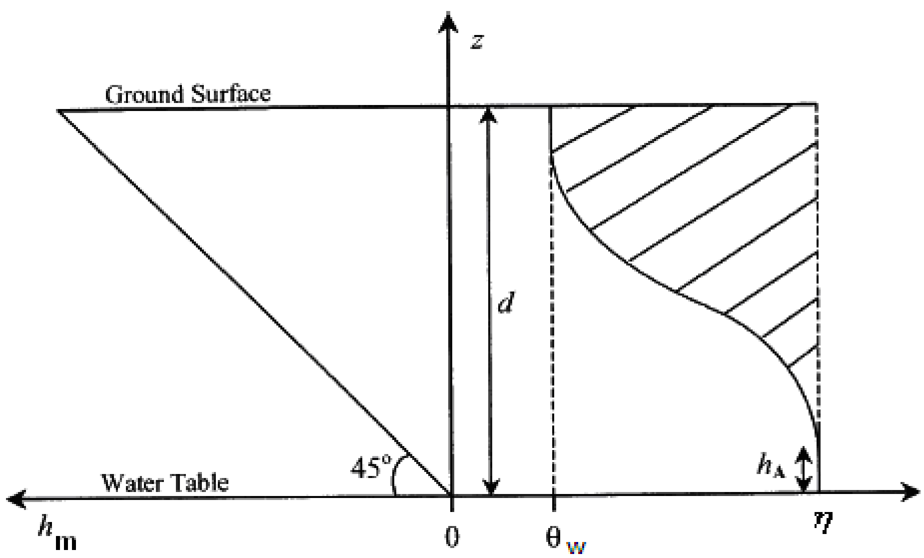

Figure 20. Diagram of relationship between the soil water potential and the volumetric soil water content.

The final variable that needed to be determined was the rate of seepage from the soil water reservoir. Monitoring of the groundwater level versus time was used to determine this rate. The measured rate, in meters per day, at which the water table was receding was determined. The amount of water stored in the top 2.44 meters (8 feet) of the soil profile was then calculated for two different water table positions, d_1 and d_2, the difference in height of these two positions was the height the elevation of the water table changes in a day. The seepage rate used in the SPAW model was then the difference in water content stored in the soil profile between the two water table positions. Equilibrium soil moisture profiles were assumed for both water table elevations.

SPAW model runs utilizing the pond module were again performed for each of the four sites. The input data was the size of the soil-water reservoir, the initial volume in the soil-water reservoir, the rate of seepage from the reservoir, daily high and low temperatures, evapotranspiration amounts, and daily precipitation amounts.

Modeling statistics and graphical comparisons were used to determine the ability of both the SPAW field and the SPAW pond module to predict monitored outflow amounts. As recommended by Moriasi (2007), three modeling statistics were used to assess the agreement between the modeled and monitored results. The modeling statistics used were the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of the monitored results (RSR). These statistics were determined for both the field and the pond module of the SPAW model.

The NSE provided an indication of how well the plot of the observed versus the modeled data fit the one-to-one line (Moriasi, 2007); the NSE was calculated to be a value between negative infinity and one. A NSE of one would indicate the models showed a perfect match; any value less than zero would indicate the use of the mean value of the monitored data was a better predictor of performance than use of the modeled results. The PBIAS measured the average tendency of the simulated data as compared to the monitored data. In this case, a value of zero would indicate the model and the monitored results predicted a similar volume of release. A positive value would indicate that the model underestimated the volume of release while a negative value would indicate model overestimates the volume of release in comparison to the monitored results. The third statistic used was the RSR, which was calculated as the ratio of the root mean square error between the simulation and the monitored results divided by the standard deviation of the monitored release (Moriasi, 2007). This statistical value could range from zero to positive infinity, with the optimum value being zero.

Moriasi (2007) also provided guidelines for when these statistics would indicate satisfactory model performance; for flow modeling these would be, a NSE $>$ 0.50, a RSR $<$ 0.70, and PBIAS of less than plus or minus 25%. Each of these modeling statistics provided an important piece of information about the comparison of these two models. It is important that the models have very little percent bias, as this value provided information on the tendency of the model to either under or over predict the amount of VTA release.

Results and Discussion

The input values calculated for both the field module inputs and the pond module inputs are shown in Table 32. These inputs were calculated as discussed above and reflect actual field conditions measured at the site. In addition to these inputs, weather files including daily high and low temperatures and the depth of precipitation on a given day were also created from the monitoring data. Additionally, evapotranspiration data collected at near-by (but not on site) weather stations was included in the weather file. The final input included was the equivalent depth of each solid setting basin release if the event had been evenly applied to the entire VTA area.

Using the field module greatly generalized local site conditions by grouping all systems according to hydrologic soil group. The inputs for the pond module were more site specific, thus model results were tailored more to the specific conditions encountered at the locations. As can be seen by the initial and total storage volumes listed in the table, hydraulic performance at many of these locations was limited by space available in the soil profile.

For the three locations with a high water table, use of the pond module provided a good indication of the overall release volume from the VTA. The NSE provided information on temporal variation between the two models, values close to one indicate that the models were predicting similar amounts of release during the same periods. Thus, the statistic provided information about whether both types of systems were stressed by the same weather patterns. Based on the results, use of the pond module provided a good overall indication of performance. Table 34 provides information on the total VTA release volumes monitored and modeled at each of the four locations. In general, the cumulative release volumes predicted with the SPAW Pond module were similar to the monitored results at all four of the locations.

In evaluating the results of this modeling effort it should be recognized that the input parameters, i.e., the SCS curve number, the initial water table depth, the storage, the initial volume, and the seepage rate were not calibrated but were estimated a priori to modeling the system. Thus this investigation can be utilized to assess the ability of the both the SPAW field and the SPAW pond module to serve as a design tool for VTA's.

Table 32. SPAW field and pond module inputs used for simulating VTA performance at the four locations.

	Field Module		Pond Module		
	SCS CN	Initial Water Table Depth (meters)	Storage (m^3)	Initial Volume (m^3)	Seepage Rate (meters/day)
Central Iowa 1	61	1.2	15,500	15,000	0.0001
Central Iowa 2	74	1.4	2,600	2,500	0.00005
Northwest Iowa 1	61	1.7	18,000	17,000	0.0005
Northwest Iowa 2	61	4.3	7,300	4,800	0.0003

Graphical analyses of the monitored and modeled results for each of the sites provide more insight into what aspects are limiting system performance as well as how monitored response is related to the modeled performance. Each of these systems will be discussed on a case-by-case basis.

Table 33. Modeling statistics describing the performance of the field and pond module performance.

	Field Module			Pond Module		
	NSE	PBIAS	RSR	NSE	PBIAS	RSR
Central Iowa 1	0.52	55	0.69	0.63	22	0.61
Central Iowa 2	0.86	28	0.38	0.45	-3	0.74
Northwest Iowa 1	0.04	79	0.98	0.60	6	0.63
Northwest Iowa 2	0.97	-384	0.17	0.99	100	0.05

Table 34. Comparison of monitored VTA release volumes to modeled release volumes. Modeled volumes were obtained using the SPAW Field and the SPAW Pond modules.

