

MODELING ALTERNATIVE TREATMENTS SYSTEMS FOR CONFINED ANIMAL
FEEDLOT OPERATIONS (CAFO) IN KANSAS

by

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Abstract

In 2003, the EPA changed Confined Animal Feedlot Operation (CAFO) regulations to allow an alternative treatment system for feedlot runoff if a 25-year simulation can show better performance for the alternative treatment system when compared to a traditional lagoon system. A continuous computer simulation model written in C was developed to compare the release of water, nitrogen (N), phosphorous (P) and chemical oxygen demand (COD) from a Vegetated Treatment Area (VTA) system and a conventional lagoon system in Kansas. The model simulates the transport of water and constituents in a feedlot, settling basin, lagoon, and VTA. The feedlot runoff is based on NRCS unit hydrograph method for the water balance and AnnAgNPS for the constituent runoff concentrations. The settling basin is a simple water balance with sediment, organic-N, P, and COD removed with settling of the solids. The VTA is designed to calculate infiltration with Green-Ampt Equation and overland flow with Manning's Law. The VTA removes organic-N and P with the Kentucky Filtration Model. The lagoon is derived from Koelliker et al. model water balance and pumping schedule with constituent balance from Miner et al. model.

VTA portion of the model was analyzed for sensitivity and calibrated with three storms. The sensitivity analysis showed that the size of the VTA and conductivity of the soil in the VTA causes the greatest variability in the release of N, P, and COD. The calibration of the release of organic-N and P for mean particle diameter showed that a diameter of 1.5 μm produced the best agreement. The model was used for a lagoon and VTA system at two sites in Kansas with 35 years of weather data. The sites were located in Ottawa and Greenwood Counties, KS. The simulated results showed that the lagoon system performed better for both sites when comparing the mean values of total-N, total-P, and COD released over the 35 years. The VTA system performance was better when median values of total-P and COD were compared at Greenwood County. This model was designed for use in Kansas, but with modifications may be useful in other areas.

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Preface

This thesis describes a computer simulation model for CAFO treatment designed specifically for use in the state of Kansas. Funding for the project was provided by the Kansas Department of Health and Environment. The intended users of this model are designers, regulators, and operators in Kansas. Therefore; the model's units used are customary U.S. This thesis expresses all input units in both U.S. with S.I. in parentheses. Equations used in the design are expressed in the U.S. system to include conversions that were necessary for the performance of this model. Outputs are expressed in S.I. units to conform to standard scientific notation.

CHAPTER 1 - Introduction

In 1972, Congress passed the Clean Water Act authorizing the Environmental Protection Agency (EPA) to develop regulations to maintain water quality for waters of the U.S (Sweeten et al., 2003). One the sources of pollution regulated under the Clean Water Act was Confined Animal Feedlot Operations (CAFO). Two years later, the EPA released the Feedlot Effluent Guidelines (ELG) that required all feedlots over 1,000 Animal Units (AU) contain all manure, wastewater, and runoff from 24-hour duration, 25-year return period storm event (24-hr, 25-yr storm) with an anaerobic lagoon with disposal by irrigation (Sweeten et al., 2003). In 1976, National Pollutant Discharge Elimination System (NPDES) permit regulations required all Animal Feedlot Operations (AFO) defined as CAFO to obtain NPDES permits (Sweeten et al., 2003). A CAFO was defined as a confinement of animals for at least 45 days a year, no live plants or grasses, and 1,000 or more AU. AFO between 300 to 999 AU and less then 300 AU could be considered medium or small CAFO if the AFO discharged through artificial waterways to waters of the U.S, directly to waters of the U.S, or was considered significant pollution contributor by the regulator agency (Sweeten et al., 2003). AFO less then 300 AU were small CAFO if they met the medium CAFO definition and were “significant pollution contributor” as defined by the regulator agency. An AFO was exempt from CAFO status if the AFO contained all runoff from a 24-hr, 25-yr storm (Federal Register, 2003).

In the late 1990s the EPA and U.S. Department of Agriculture (USDA) began jointly reviewing the CAFO regulations (Federal Register, 2003). This review resulted in the release of the Final Rules for CAFO in 2003. Two changes were a switch from AU to actual animal number, and the 24-hr, 25-yr storm exception for NPDES permits was removed (Federal Register, 2003). Table 1.1 shows some of the thresholds used in defining small, medium, and large CAFO (Federal Register, 2003). Another change to the rules allows alternative treatment systems to be used if it performs better than the basic ELG system. The two systems are to be compared with a continuous simulation computer model running with 25 years of weather data.

Table 1.1. CAFO thresholds for different animal types (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	750-2,499	1-749
Swine (less than 25 kg)	10,000 or more	3,000-9,999	1-2,999

The model must show the total discharge of pollutants (e.g. nitrogen (N), phosphorus (P), Biological Oxygen Demand (BOD)/Chemical Oxygen Demand (COD)) for both systems (Federal Register, 2003).

One proposed alternative treatment system is a Vegetated Treatment Area (VTA). Ikenberry and Mankin (2000) defined a VTA as an area of vegetation designed to reduce pollutions in water through sedimentation, filtration, and infiltration. For the purpose of this thesis, VTA is further defined as an engineered filter strip designed to minimize erosion and increase infiltration. A VTA has dense vegetation with slopes less than 5% that encourage overland flow. Several studies have shown that VTA or filter strips can reduce pollutants loads. Barker and Young (1984) diverted runoff from 54 dairy cows into a settling basin and 91-m long VTA system. The VTA was able to remove 96% of COD, 97% of total-N, and 98% of total-P as measured by concentration. The Barker and Young (1984) study also showed that COD, total-N, and total-P mass were reduced by 100%. Dickey and Vanderholm (1981) studied four VTA systems for 17 months and were able to reduce COD by 58.4-92.1% and total-N by 71.1-88.9% in concentration. In a three-year study Edwards et al. (1986) found that a 56-head beef feedlot fitted with a VTA and settling basin system could reduce the mass COD by 83% and total-N by 78% and ortho-P by 74%. Finally, Mankin and Okoren (2003) in a year-long study of a 300-head dairy feedlot showed that a feedlot and VTA could reduce the mass of BOD by 68%, total-N by 77% and total-P by 79%. These four studies showed that VTA systems can reduce BOD/COD, N and P from feedlot runoff substantially in both concentration and mass. The amount of reduction varies between the studies.

The objective of this thesis was to develop a continuous computer simulation model for the state of Kansas to simulate N, P, and COD transport off a feedlot, and through a settling basin, lagoon, or VTA. This model should meet the EPA requirements for modeling an alternative treatment system for CAFO. The model should allow operators, engineers, and regulators to compare a VTA treatment system to the standard lagoon treatment system.

CHAPTER 2 - Literature Review

Different models have been developed over the years to simulate the transport of water and nutrients through the environment. These models were designed to function on various scales and simulate different situations of the environment. Models were developed to function on a watershed, field, farm or urban basis. Although the purposes of the models may be different, most of the models utilize similar governing equations. The first step in the development of the CAFO model is to research similar models and incorporate governing equations that allow for the simulation of a feedlot, settling basin, VTA, and lagoon.

Koelliker Feedlot/Lagoon Model

In the 1970s, Koelliker et al. (1975) developed a feedlot and lagoon water balance model for Kansas that used U.S. customary units. The model was designed to operate for 30 years in daily time steps. The weather data was taken from 1941 through 1970 including daily precipitation, and minimum and maximum temperatures. Runoff from the feedlot was calculated with the USDA Natural Resources Conservation Service (NRCS)¹ curve number method. Equation 2.1 shows the NRCS runoff calculations. For the Koelliker et al. model, the curve numbers were set to 91 for earthen feedlot and 94 for surfaced feedlot under Antecedent Moisture Condition (AMC) II. The AMC is a measure of the wetness of the soil and is divided into AMC I for dry conditions, AMC II for normal conditions, and AMC III for wet conditions (NRCS, 2004). Koelliker et al. (1975) would switch to AMC III curve numbers of 97 for earthen and 98 for surfaced based on the previous five days precipitation amounts. If snow depth was greater than zero, then precipitation was assumed to be snow and runoff would not occur until snow depth was zero again.

¹ The Natural Resource Conservation Services originally called the Soil Conservation Service (SCS). The name was changed in the early 1990s.

$$R = \frac{(P - 0.2S)^2}{P + 0.8S} \text{ where } P > 0.2S \text{ otherwise } R = 0 \quad (2.1)$$

where, R is runoff depth (mm)

P is rainfall depth (mm)

S is soil retention factor $S = 25,400 / CN - 254$ (mm)

CN is NRCS curve number

The lagoon system used a traditional water balance where inputs (rainfall and runoff) minus outputs (evaporation, irrigation, and overflow) equal the change in storage volume. Rainfall for the lagoon was the depth of precipitation times the top surface area. Runoff came from the feedlot according to Equation 2.1. Equation 2.2 was used to estimate the evaporation amount.

$$Evap_d = \frac{Evap_m}{30(Temp_m)} Temp_d \quad (2.2)$$

where, Evap is evaporation

Temp is mean temperature

d is daily

m is monthly

Evaporation was zero when the ground was frozen. Pumping occurred when the following conditions were met:

- Average daily temperature above 32°F (0°C)
- Previous three days cumulative precipitation less than 0.05 in. (1.3 mm)
- No snow on ground
- Ground not frozen
- Lagoon volume greater than or equal to one-day's pumping volume

The pumping volume was assumed to be one tenth of the lagoon volume between April and October and one twentieth for the rest of the year. The soil was considered frozen when today's and yesterday's mean temperature were both below 32°F (0°C). Soil was unfrozen when today's, yesterday's, and previous day's mean temperature were all above 32°F (0°C). Overflow occurred when the water volume exceeded the lagoon volume.

Five sites in Kansas were simulated for a lagoon sized to contain a 24-hr, 25-yr storm or a 24-hr, 10-yr storm. Figure 2.1 shows that the 25-yr storm size was more

effective controlling the runoff water, but only one of the sites had 100% containment. The results indicate that the traditional “zero discharge” design for CAFO does not contain all the water.

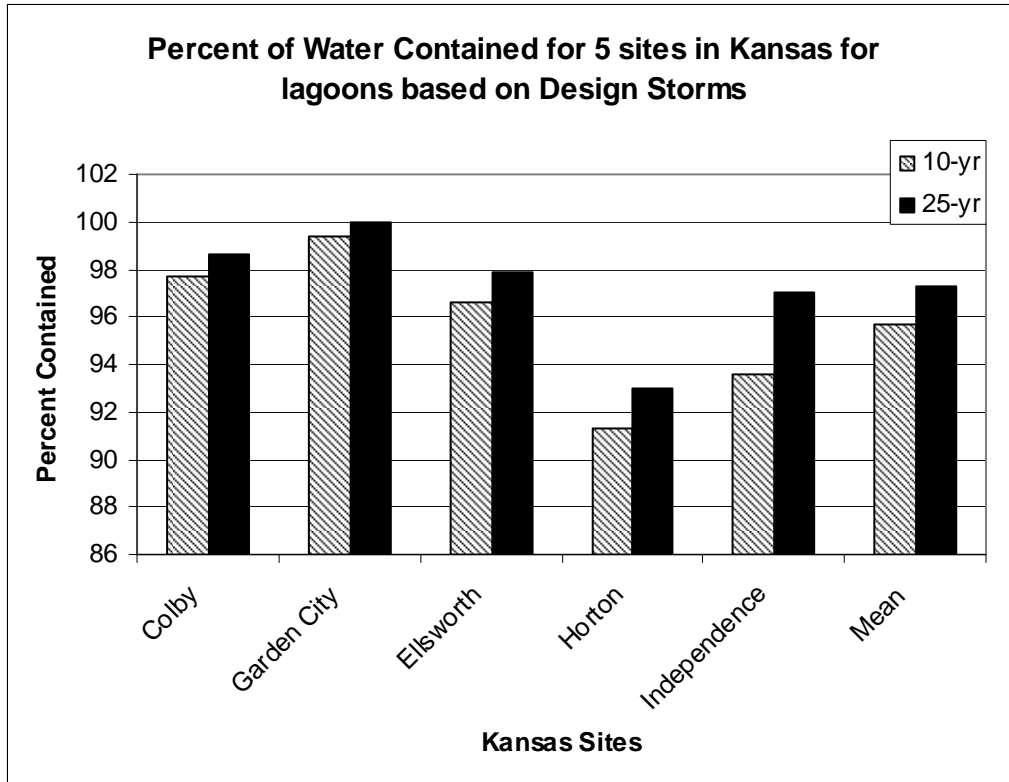


Figure 2.1. Percent of Water Contained for lagoon sized for 24-hr, 10-yr and 25-yr storms. (Koelliker et al., 1975)

The Koelliker model performs the water balance for a feedlot and lagoon system on a daily time step. The model’s time step allowed it to maintain a water balance for the lagoon, but it did not include any nutrient balances. The quantity of water released can be calculated, but the model did not estimate water quality. Also, the model does not provide enough detail to calculate the rate of flow of water through the system for discharge to a VTA system.

CREAMS

Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) is a field-scale daily time step model developed by the USDA to determine runoff, sediment and chemical loads (Knisel, 1980). The model is physically-based and

derived from available models. The model is divided into three components of hydrology, sediment, and chemistry. CREAMS calculates runoff for each subarea with the NRCS method (Equation. 2.1). If inputs include hourly rainfall intensities, then CREAMS has the ability to model water runoff by determining the infiltration. Infiltration provides a can better estimate of the runoff values compared to NRCS method, but requires more computation time. CREAMS calculates infiltration with on Green and Ampt method (Equation 2.3) (Knisel, 1980).

$$f = \min\left(K_s\left(1 + \frac{\Psi\Delta\Theta}{F}\right), i\right) \quad (2.3)$$

where, f is infiltration rate (length/time)

K_s is saturated conductivity (length/time)

Ψ is wetting front section head (length)

$\Delta\Theta$ is moisture deficiency (saturation-current water content)

i is rainfall intensity (length/time)

$\min()$ is minimum of two values.

CREAMS also estimates evapotranspiration (ET) and percolation to allow for continuous operation.

Sediment transport is based on determining if detachment of sediment from the land or the carrying capacity of the water is limiting. If the water is unable to carry all the sediment, then deposition occurs and some of the sediment is returned to the soil. Detachment occurs if the actual amount of sediment transported is less than the waters' carrying capacity. Interrill detachment rate is estimated with a modification to the USLE by Foster et al. (1977) (Equation. 2.4).

$$R = 0.210EI\left(s + 0.014\right)\left(\frac{q_p}{V}\right)KCPLS \quad (2.4)$$

where, R is detachment rate (lbs/ft²/s)

EI is rainfall erosivity (100 ft-tons/acre) (in/hr)

$EI=8.0V^{1.51}$

V is runoff volume (in.)

q_p is peak flow rate (in./s)

K is soil erodibility factor

C is crop management factor

P is contour factor

LS is slope length factor

The nutrient model divides nutrients into sediment-bound N, soluble N, soluble and P, sediment-bound P. Sediment-bound N and P losses are calculated based on the amount of sediment detached from the soil with Equation 2.5. CREAMS sets the enrichment coefficients to 7.4 for a, and -0.2 for b for both N and P. The enrichment ratio may never be less than one.

$$T_x = SC_x ER \quad (2.5)$$

where, T_x is amount transport x (kg/ha)

S is sediment detached (kg/ha)

C_x is the concentration of x in the soil (kg/kg soil)

ER is enrichment ratio, $ER = \min(aS^b, 1)$

x is sediment-bound N or P

a and b are enrichment coefficients

The soluble N and P in runoff are assumed to come from the water interacting with the top 10 mm of soil. The initial soil concentration is based on applied fertilizers and residue. For N, the addition of N in the rainfall changes the concentration in the soil layer. At first N is leached, so when runoff occurs the N concentration is set C_1 (Equation 2.6). After runoff stops, the soil N concentration becomes C_2 (Equation 2.7). Equation 2.8 calculates the average concentration of soluble N in the runoff. Finally, the amount of soluble N in runoff can be calculated with Equation 2.9.

$$C_1 = (C_0 - C_r)e^{-K_1 F} + C_r \quad (2.6)$$

$$C_2 = (C_1 - C_r)e^{-K_2 Q} + C_r \quad (2.7)$$

$$\bar{C} = \left(\frac{C_1 - C_r}{K_2 Q} \right) (1 - e^{-K_2 Q}) + C_r \quad (2.8)$$

$$R = \bar{C} d \phi K_2 Q (0.01) \quad (2.9)$$

where, C_0 is initial concentration (ppm)

C_1 is concentration at start of runoff (ppm)

C_2 is concentration at end of runoff (ppm)
 C_r is concentration in rain (ppm)
 \bar{C} is the average runoff concentration (ppm)
 R is runoff of soluble N (kg/ha)
 K_1 is rate constant for downward movement
 K_2 is rate constant for runoff
 Q is volume of runoff (mm)
 d is depth of soil layer for interaction (10 mm)
 ϕ is porosity of soil layer

The calculation of P is in a similar approach, but there is no P in rainfall or leaching. This means that $C_r=0$ and $C_1=C_0$ for P and Equation 2.6 is not used. To calculate P runoff, Equation 2.8 is used to determine the average concentration in the runoff and Equation 2.9 gives the amount of soluble P (Knisel, 1980).

The big disadvantage of the CREAMS model for this work is that it simulates P and N runoff from a field site and not from a feedlot. So use of its algorithms in this model must be used with caution. The model does include calculations of runoff by the NRCS method and also includes runoff estimations by Green-Ampt infiltration.