	Monitored Release m^3	Modeled Release SPAW Field Module m^3	Modeled Release SPAW Pond Module m^3
Central Iowa 1	11,743	5,244	9,214
Central Iowa 2	1,040	748	1,073
Northwest Iowa 1	2,966	630	2,801
Northwest Iowa 2	42	205	0

Central Iowa 1

The VTS at this site consisted of a settling basin followed by a VTA. The settling basin outlet was actively managed with release onto the VTA being controlled by a gate valve. The operator determined when and how much effluent to release onto the VTA, limiting the volume to the amount the VTA could absorb unless the settling basin was near capacity and rainfall was expected. This site experienced an extremely wet year in 2007 with approximately 49 inches of rainfall during the monitoring year (April 1 – October 31), as opposed to an average year in which approximately 36 inches of rainfall would be received over the entire year. In addition to the direct rainfall onto the VTA, the equivalent of an additional 20 inches of effluent was applied.

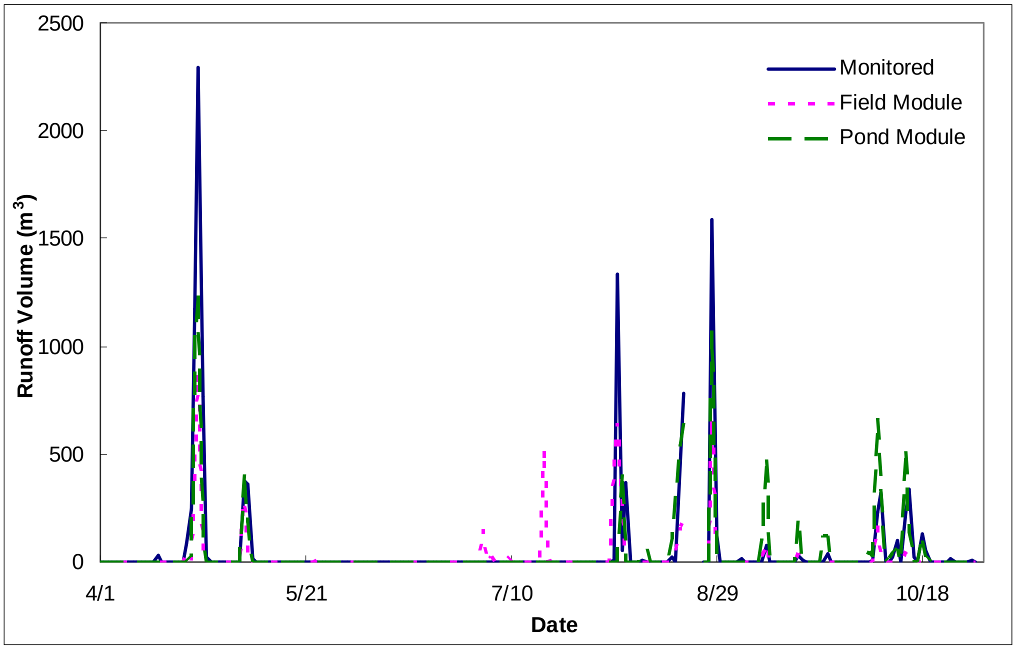

Figure 21. Comparison of monitored and modeled performance for the vegetative treatment system at Central Iowa 1.

Figure 21 shows that in general both the field and pond module did a reasonable job in following the trend of when release from the VTA occurred; the pond module performed with slightly more accuracy. There were several times when the models appeared to struggle, particularly with the largest release event that occurred on 4/24 and 4/25. For this event, the model drastically underestimated the VTA release volume that was measured. However, there was evidence that a measurement error occurred at the settling basin outlet and that the monitored data were incorrect. During this event, the producer completely emptied his settling basin, but only 1,190 m^3 of outflow from the solid settling basin outlet was measured. The basin has a capacity of 2,500 $m^3$and it went from full to empty, so the expected SSB release volume was 2,500 m^3. Because settling basin release and rainfall were the driving forces for VTA release, any measurement error here could have substantial error in the modeled VTA release volume. Furthermore, it should be noted that the pond module model of the VTA did predict a VTA release, thus any additional effluent released from the settling basin would also be monitored to be released from the VTA. When a settling basin release of 2,500 m^3 was used in the modeling scenario, the simulated and monitoring results were very similar, particularly those of the pond module.

Also of note was that on the dates 8/24 through 8/27 no data were available for the amount of effluent exiting the VTA. This was a very rainy period and water ponded at the VTA outlet causing extraneous depth readings in the measurement flume. Thus, release volumes from the VTA could not be measured during this time. During September and October, the estimated release volumes were overestimated by the pond module simulation of the vegetative treatment area.

Along with predicting the amount effluent released from the VTA, the SPAW pond module results can also be utilized to predict water table fluctuations. This requires that we assume that the water content in the soil profile is always in hydrostatic equilibrium with the water table depth. Using this assumption, and the water content – soil water potential relationship shown in equation 13 the water table depth level can be tracked. An example of this is shown for Figure 22. As can be seen, the SPAW model results seem to be doing a reasonable job of tracking water table level, expect during late July when the monitored water table depth was several feet higher than the model results predict.

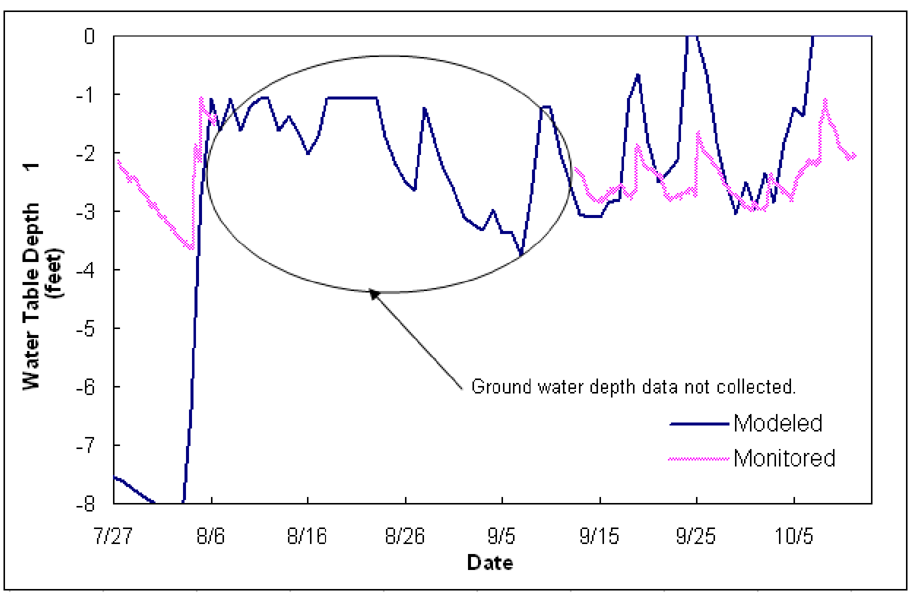

Figure 22. Monitored and modeled water table depth below the VTA.

Central Iowa 2

This system consisted of a solid settling basin, a vegetative infiltration basin, and a vegetative treatment area. For Central Iowa 2, both the field module and the pond module provided reasonable simulations of the monitored performance. At this location the Pond module predictions proved more accurate than the field module results at predicting the overall volume of effluent released from the vegetative treatment area; however, the results of the field module results provided a better temporal agreement of when these release events occurred as evidenced by the higher Nash-Sutcliffe modeling efficiency.