AgNPS/AnnAgNPS Model

Agricultural Non-Point Source Pollution (AgNPS) model was originally developed by Young et al. (1987) for the Agricultural Research Service. AgNPS is a single-event, watershed-sized model. AgNPS is designed to divide the watershed into cells. Each cell has a constituent and water balance performed. AgNPS simulates the transport of COD, soluble and sediment-bound P and N. The model estimates runoff with the NRCS curve number method (Equation 2.1). Sediment is estimated with the modification to universal soil loss equation (USLE) developed by Wischmeier and Smith (1978). N and P field runoff is determined by the same equations used by CREAMS. The sediment and pollutants are then routed with runoff through each cell based upon the properties of the cell.

Feedlot component

An important element of the AgNPS model used for the development of this model is the feedlot model component. Feedlot runoff is treated as a point source pollutant that is imported into the total flow from the watershed. The feedlot component estimates the amount of COD, total-N, and P that leaves the feedlot. The feedlot component also estimates the decrease of pollutants from a filter strip below the feedlot and is based on a model developed by Young et al. (1982)

Young et al. (1982) model is a feedlot pollution potential model for COD and total-P. It is designed to estimate the maximum potential effect a feedlot has on the environment. The model first estimates the amount of runoff with the NRCS curve number method (Equation 2.1). The model assumes that the maximum concentration that can occur is when a beef feedlot has 100 head per acre after 10 days of operation when the feedlot has a 100% manure pack. The manure pack for COD and P are calculated with Equation 2.10.

$$MP_X = \frac{\sum N_i F_{xi}}{100(A)} \quad \text{For } MP < 1.00 \text{ otherwise } MP = 1.00 \quad (2.10)$$

where, MP is manure pack

A is area (acres)

N_i is number of animals

F_i is animal factor for COD or P for each animal type

i is animal type

X is COD or P

The manure pack can never be greater than 100%. Table 2.1 shows the animal factor for total-N, P, and COD. N amounts were developed for the AgNPS model (Young et al., 1987). The concentration of P and COD in the runoff is calculated by Equations 2.11a and b. AgNPS added total-N concentration with a similar procedure except using Equation 2.11c and an N animal factor from Table 2.1 (Young et al, 1987).

$$C_{COD} = 4,500(MP_{COD}) \quad (2.11a)$$

$$C_P = 18(MP_P) \quad (2.11b)$$

$$C_N = 300(MP_N) \quad (2.11c)$$

where, C is concentration of runoff (mg/L)

MP is manure pack

COD, P, and N are COD, P, and N respectively

Table 2.1. Animal factor for select animal types for nitrogen, phosphorus, and COD (Young et al., 1982) (Young et al., 1987)

Type of Animal	Weight kg (lbs)	COD	Phosphorus	Nitrogen
Steer	454 (1,000)	1.00	1.00	1.00
Young Beef	227 (500)	0.50	0.51	0.60
Dairy cow	635 (1,400)	1.96	0.92	1.68
Swine	91 (200)	0.017	0.27	0.26
Feeder pig	23 (50)	0.04	0.07	0.50

AnnAgNPS

AnnAgNPS is a continuous, watershed and pollutant-load model that evolved from AgNPS. AnnAgNPS is still designed to divide a watershed into cells, but it will run with multiple events. AnnAgNPS has extended its capacity by incorporating several modules into its design (Bingner and Theurer, 2005). One of the modules is a time-variant feedlot pollution model developed by Baker (2005). The module is designed to estimate the concentration of total-N, P, and organic carbon in feedlot runoff. Baker (2005) adapted the original AgNPS feedlot component to change concentrations with time depending on animal types and management operations.

Baker's (2005) module varies constituent amounts by performing a daily constituent mass balance. The module inputs the types and number of animals, entry and exit dates, and beginning and ending weights. Also, the initial amount of organic carbon, N, and P can be specified or the module assumes a five-day starting amount. Baker (2005) calculates runoff with NRCS curve number method (Equation 2.1) and concentrations of organic carbon, N, and P are calculated with AgNPS method (Equation 2.11). Organic carbon replaces COD and the 4,500 coefficient is substituted with 1,680. AgNPS manure pack calculations are replaced model with Equation 2.12.

$$MP_x = \frac{m_x}{MPF_x(A)} \quad (2.12)$$

where, MP_x is manure pack

m_x is mass of x on feedlot (kg)

A is area (ha)

MPF_x is mass equivalent of x to manure pack=1 (kg/ha)

x is organic carbon, P, or N

The MPF for organic carbon, P, and N are respectively 3,250, 103, 380 kg/ha.

Baker (2005) calculates the masses of organic carbon, N, or P with a daily constituent balance. At the beginning of the day, the removal of constituents when scraping occurs. This is based on a user specified removal efficiency and scraping schedule. Next, the runoff concentrations are calculated as described above. Also, the decomposition of N and P are calculated. Equation 2.13 gives the decomposition rate of organic carbon, but no decomposition rate of N is given.

$$R = m_C \exp\left(\frac{30.0(m_N)}{m_C}(0.0693T_{avg} - 6.867)\right) \quad (2.13)$$

where, R is amount of decomposition of organic carbon (kg)

m_N is mass of N on feedlot (kg)

m_C is mass of organic carbon of feedlot (kg)

T_{avg} is average daily temperature ($^{\circ}\text{C}$)

Finally, the mass of constituents added is calculated with Equation 2.14. The mass of each animal type each day is calculated by assuming linear growth rate of the animal between the beginning and ending weights during confinement period. Table 2.2 shows that expected amount of organic carbon, P, and N produced per kg of animal per day. These values were developed from ASAE Standard (ASAE, 1999).

$$ma_x = \sum N_i m_i a_{ix} \quad (2.14)$$

where, ma_x is mass x added (kg)

N_i is number of animals i

m_i is mass of animal i (kg)

a_{ix} is mass x produced per kg of animal i (kg x/kg animal/day)

x is organic carbon, N, P

Table 2.2. Amount of nitrogen, phosphorus, and organic carbon produced per animal per day (ASAE, 1999) (Baker, 2005)

Animal Type	Amount produced per mass of animal per day (kg/kg-animal/day)		
	Nitrogen	Phosphorus	Organic Carbon
Dairy Cattle	0.00045	0.000094	0.0041
Beef Cattle	0.00034	0.000092	0.0029
Veal	0.00027	0.000066	0.0020
Swine, full-feed	0.00520	0.001800	0.0032
Swine, limit feed	0.00026	0.000090	0.0016

The AgNPS/AnnAgNPS feedlot component provides the concentration of total N, P, and COD/organic carbon from a feedlot. The advantage of this model is that it is specifically designed for feedlot calculations and comes from a model produced by USDA Agricultural Research Service. Disadvantages of the model are that the amounts of N and P are not divided into individual constituent species.

EPIC/APEX

EPIC was first conceived as the Erosion-Productivity Impact Calculator by the Agricultural Research Service (ARS) committee that first convened in 1981 (William et al., 1983). The 1983 version of EPIC was designed to model hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics. It is designed to work on the field-scale with homogenous inputs. The model was based on previously-developed algorithms that were linked into an overall model. EPIC operates continuously on a daily time-step for all of the environmental processes.

The EPIC's hydrology component from Williams et al. (1983) predicts surface runoff with the NRCS curve number method (Equation 2.1) similar to the CREAMS model except a soil moisture balance is maintained to determine the AMC. Peak flow rate is calculated with Equation 2.15, a modification of the rational formula. The time of concentration is calculated with combination of the overland and channel flow. EPIC also calculates subsurface lateral flow and percolation.

$$q_p = crA \tag{2.15}$$

where, q_p is peak flow rate

c is coefficient representative of the watershed

r is rainfall intensity at time of concentration for the watershed

A is area of the watershed

The 1983 EPIC model calculated both wind and water erosion. The amount of soil eroded by water with runoff occurring from a single-event storm was calculated with modifications to the USLE by Onstad and Foster (1975) in Equation 2.16. The crop, contour, slope length, and soil erodibility factors were the same as the original USLE. Equations 2.17 and 2.18, respectively, calculate the rainfall energy factor EI and slope length factor, LS , for EPIC (Williams et al., 1983).

$$Y = (0.646EI + 0.45Qq_p^{0.333})KCPLS \quad (2.16)$$

where, Y is sediment loss (Mg/ha)

EI is rainfall energy factor (metric units)

Q is runoff depth (mm)

q_p is peak flow rate (mm/hr)

K, C, P, LS are USLE parameters as listed in Equation. 2.4

$$EI = \frac{Rr_{0.5} (12.0 + 8.9(\log r_p - 0.043))}{1000} \quad (2.17)$$

where, EI is rainfall energy factor (metric units)

R is rainfall amount (mm)

$r_{0.5}$ is 30-minute rainfall intensity (mm/hr)

r_p is peak rainfall intensity (mm/hr)

$$LS = \left(\frac{\lambda}{22.1} \right)^{0.6(1 - \exp(-35.835S))} (65.41S^2 + 4.56S + 0.065) \quad (2.18)$$

where, LS is slope length factor

λ is slope length (m)

S is slope (m/m)

EPIC divided the transport of nutrients by water similar to CREAMS for organic-N, nitrate-N, insoluble-P, and soluble-P. Williams et al. (1983) calculated organic-N and insoluble-P transport with the CREAMS method (Equation 2.5). Equation 2.19 calculated the concentration of nitrate-N in runoff, percolation, and subsurface flow. The

amount of nitrate-N in the runoff is simply the volume of water times the concentration with appropriate conversion of units. The soluble-P was calculated with Equation 2.20.

$$C = \frac{A_{10mm}}{V_T} \left(1 - \exp\left(\frac{-V_T}{\phi}\right) \right) \quad (2.19)$$

where, C is concentration of nitrate-N (ppm)

A_{10mm} is amount of nitrate in first 10 mm of soil (mg)

V_T is total volume of runoff, percolation, and subsurface flow (L)

ϕ is porosity of soil layer

$$Y = 0.01c \frac{Q}{k_d} \quad (2.20)$$

where, Y is soluble-P yield (kg/ha)

c is concentration of labile P in top 10mm of soil (g/Mg)

k_d is ratio of soil to water (m^3/Mg) EPIC used 175

Q is runoff volume (mm)

EPIC was revised by Williams et al. (1983) to include an irrigation component that calculated sediment transport with the Modified Universal Soil Loss Equation (MUSLE) developed for single event-storms (Equation. 2.21).

$$Y = 11.8(Qq_p)^{0.56} KCPLS \quad (2.21)$$

where, Y is sediment yield (Mg/ha)

Q is runoff (mm)

q_p is peak flow rate (mm/hr)

K,C,P,LS are USLE parameters as listed in Equation 2.4

APEX

EPIC was designed as a field-scale model up to 100 ha in size with homogenous properties. EPIC subroutines were extended to a whole farm model with the Agricultural Policy/Environmental eXtender (APEX) model (Williams and Izaurralde, 2006). APEX contains an updated version of EPIC for simulating individual fields, but it also contains water, nutrient, and pesticides routing across the different fields. This allows APEX to function on small watersheds with inhomogeneous properties.

The updated EPIC model incorporated in APEX allows runoff to be calculated using either the NRCS curve number or Green-Ampt methods. EPIC sediment erosion also added three additional derivations of a single-event USLE, besides the two previously mentioned. Equation 2.22 shows the erosions prediction equations of MUST (a), MUSS (b), and MUSI (c). Erosion of manure from the land can be estimated with an alteration to MUST in Equation 2.23.

$$Y = 2.5(Qq_p)^{0.5} KCPLS \quad (2.22a)$$

$$Y = 0.79(Qq_p)^{0.65} A^{0.009} KCPLS \quad (2.22b)$$

$$Y = c_1 Q^{c_2} q_p^{c_3} A^{c_4} KCPLS \quad (2.22b)$$

where, Y is sediment yield (Mg/ha)

Q is runoff volume (mm)

q_p is peak flow rate (mm/hr)

A is area (ha)

c₁, c₂, c₃, and c₄ are user-specified coefficients

K,C,P,LS are USLE parameters as listed in Equation 2.4

$$Y = 0.25(Qq_p)^{0.5} M^{0.5} \exp(-0.15C_s) PSL \quad (2.23)$$

where, Y is manure yield (Mg/ha)

Q is runoff volume (mm)

q_p is peak flow rate (mm/hr)

M is manure (Mg/ha)

C_s is standing live or dead plant material

P and SL are USLE parameters as listed in Equation 2.4

SWAT

Soils and Water Assessment Tools (SWAT) is a large-scale watershed model used to predict the fate of water, sediment, and agricultural chemicals (Neitsch et al., 2005). SWAT was developed in the 1990s to merge Simulator for Water and Resources in Rural Basins (SWRRB) and Routing Outputs to Outflow (ROTO) models into a single model. SWAT includes algorithms from CREAMS and EPIC. SWAT's 2005 technical

documents show that water, sediment, and nutrient transport equations are derived from the CREAMS and EPIC models. These models have been previously discussed.

VFSSMOD

VFSSMOD is a single-event, vegetated-filter-strip model for water and sediment (Munoz-Carpena and Parson, 2005). VFSSMOD is designed to route a hydrograph and sediment graph directly from a field through a filter strip. Infiltration within VFSSMOD is modeled with Green-Ampt, while runoff transport is calculated by approximation using Equation 2.24. At the start of a simulation, the depth throughout the filter strip is zero and for any time after the depth at the upper end of the filter strip is related to the input hydrograph. Depth and flow rate are related to each other with Manning's equation (Equation 2.25). A rainfall hyetograph is synthesized based on location and the type of NRCS storm encountered (Munoz-Carpena and Parson, 2005). NRCS (1989) divided the United States type I, IA, II, and III storms hyetograph. The hyetographs are multiplied by the rainfall amount to create a synthetic storm distribution. The input hydrograph is created with a unit hydrograph times the NRCS curve number total runoff (Munoz-Carpena and Parson, 2005). Sediment is calculated with the MUSLE erosion equation

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i(t) \quad (2.24)$$

where, $i(t)$ is rainfall excess intensity (rain-infiltration) (m/s)

h is depth (m)

q is flow rate per unit width (m^2/s)

t is time (s)

x is location along length of flow (m)

$$q = \frac{\sqrt{S}}{n} h^{5/3} \quad (2.25)$$

where, q is flow rate per unit width (m^2/s)

h is depth of flow (m)

n is Manning's coefficient

S is slope (m/m)

Sediment removal is modeled with the Kentucky Filtration Model designed to estimate sediment removal in a filter (Barfield et al., 1979). Figure 2.2 shows the model four zones. Larger sediment is deposited at the entrance of the filter strip in Zone B. When sediment reaches the top the vegetation, the area becomes part of Zone A and no more deposition occurs. Zones C and D are where smaller sediment is deposited. Zone C is where surface irregularities are filled with sediment, while Zone D still needs to be filled. As time passes, each of the zones moves down the filter strip. Equation 2.26 shows the removal rate for sediment in Zones C and D.

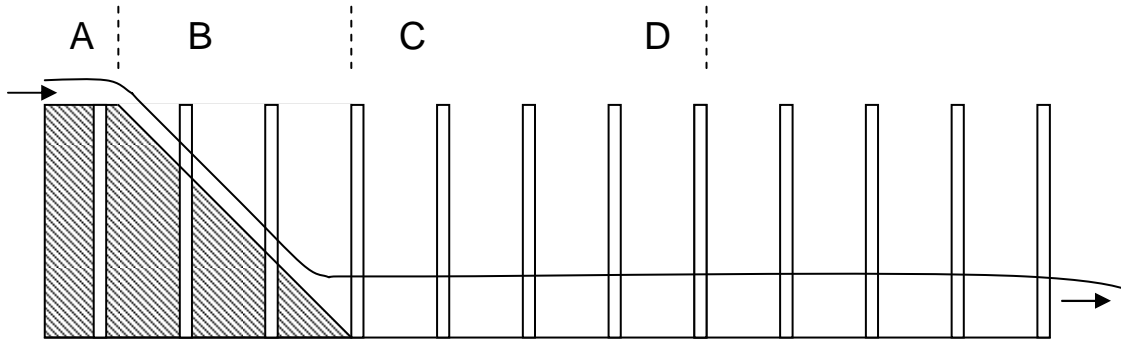


Figure 2.2. Diagram of the Kentucky Filtration Model with four zones. Zone A is filled with large sediment, Zone B is filling with large sediment, Zone C irregularities are filled with small sediment, Zone D irregularities are unfilled with small sediment (Barfield et al., 1979).

$$q_r = q_i \exp \left(-0.00105 \left(\frac{VR_s}{\nu} \right)^{0.82} \left(\frac{LV}{V_s d} \right)^{-0.91} \right) \quad (2.26)$$

where, q_r is sediment removed (kg)

q_i is inflow sediment (kg)

V is mean flow velocity (m/s)

R_s is hydraulic radius $R_s = \frac{Sd}{S + 2d}$

d is depth of flow (m)

L is flow length for zone C and D (m)

V_s is settling velocity (m/s)

S is plant spacing (m)

ν is kinematic viscosity (m^2/s)

Iowa State ELG/VTA Model

Wulf and Lorimor (2005) at Iowa State University designed an ELG/VTA model to compare the water and constituent output from a lagoon and VTA systems. The model was programmed using ModelMaker® 4 and was designed to eventually simulate 25 years with of daily weather data. The model is designed to meet the requirements to compare alternative treatment systems that the EPA requires. It represents a first step in the design of such a comparison system.

ELG Model

The ELG model developed by Wulf and Lorimor (2005) is a reconstruction of the Koelliker et al. model with daily time steps and runs in 13-year increments. The model must be run twice without resetting the variables to obtain a full 25 years of results. The model added a degree-day snowmelt method and constituent balance. Table 2.3 shows the concentrations of pollutants in feedlot runoff for each type of surface used by the Iowa State Model. The concentrations do not vary for any runoff amount or animal density. The lagoon constituent balance is a simple mass balance with no treatment component for the system. Wulf and Lorimor (2005) added the ability to calculate runoff from four extraneous drainage areas including a second feedlot.

Table 2.3. Runoff concentrations for earthen and surface feedlots for Iowa State Model.

Pollutant	Earthen (mg/L)	Concrete (mg/L)
Total Kjeldahl Nitrogen	65.0	97.5
Ammonium ² Nitrogen	50.0	75.0
Total P	20.0	30.0
Total Solids	2,000.0	3,000.0
COD	2,650.0	3,975.0

² For purpose of this thesis ammonium is in reference to the sum of the ammonium ion (NH₄⁺) and ammonia (NH₃). The actual model does not separate the terms into individual species.

VTA Model

The VTA model by Wulf and Lorimor runs for 5 years on 5-minute time steps. The model must be run five times without resetting to create a 25-year simulation. The model takes about 15 minutes per 5 years to run the simulation. The feedlot runoff for the VTA is calculated similar to the ELG model, but utilizes synthetic hyetographs and unit hydrographs. The hyetograph is a randomly-modeled one that uses an NRCS type II storm or Huff Quartile storms for durations of 0.5, 1, 2, 3, 6, 12, 18, and 24 hours for a certain depth of daily rainfall. The probability for duration and storm type was based on Iowa's rainfall data. The NRCS unit hydrograph was used to model runoff from the feedlot. The runoff amount for each time step was determined by summing each rainfall excess times the unit hydrograph for the previous time periods.

All runoff from the feedlot and other drainage areas were routed to a settling basin with a simple water balance. For each time step, the volume of runoff and rain were added and outflow was calculated with an orifice design. If water volume exceeded storage volume, overflow of the settling basin would occur. The constituent balance was a simple mass balance.

Table 2.4. Constituent concentrations from the settling basin based on feedlot surface type and design capacity of settling basin. (Wulf and Lorimor, 2005)

Constituent	Earthen Feedlot (ppm)		Concrete Feedlot (ppm)	
	Capacity >5 in.	Capacity <5 in.	Capacity >5 in.	Capacity <5 in.
Total-N	67	135	135	200
Ammonium-N	50	100	100	150
Total-P	20	60	60	90
Total Solids	2,000	4,000	4,000	6,000
COD	2,650	5,300	5,300	7,950

The orifice outflow and overflow were routed to a VTA. The VTA was divided into 100 sections with individual water balances. The water balance is composed of both a surface and a soil balance. The surface water balance includes added inflow and rainfall, and subtracted outflow and infiltration. Inflow came from the settling basin or previous section. Outflow per effective width from overland flow was solved through

iteration with a version of Manning's equation (Equation 2.27). Effective width was based on the slope, length of flow, and plant type. Effective width could be reset if a spreader for redistribution of flow was in place. Infiltration for the VTA was handled by the Green-Ampt method. Green-Ampt's parameters were changed as infiltration occurred to account for the four soil layers. The soil water balance included added infiltration/redistributions and subtracted percolation and evapotranspiration (ET). Infiltration is the same as the surface water balance. Redistribution is calculated if infiltration is not occurring and moves water from one layer to another. Percolation occurs if the water leaves the bottom of the soil layer. ET is the loss of water through plants and evaporation. ET is calculated with potential ET from the weather data with adjustments to plant type and availability of water. ET is removed only from the top layer. Constituent balance is a mass balance only with removal through infiltration.

$$v = \frac{1.5\sqrt{S}}{n} \left(\frac{s_p d}{2 * d + s_p} \right)^{2/3} \quad (2.27)$$

where, v is velocity (ft/s)

S is slope (ft/ft)

n is Manning's number

s_p is plant spacing

d is depth of flow (ft)

Miner's Lagoon Model

Miner et al. (1980) is a feedlot runoff and lagoon model with daily time steps. It simulates the transport and fate of organic-N, ammonium-N, and P. The decay rate models are mostly first-order rate models. The model was calibrated in eastern Illinois for a summer. Algorithms will be discussed further in the with the lagoon module in Chapter 3. Miner et al. (1980) represents a complete constituent balance for a lagoon system.

CHAPTER 3 - Model Design

The CAFO model for the state of Kansas is programmed in C language. The model is designed to run in five-minute time steps with the exception of the lagoon portion. The model simulates the transport of water, sediment, organic-N, ammonium-N, P, and COD. It is designed in a modular nature with each structure being a stand-alone executable component. The modular nature allows the user to link different treatment components together. Also, the modular nature allows the user to change the design of a component without having to rerun any of the components upstream of it. The model contains modules to simulate a feedlot, settling basin, VTA, and lagoon. Also, two support modules are used. The Hyetograph module converts the daily rainfall into a five-minute hyetograph. The Soil module is designed to estimate soil properties for the VTA and convert the properties into the correct format. Daily precipitation (in.); solar radiation (lg/day); grass reference ET (in.); average wind speed (mph); maximum, minimum, and dew point temperature (°F) are the weather data required to run the simulation.

Models Basic Algorithms

The model uses the same basic algorithms for calculating the water balance including the settling basin outflow, VTA overland flow, VTA outflow from redistribution structures, and lagoon and settling basin current water depth. The basic algorithms are Manning's equation, weir flow, orifice flow, lagoon volume and depth. These algorithms are used for calculating flow rates (Manning's, weir and orifice) or water storage (lagoon volume and depth).

Manning's Algorithm

Manning's algorithm calculates the flow rate in cfs based on Manning's equation. This algorithm is used for open channel and overland flow. The model uses Equation 3.1 for determining flow rate from Chow (1964).

$$Q = \frac{1.50}{n} A(s)^{0.5} (R)^{2/3} \quad (3.1)$$

where, Q is flow rate (cfs)

n is Manning's roughness

A is area (ft²)

s is slope (ft/ft)

R is hydraulic radius (ft) = area/wetted perimeter

Weir Algorithm

The weir algorithm calculates the flow rate of water through a broad- or sharp-crested rectangular weir. The algorithm can represent either weir by changing the discharge coefficient. Flow rates are based on Equation 3.2 with a discharge coefficient C_d of 3.00 for a broad-crested weir and 3.33 for a sharp-crested weir (Chow, 1964).

$$Q = C_d L (d)^{3/2} \quad (3.2)$$

where, Q is flow rate (cfs)

C_d is discharge coefficient

L is the weir length (ft)

d is depth above weir (ft)

Orifice Algorithm

The orifice algorithm calculates flow rate through a circular orifice. The discharge is modeled when a small opening becomes submerged by water using Equation 3.3 (Chow, 1964).

$$Q = C_d A \sqrt{2gH} \quad (3.3)$$

where, Q is flow rate (cfs)

C_d is discharge coefficient (0.60)

A is cross-sectional area of the orifice (ft²)

g is gravitational acceleration (32.2 ft²/s)

H is hydraulic head (ft)

Lagoon Volume Algorithm

The lagoon volume algorithm calculates the lagoon's or basin's volume. The volume is a 3-D shape with two similar rectangles on the top and bottom connecting the sides with trapezoids of equal slopes. The volume formula is Equation 3.4.

$$V = lwd + (l + w)sd^2 + \frac{4}{3}s^2d^3 \quad (3.4)$$

where, V is volume (ft³)

l is smaller rectangle's length (ft)

w is smaller rectangle's width (ft)

d is depth (distance) between two rectangles (ft)

s is side slope (run to rise)

It was derived by adding the volume of the rectangular prism formed by the smaller rectangle (Equation 3.5a), two-sided triangular prism adjacent to the length and width (Equations 3.5b and 3.5c), and four rectangular pyramids formed at the corners of the shape (Equation 3.5d)

$$V=lwd \quad (3.5a)$$

$$V=lsd^2 \quad (3.5b)$$

$$Vwsd^2 \quad (3.5c)$$

$$V=1/3s^2d^3 \quad (3.5d)$$

The different shapes are summed in Equation 3.6 and simplified to Equation 3.4

$$V= lwd+2(lsd^2)+2(wsd^2)+4(1/3s^2d^3) \quad (3.6)$$

Lagoon Depth Algorithm

Lagoon depth algorithm calculates the depth for the shape described in the lagoon volume algorithm for a given volume, length, and width. The algorithm calculates depth through iteration using Equation 3.4. Depth is started at zero and incremented up until the calculated volume is greater than the given volume. Then, depth is incremented down once and the incremental level is decreased by an order of magnitude. This is repeated until the desired iteration accuracy is reached. The iteration incremental level starts at 10 and stop with 10⁻⁶.

Snowmelt Algorithm

A snowmelt algorithm is utilized in all modules except the lagoon module. The NRCS National Engineering Handbook (Van Mullen and Garen, 2004) divides snowmelt procedures into a degree method and an energy balance method. The degree method uses the difference between average daily temperature and a base value temperature times a coefficient. This coefficient can range from 0.035 to 0.13 in./°F depending on location and time of year (Van Mullen and Garen, 2004). The second approach is the energy balance method. Van Mullen and Garen (2004) recommend the energy balance developed by the US Corps of Engineers for the HEC-1 model. The equations listed in the Handbook are for areas that are heavily forested. The energy based method was selected for this model because it accounts for solar radiation and wind within it. The Corps of Engineering (1998) snowmelt is an energy balance that has different formulas depending on the percent forested and if rainfall occurs. For the purpose of this model, the open area with less than 10% tree cover was selected. This is assumed because the feedlot, VTA, settling basin and lagoon should have few if any trees on them. The Corps of Engineering (1998) snowmelt equations only calculate daily amount based on daily temperature. The amount melted in each five minutes was determined by determining the temperature over the course of the day for each 5-minute period with a sine wave peaking at 1 p.m.

Snowmelt replaces the hyetograph values when it is snowing or snow is on the ground. Precipitation is assumed to be snow when the day's average temperature is equal to or less than 32°F (0°C) or snow is on the ground (Koelliker et al, 1975). Snowmelt is calculated by the energy-based equations for open areas. Equation 3.7 is used when precipitation occurs and Equation 3.8 is used when no precipitation occurs. For Equations 3.7 and 3.8, the wind exposure coefficient k is set at 1.0 for an unforested plain, because it describes the assumed conditions of the CAFO. Also, the short wave melt factor k' is 1.0, because the land surfaces are assumed to be balanced facing north and south or gently sloping. The estimated cloud cover is assumed to be zero due to inability to obtain cloud temperatures. The snow surface temperature is assumed to be at freezing. The wind speed must be adjusted with Equation 3.9 (Corp of Engineers, 1998) because the wind speed provided in the weather dataset is measured at 3 m. For each

individual time step the air temperature is estimated with the sine curve (Equations 3.10) with the maximum temperature at 1 pm (Van Mullen and Garen, 2004).

$$M=(0.029+0.0084kv+0.007P)(T_a-32)+0.09 \quad (3.7)$$

$$M=k'(0.00508I)(1-a)+(1-N)(0.0212(T_a-32)-0.84) \quad (3.8)$$

$$+N(0.029)T_c+k(0.0084v)(0.22(T_a-32)+0.78(T_d-32))$$

where, M is snowmelt (in./day)

k is basin wind coefficient (1.0)

v is wind velocity at 15.2 m (mph)

P is precipitation (in./day)

T_a is air temperature at 3 m (°F)

I is solar intensity (lg/day)

T_d is dew point temperature (°F)

a is albedo

k' is short wave melt factor (1.0)

T_c is difference in cloud base and snow surface temperatures (°F)

N is estimated cloud cover expressed, decimal fraction (0)

$$CF=1.92Z^{1/6} \quad (3.9)$$

where, CF is wind adjustment factor

Z is measure height (ft)

$$T = \frac{T_{\max} + T_{\min}}{2.0} + \left(\frac{T_{\max} - T_{\min}}{2.0} \right) \sin \left(\frac{\pi}{12.0} (t - 7) \right) \quad (3.10)$$

where, T is time-step temperature (°F)

T_{\min} is daily minimum temperature (°F)

T_{\max} is daily maximum temperature (°F)

t is time (hours, 24)

To calculate the snowmelt in a 5-minute interval, the snowmelt model performs the following steps:

1. At beginning of day, daily running total of snowmelt is reset zero.
2. Rainfall for 5-minutes interval added to total snow depth.

3. Maximum daily snowmelt allowed calculated with Equation 3.7 or 3.8 with the average temperature used for air temperature.
4. Individual time-step temperature calculated with Equation 3.10.
5. Snowmelt for time-step calculated with Equation 3.7 or 3.8 with individual temperature used for air temperature. Snowmelt divided by 288 to convert from in./day to in./5-minutes.
6. Check that snowmelt and running total is less than maximum snowmelt. If not set snowmelt to maximum daily snowmelt remaining
7. Check that snowmelt is less than remaining snow depth. If not, snowmelt is set to the remaining snow depth.
8. Add snowmelt to running total and subtract snowmelt from snow depth.

Albedo Algorithm

Albedo must be calculated daily for snowmelt calculations. Albedo is the measurement of the portion of sunlight reflected and is needed for the snowmelt module (Corps of Engineering, 1998). The Corps of Engineer (1998) calculates albedo with an exponential decay with an experimentally-determined coefficient. This method was rejected because of the difficulty of determining the system. The albedo model algorithm is instead based on the procedure described in Wulf and Lorimor (2005) on a daily basis.

Wulf and Lorimor (2005) first determine the snow phase. Snow phase describes the current environmental conditions. Snow phases are designated as Phase 0, 1, and 2. Phase 0 occurs when snow falls on the ground with no snow on the ground at start of the day. The model switches from Phase 0 to Phase 1 when today's average temperature is above 32°F. Phase 0 changes back when today's and the previous two days' average temperatures are at or below 32°F. Phase 2 is for spring snows. Phase 2 occurs when snow is not on the ground at the start of the day, the temperature is below freezing, and the date is between April 1st and June 30th.

Second, albedo is calculated depending on the snow phase. Albedo is calculated in a similar manner for all modules, except the feedlot has different values. The livestock tend to cause albedo to decrease more rapidly. *For the discussion in albedo calculations, the feedlot module's changes in albedo numbers are shown in brackets.* Also, above

freezing is defined as any day with mean temperature above 32°F and below freezing is any day with mean temperature less than or equal to 32°F. The lower limit for albedo is 0.15 for the albedo of soil.

Phase 0

Phase 0 always occurs below freezing because of its definition. During Phase 0, albedo starts at 0.85 [0.85] and is reset to this value anytime precipitation is greater than or equal to 0.2 in. of water. If precipitation is less than 0.2 in. of water, the albedo is the average of yesterdays albedo and 0.85 [0.85] albedo for the precipitation weighted with the equivalent depth of water (Equation 3.7). When no precipitation occurs, albedo is reduced by 0.01 [0.25] per day, unless albedo is 0.45 [0.35].

$$albedo = \frac{(yesterdays_albedo)(snow_depth) + (0.85)(precipitation)}{snow_depth + precipitation} \quad (3.11)$$

Phase 1

Phase 1 albedo is dependent upon the temperature and amount of precipitation that occurs. If no precipitation occurs and the temperature is below freezing, then albedo is reduced by 0.03 [0.05] per day. When the temperature is above freezing and no precipitation occurs, albedo is reduced by 0.01 [0.025]. On days with average temperature below freezing precipitation is assumed to be snow, temperatures between freezing and 35.6°F (2.0°C) have a rain/snow mix and temperatures above freezing have rain. If less than 0.2 in.(5 mm) of precipitation occurs, albedo is averaged with yesterday (Equation 3.11) for snow, remains the same for rain/snow mixed, or is reduced by 0.05 [0.075] for rain. When precipitation is between 0.2 in. (5 mm) and 0.5 in. (13 mm), albedo is reset to 0.85 [0.85] for snow, reduced by 0.05 [0.075] for rain/snow mix, and reduced by 0.10 [0.125] for rain. Finally, any day with precipitation over 0.5 in. (13 mm), albedo is reset to 0.85 [0.85] for snow, reduced by 0.10 [0.125] for rain/snow mix, and is reduced by 0.15 [0.20] for snow.

Phase 2

Phase 2 represents snow that occurs in late spring. Albedo is reduced by 0.15 [0.20] for days above freezing regardless of amount of precipitation. Albedo is treated the same as Phase 0 when average temperature is below freezing and precipitation occurs. With temperatures below freezing and no precipitation, albedo is reduced by 0.03 [0.05]. For albedo in Phase 2, the minimum value is 0.22 [0.16].

Hyetograph Module

The hyetograph module is a support module designed to create synthetic storms based on daily rainfall amounts. The weather data in Kansas is mostly available in daily amounts. To run the model in 5-minute time-steps, the daily rainfall must be fitted to a design storm distribution. The hyetographs are created based on the NRCS type-II storm, since Kansas is located in the geographical area where the type-II storm best represents design storms (NRCS, 1989).

The module first prompts the user to open the weather and hyetograph files. The weather data is then imported one day at a time. If rainfall occurs, a hyetograph is generated. First, the duration of the storm is determined based on the rainfall amount. Table 3.1 shows the total maximum amount of rainfall allowed for each storm duration. The maximum amount is the storm size with a 2-year return period in central Kansas for the particular duration (Herschfield, 1961) (Frederick et al, 1977). Central Kansas was selected because it is at the center of the state. The 2-year return period was chosen, because the storm has a 50% probability of appearing in a given year.

Rainfall amounts for each 5-minute period are then calculated. Equation 3.12 is used to determine a unit hyetographs cumulative amount unadjusted for duration up to time for a 24-hour storm (Haan et al., 1994). Haan et al. (1994) provides an estimate of type II storm that can be easily calculated by the computer. The amount of rain for each time is found with Equation 3.13. Rainfall for the last 5-minute increment is the total rainfall minus the sum of all the previous rainfall amounts. This calculation ensures that errors due to rounding do not occur. Finally, the hyetographs are outputted to the hyetograph file. The module then inputs the next day's rainfall amount. Figure 3.1 shows hyetographs for a 1-in. and a 5-in. storm between 10 a.m. and 2 p.m.