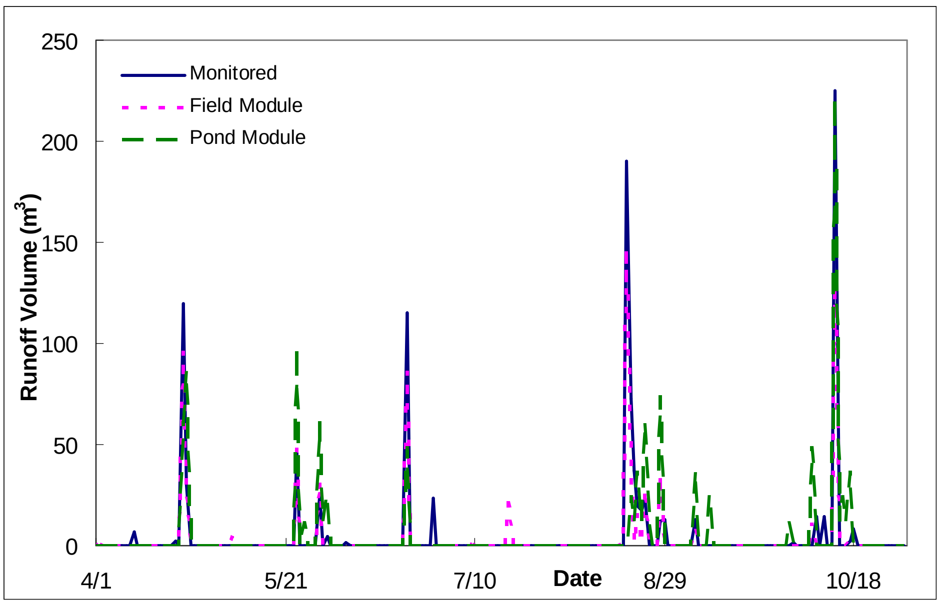

Figure 23. Comparison of monitored and modeled performance for the vegetative treatment system at Central Iowa 2.

In general, using the pond module to predict performance provided both good temporal accuracy of when a VTA release would occur as well as a good prediction of release volume. The field module also provided a good simulation of the modeled results; however, the amount of release occurring was not predicted with as much accuracy as with the pond module. In addition, the field module predicted a release in July when no release actually occurred. The success of the pond module, along with groundwater monitoring data shown in Figure 24, indicate that the performance of the VTA at this site was limited by the space available in the soil profile. The only time the pond module showed substantial error in the simulation was for the 8/19 event. This pond module simulation predicted that this event was refilling the soil-water reservoir to capacity, while monitoring data would suggest that most of the effluent and rainfall applied onto the VTA during this event resulted in runoff from the VTA. This was likely caused by the SPAW pond module predicting the water table was deeper than the monitored value prior to the 8/19 event.

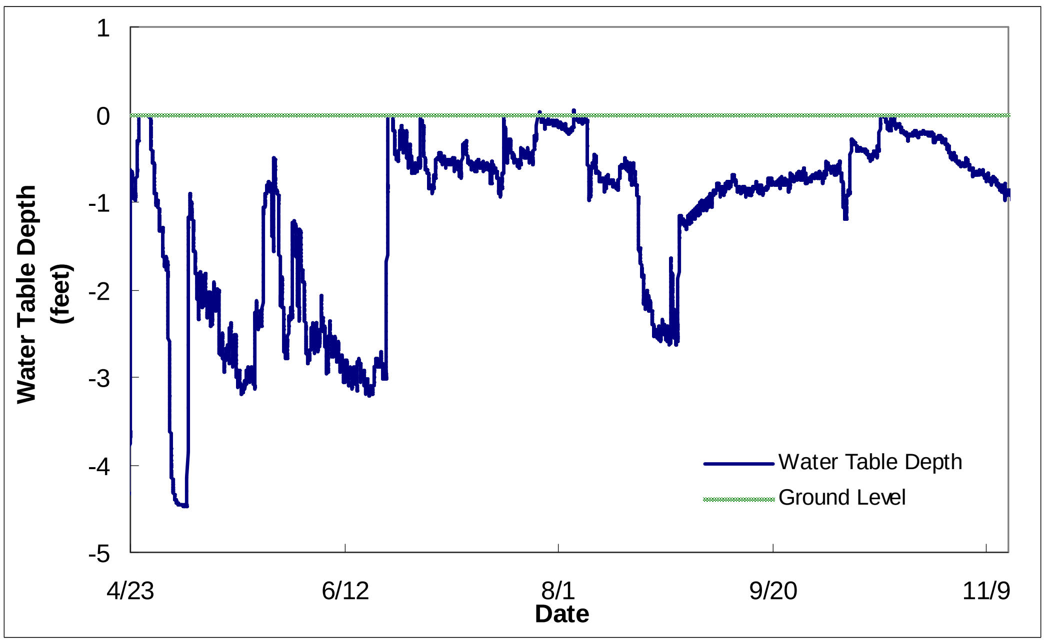

Figure 24. Groundwater depth data under the VTA at Central Iowa 2.

Northwest Iowa 1

The Northwest Iowa 1 site consisted of a settling basin followed by a vegetative treatment area. The settling basin outlet at this location was again actively managed, as this provided the producer with a greater level of control over system operation. The producer worked to match settling basin releases to the VTA conditions. At this location, the field module showed a poor ability to predict when a VTA release would occur; however, the pond module model of the VTA achieved good performance in all three modeling statistics. The pond module predicted both the releases in early spring and during the fall, providing some evidence that the performance of this system was limited by the presence of a shallow groundwater table creating periods of complete soil profile saturation.

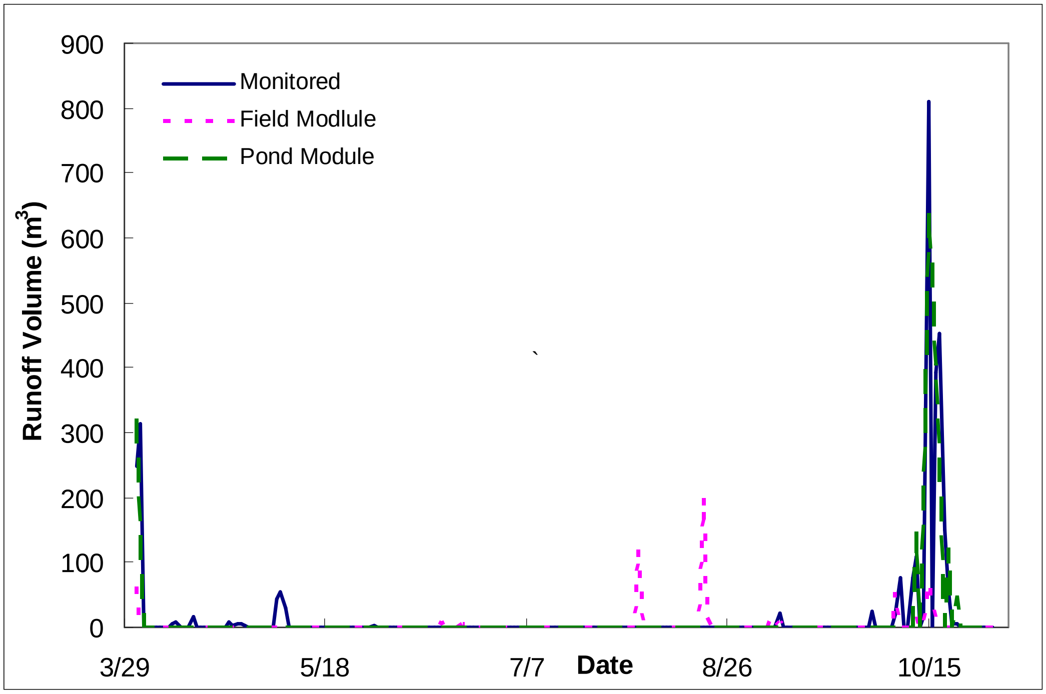

Figure 25. Comparison of monitored and modeled performance for the vegetative treatment system at Northwest Iowa 1.