Table 3.1. Total maximum rainfall amounts for each storm duration. Amounts are based on a 2-year return storm in central Kansas (Herschfield, 1961) (Frederick et al, 1977).

Storm Duration (hr)	Total maximum storm amount (in.)
0.5	1.39
1.0	1.61
2.0	1.85
3.0	2.01
6.0	2.30
12.0	2.63
24.0	infinite

$$c = 0.5 + \left(\frac{t - 12}{24} \right) \left(\frac{24.04}{2|t - 12| + 0.04} \right)^{0.75} \quad (3.12)$$

where, c is cumulative rain amount unadjusted for duration (in.)

t is time (hr)

$$r_t = \frac{(c_t - c_{t-5/60})P}{c_{end} - c_{start}} \quad (3.13)$$

where, r is rain amount (in.)

c is cumulative rain amount (in.)

P is total daily rainfall (in.)

t is current time step (hr)

t-5/60 is last time step (hr)

end is time at the end of storm (hr)

start is time at the start of storm (hr)

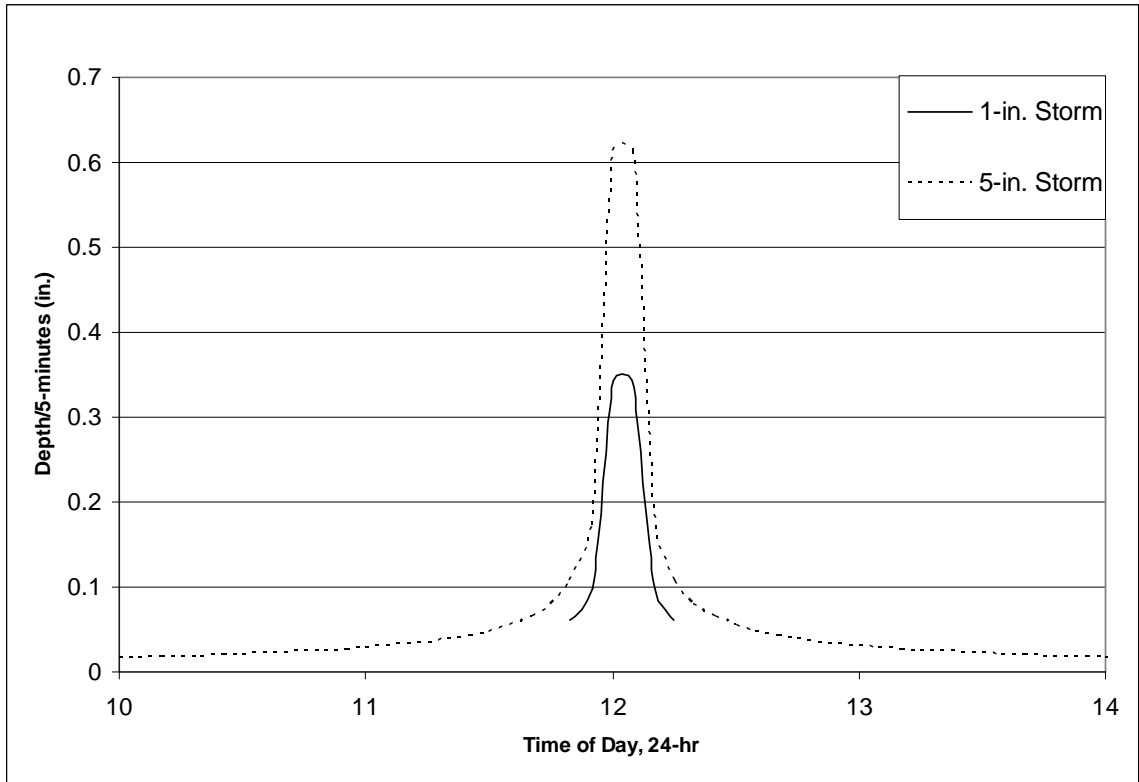


Figure 3.1. Example of hyetographs for a 1-in. and 5-in. storm between the hours of 10 a.m. and 2 p.m.

Feedlot Module

The feedlot module is designed based on the Koelliker et al. (1975) model, except with 5-minute time steps and constituent concentrations. The module outputs the hydrographs to an outflow file. This file can then be used as the inflow file for the next module down stream of the feedlot. For the outflow file, outflow is defined as the runoff from the feedlot, and overflow is nonexistent. The module performs the following tasks to generate the outflow module:

1. Ask user input data
2. Generate unit hydrograph for the feedlot
3. Compute antecedent moisture content
4. Determine rainfall excess
5. Calculate hydrograph
6. Calculate constituent balance and runoff concentration

User Inputs

The user inputs for the feedlot are the data necessary to calculate runoff. The user is prompted with a series of questions asking for information. The feedlot length and width (ft) are requested. Width is assumed to be perpendicular to the slope. The slope in percent is used to calculate peak flow. Longest length (ft) is the longest path that the water must travel to the outlet of the feedlot and is used to determine the travel time of the feedlot. The module asks for the percent of the feedlot that is surfaced (concrete) and with impervious (roads and roofs). The surfaced feedlot is separated from the impervious areas, because the curve number for the surfaced is different from the impervious area according to Koelliker et al. (1975). A weighed curve number is calculated from this information. For the constituent balance, the module needs the type of animals, average weight (lb), number of animals, entering date, and exiting date. This set of information can be enter up to three times to allow for different animal groups and packing rates in the feedlot either at the same time or during different times of the year.

For determining the removal of manure and pollutants from the feedlot by scraping, a scraping schedule is needed. The user has the option to use the default settings or input their own. The following are the three scraping schedule options:

1. Scrape after a user-specified number of days of operation
2. Scrape on certain days of the week
3. Scrap on certain days of the year (up to 7)

The efficiency of scraping removal is defined by the user as a decimal. If total rain in the past 5 days exceeds a user-defined threshold, then the module can perform the following options:

1. Wait 1 week before scraping
2. Skip scraping for this period
3. Continue scraping at a lower efficiency defined by the user

Finally, the file directory location of the weather and hyetograph data files are needed along with the directory location to save the feedlot outflow data file.

Unit Hydrograph

The unit hydrograph for the feedlot is created using the NRCS unit hydrograph method. This is performed at the beginning of the program. A unit hydrograph is the flow rate at the outlet of a watershed (feedlot) at different times from 1.00 inches of rainfall (rainfall excess) occurring in a 5-minute period. First, Equation 3.14 is used to calculate the time of peak discharge (Snider, 1972). The curve number is taken for antecedent moisture condition (AMC) II. The same hydrograph is used for both AMC II and III. The peak discharge time is then rounded to the nearest 5-minute interval with a minimum value of five minutes, so the peak discharge will occur within a time period. Next, an array is dynamically created to hold the feedlot and peak discharge is calculated. Equation 3.15 is used for peak discharge (NRCS, 1989). The 60 and 640 are for unit conversions of area to square miles and time into hours.

$$T_p = \frac{D}{2} + 60 \left(\frac{L_t^{0.8} (S+1)^{0.7}}{1900\sqrt{Y}} \right) \quad (3.14)$$

where, T_p is time of peak discharge (min)

D is storm duration (5 min)

L_t is longest flow path length for the feedlot (ft)

S is maximum potential abstraction of rainfall (in.)

$S = \frac{1000}{CN} - 10$ for curve number CN

Y is slope in percent

$$q_p = 484 \left(\frac{60A}{640T_p} \right) \quad (3.15)$$

where, q_p is peak discharge (cfs)

A is area (acres)

T_p is time of peak discharge (min)

Finally, the unit hydrograph is created by calculating the flow rate with Equation 3.16 for 5-minute intervals between time zero to five times the peak discharge time (Haan et al., 1994). This interval is consistent with the NRCS unit hydrograph (NRCS, 1989). Equation 3.16 is an approximation of the NRCS unit hydrograph. Figure 3.2 shows the differences between Haan's approximation hydrograph and the NRCS design unit

hydrograph. Although Haan et al. (1994) approximation is slightly different; it is used because the equation can be computed. Because the peak discharge time is rounded to the nearest five-minute interval, the hydrograph may not be an exact unit hydrograph (amount of runoff for 1.00 in. over the watershed area). The peak discharge is adjusted and amounts are recomputed until a unit hydrograph is created within 10^{-6} . This unit hydrograph is multiplied by the rainfall excess depth for a 5-minute interval to generate an individual hydrograph. Because the peak discharge time is rounded to the nearest five-minute interval, the hydrograph may not be an exact unit hydrograph (amount of runoff for 1.00 in. over the watershed area). The peak discharge is adjusted and amounts are recomputed until a unit hydrograph is created within 10^{-6} .

Then, the total discharge during each 5-minute interval is determined by summing the discharge rate from all individual hydrographs for each particular 5-minute interval. More details about the calculations of the total discharge are described in the next section.

$$q(t) = q_p \left(\frac{t}{T_p} \exp \left(1 - \frac{t}{T_p} \right) \right)^{3.77} \quad (3.16)$$

where, $q(t)$ is outflow for time t (cfs)

t is 5-minute interval

T_p is time of peak discharge (min)

q_p is peak discharge (cfs)

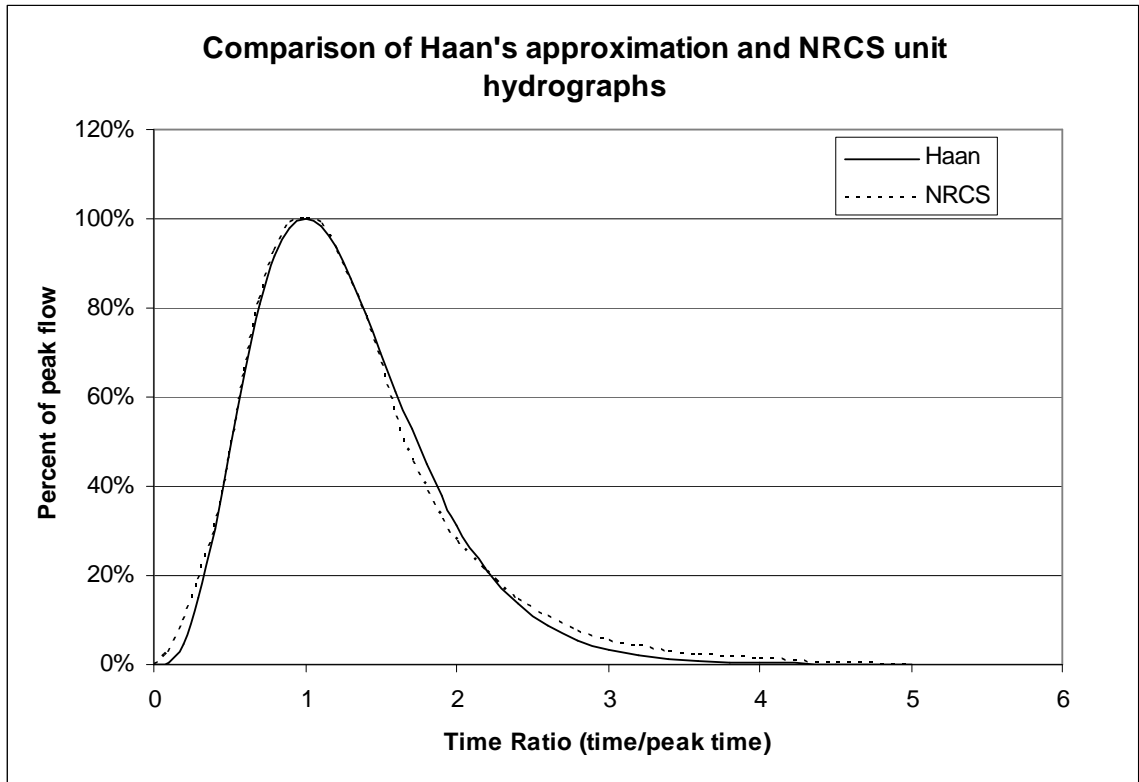


Figure 3.2. Comparison of Haan’s estimate and NRCS unit hydrographs

Individual Storm Runoff Events

Before calculating runoff from a storm, the following algorithms are run:

- Input daily weather data
- Reset running totals
- Determine AMC and daily curve number
- Calculate albedo for feedlot
- Perform constituent balance

The current AMC is determined by the amount of rainfall received in the past five days (Koelliker et al., 1975). AMC III occurs if five-day rainfall is greater than 2.11 in. between May and September and 1.11 in. for rest of the year, otherwise the storm is AMC II. Curve number for AMC II is the average curve number calculated from the user inputs. Curve number for AMC III is calculated with Equation 3.17 (Neitsch et al., 2005). The animals and manure are assumed to add enough moisture that AMC I is never reached.

$$CN_{III} = CN_{II} \exp(0.00673(100 - CN_{II})) \quad (3.17)$$

where, CN_{III} is curve number a AMC III

CN_{II} is curve number a AMC II

After the constituent balance is calculated, the module computes the storm runoff in 5-minute steps. The runoff is calculated with a process derived from Snider (1972) example for hydrographs. This process is used in Wulf and Lorimor (2005) for feedlot runoff. For each step, the modules inputs rainfall amount for the time step, determines rainfall excess, sums individual hydrographs, and outputs runoff and constituent concentrations to the outflow file. Rainfall amounts come from the hyetograph file and can be overridden by the snowmelt algorithm. Runoff depth for a time period is computed with Equation 3.18, which was derived Snider (1972). The runoff depth is the difference in runoff with NRCS curve number method between the current time period and the previous period. The NRCS algorithm is the curve number method (Equation 2.1) for precipitation amounts in the parentheses. The running total of rainfall is the sum of all rainfall between the start of the storm and the last time step. The difference in the curve number method is used to account for the affects of the soil retention factor on rainfall.

$$\begin{aligned} e_t &= NRCS(R_t + P) - NRCS(P) \\ P &= P + R_t \end{aligned} \quad (3.18)$$

where, e_t is depth amount in time t (in.)

R_t is rainfall from time t (in.)

P is running total of rainfall

NRCS(x) is Equation 2.1 with x beginning rainfall depth

Next, the runoff depth is multiplied by the unit hydrograph to yield a hydrograph for that time period's runoff. Because the hydrograph spans multiple time steps starting with it own, a time step can have several overlapping hydrographs. All the overlapping hydrographs that outflow for a particular time step are summed together to yield the total runoff flow rate. This is accomplished in the model by utilizing two arrays. One array stores the unit hydrograph flow rates and the other holds the runoff depths. When a new runoff depth is calculated, the runoff array shift all cells in the array forward one with the first cell equal to the current runoff depth (Equation 3.19a). Next, the multiple runoff and

corresponding hydrograph cells are summed together (Equation 3.19b). Runoff amount is written to outflow files as outflow. There is no overflow for the feedlot. If snow is present on the feedlot during the day, the snow flag is set to 1 on the outflow file, else snow flag is zero. This is used for lagoon module.

$$d_i = d_{i-1} \text{ for } i > 1, \text{ otherwise } d_1 = r \quad (3.19a)$$

$$\sum_{i=1}^{lastcell} d_i h_i \quad (3.19b)$$

where, d_i is runoff depth for cell i

r is runoff excess

h_i is unit hydrograph for cell i

Constituents' Model

The constituents' balance and runoff concentrations are based on the AnnAgNPS model (Baker, 2005). Constituents include of N and P plus COD. When evaluating constituents in runoff models, two main algorithms were used frequently. The first was the feedlot runoff amounts found in AgNPS. The second was the field runoff used by EPIC/APEX, SWAT and partially by CREAMS (see Chapter 2). For the EPIC model, constituents in runoff are modeled for organic N, nitrate-N, and P. This model was rejected because of the lack way for ammonium-N and COD to be account for in the runoff. The AgNPS feedlot model was selected because it was specifically designed for feedlots and accounts for ammonium-N with its total N. EPIC algorithm ignores ammonium-N runoff and concentrates on nitrate-N. For feedlots, ammonium-N is expected in higher concentrations than nitrate-N (ASAE, 1999). For the actual model, the AnnAgNPS feedlot component developed by Baker (2005) was modified for this model.

Figure 3.3 shows the flowchart of the constituents' balance for the feedlot module. Constituents are added each day to the total based on if the animals are present for that day as determined by the entrance and exist dates. The amounts of constituents are calculated with Equation 2.3 and values from Table 2.2. Sediment added is calculated in a similar manner, but with Table 3.2.

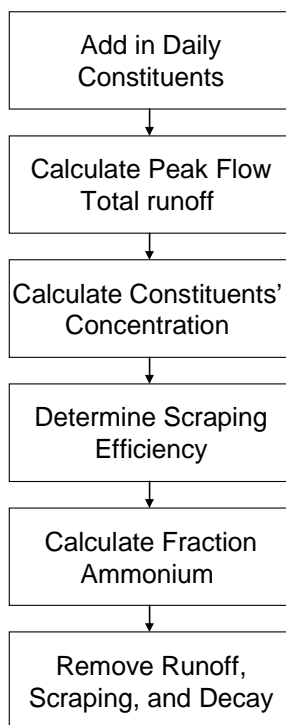


Figure 3.3. Flowchart of constituents' balance for feedlot module (constituents also include sediment for the flowchart).

Table 3.2. Estimate amounts of solids from animals types (ASAE, 1999).

Animal	Total Solids (kg/kg-animal/day)
Dairy	0.012
Beef	0.0085
Veal	0.0052
Swine	0.011

Next in Figure 3.3, peak flow and total runoff are calculated the same way for individual storms by finding the largest flow rate. Constituent concentrations are calculated with Equation 2.12 for N, P, and COD. Sediment runoff is calculated with MUST from Equation 2.23. There is several USLE-derived sediment erosion models, but MUST is designed for manure runoff. The slope length factor is calculated with Equation 2.18. Practice factor is assumed to be 1.0 indicating there are no contours or other erosion controls practices on the feedlot. The amount of plants is set to zero to conform to the definition of a CAFO. Scraping efficiency is the user-specified value if

scraping should occur based on schedule options described in user input section. Ammonium-N fraction will be discussed in below. Decay only occurs for organic carbon/COD with Equation 2.13. The losses due to runoff, scraping and decay are removed from the constituents' balance. Scraping is assumed to have no enrichment ratio and all constituents and sediment are removed with the same rate. The concentrations of constituents are constant for a day, but it is possible that hydrographs for two days can overlap at the beginning of the second day. If this occurs, the concentrations are the average concentration for both days weighted with runoff flow rates.

The fraction of ammonium-N is the percent of the total-N that is assumed to be ammonium-N. AgNPS does not separate species of N, but organic-N can behave differently than ammonium-N in some of the systems. Nitrate-N is assumed to be zero due to the low levels of nitrate produced by the animals and on manure-laden surfaces (ASAE, 1999). The calculation of ammonium-N fraction comes from the Miner et al. (1980) model. In that model, N is calculated similar to AgNPS with only total-N given in the runoff. To account for the ammonium, fraction of ammonium is calculated and subtracted from the total N. The feedlot module performs calculations for fraction of ammonium-N using Equation 3.20. This fraction is multiplied by the concentration of N to get ammonium-N concentration. The remaining N is considered organic-N. In Equation 3.20, the lot temperature is the last five days temperature (Equation 3.21), lot moisture is amount of water on lot (Equation 3.22), and lot moisture capacity is 100 mm for earthen and 50 mm for concrete.

$$F = 0.4 \left(10^{0.018T_s - 0.38} \frac{LM}{LMHC} \right)^2 \quad (3.20)$$

where, F is fraction ammonium-N

T_s is lot temperature (°C)

LM is lot moisture

LMHC is lot moisture capacity

$$T_s = \frac{5T_1 + 4T_2 + 3T_3 + 2T_4 + T_5}{15} \quad (3.21)$$

where, T_s is lot temperature

T_i is daily average temperature for *i*th previous day

$$LM = LM_y + P - R + ET \quad (3.22)$$

where, LM is lot moisture

LM_y is yesterday's lot moisture

P is yesterday's precipitation/snowmelt

R is yesterday's runoff depth

ET is yesterday's evaporation amount.

Basin Module

The basin module is designed to simulate transport and removal of constituents through a settling basin. Constituents are removed through settling and ultimately transport out of the basin. The module runs on five-minute time steps. Figure 3.4 shows the flowchart of basic components of the settling basin. User inputs and stage discharge are performed once, while water balance and constituents' removal are calculated every five minutes.

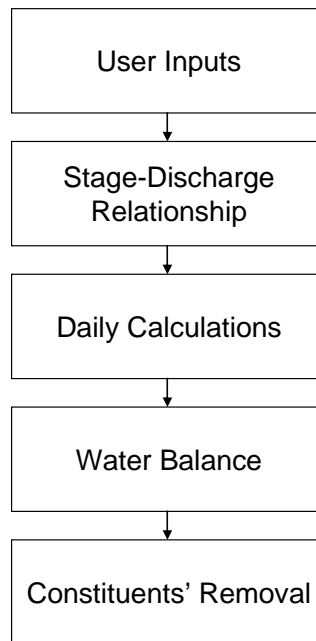


Figure 3.4. Flowchart of basin module basic components and order of processing.

User Inputs

Inputs needed from the user include the length and width at the top of the settling basin along with the total depth all in feet and the side slopes and seepage rate along with

the location of the weather, hyetograph, and inflow data files. The inflow file also asks if outflow or overflow of the previous structure should be used as inflow. Finally, the directory location where the outflow file is to be written is needed.

Stage-Discharge

Outflow and overflow from the system can be computationally-intensive depending on the outflow structure. To minimize the module run time, a stage-discharge array is created at the beginning. The array holds values of the discharge in 0.1-ft increments to a maximum height of 2 ft above the top of the basin. The outflow structure inlet can have either a horizontal pipe or a two-stage vertical riser. The outlet from the structure can either be a simple pipe or irrigation pipe. Overflow is handled by overtopping the basin or through a broad-crested weir. For each stage, the inlet and outlet parts are checked to determine which one is limiting. The limiting part is the one with the lower flow rate. Each structure requires different user-specified information. Discussion on each structure's inputs and flow rate calculations are found in the following paragraphs. The user can also input a stage-discharge table from a file. The file requires three columns, depth (ft), outflow (cfs), and overflow (cfs) in that order. All options ask for the length of pipe, change in elevation between the bottom of the basin and the outlet, and the number of 90°- and 45°-bends. Manning's number for the pipe in the outflow system can be selected from lists of materials in Table 3.3 or specified by the user (Schwab et al., 1993).

Table 3.3. Manning's numbers for selected materials (Schwab et al., 1993)

Material	Manning's n
Concrete	0.014
Corrugated Plastic (Diameter < 12 in.)	0.017
Corrugated Plastic (Diameter ≥ 12 in.)	0.020
Smooth Plastic	0.009
Corrugated Metal	0.025

A horizontal pipe inlet assumed to be at the bottom of the basin requires no additional inputs. For stages smaller than the diameter of the pipe, flow rate is calculated

as a broad-crested weir (Equation 3.2) with weir depth equal to the stage and weir length equal to the cross-sectional area of water divided by depth of the water. This is a rough estimate of flow to represent the low flows where water volume can become limiting. Also, Manning's equation (Equation 3.1) is checked with area and wetted perimeter equal to cross-sectional area and wetted perimeter covered by water and slope equal to change in elevation/pipe length. The area and wetted perimeter for a circular area are shown in Equation 3.23a and b. Equation 3.23a and b were derived from basic geometry. For stages above the pipe diameter, flow rate is calculated by orifice flow (Equation 3.3) with area equal to the cross-sectional area of pipe and depth equal to stage minus half the diameter of pipe. The depth comes from the average water depth for the pipe orifice.

$$P = 2R \cos^{-1} \left(\frac{R-d}{R} \right) \quad (3.23a)$$

$$A = R^2 \cos^{-1} \left(\frac{R-d}{R} \right) + 2(d-R) \sqrt{R^2 - (d-R)^2} \quad (3.23b)$$

where, P is wetted perimeter (ft)

A is area (ft²)

R is radius (ft)

D is depth (ft)

A diagram of the two-stage riser is shown in Figure 3.5. Additional user-inputs required are orifice height, width, depth, and riser height and diameter. Riser diameter is not necessary the same as pipe diameter. Flow rate is the combination of the two stages and assumes the two stages do not interfere with one another's flow rates. For the first stage, flow rate is divided into three possibilities. The first possibility is that the stage is below orifice height and flow rate is zero. Second possibility is stage is between orifice height and orifice height plus depth and sharp-crested weir flow is occurring (Equation 3.2) with length equal to orifice width and depth equal to stage minus orifice height. The third possibility is stage is completely covering the first-stage and flow rate is orifice (Equation 3.2) flow with area equal to orifice width times depth and depth equal to stage minus orifice height minus half of orifice depth. For the second stage, no flow occurs if stage is below the riser height. Stages above riser depth have two possibilities. Stages just over the riser behave like a sharp-crested weir (Equation 3.3) with depth of stage

minus riser depth and length is the circumference of the riser. As the stage increases, the second stage acts as an orifice with the depth equal to the total depth minus riser height and area equal to the cross-sectional area of the riser. Both weir flow and orifice flow are calculated and the smaller one is the second stage's flow rate. Sharp-crested weirs are assumed because the riser should have a relative's small edge width.

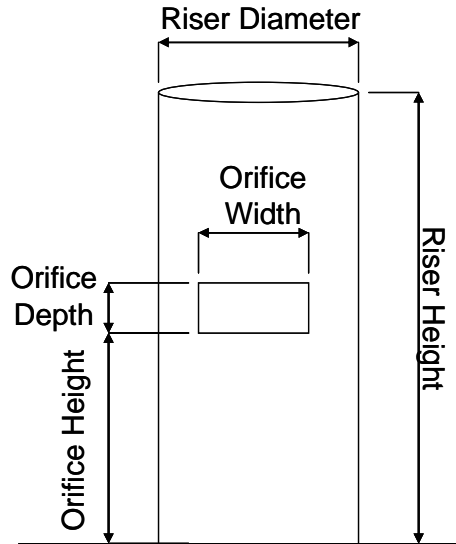


Figure 3.5. Diagram of the two-stage riser used as inlet to outflow structure.

Outflow from a normal pipe requires no extra inputs. Equation 3.24 is used for the calculation of the pipe discharge (McCuen, 2005). This is the basic equation for pipe flow assuming the inlet is a sharp edged. Friction loss for bends and the pipe are computed with Equation 3.25 (McCuen, 2005). Normally,

$$Q = A \sqrt{\frac{2gh}{1+f}} \quad (3.24)$$

where, Q is flow rate (cfs)

A is cross-sectional area (ft²)

g is gravitation acceleration (32.2 ft/s²)

h is head (stage+elevation) (ft)

f is friction loss

$$f = n \frac{(90b_{90} + 45b_{45})}{3} + \frac{5100Ln^2}{d^{1.33}} \quad (3.25)$$

where, f is friction loss factor for English units

n is Manning's numbers

b is number of 45° and 90° bends

L is length of pipe (ft)

d is diameter of pipe (in.)

The irrigation pipe outlet allows the user to simulate using a flood irrigation pipe with 1-in. orifices spaced 30 inches apart. This is one possible way to spread water over an entire VTA width. The required input is the length of irrigation pipe and slope of irrigation pipe. A minimum slope of 0.5% is required to allow for drainage. The orifices are assumed to be near the bottom of the irrigation pipe. To solve the flow rate from the pipe requires knowing the head at each outlet, which is dependent on the friction loss between each orifice. Friction loss is dependent on the flow rate of the pipe. This causes a circular logic that can be solved with iteration and some assumptions. The known conditions of the system are the head at the inlet is the depth of water in the basin and flow rate in the pipe after the last orifice is zero. With these two conditions, a solution can be found by adjusting the flow rate at the inlet until flow rate after the last orifice is zero. Iteration is done in a similar manner to the lagoon depth calculations. Assumptions made are that velocity is the average velocity through the full pipe. Also, friction loss between two orifices is constant, and friction loss caused by flow through each orifice is negligible. Also, when the head in the pipe is less than the diameter, channel flow is assumed to take over and is determined with Manning's equation. This is the reason for requiring a slope with the irrigation pipe. Manning's equation must also be solved by iteration.

The procedure for calculating the flow rate for the irrigation pipe is as follows:

1. Increase the initial flow by one increment and set total flow to initial.
2. Calculate total head at first orifice with Equation 3.26 (McCuen, 2005)
3. If total head minus velocity head is greater than zero (pipe flow), then
 - a. Subtract flow through one 1-in. orifice (Equation 3.3) from total flow
 - b. Depth for orifice is the total head at the orifice
 - c. Subtract friction loss between this and the next orifice from total head (Equation 3.27)
4. Else pipe is no longer pressurized and Manning's equation takes over
 - a. Calculate depth of flow through iteration similar to lagoon depth

- b. Stop iteration when Manning's flow rate equals total flow rate (Equation 3.1)
 - c. Area and wetting perimeter for Manning's equations are shown in Equation 3.22
5. If total flow is greater than zero and not at the end of the pipe, then go to Step 3
 6. If total flow is less or equal to zero, then go to Step 1
 7. Else decrease initial flow by one increment and decrease increment by an order of magnitude
 8. Repeat procedure with the new increment if increment is greater than 10^{-7}
 9. Otherwise, return initial flow rate as irrigation flow

$$h_1 = s + e - 0.5 - \frac{n\theta}{3} - n^2 \left(\frac{q_i}{\pi r} \right)^2 \frac{L}{2.22r^{1.33}} \quad (3.26)$$

where, h_1 is head at first orifice (ft)

s is stage (ft)

e is elevation change (ft)

0.5 is friction loss due to inlet

n is Manning's number

q_i is initial flow rate (cfs)

r is radius of pipe (ft)

L is length of pipe from inlet to first orifice (ft)

θ is total angles of all bends ($^\circ$)

$$h = h - n^2 \left(\frac{q}{\pi r} \right)^2 \frac{L}{2.22r^{1.33}} + Ls \quad (3.27)$$

where, h is head (ft)

n is Manning's number

q is pipe flow rate (cfs)

r is pipe radius (ft)

L is length between orifices (2.5 ft)

s is slope of irrigation pipe (ft/ft)

If a weir is used for overflow the user must input the depth of weir from the top of the basin and length of the weir. Flow rate is calculated assuming a broad-crested weir

(Equation 3.2) with length of weir and depth of stage over the weir. If the stage is above the depth of the basin, overflow adds flow rate from the broad-crested weir (Equation 3.2) with length equal to the width of the basin and depth is stage above the top of the basin.

Water Balance

After albedo is calculated and sediment removed, the basin module performs the water balance in five-minute intervals. Figure 3.6 is a flowchart of the procedure. Basin depth and water depth are calculated with the lagoon depth algorithm. Surface area is computed with Equation 3.28.

$$A = (l + 2sd)(w + 2sd) \quad (3.28)$$

where, A is surface area (ft²)

l is bottom length (ft)

w is bottom width (ft)

d is basin depth (ft)

s is side slopes (s:1)

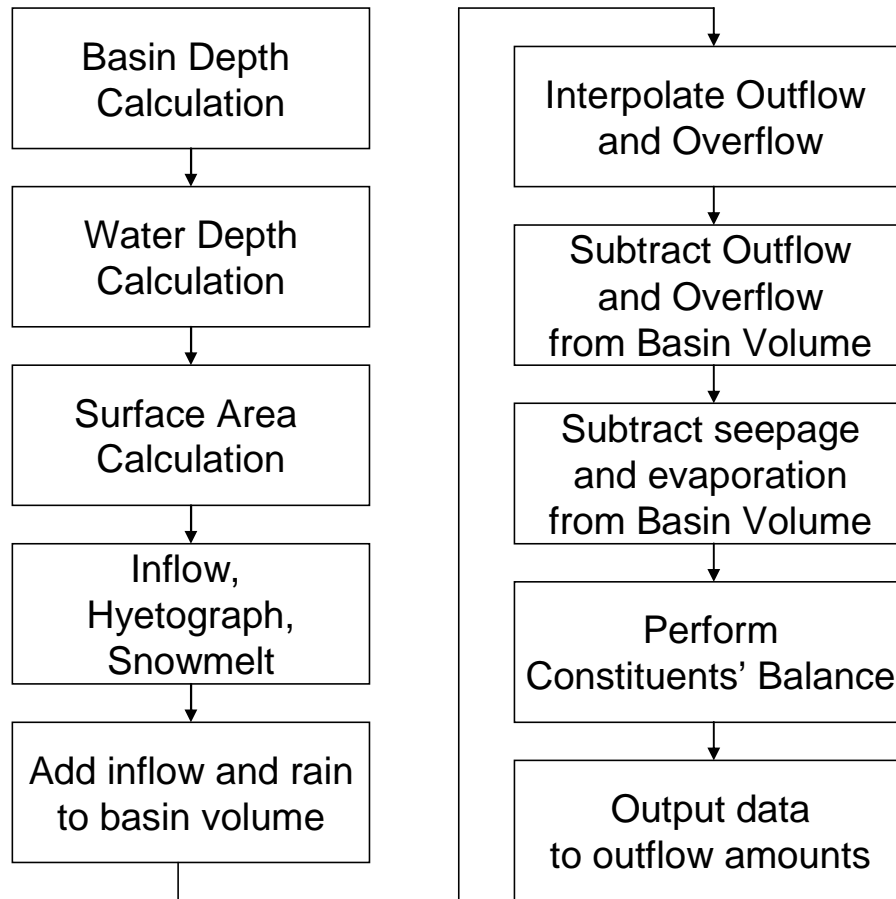


Figure 3.6. Flowchart of settling basin module five-minute time steps procedure.

Inflow and rainfall are added to the system. Rainfall depth is converted to volume using the surface area at the top of the basin. The snowmelt model overrides the rainfall. Due to limitations of the snowmelt algorithm, the assumption that water does not melt due to inflow water must be made. If there is snow in the basin, then the inflow water is snowmelt, too. This water should be close to freezing. Also, if runoff occurs, mostly rainfall has also occurred, so the rain should have already affected the snowmelt. For these two reasons, the assumption is believed to be correct.

Outflow and overflow are linearly-interpolated from the stage-discharge array calculated at the start of the model. The basin depth is used for stage calculations. The sediment adds volume to the water, and raises the stage of the basin. Outflow and overflow are adjusted if the volume of water is limiting. This is done to ensure that the water balance is accurate. Both outflow and overflow are subtracted from the basin. Next, the seepage and evaporation for five-minute periods are subtracted from the water volume. If the water volume is limiting, then seepage and evaporation are adjusted

proportionally to their removal rates. Outflow and overflow assumes that depth of water remains constant for the time step, because the basin retention time should be greater than five minutes and outflow represents a fraction of the total volume. Seepage rate is a user-defined input and evaporation is estimated from the daily ET values. Both use the current surface area for volume calculations. Finally, the constituent balance is performed and data is outputted. The outflow snow flag is set to follow the inflow snow flag. At end of the outflow file, the total water and constituent losses are printed out as user information.