Several monitored releases that occurred from the VTA throughout April and May were not predicted by the pond module. However, the pond module releases, or non-releases, during April and May only reflected direct rainfall on the system and not settling basin releases. Because of system modification, monitoring equipment was not installed at the settling basin outlet during that time period and basin outlet flow was not recorded. In actuality, releases from the settling basin did occur during this time, and these releases would have affected the water balance and may have resulted in a modeled VTA release. Modeling results showed that the soil water reservoir was at or near capacity during this time; therefore any additional effluent applications most likely would have resulted in a modeled release.

Northwest Iowa 2

The Northwest Iowa 2 site consisted of a settling basin, a vegetative infiltration basin, and a vegetative treatment area. Only two small release events occurred during the monitoring period at this site, both in early April. Simulation results showed that the pond module predicted no release. The water table at this site was deeper than at the other sites, therefore enough water was not applied to completely saturate the soil profile and induce runoff. The field module simulation predicted several runoff events from the treatment area, specifically in August when none were recorded. These release events resulted from larger rainfall events; however, soil conditions during these events was relatively dry, allowing the entire volume to infiltrate into the soil profile.

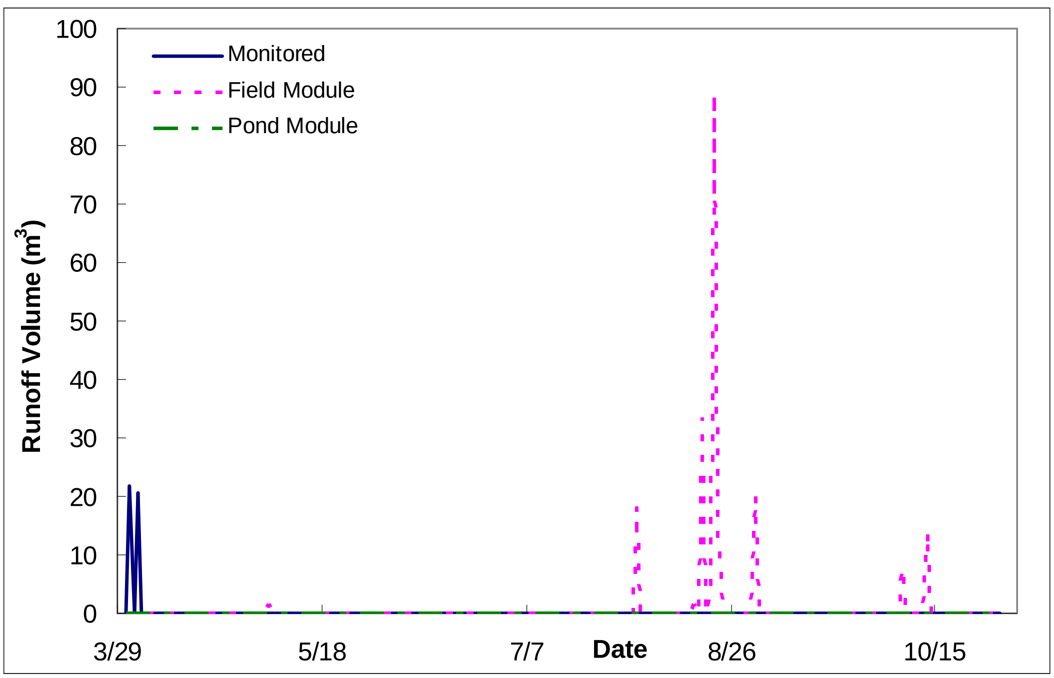

Figure 26. Comparison of monitored and modeled performance for the vegetative treatment system at Northwest Iowa 2.

Conclusions

The use of the Soil-Plant-Air-Water (SPAW) model, both the pond module and the field module, to predict the hydraulic performance of four different vegetative treatment areas (VTAs) was investigated. Based on the above results, it was determined that the SPAW pond module could provide a reasonable prediction of VTA hydraulic performance with little or no calibration, specifically for areas with a high water table where VTA performance was limited by the storage available in the soil profile. The inputs for simulation were easily obtainable and included items such as water table depth, water table seepage rate, and the soil-water retention curve. Use of these three properties allowed calculation of the storage capacity of the soil-water reservoir, the initial amount of water in the reservoir, and the rate water was exiting the reservoir.

Three modeling statistics were used to assess model performance, these included the Nash-Sutcliffe modeling efficiency (NSE), the percent bias (PBIAS), and the ratio of the root mean square error between the simulation and the monitored results divided by the standard deviation of the monitored release (RSR). For the pond module, the NSE ranged from 0.45 to 0.99, which indicated good temporal agreement between the simulated releases and the monitored releases. In addition, the percent bias of the pond module simulations was -3 to 6% for locations with a high water table. For the one location with a deep water table, no release was simulated so the percent bias was 100%. Thus for high water table locations the pond module provided a good indication of the expected hydraulic performance of the VTA.

For Central Iowa 1, Central Iowa 2, and Northwest Iowa 1 the modeling results, along with monitoring of the groundwater table, indicate that saturation overland flow was the probable mechanism for many of the VTA release. This was caused by a combination of a high water table and effluent/rainfall applications that were of a size that was sufficient to completely saturate the soil profile. Along with the model results which indicate that complete saturation of the soil profile may be occurring, monitoring results from tracking groundwater levels in the VTA verify water table levels due respond to rainfall events and that space available in the soil profile is limited. According to the SPAW pond module, Northwest Iowa 2 did not experience these saturated conditions. Furthermore, monitoring of groundwater levels at this location have shown groundwater depths ranging from 8 to 20 feet below the surface of the VTA, which again provides evidence that release events at this location are not caused by saturation overland flow, but instead by Hortonian overland flow.

Thus, based on this study it may be possible to utilize the SPAW model to design VTA's to achieve a specified level of hydraulic control. The process of using the SPAW model to design a VTA would be as follows. First, the necessary soil parameters such as water table depth, the soil porosity, and the soil texture need to be determined. Historical weather data for the area would then need to be located; this data would need to consist of daily high and low temperatures, the amount of precipitation occurring on a daily basis, and a daily value for the amount of evapotranspiration that occurred. The SCS curve number method could then be used to predict the volume of runoff from the feedlot occurring as a result of the precipitation. Based on the calculated runoff data, a pattern of how the producer would release from the basin would need to be developed. This could range from a completely passive management system where all runoff from the feedlot is released onto VTA the day of the precipitation event, to a very controlled system where effluent is slowly released from the basin as the moisture conditions in the VTA allow. In either case, the amount of effluent released needs to be normalized to the equivalent application depth on the VTA. The equivalent application depth added to the daily precipitation and substituted into the weather file. The dominant flow mechanism, i.e., Hortonian overland flow or saturation overland flow, for the site should then be determined. Based on the dominant flow mechanism the best modeling approach can be determined. For sites that experience saturation overland flow as the dominant release mechanism from the VTA, the pond module would then be used to model performance of the vegetative treatment system; however, for sites that frequently experience Hortonian overland flow this approach would not be appropriate. Different VTA areas can then be investigated to determine the level of performance being achieved by the system. Furthermore, it may be possible to utilize the SPAW model to investigate the water table depth, seepage rate, and the soil properties necessary to obtain a specified level of hydraulic control from vegetative treatment systems.

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CHAPTER 4. CONCLUSIONS

The final section will discuss the implications of the research papers presented in this thesis. Specifically, this section will discuss the practicality of the information presented and its use in modeling both traditional containment based systems and vegetative treatment systems. Implications this research has on designing and siting vegetative treatment areas is also presented. Future research needs are also highlighted.

Implications of Modeled Containment Basin Performance

Containment basins are currently the accepted standard for feedlot runoff control systems, and as such they are the standard to which all other runoff control systems are compared. In order to ensure that alternative technologies are fairly compared, it is imperative that containment basin performance be accurately modeled. Thus researchers must continue to improve and verify modeling results for traditional containment systems.

The research presented in the section of this thesis titled *Comparison of the Iowa State University – Effluent Limitation Guidelines Model with the Soil-Plant-Air-Water Model to Describe Holding Basin Performance* is a first step in critically evaluating the performance of a containment basin model. This evaluation showed that for many locations in Iowa the ISU-ELG model over-predicts containment basin performance in comparison to the SPAW model. Furthermore, this modeling effort demonstrated a strong connection between the land application area and the performance of the containment basin, with the size and the soil conditions in the land application area being critical factors in basin performance.

The Iowa DNR has developed graphs to assist producers in sizing a containment basin for their facility; an example of this graph is shown in Figure 27. The Iowa DNR guidelines state that land application should take place on days when weather and soil conditions are suitable (Iowa DNR, 2006). Furthermore, the Iowa DNR states that normally days are suitable for land application if the land application area is not frozen or snow-covered, the temperature during application is greater than 32°F, precipitation has not exceeded 0.05 inches per day for each of the three days immediately preceding application, and no precipitation is occurring on the day of application (Iowa DNR, 2006). However, the research presented here showed that soil conditions, based on soil moisture criteria, may not be suitable for land application three days following a rainfall event in many parts of Iowa. Therefore, basins designed according to the Iowa DNR graphs may have a lower level of control than originally projected for much of Iowa. Figure 28 shows how performance of these basins is reduced by switching from the original ISU-ELG model, with the three drying day criteria, to an ISU-ELG model calibrated for Ames conditions (five drying day criteria).

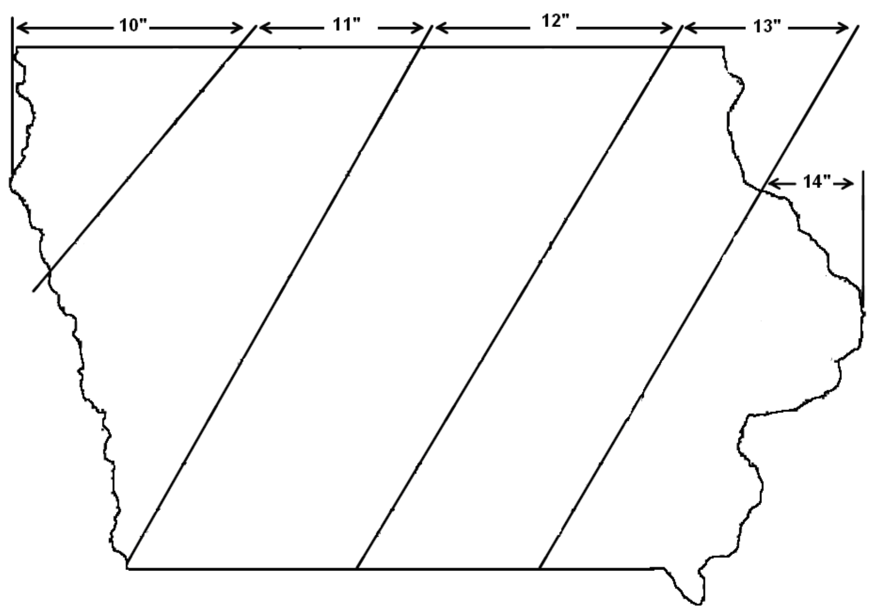

Figure 27. Feedlot runoff value, in inches, for determining required capacity of the System 1 – One effluent application period per year from Effluent Control Alternative for Open Feedlot Operation (Iowa DNR).

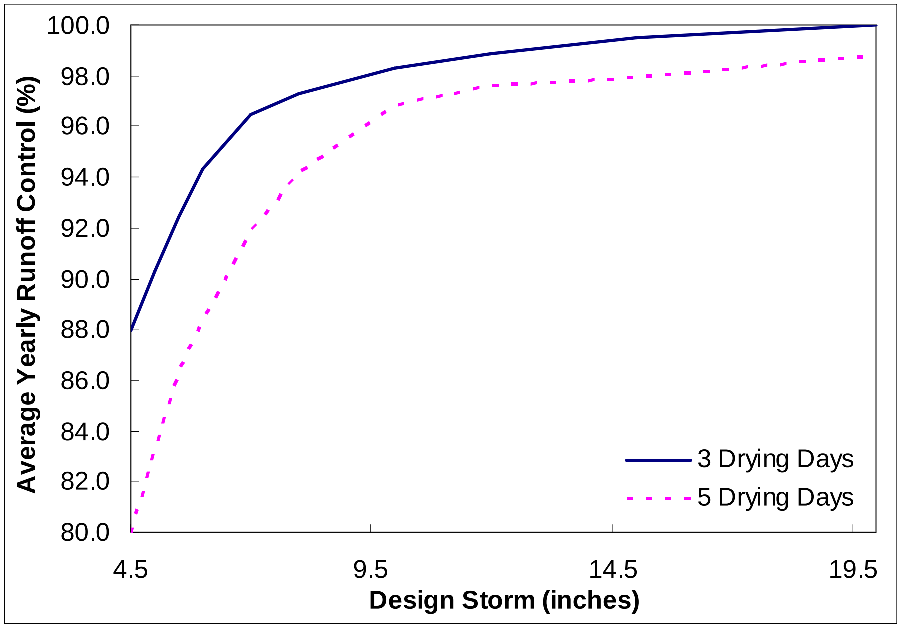

Figure 28. Runoff control performance as a function of basin size and the drying day requirement for Ames, Iowa.

As would be expected, the number of drying days required before land application can begin has a larger effect on the percentage of runoff controlled for smaller basin than for larger basins. This is caused by the basin reaching full capacity sooner, leaving the operator with less flexibility as to when they must either dewater or risk overflow from the basin. This can be verified by examining the average annual runoff control levels for a basin sized for a 4.5 inch storm. This basin would provide 88% and 80% runoff control respectively for the three drying days and five drying days requirements. However, for a ten-inch design storm the average annual runoff controls are 98% and 97% respectively for the three dry days and five dry days requirement. Moffitt et al. (2003) also noted that larger holding ponds allowed producers more flexibility in determining when to dewater.