Constituent Balance

At the beginning of the day, sediment settled from inflow water can be removed based on the solid-removal schedule. This schedule is different from the feedlot, because the user has no control over the schedule. Removal of solids occurs on the first day after the beginning of the month to meet the following conditions:

- No snow on feedlot
- Average daily temperature above freezing
- Seven days have pass since the last rainfall event

Removal efficiency of sediment and all constituents are assumed to be 95% of the amount settled. This assumes an enrichment ratio of one, which is probably accurate given the percentage of sediment removed from the basin.

For the 5-minute constituent balance, the basin has two pools. One is the water suspended and the other is the settled pool. Water suspended is the only pool that can discharge constituents. The settled pool is assumed never to resuspend constituents. The procedure for constituent balance is the following:

1. Add constituents and sediment from inflow into the water pool
2. Calculate constituents and sediment settled
3. Subtract settled constituents from water pool and add to settled pool
4. Calculate outflow and overflow masses with Equation 3.29
5. Subtract outflow and overflow masses from the water pool
6. Divide constituent masses by outflow and overflow volume to get concentration

$$x_o = x_v \frac{300(out + over)}{300(out + over) + V} \quad (3.29)$$

where, x_o is mass of constituent outflow and overflow

x_v is mass in water pool

out is outflow (cfs)

over is overflow (cfs)

V is water volume at the end of the day (ft^3)

Removal of sediment and constituents is through the settling of solids out of the water. The removal rate of the solids is dependent on the flow and settling velocity. Figure 3.7 shows the process by which solids can be settled from water. Assuming the particles are evenly distributed at the beginning of the basin, then the particles near the bottom should be the first to settle out. As time passes, Figure 3.7 shows that almost all the particles settle out of the water. The percent of solids settled is dependent on the settling time (settling velocity time depth) and retention time of the basin. This is an idealize form without turbulence and resuspension.

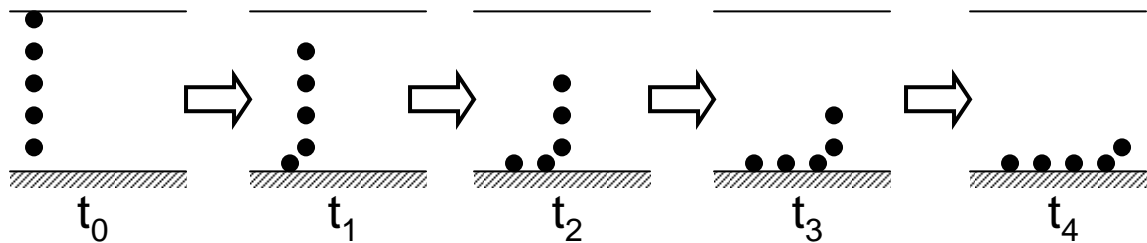


Figure 3.7. Process of settling for solids in water as move through time.

The actual removal rate of the system is modeled with the removal rate formula developed by the EPA (1986) for a detention/settling basins in Equation 3.30. The efficiency factor, n , depends on the basin design with larger n for better systems. EPA (1986) describes $n=1$ as poor and $n=2$ as average. For this work, the settling basin module is assumed to be average structure design with $n=2$. Volume of water is the amount of water at the start of the time period. Flow rate is outflow and overflow summed together. Settling velocity is computed with Stokes' Law (Equation 3.31a) or Rubey-Watson's Law (Equation 3.31b) (Warner, 2006). According to Warner (2006) Rubey-Watson's Law corrects for drag forces experienced with larger particles ($>0.2mm$) than Stokes' Law. For purposes of this modeling, settling velocity for particle diameters greater than 0.2 mm is computed with Rubey-Watson's Law. The model assumes water

density is 1,000 kg/m³ and particle density is the same as for soil particle density of 2,650 kg/m³ (Maidment, 1995). Estimated dynamic viscosity is calculated with Equation 3.32 from Maidment (1995). Equation 3.30 was modified to work with the basin module's time steps. The EPA removal rate method is designed to estimate removal for the entire of the retention time of the basin. However, the 5-minute time step is usually shorter than the retention time, so the Equation 3.30 has an extra component x. If the retention time (flow rate/volume) is less than five minutes x=1, otherwise x=5 minutes/retention time. Table 3.4 shows the amount remaining in time for different time intervals. As seen in Table 3.4, at 20 minutes the amount remaining is still the same amount.

$$R = 1 - \left(1 + n^{-1} \frac{v_s V}{qd} \right)^{-nx} \quad (3.30)$$

where, R is fraction of solids removed

n is efficiency factor (n=2 for average)

v_s is settling velocity (ft/s)

V is volume (ft³)

q is flow rate (cfs)

d is water depth (ft)

x modification for module's time period

$$v_s = \frac{(\rho_s - \rho)gd^2}{18\mu} \quad \text{for } d \leq 0.2 \text{ mm} \quad (3.31a)$$

$$v_s = \frac{-1.87\mu + \sqrt{3.48\mu^2 + 0.0884\rho g(\rho_s - \rho)d^3}}{0.256d\rho} \quad \text{for } d > 0.2 \text{ mm} \quad (2.31b)$$

where, v_s is settling velocity (m/s)

g is gravitational acceleration (9.81 m/s²)

μ is dynamic viscosity (kg/m/s)

d is particle diameter (m)

ρ is density of water (1,000 kg/m³)

ρ_s is density of particle (2,650 kg/m³)

$$\mu = 0.01(10)^{\frac{1301.0}{998.333+8.1855(T-20)+0.00585(T-20)^2}-1.30233} \quad \text{for } T \leq 20^\circ\text{C} \quad (3.32)$$

$$\mu = 0.001002(10)^{\frac{1.3272(20-T)-0.001053(T-20)^2}{T+105.0}} \quad \text{for } T > 20^\circ\text{C}$$

where, μ is dynamic viscosity (kg/m/s)

T is average daily temperature ($^\circ\text{C}$)

Table 3.4. Comparing time intervals for different time intervals.

Time (min.)	Amount remaining for Time Interval	
	5-minute	20-minute
0	100.0	100.0
5	94.3	
10	88.9	
15	83.8	
20	79.0	79.0

The actual procedure for determine settling is to divide the sediment into a particle distribution of beef cattle manure based on measurements from Chang and Rible (1975). Chang and Rible (1975) experimented with different manures to obtain percent of manure in different particle ranges. Also for each particle range, the percent of N, P, and crude fiber were measured. Fresh beef cattle manure was selected as the default because of the large number of beef CAFO in Kansas. Chang and Rible (1975) collected and measured 3 samples of fresh manure. Table 3.5 shows the diameter range; percent of manure for each range; and percent of N, P, and crude fiber. Crude fiber was converted to COD by assuming all the fiber was organic carbon and dividing by 2.67. This conversion factor was determined by dividing AgNPS runoff concentrations for COD (4,500 mg/L) by organic carbon (1,680 mg/L) (Young et al, 1987) (Baker, 2005). Table 3.5 also shows the diameter used for determining settling velocity. The minimum value was used for each range to represent a conservative estimate. For the last range, the largest diameter of clay was used as an estimate. All the N is assumed to be organic-N.

Table 3.5. Particle distribution for fresh beef manure, and percent of constituents for each of the particle ranges (Chang and Rible, 1975)

Particle Range (mm)	Percent of Total Manure	Settling Diameter (mm)	N (%)	P (%)	Crude Fiber (%)	COD (%)
>1.00	30.7	1.000	1.7	0.83	43.7	16.3
1.00-0.50	9.0	0.500	2.2	0.39	58.7	21.9
0.50-0.25	6.7	0.250	2.5	0.41	32.8	12.2
0.25-0.105	6.1	0.105	2.7	0.73	27.6	10.2
0.105-0.053	3.6	0.053	2.8	1.07*	16.6	6.2
<0.053	43.6	0.002	4.9	1.42	10.2	3.8

*No Value Recorded. Value is average of particle ranges above and below

The amount of sediment, COD, organic-N, and total-P removed is computed with the following procedure:

1. Calculate the fraction of sediment removed for each particle range (Equation 3.30)
2. Calculate total sediment, total-P, COD and organic-N removed with Equations 3.33 a and b.

$$Y_r = Y_T \sum R_i x_i \quad (3.33a)$$

$$N_r = Y_T \sum R_i x_i n_i \quad (3.33b)$$

where, Y_r is sediment removed

Y_T is total sediment in basin

N_r is COD, total-P or organic-N removed

R is removal percentage (Equation 3.30)

x is percent of total sediment (Table 3.5)

n is percent COD, total-P, or organic-N (Table 3.5)

i is particle range

3. If removed sediment is greater than the maximum sediment removed (Equation 3.34), then,

$$Y_{\max} = Y_T \left(1 - \left(\frac{1}{3}\right)^f\right) \quad (3.34)$$

where, Y_{\max} is maximum sediment removed

Y_T is total sediment in basin

f is detention factor, minimum value of 1 or $300/\text{retention time}$

- a. Removed sediment equals maximum sediment removed.
 - b. Removed COD, organic-N, and total-P are reduced by the same proportion as sediment removed.
4. If removed COD, organic-N, or total-P are greater than total in the basin, then the removed COD, organic-N, or total-P is equal to total amount times sediment removed divided by total sediment.

For the basin model, all of the N removed is assumed to be organic-N. The maximum sediment removed is based on KDHE Design Standards for Confined Feeding Facilities (2006). The settling basin maximum removal rate is set at 66.7% to match KDHE standard. In the design standards, the volume of sediment a lagoon must store is reduced by two thirds with a settling basin.

Lagoon Module

The lagoon module is designed to simulate the water and constituent balance in an anaerobic lagoon on daily time steps. The lagoon water balance is derived from Koelliker et al. (1975) and the constituent balance is based on Miner et al. (1980). The lagoon outflow file is a separate design from the feedlot, basin, or VTA modules outflows. A daily time step is used instead of the five minute because such a detailed outflow rate is not required.

User Inputs

The required inputs for the lagoon module are the lagoon's dimensions of top length, top width, depth with freeboard, and side slopes. The freeboard is set at two feet to match the Kansas freeboard requirement for earthen lagoon structures (KDHE, 2006). The module must also be given the starting depth, conservation depth, seepage rate, pumping rate and time, and any periods during the year when pumping can not occur. The starting depth is the depth of water at the beginning of the simulation, while the conservation depth is the depth below which the water can not be pumped. Seepage rate maximum value is 0.25 in./day (6.4 mm/day) because this is the maximum seepage rate allowed for lagoons not within a sensitivity groundwater area (KHDE, 2007). For

sensitivity groundwater areas, the maximum seepage rate is 0.10 in/day (2.5 mm/day) (KHDE, 2007). The periods when pumping can not occur are up to three specified by entering beginning and ending dates when the system should not pump out water. These periods should be considered in the design volume for additional storage can be provided for during these periods.

Allowed Pumping Days

Pumping of the lagoon can occur if all the following conditions are met:

- Feedlot has no snow on it
- Ground is not frozen.
- Average daily temperature is above freezing.
- Sum of previous three days rainfall is less than 0.05 in.
- Volume above conservation depth is greater than one day's pumping volume.
- Date is not during non-pumping periods

If all the above conditions are met, then pumping can occur on this particular day. Snow on the feedlot is determined with the snow flag in the input file with one indicating snow on the feedlot. Ground is frozen when today's and yesterday's average temperatures are below freezing and remains frozen until today's and the two previous day's average temperatures are above freezing. Pumping should never lower the lagoon volume below the conservation depth. This allows the user to set a minimum depth that can not be pumped below to maintain the liner, prevent the pumping of sediment, or other reasons the user may want.

Water Balance

The water balance is based on Koelliker et al. (1975) model, with some minor variations. The following is the daily procedure for performing the water balance:

1. Current depth of water is calculated with Lagoon Depth Algorithm.
2. Water surface area is calculated with Equation 3.28
3. Check if pumping of lagoon water is allowed (see above)
4. Remove pumping volume from total volume

5. Add inflow to total volume
6. Add rainfall to total volume
7. Remove seepage and evaporation volume from total volume
8. If total volume exceeds that lagoon volume, then excess volume of water is overflow (overflow = total volume – lagoon volume)
9. Perform constituent balance

The water balance is simply the inflow minus outflow equals change in storage. The pumping volume is the pumping rate times pumping time. Rainfall was altered from Koelliker et al. (1975) model, so the depth of water for rain that lands on the exposed area (total area – water surface area) are computed with the NRCS curve number method for impervious surface (curve number = 98). Equation 3.35 shows the calculations of rainfall volume. This method was developed to estimate the water losses due to the capture of water on the exposed area. Seepage and evaporation volumes are computed with water surface area and checked if volume is limiting for either. Overflow is assumed to drain within the day.

$$V_r = \frac{A_w d_r + (A_T - A_w) d_{NRCS}}{12.0} \quad (3.35)$$

where, V_r is volume of rainfall (ft³)

A_w is water surface area (ft²) (Equation 3.28)

d_r is rainfall depth (in.)

A_T is total area at top of lagoon (ft²)

d_{NRCS} is depth from NRCS curve number method (Equation 2.1 CN=98)

Constituent Balance

The constituent balances (COD, N, and P) are based on Miner et al. (1980). Their model was calibrated in with one study in Illinois. All of the model constant parameters are set for the values after calibration. The algorithms of this model were selected, because they offer a complete constituent balance for N (organic and NH₄⁺), P, and COD. The module assumes that no constituents are lost in seepage, because the seepage rate is very low and most of the constituents get trapped in the sludge. The water temperature

for all the constituent balances is the calculated with equation 3.3. For the purpose of the constituent balance, outflow is in reference to the pumping volume and overflow volume.

$$T_s = \frac{T + T_1 + T_2 + T_3 + T_4}{5} \quad (3.36)$$

where, T_s is the water temperature ($^{\circ}\text{C}$)

T is today's average temperature ($^{\circ}\text{C}$)

T_i is average temperature i days earlier

COD Balance

The COD balance divides COD into four pools of degradable COD in solution (COD_{DL}), non-degradable COD in solution (COD_{NL}), liquefiable COD in sludge (COD_{LS}), and non-liquefiable COD in sludge (COD_{NS}). Inflow is divided between the four pools. Outflow and overflow concentrations are calculated with COD in solution. COD can be removed through degradation of the COD_{DL} pool. COD is transferred from sludge to liquid by liquefying the COD_{LS} pool. The procedure and algorithms below are used to compute the COD constituent balance.

1. The amount of COD in outflow and overflow (COD_o) is calculated by

$$\begin{aligned} \text{COD}_o &= (\text{COD}_{\text{NL},o} + \text{COD}_{\text{DL},o}) \\ \text{COD}_{\text{NL},o} &= \text{COD}_{\text{NL}} \frac{\text{OUT}}{V + \text{OUT}} \\ \text{COD}_{\text{DL},o} &= \text{COD}_{\text{DL}} \frac{\text{OUT}}{\text{OUT} + V} \end{aligned} \quad (3.37)$$

2. The amount degraded COD (COD_D) is calculated is calculated by

$$\begin{aligned} \text{COD}_D &= \text{COD}_{\text{DL}} (10)^{-KC_T} \\ KC_T &= KC_{20} (1.07)^{T_x - 20} \end{aligned} \quad (3.38)$$

3. If degraded COD is greater than COD_{DL} minus $\text{COD}_{\text{DL},o}$, then

$$\text{COD}_D = \text{COD}_{\text{DL}} - \text{COD}_{\text{DL},o} \quad (3.39)$$

4. The amount of COD liquefied (COD_L) is calculated by

$$\begin{aligned} \text{COD}_L &= \text{COD}_{\text{LS}} (10)^{-KL_T} \\ KL_T &= KL_{20} (1.45)^{T_s - 20} \end{aligned} \quad (3.40)$$

5. The constituent balances for each of the COD pools is as follows:

$$COD_{DL} = COD_{DL} + a(COD_{IN}) + COD_L - COD_{DL,O} - COD_D \quad (3.41a)$$

$$COD_{NL} = COD_{NL} + b(COD_{IN}) - COD_{NL,O} \quad (3.41b)$$

$$COD_{LS} = COD_{LS} + c(COD_{IN}) - COD_L \quad (3.41c)$$

$$COD_{NS} = COD_{NS} + d(COD_{IN}) \quad (3.41d)$$

where, OUT is outflow and overflow volume

V is water volume at end of day

COD_O is COD in outflow amount (kg)

COD_D is degraded COD (kg)

COD_L is liquefied COD (kg)

COD_{IN} is total COD from inflow (kg)

COD_{DL}, COD_{NL}, COD_{LS}, and COD_{NS} are pools listed above

T_s is water temperature (°C) (Equation 3.35)

KC_T and KL_T are decay constant at temperature T

KC₂₀ and KL₂₀ are 0.045 and 0.005

a,b,c,d are inflow constants of 0.24, 0.36, 0.28, and 0.12, respectively

Nitrogen Balance

The N balance is similar to COD except for an additional pool and a slightly different path for N removal. Nitrogen's five pools are degradable organic-N in solution (N_{DL}), non-degradable organic-N in solution (N_{NL}), liquefiable organic-N in sludge (N_{LS}), non-liquefiable organic-N in sludge (N_{NS}), and ammonium-N (NH_{4P}). The pathway for removal of N is liquefiable organic in sludge N liquefies into degradable organic-N in solution, which in turn mineralizes into ammonium and ammonium volatilizes into the air. The procedure and algorithms below are used to compute the N balance.