In a practical sense, the importance of these data is not that the level of control is reduced, but that a larger basin must be constructed to provide the same level of runoff control. For example, currently the basin design requirement for most of Iowa is a five-inch storm. With of basin of this size, a feedlot operator near Ames would be expected to average 90% runoff control annually according to the original

ISU-ELG Model. However, if a producer wished to maintain this level of runoff control and only apply runoff from the basin during ideal land application conditions, he/she would need to construct a basin for a 6.5 inch storm event. For a five-acre feedlot drainage area, the containment basin size would increase from 2,047 m^3 (72,274 ft^3) to 2,800 m^3 (98,869 ft^3), which is a 37% increase in the required size of the containment basin.

Moreover, if a feedlot near Ames chose to construct a containment basin sized according to Iowa DNR System 1 – One land application period per year the size of the containment basin required would be determined from Figure 27. Based on this figure, the producer would be required to construct a basin sized to hold 12" of runoff from the contributing drainage area plus all runoff and direct precipitation resulting from a 25-year, 24-hour storm. The producer would then be able to select when this land application period would occur, typically either in the spring (taken as the month of April in this example) or fall (taken as the months of October and November). The predicted containment basin performance for both the three dry day and the five dry day requirements performance was determined and is shown in Table 35. As can be seen basin performance was reduced for both the spring application and fall application systems. In order to avoid this reduction in the level of runoff control the producer would be required to dewater in either less than ideal conditions or to dewater during periods outside the selected land application period.

Table 35. Modeled performance of a containment basin located near Ames, Iowa sized for one land application period per year with both the 3-dry day requirement used in the original ISU-ELG model and for a 5-dry day requirement as per the ISU-ELG model calibrated for Ames.

	Spring Application		Fall Application	
	3-Dry Days	5-Dry Days	3-Dry Days	5-Dry Days
Average	84%	78%	96%	93%
St. Dev.	22%	32%	15%	18%

If beef feedlot runoff containment basins are undersized in Iowa, then why aren't more releases reported? Although this question cannot be answered conclusively, several possible explanations are available. One explanation would be that overflow events occur, but are never reported. A second, and more plausible, explanation is that producers are simply forced to dewater their containment basin during less than ideal soil or weather conditions. This possibility is supported by a study by United States Department of Agriculture Risk Management Agency (USDA RMA) in which it was determined that 21% of animal waste management failures occurred during land application (USDA RMA, 2003). Furthermore, this study notes that land application and waste storage failures were both caused by allowing manure and wastewater to accumulate beyond the systems ability to store it appropriately (USDA RMA, 2003). However, for the case of open feedlots in Iowa, it may not be that manure and wastewater are being allowed to accumulate inappropriately, but simply that basins designed according to the Iowa DNR graphs are undersized and some portion of the land application must occur during inappropriate conditions.

Implications of SPAW modeling of VTA

As was demonstrated in the section of this thesis titled *The Use of the Soil-Plant-Air-Water Model to Predict the Hydraulic Performance of Vegetative Treatment Areas for Controlling Open Lot Runoff* the SPAW model, specifically the pond module, proved relatively accurate at predicting VTA performance. Furthermore, this modeling effort verified that the performance of three of the four vegetative treatment areas was limited by the presence of a shallow water table. Specifically, using the pond module and the soil water reservoir concept, modeling showed that the soil profile would become completely saturated and runoff would result.

As the presence of a shallow water table is important to the hydraulic performance of the vegetative treatment system, it is important that any model attempting to predict VTA performance be able to accurately predict water table movement. As the SPAW model proved effective at predicting VTA performance, it may also be able to predict the water table fluctuations occurring in response to rainfall and feedlot runoff events.

Water table predictions can be made by using the SPAW pond module and assuming water content in the soil profile is in hydrostatic equilibrium with the with the water table depth. This analysis was performed for Central Iowa 1 and is displayed in Figure 29. The modeled water table level does a reasonable job of following monitored water table depth, with the exception of late July; at this point modeled water table depth reached more than eight feet below the surface, while monitored water table depth neared four feet.

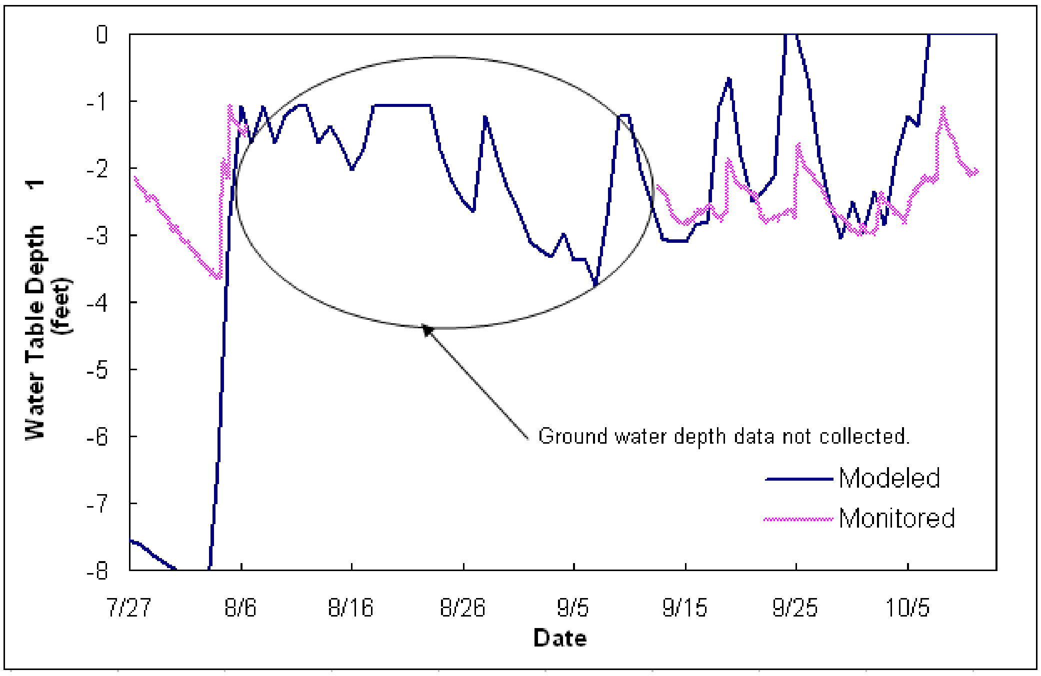

Figure 29. Comparison of measured and monitored water table response to precipitation and effluent application events at Central Iowa 1.

As demonstrated in Figure 29, the SPAW model seems to be doing a reasonable job simulating the water table response to rainfall and feedlot runoff events. This provides confidence that the soil-water reservoir concept used in *The Use of the Soil-Plant-Air-Water Model to Predict the Hydraulic Performance of Vegetative Treatment Areas for Controlling Open Lot Runoff* section of this thesis can provide an accurate simulation of the hydraulic performance of VTA and the water table depth. This concept can be used to provide siting criteria regarding the required the water table depth necessary to infiltrate a design storm.