1. The amount of organic-N in outflow and overflow (N_O) is calculated by

$$N_O = (N_{NL,O} + N_{DL,O})$$

$$N_{NL,O} = N_{NL} \frac{OUT}{V + OUT} \quad (3.42)$$

$$N_{DL,O} = N_{DL} \frac{OUT}{OUT + V}$$

2. The amount of ammonium (NH_{4O}) in the outflow and overflow is calculated by

$$NH4_o = NH4_p \frac{OUT}{OUT + V} \quad (3.43)$$

3. The amount of volatilized ammonium (NH_{4V})

$$NH4_v = NH4_p (K_v) (36.123v)^{0.8} (T_A + 273)^{-1.4} \frac{A}{10.76} x$$

$$x = NH4_{con} (10)^{(0.057T_s - 4.02)} - 0.1 \quad (3.44)$$

$$NH4_{con} = \frac{35,310(NH4_p)}{V + OUT}$$

4. If NH_{4V} is greater than NH_{4P} minus NH_{4O}, then

$$NH4_v = NH4_p - NH4_o \quad (3.45)$$

5. The amount of mineralized organic-N (N_M) is calculated by

$$N_M = N_{DL} (10)^{-KA_T}$$

$$KA_T = 50.5KA_{20} (10)^{7.71 - \left(\frac{2758}{T_s + 273}\right)} \quad (3.46)$$

6. If mineralized organic-N is greater than N_{DL} minus N_{DL,O}, then

$$N_M = N_{DL} - N_{DL,O} \quad (3.47)$$

7. The amount of organic-N liquefied (N_L) is calculated by

$$N_L = N_{LS} (10)^{-NKL_T}$$

$$NKL_T = NKL_{20} (1.45)^{T_s - 20} \quad (3.48)$$

8. The nutrient balances for each of the NH₄ pools is as follows:

$$NH4_p = NH4_p + NH4_{IN} + N_M - NH4_v - NH4_o \quad (3.49a)$$

$$N_{DL} = N_{DL} + f(N_{IN}) + N_L - N_{DL,O} - N_M \quad (3.49b)$$

$$N_{NL} = N_{NL} + g(N_{IN}) - N_{NL,O} \quad (3.49c)$$

$$N_{LS} = N_{LS} + h(N_{IN}) - N_L \quad (3.49d)$$

$$N_{NS} = N_{NS} + i(N_{IN}) \quad (3.49e)$$

where, OUT is outflow and overflow volume (ft³)

V is water volume at end of day (ft³)

N is organic-N

NH₄ is ammonium-N

P_o and P_{IN} are outflow and inflow amounts (kg)
 N_M and N_L are mineralized and liquefied N (kg)
 $NH4_V$ is volatilized amount (kg)
 $NH4_P$, N_{DL} , N_{NL} , N_{LS} , and N_{NS} are pools listed above
 $NH4_{con}$ is concentration of ammonium-N (mg/L)
 T_s is water temperature ($^{\circ}C$) (Equation 3.35)
 T_A is daily air average temperature ($^{\circ}C$)
 v is average wind speed (mph)
 A is surface area (ft^2)
 KA_T and NKL_T are decay constants at temperature T
 KA_{20} , NKL_{20} and K_V are 0.055, 0.005, and 0.0125 (-)
 f, g, h, i are inflow constants of 0.24, 0.36, 0.28, and, 0.12,
 respectively

In Equation 3.44, the 39.123 is needed to convert mph at 3 m into km/day at 2 m (Corps of Engineers, 1998). The conversion of height of measured wind speed is adjusted using the same method for the snow melt algorithm adjustment (Equation 3.9).

Phosphorus Balance

The P balance for Miner et al. (1980) is very different than COD or N balances. Phosphorus has only two pools of soluble and insoluble P. All inflow of P starts in the soluble state. If the concentration of soluble P reaches beyond a threshold, then any amount above the threshold precipitates. The threshold is dependent on the ammonium concentration before the N balance is performed. Phosphorus is assumed to be unable to move back into the soluble form. The procedure and algorithms used for the P balance are the following:

1. The amount of P in the outflow (P_o) is computed by

$$P_o = P_s \frac{OUT}{OUT + V} \quad (3.50)$$

2. The threshold amount of P that can be soluble is

$$P_{max} = \frac{120V}{31,310} \quad \text{if } 120 < 0.33(NH4_{con}) + 24.4 \quad (3.51)$$

$$P_{\max} = \frac{V(0.33(NH4_{con}) + 24.4)}{31,310} \text{ otherwise,}$$

3. The precipitation amount is calculated by

$$P_{prec} = P_S - P_O - P_{\max} \quad \text{if } P_{\max} < P_S - P_O \quad (3.52)$$

$$P_{prec} = 0 \quad \text{otherwise,}$$

4. The P balance is calculated by

$$P_S = P_S + P_{IN} - P_O - P_{prec} \quad (3.53a)$$

$$P_I = P_I + P_{prec} \quad (3.53b)$$

where, P_O is outflow amount (kg)

P_{\max} is threshold amount that can still be soluble (kg)

P_{prec} is the amount that precipitates (kg)

P_{IN} is inflow amount of P (kg)

P_S is soluble P pool (kg)

P_I is insoluble P pool (kg)

OUT is outflow and overflow volume (ft³)

V is water volume at the end of day (ft³)

$NH4_{con}$ is ammonium-N in the lagoon at the start of the day (mg/L)

Soil Module

The soil module is designed to create a soil input file for the VTA module. This is a support module that processes raw data and creates an input file with the correct format and units. The soil module also estimates soil properties from available information. The output file has five soil layers. Each layer contains the following data:

- depth (in.)
- wilt point
- field capacity
- saturation (in./in.)
- conductivity (in./s)
- suction (in.) for Green-Ampt.

The first layer also contains the readily evaporated water (in.). The first layer depth is three inches while the other four divide the layers evenly among the remainder of the root depth.

User Inputs

The input file is a tab-delineated text file with the first row reserved as the header of each column. Columns are separated by a single tab. The other rows contain the raw data for each soil layer. These layers will have their properties averaged together to create the five layers. The header for each column must be a keyword for a particular input parameter. The parameters are required for estimating different properties. Table 3.6 has the header labels and units for each column listed along with a description of the soil property. The headers are not case sensitive and can be in any order, but must be entered with the exact lettering. Different header units are required for estimating the needed soil properties. Null data for any column is represented by leaving the field blank with only a tab between it and the next column. Only one tab should be between the columns. The required information for each estimate will be described in the following sections. The bottom depth is required for all layers. Information for a soil type can be found at the NRCS website under Soils. The only other input requirement is the number of layers the user wants incorporated into the formatted soil file. Organic carbon is converted into organic matter by multiplying by 1.7 (Rawls et al., 1993).

Table 3.6. Header Labels and Units for the input file of the soil water module.

Header Label	Units	Soil Property Description
Depth	cm	Depth to bottom of layer
Bulk Density	g/cm ³	Bulk Density of soil layer
Saturation	cm/cm	Water Content at Saturation
Field Capacity	cm/cm	Water Content at Field Capacity (33 kPa)
Wilt Point	cm/cm	Water Content at Wilting Point (1500 kPa)
Conductivity	cm/hr	Conductivity for Green-Ampt
Suction	cm	Suction Head for Green-Ampt
Clay	%	Percent of sand, silt, and clay that is clay (<0.002-mm diameter)
Silt	%	Percent of sand, silt, and clay that is silt (0.002 to 0.05-mm diameter)
Sand	%	Percent of sand, silt, and clay that is sand (0.05 to 2-mm diameter)
Organic Matter	%	Percent of sand, silt, and clay that is organic matter
Organic Carbon	%	Percent of sand, silt, and clay that is organic carbon
Gravel	%	Percent of total weight of soil over 2-mm diameters
CEC	CEC/clay	Ratio of Cation Exchange Capacity to Clay
REW	mm	Soil water that can be readily evaporated

Evaporative Available Water

Readily evaporative water (REW) is used to define the depth of water that can be easily evaporated from the first layer of soil. This property is only needed for the first 3 in. (76.2 mm) of soil. If the property is not available in the raw soil file, then it can be estimated based upon the percent sand, silt, and clay in the soil. REW is estimated by calculating the USDA soil texture of the soil and selecting the appropriate estimate based on the texture. The USDA soil texture is a division of soils based on the percentage of sand, silt, and clay contained within them. Figure 3.8 shows the USDA soil triangle. This relates the percent of sand, silt, and clay to a soil texture. The REW values for each texture were developed from the United Nations FAO 56 Report (Richard et al., 1998)

and are shown Table 3.7. Sandy clay, clay loam, and sandy clay loam had no values given in the Richard et al. (1998), so the values were assumed to be the same as for loam.

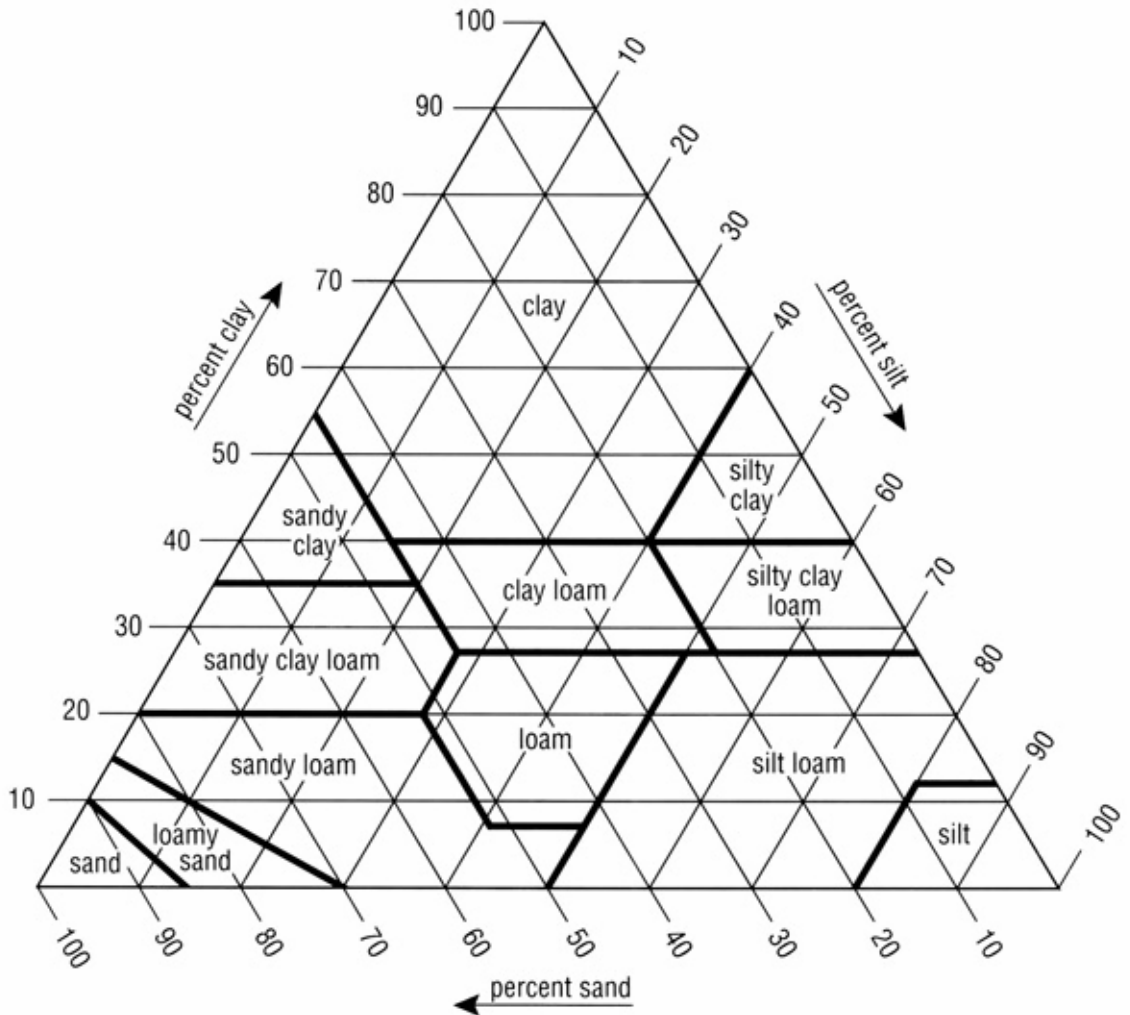


Figure 3.8. USDA soil triangle showing the soil textures in relationship to sand, silt, and clay. (Soil Survey Division Staff, 1993)

Table 3.7. Estimated values of REW for different soil textures (Richard et al., 1998).

Soil Texture	REW (mm/mm)
Clay	0.131
Silty clay	0.131
Sandy clay	0.118
Silt clay loam	0.125
Clay loam	0.118
Sandy clay loam	0.118
Silt	0.125
Silt loam	0.125
Loam	0.118
Sand	0.059
Loamy sand	0.079
Sandy loam	0.105

Conductivity

The conductivity for the Green-Ampt method is used for infiltration calculations. If conductivity is not given in the raw soil data file, it can be estimated from soil properties of sand content, clay content, field capacity and saturation. Several different methods have been developed for estimating conductivity including Rawls and Brakensiek, (1985), Saxton et al. (1986), Rawls et al. (1993), and Rawls et al. (1998). Stahr et al. (2004) tested several methods to estimate conductivity on perennial vegetation on riparian buffer strips and found that the method described in Rawls et al. (1998) was a good predictor of conductivity. Because the VTA is covered in perennial grasses similar to the buffer strips, the method by Rawls et al. (1998) is used to estimate conductivity in Equation 3.54. The pore index is calculated in Equation 3.55 by the relationship described by Brooks and Corey as listed in Rawls and Brakensiek (1985). Pore index is restricted to soils within the ranges of clay 5% to 60% and sand 5% to 70%. Any value outside these ranges had pore index calculated with the closest valid value.

$$K = 193.0(\phi - FC)^{3-2} \tag{3.54}$$

where, K is conductivity (cm/hr)

FC is field capacity (cm/cm)

ϕ is saturation (cm/cm)

λ is pore index

$$\lambda = \exp \left(\begin{array}{l} a + bS + c\phi + dS^2 + eC^2 + f\phi^2 + gS\phi \\ + hS^2\phi^2 + iC^2\phi^2 + jS^2C + kC^2\phi + l\phi^2C \end{array} \right) \quad (3.55)$$

where, λ is pore index

ϕ is saturation (cm/cm)

C is clay (%)

S is sand (%)

a,b,c,d,e,f,g,h,i,j are constants listed in Table 3.8

Table 3.8. Constants for pore index in Equation 3.55. (Rawls and Brakensiek, 1985)

Constant	Value	Constant	Value
a	-0.7842831	g	-0.03088295
b	0.0177544	h	0.00026587
c	-1.062498	i	-0.00610522
d	-0.00005304	j	-0.00000235
e	-0.00273493	k	0.00798746
f	1.11134946	l	-0.00674491

Suction Head

The suction head for the Green-Ampt method can be estimated if unknown by using sand and clay percentages. Originally, suction head was estimated with methodology found in Rawls and Brakensiek (1985), but this method proved difficult to implement. The method tended to overestimate suction for loamy and sandy loam soils when compared to the average value. Instead, the soil module estimated the averages for different textures as listed in Haan et al. (1984). The suction head for each texture are shown in Table 3.9.

Table 3.9. Estimated values of suction head for different soil textures (Rawls et al., 1983).

Soil Texture	Suction Head (cm)
Clay	31.63
Silty clay	29.22
Sandy clay	23.90
Silt clay loam	27.30
Clay loam	20.88
Sandy clay loam	21.85
Silt	16.68*
Silt loam	16.68
Loam	8.89
Sand	4.95
Loamy sand	6.13
Sandy loam	11.01

*No silt given assumed silt loam for suction purposes.

Saturation, Field Capacity, and Wilt Point

Water content at saturation, field capacity, and wilt point are used with the soil water balance. Water content at all three points can be dependent upon one another. They can be estimated individually or by using data from each other. The independent estimates will be discussed before the dependent relationship methods.

Saturation can be estimated from bulk density as described in Rawls et al. (1993). This is derived from the definition of saturation. Equation 3.56 is used to calculate saturation and assumes the density of the soil particles are 2.65 g/cm³. If bulk density is not available, saturation can be estimated from sand, clay, organic matter or carbon, and gravel contents. Equation 3.57 is used for this estimate from Rawls et al. (1993).

$$\phi = 1 - \frac{\rho_B}{\rho_s} \quad (3.56)$$

where ϕ is saturation (cm/cm)

ρ_B is bulk density (g/cm³)

$$\rho_s \text{ is solid density (2.65 g/cm}^3\text{)}$$

$$\rho_B = 1.51 + 0.025S - 0.0013SO - 0.0006CO - 0.0048CI$$

$$\alpha = 1 - \frac{G}{100\rho_s} \left(\frac{100}{(100-G)\rho_B} + 1 \right) \quad (3.57)$$

$$\phi = \alpha \left(1 - \frac{\rho_B}{\rho_s} \right)$$

where ϕ is saturation (cm/cm)

ρ_B is bulk density (g/cm³)

ρ_s is solid density (2.65 g/cm³)

S is sand (%)

C is clay (%)

O is organic matter (%)

I is CEC (CEC/clay)

G is gravel (%)

Wilt point is used for the calculations in the soil water balance. If wilt point is not available in the soil raw data file, it is estimated from clay and organic matter content.

Rawls et al. (1993) is used to compute wilt point with Equation 3.58.

$$WP = 0.0260 + 0.0050C + 0.0158O \quad (3.58)$$

where, WP is wilt point (cm/cm)

C is percent clay (%)

O is organic matter (%)

Field capacity is also used in the calculation of the soil water balance. Sand, clay, organic matter are needed to estimate field capacity if no value is available for wilt point.