To develop these requirements the first step is to determine the design storm size that must be infiltrated, for this example a design storm of 12.95 cm (5.1 inches) is used. This storm size is approximately the 25-year, 24-hour storm for much of Iowa. There must then be sufficient pore space in the soil profile to infiltrate this depth of precipitation, i.e. the current air filled porosity of the soil must be equal to the design storm. Equation 14 shows how the available depth in the soil profile was calculated. Equation 15 shows the soil moisture-matric potential tension relationship used in calculating the volume of water stored in the soil profile. As was done previously, the soil profile was assumed to be at hydrostatic equilibrium with the water table. In determining the required water table depth there are several soil properties that need to be determined, these include the porosity, the field capacity, the air entry pressure, and the pore size distribution index. For each soil type these soil properties were determined using regression equation presented by Saxton and Rawls (2006). The required inputs to use these models are the sand content, the clay content, and the organic matter content. For all soil types the organic matter content was set at 2%.

$$Available\_Depth = d\eta - \int_0^d \theta_v dz \quad \textbf{(14)}$$

$$\theta_v = \begin{cases} \eta, & h \le h_a \\ \left(\dfrac{33kPa - h}{33kPa - h_a}\right)(\eta - \theta_{33}) + \theta_{33}, & h_a < h < 33kPa \\ \left(\dfrac{h}{h_a}\right)^{-\lambda}, & h \ge 33kPa \end{cases} \quad \textbf{(15)}$$

For each soil texture a representative sand and clay content was selected and then the soil properties were calculated. After determining the soil properties the required water table depth to have sufficient air-filled porosity to infiltrate 5.1 inches of rainfall was determined. The results for various soil textures are shown in Table 36. As can be seen, these depths ranged from 1.5 m (4.9 feet) for sand to 3.8 m (12.5 feet) for clay soils.

Table 36. Required water table depth to have available pore space to infiltrate a 5.1 inches of water.

Soil Type	% Sand	% Clay	Required Water Table Depth m (ft)
Clay	30	50	3.8 (12.5)
Clay Loam	33	30	3.3 (10.7)
Loam	42	18	2.7 (9.0)
Loamy Sand	82	6	1.6 (5.3)
Sand	92	5	1.5 (4.9)
Sandy Clay	52	42	3.6 (11.8)
Sandy Clay Loam	60	28	2.6 (8.7)
Sandy Loam	65	10	2.0 (6.5)
Silt	7	6	3.7 (12.3)
Silty Clay	7	47	3.6 (11.7)
Silty Clay Loam	10	34	3.6 (11.8)
Silt Loam	20	20	3.4 (11.3)

Table 36 lists the required depth to groundwater to infiltrate direct rainfall directly onto the VTA; however, for a VTS to be successful it must also have space in the soil profile to infiltrate runoff from the feedlot. Again, assuming a 5.1 inch design storm the volume of runoff from a feedlot can be determined using the SCS curve number method. For a 5.1-inch storm, approximately 4.08-inches of runoff would be expected from the feedlot. The effect of this runoff on the required VTA depth can be minimized by storing the effluent into a containment basin until the water table level in the VTA has receded; however, if the producer wishes to release this effluent onto the VTA during or shortly after the storm, the required depth of the water table would increase. In this case the required depth is a function of two parts, first, the required depth to infiltrate all direct rainfall onto the VTA (which was presented in Table 36), and secondly the depth infiltrate all the feedlot runoff. Thus in this case the required water table depth is also a function of the VTA to feedlot area ratio. For instance, for 5.1-inch storm and VTA to feedlot area ratios of 0.5:1, 1:1, 2:1, and 4:1 the VTA would need to have the available space to store 13.3, 9.2, 7.1, and 6.1 inches of water respectively. Thus as the VTA to feedlot area ratio gets larger, the water table depth becomes less restrictive. Figure 30 shows the required water table depth to infiltrate a design storm and the feedlot runoff resulting from this storm as a function of the VTA to feedlot area ratio for clay, loam and sand soil types. For each of these three soil types the properties were determined based on the sand and clay contents using the correlations of Saxton and Rawls (2006).

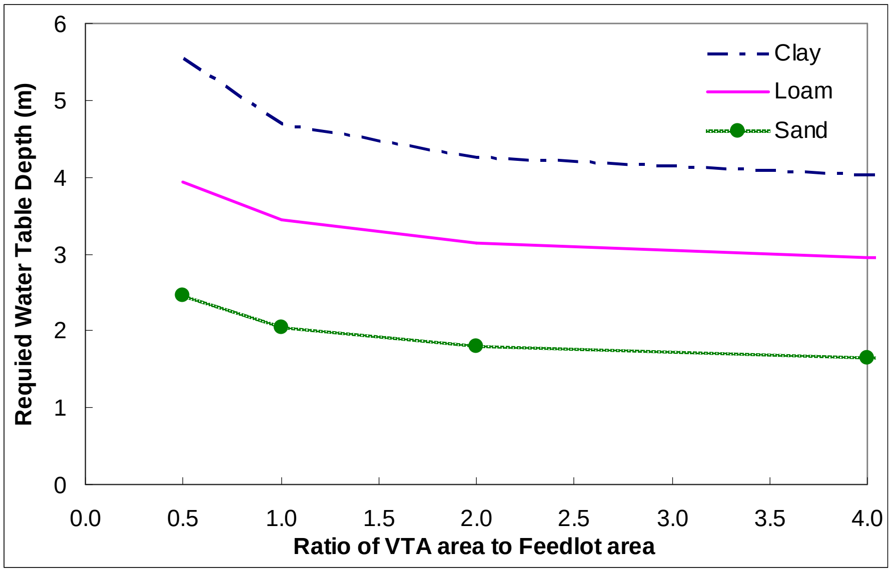

Figure 30. Water table depth requirement as a function of the ratio of VTA area to feedlot area.

In addition to the water table depth, the rate of recession of the water table also plays a crucial role in determining whether a VTA will operate successfully as this recession rate determine how quickly the system can be ready for the next rainfall event. Currently the ISU-ELG model assumes that a containment basin would be emptied within 13 days of a design storm. For a VTA that just meets the water table depth requirements listed in Figure 28 to maintain the same level of hydraulic control as the containment basin the VTA system must be "reset", i.e. capable of infiltrating a design storm, within 13 days. For a 5.1-inch design storm and a one-to-one VTA to feedlot area ratio this would imply that the VTA must utilize 0.7 inches of water per day. This water could be lost to either seepage or evapotranspiration.

In this case, the amount of water that the VTA must utilize is again a function of the VTA to feedlot area ratio. This relationship is shown in Figure 31, as can be seen, smaller VTA to feedlot area ratios require the VTA utilize more water. In addition to the water utilization rate, the average evapotranspiration rate during the growing season is also shown as a dashed line. The difference between these two lines is the amount of water that must be lost to seepage. Even for large VTA to feedlot ratios approximately 0.25 inch of water per day must be lost to seepage.

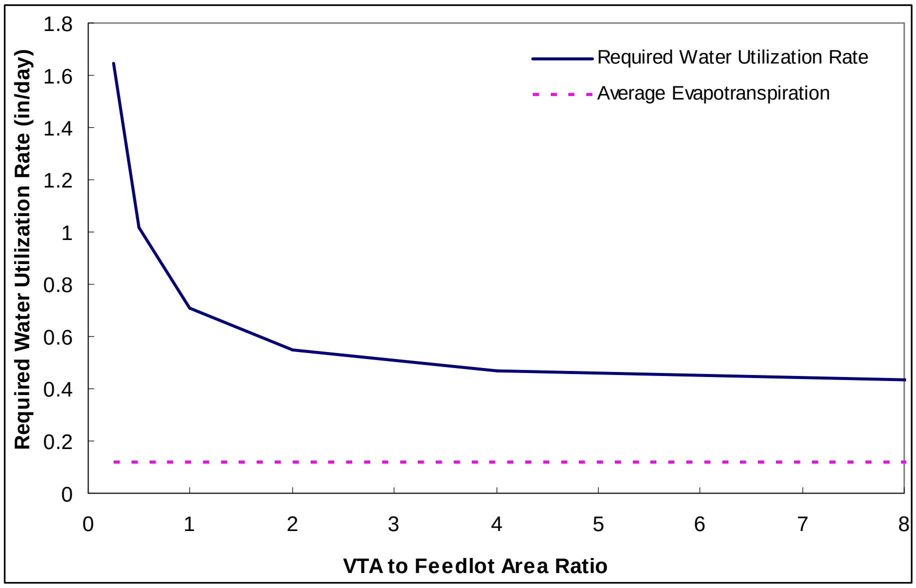

Figure 31. Relationship between the VTA to Feedlot Area ratio and the required water utilization rate.

Future Research Needs

- Modeling the performance of a runoff containment basin system “holistically”
- Monitoring the performance of a containment basin runoff control system
- Investigate the waste treatment mechanisms occurring in a VTS

Modeling the performance of a runoff containment basin system holistically

The 2003 concentrated animal feeding operation (CAFO) rules allow consideration of alternative manure treatment systems for National Pollutant Discharge Elimination System (NPDES) permitted CAFO operations that have on net, no additional discharge as compared to traditional containment systems.

Concentrated animal feeding operations that utilize alternative manure treatment systems under an NPDES permit are required to demonstrate that their alternative system has an equal or lesser nutrient mass release than from a conventional manure management system. These guidelines specifically target wastewater discharges from the production area, but state that the operation should consider environmental releases "holistically". Furthermore, the effluent guidelines state that land application areas are "integral to CAFO operations". Thus to fully quantify the mass of nutrients released from a traditional containment system all components need to be considered.

A USDA RMA study (2003) provides a mechanism by which to view waste management systems holistically. In this study, the waste management system was broken into five components; these included waste collection, waste transport, waste storage/treatment, waste conveyance to the land application field, and land application. A diagram of these stages is shown in Figure 32. The study also broke down the percentage of failures occurring in each part of the waste management system; these are displayed in Table 37. As can be seen, failures of the containment treatment structure accounted for the largest portion of failures (45%), but system failures were also caused by the other system components. Therefore, to determine the total impact of an animal feeding facility all aspects of the waste management system must be considered. Furthermore, to make a fair comparison between an alternative treatment system and a traditional containment system, all mechanisms of nutrient transport from both systems need to be considered. This is especially true if the alternative system either eliminates, or incorporates, additional stages of the waste management system into the storage/treatment component.

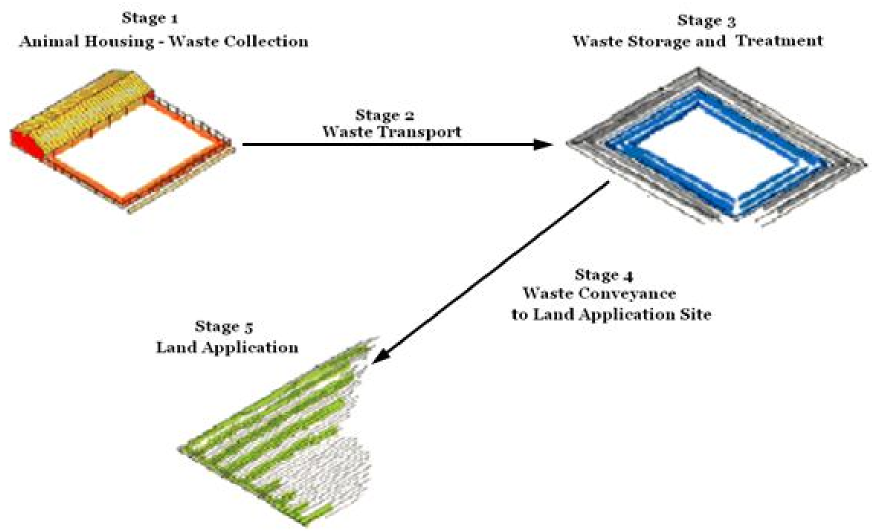

Figure 32. Conceptual model of the five stages to waste treatment.

For example, in a vegetative treatment system the vegetative treatment components serve as both a treatment component and as the final disposal mechanism, where by non-point source associated with land application is eliminated. However, currently Iowa NPDES permit requirements state that the ISU-ELG modeled nutrient release, which only includes nutrient releases due to containment basin overflow events, should be compared to the mass of nutrients released from the VTS system. However, the mass of nutrients released from a VTA is determined based on all five stages of the waste treatment system, collection through land application, where as for a traditional containment system, non-point source pollution resulting from land application are not considered.

Table 37. Percentage of failures occurring in each stage of the waste management system.

Stage	% of Failures
Animal Housing / Waste Collection	18%
Waste Transport	10%
Waste Storage and Treatment	45%
Waste Conveyance	7%
Land Application	21%

Monitoring the performance of a containment basin runoff system

The literature review performed for this thesis found limited data on the performance of containment basin runoff control systems, with only two data sets (Gilbertson and Nienaber, 1973; Moffitt and Wilson, 2004) located. In both cases, the studies lasted approximately one year in duration, thus neither study quantified long-term performance of the containment system. Therefore, studies focusing on monitoring the long-term performance of a containment basin are required to verify containment basin performance. Furthermore, these data are required so that existing containment basin models can be validated. This validation process would ensure that containment basin models can be used to accurately predict the performance of containment basins under the variety of climatic conditions and management strategies expected to be encountered at animal feeding operations.

Moreover, these monitoring projects should take a “holistic” approach to determining the impact of an animal feeding operation. This will ensure that as new models are developed the data necessary to calibrate and validate them will be available. Moreover, these data could also be used to refine the management practices concerning land application of feedlot runoff; specifically, on how different basin management techniques, i.e., dewatering schedules effect performance of a containment basin and the amount of non-point source pollution originating from the land application area.

Investigation of the treatment mechanisms occurring in a VTS

Future research on VTS’s should focus on understanding and modeling the chemical and biological treatment mechanisms occurring during effluent treatment in a VTS, specifically those mechanisms for treating phosphorus, nitrogen, and COD. This will allow researchers to better understand the fate and transport of these parameters throughout the treatment process and through removal from the system. Thus far, several researches have proposed various treatment mechanisms that may be occurring in VTS’s; these include sedimentation, filtration, denitrification, nitrification, sorption to soil particles, plant uptake, and infiltration (Koelsch et al., 2006); however, no research has been performed to quantify the contribution of each treatment mechanism. By studying these mechanisms, the ultimate fate of each of these nutrients can be better quantified.

Furthermore, current VTS models (Wulf and Lorimor, 2005; Tolle, 2007) only account for dilution as rainwater is added to the system, sedimentation of solid particles, and uptake of nitrogen and phosphorus by the vegetation. Thus, many of the treatment mechanisms that may be occurring are not considered. This limits the ability of these VTS models to predict effluent quality and nutrient transport through the various stages of the treatment process. In order to better understand overall impacts of VTSs it is important that the nutrient transformation, specifically those of nitrogen, are more fully considered. Moreover, inclusion of phosphorus treatment mechanism may provide insight into the long term effects VTSs will have on phosphorus levels in the soil. Additionally, improved understanding of the different treatment mechanisms will allow designers to optimize the treatment efficiency of different VTS components. Finally, as a VTS is compared to a traditional system on the basis of nutrient mass released from the system, the ultimate success or failure of the system must be based on its level of nutrient control.

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