If wilt point is given, then field capacity is estimated with Equation 3.59a, otherwise

Equation 3.59b (Rawls et al., 1993) can be used.

$$FC = 0.2391 - 0.0019S + 0.0210O + 0.72WP \quad (3.59a)$$

$$FC = 0.2576 - 0.0020S + 0.0036C + 0.0299O \quad (3.59b)$$

where, FC is field capacity (cm/cm)

WP is wilt point (cm/cm)

S is sand (%)

C is clay (%)

O is organic matter (%)

As mentioned earlier, all three values of water content are related to one another, because they represent the same soil at different moisture contents. Estimates for wilt point, field capacity, and saturation were all derived from the same dataset, and there should be relationships among them. A problem arises when one or two of the three water content values are added into the raw soil file, and the others are estimated. It is possible that the added and estimated values represent two different conditions. To prevent this problem it was decided to adjust the estimated values with the added values. If one of the values is given, the estimates of the other are multiplied by the ratio of the available value to its estimated value. If two of the values are added, the estimate of the third one is adjusted by linear interpolation with the two added. For the purposes of scaling, adding bulk density is the same as adding saturation. This is because saturation is calculated from bulk density and the definition of saturation is derived from bulk density. As a final check, if field capacity is greater than saturation, then field capacity is set at a moisture content 75% of the way between wilt point and saturation.

Creation of Soil File

Once all of the missing properties of the raw soil layers properties have been estimated, the soil file can be generated. At this time the user can enter a soil name. This is only for the user's benefit. The soil file outputs values for five soil layers. The first layer is three inches thick and the others are divided equally for the remainder of the rooting depth. Properties for each layer are calculated by averaging the values for the raw layers by weighing with depth within the output layers.

VTA Module

The VTA module is designed to simulate transport and fate of surface runoff and constituents in a VTA system. The VTA does not include the transport of background concentrations of constituents that may occur in the runoff. The main treatment is the infiltration of water into the soil, where it can be utilized by plants. As per the objectives of this project, the VTA module simulates the removal of constituents from surface runoff. Water and constituent calculations are performed by dividing the VTA into sections ten feet (3.048 m) in length. The VTA can simulate the use of control structures

(spreaders) to redistribute the water across the entire width again. Due to the constituent balance, the outflow and overflow of the VTA are outputted to two different files.

As water travels down the slope, it begins to converge and form a finger-like pattern on the VTA. If these fingers were gathered together, then the water would have an effective width for each section. By estimating the convergence from the start of the VTA or a redistribution structure, the effective width for the effluent water can be calculated for each section. The area covered by the effective width forms part of the section that is referred as the effluent part. The remainder of the width not associated with the effluent effective width becomes an area that is referred as the rain part, because it only receives rain water. Each area has its own water and constituent balance that occasionally merges because of a spreader. The rain part is monitored because it can dilute the constituents.

User Inputs

To operate the computer simulation model, the user must input the length, width, and slope of the VTA along with the depth of berms along the sides to prevent overflow. If a spreader is used, the user must input the type and dimensions of the spreader. The type of plant grown in the VTA and the directory location of the soil input file are needed as well. Finally, the directory locations of the data files for weather, inflow, hyetograph, and outflow file must be given. A separate overflow file is used because the concentration of constituents can be different from the concentrations in the outflow. The overflow file location is the same as the outflow file, except the extension .ovr is added to the end. The second overflow file is needed, because the concentrations of constituents in the outflow and overflow are not the same. The user must also enter the directory location for a second output file containing the soil water balance for each section for the entire simulation.

Spreader Stage-Discharge

As mentioned earlier, the user can decide to include spreaders that help reestablish overland flow across the width of the VTA. The spreader can act as mini-dams that can have water pool behind them. If spreading does occur, a stage-discharge

curve is developed for the spreaders. This curve is an array with 0.5-inch (13-mm) steps to the top of the side berm. The spreader structure can be any of the following types:

- Multiple 90° V-notch weirs
- Multiple orifices openings
- A sharp-crested weir
- A gravel pile

All four structures need the distance along the VTA between each spreader, which must be a multiple of the section length.

The multiple 90° V-notch weir system consists of a number of V-notches spaced evenly across the width of the VTA with a top that serves as a sharp-crested weir. Figure 3.9 shows the set and required dimensions for the V-notch system. Calculations of discharge for a particular stage can be divided into three parts. For depths below the bottom height, no discharge occurs. For depth between the bottom and spreader height, discharge is the number of weirs present times the discharge of each weir from Equation 3.60 (McCuen, 2005). For depths greater than the height of the spreader, discharge is sharp-crested weir with depth over the spreader height (Equation 3.2) plus V-notch discharge with water depth at the height of the spreader (Equation 3.60).

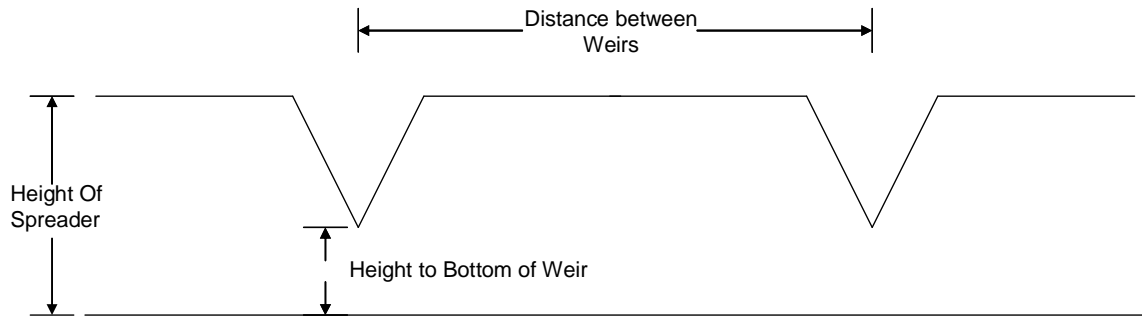


Figure 3.9. Diagram of the V-notch spreader with the required dimensions.

$$q = 2.5(d_w - d_b)^{2.5} \tag{3.60}$$

where, q is discharge (cfs)

d_w is water depth (ft)

d_b is height of the bottom of weir (ft)

The multiple orifice system consists of a number of orifices spaced evenly across the width of the VTA with a top of the spreader acting as a sharp-crested weir. Figure 3.10 shows the set and required dimension for the orifice system. The discharge from the orifice system can be divided into four parts. Depths below the bottom of the orifices have zero discharge. Depths between the bottom and top of the orifice, discharge is assumed to be the number of orifices times the discharge of a sharp-crested weir (Equation 3.2) with the weir length equal to the water-filled area (Equation 3.23b) divided by the depth of water in the orifice. For depths between the top of the orifice and height of spreader, discharge is the number of orifices times discharge of an orifice (Equation 3.3). Depth of the orifice is the water depth minus height of the center of the orifice. For depths above the spreader height, discharge is the total orifice discharge plus sharp-crested weir (Equation 3.2) for above the spreader height.

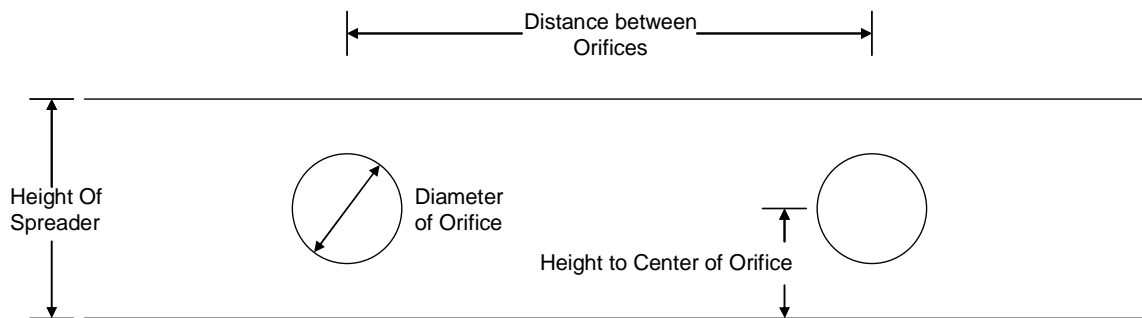


Figure 3.10. Diagram of orifice system with the required dimensions.

The sharp-crested weir is simply a weir that goes across the entire width of the VTA. The only dimension is the height of the spreader. Discharge is zero if depth of water is below spreader height. Above the spreader height, discharge is a sharp-crested weir (Equation 3.2).

The gravel system is the final spreader structure. Figure 3.11 shows a diagram of the side view of the gravel system with its required dimensions. The conductivity of the gravel is also required. The gravel system is made up of gravel or rocks that allow water to flow through the structure. Discharge is divided into two parts. First is when depth is below the height of the spreader. Discharge through the gravel is similar to flow through an earthen embankment and is calculated with the maximum discharge rate with Equation 3.61 (Schwab et al., 1993). Equation 3.62 was derived from finding maximum discharge

with Equation 3.61 through differentiation. When depth is over the height of the spreader, discharge is assumed to be broad-crested weir (Equation 3.2) plus Equation 3.61 with depth of water set to the height of the spreader.

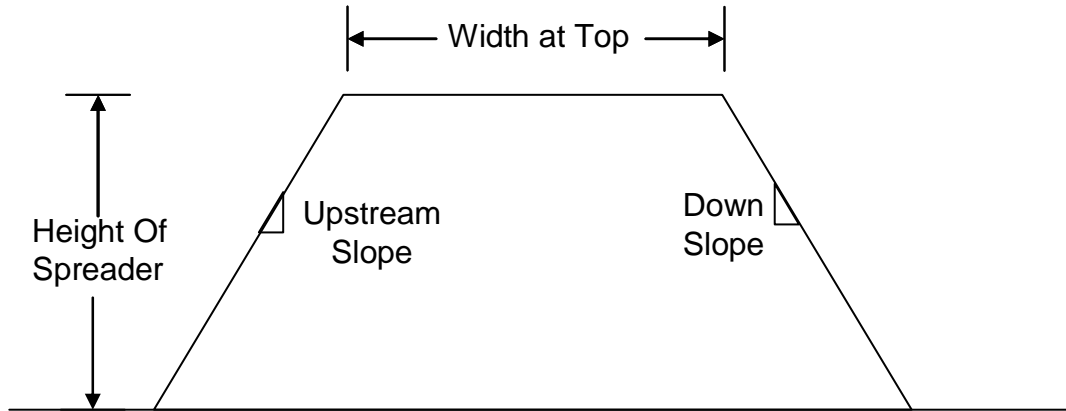


Figure 3.11. Diagram of gravel system with requires dimensions (Side View).

$$q = \frac{WK(d^2 - h^2)}{2(w + a(H - d) + b(H - h/2))} \quad (3.61)$$

$$h = \frac{2(W + H(a + b) - bd) - \sqrt{4(W + H(a + b) - bd)^2 - b^2 d^2}}{b} \quad (3.62)$$

where, q is discharge (cfs)

W is VTA width (ft)

w is width at top (ft)

a is upstream slope as a:1

b is downstream slope at b:1

H is height of spreader (ft)

d is depth of water (ft)

h is downstream height, solved to maximize discharge (ft)

K is conductivity of gravel (ft/s)

Effective Width

As water flows downhill, it begins to converge. The VTA module simulates this convergence by estimating the effective width in each section of the VTA. This divides each section of the VTA into two parts. The effective width is calculated for Equation

3.63 from Wulf and Lorimar (2005). For each section, the distance from the beginning of the spreader is measure from the halfway point. This should give the average effective width of the section. If the plant is a row crop with rows running along the contour, then effective width is set to 90% of VTA width due to the rows acting as minor spreaders. However, row crops are not well suited for a VTA.

$$w_e = w_{VTA} - \frac{(w_{VTA} - w_L)L}{L_L} \quad \text{for } L < L_L \quad (3.63a)$$

$$w_e = w_L \quad \text{for } L < L_L \quad (3.63b)$$

$$L_L = 500 - 30(s - 1) - 20(R - 1) \quad (3.63c)$$

$$w_e = w_{VTA}(0.6 - 0.02((s - 1) + (R - 1))) \quad (3.63d)$$

where, w_e is effective width (ft)

w_{VTA} is VTA width (ft)

L is length from start of VTA or spreader (ft)

w_L and L_L are width and length limit

s is slope (%)

R is plant retardance factor (Appendix A)

Infiltration

Infiltration is calculated with the Green-Ampt method. The Green-Ampt method was selected because it allows the module to adjust for varying initial water contents and storm sizes, while the soil properties can be readily calculated or measured. Green-Ampt assumes that infiltrated water moves as a block down the soil profile with saturated and original unsaturated zones (McCuen, 2005). Green-Ampt does not have a transitional wetting front zone between the two layers. A difficulty in having the five soils layers is that conductivity changes between them. Green-Ampt requires conductivity to be one value. An effective conductivity is used with the Green-Ampt method to incorporate all conductivities within the saturated zone. Effective conductivity is calculated with Equation 3.64 (Hillel, 1998). If the saturated zone is deeper than the five layers, the extra depth is assumed to have the same soil properties as the fifth soil layer. This method for calculating effective conductivity was chosen because it is used to calculate Darcy's Law

effective conductivity with multiple-layered soil and Green-Ampt can be derived from Darcy's Law with a few assumptions (Hillel, 1998) (McCuen, 2005).

$$K_e = \frac{\sum d_i}{\sum \frac{d_i}{K_i}} \quad (3.64)$$

where, K_e is effective conductivity (in./s)

d_i is depth of soil layer i within saturated zone (in.)

K_i is conductivity of soil layer i within saturated zone (in.)

For the VTA module, the infiltration rate at the start of each period is used to calculate infiltration during the five-minute time step. This assumes the infiltration rate remains constant for the entire time step. Equation 3.65 from Haan et al. (1994) is the Green-Ampt formula used to calculate infiltration. First time step of an infiltration event has no saturated zone, so a value of 0.001 in. is assumed to prevent dividing by zero. The amount infiltrated represents the maximum amount that could infiltrate, but infiltration is checked against the total amount of water it is exposed to in that time step. If the water is less, then the infiltration is all the exposed water. If the ground is frozen, then no infiltration will occur (Koelliker et al., 1975). The volume of infiltrated water is moved from the surface to the soil layer that is unsaturated.

$$f = K_e t \frac{d + L + \psi}{L} \quad (3.65)$$

where, f is infiltration (in.)

K_e is effective conductivity (in./s)

t is time step (300 s)

ψ is suction head (in.)

d is depth of the surface water at beginning of time step (in.)

L is the depth of the saturated zone in the soil profile (in.)

Percolation of Water

Percolation is the movement of water through the soil profile after an infiltration event occurs. The movement by percolation is limited to those soil layers above field capacity. The percolation algorithm was developed from the percolation equations in EPIC and SWAT models (Williams et al., 1983) (Neitsch et al., 2005). From both

models, percolation was computed with Equation 3.66a. Equation 3.66 will give the total percolation amount if no inflow occurs, but layered soil can have percolation moving into and out of a layer. The inflow percolation essentially resets the initial water contents and requires that percolation be calculated with small time steps. The 5-minute time step is used for percolation calculations to match that of the other VTA modules. For days when an infiltration event occurs, the percolation algorithm is executed before infiltration begins and after infiltration stops.

$$P = (W - FC)d \exp\left(\frac{-tK}{(\phi - FC)d}\right) \quad \text{for } P > 0.01(\phi - FC) + FC \quad (3.66a)$$

$$P = \phi - FC \quad \text{else} \quad (3.66b)$$

where, P is percolation amount (in.)

t is time step (300 s)

d is soil layer depth (in.)

K is conductivity (in./s)

W is initial water content (in./in.)

FC is field capacity (in./in.)

ϕ is saturation (cm/cm)

The percolation algorithm is designed to run in a loop for the amount of time that percolation could occur for a day. If Equation 3.66a were used alone, the algorithm would calculate extremely small values of percolation when water content is near field capacity. The percolation calculations would never allow water content to reach field capacity because Equation 3.66a has an asymptote at field capacity. This asymptote forces the algorithm to run continuously while minimal percolation occurs. This increases computation time. To decrease the module run time, Equation 3.66b is added to the VTA module to make percolation equal zero.

The percolation algorithm is executed on the day of an infiltration event for every 5-minute time step until infiltration starts and at the end of the day for the amount of time since infiltration stop with 5-minute time steps. On days with no infiltration, the percolation algorithm is executed for the entire 24 hour in 5-minute time steps. The percolation algorithm follows the following procedure:

1. Run the loop for time number of 5-minute time steps needed to complete the interval (288 times for 24-hr period)
2. For each soil layer starting at the bottom
 - a. Calculate percolation with Equation 3.66
 - b. If saturation-water content < percolation, then percolation = saturation-water content
 - c. Subtract percolation from the water content of the soil layer
 - d. Add percolation to the next lower soil layer or if bottom layer to seepage amount
3. If no percolation occurred for this time step, then stop the calculation.

Evapotranspiration

Evapotranspiration (ET) is the combined removal of water by evaporation and transpiration from the soil. The two steps for ET algorithms are to calculate the ET coefficient and to remove ET from the appropriate soil layer. The ET coefficient is used to adjust the reference ET value from the weather data based upon the type of plant and growth condition for the particular day of the year. The ET coefficient is modeled with three different models. The models were developed from Richard et al. (1998). The values for ET coefficients (ETK) and time (DOY) are expressed in general terms. The actual values for each plant type are found in Appendix A.

The first model is of a cool season grass shown in Figure 3.12. At the start of the year, the cool season grass coefficient is ETK_{winter} for the winter dormant period. On DOY0, the plants enter the initial growth states with a constant ET coefficient of $ET1$. Between DOY1 and 2, the grass begins to develop rapidly. The ET coefficient increases linearly between $ET1$ and $ETK2$ values. Because this is a cool season grass, the ET coefficient is reduced for water stress during the hot Kansas summer and then recovers. The coefficients for the stress and recover periods are linear changes with the respective ETK values as shown in Figure 3.12. After recovering to DOY4, the grass begins its senescent period, which ends at DOY5. After senescence, the grass enters the winter dormant period again until DOY0 the next spring.

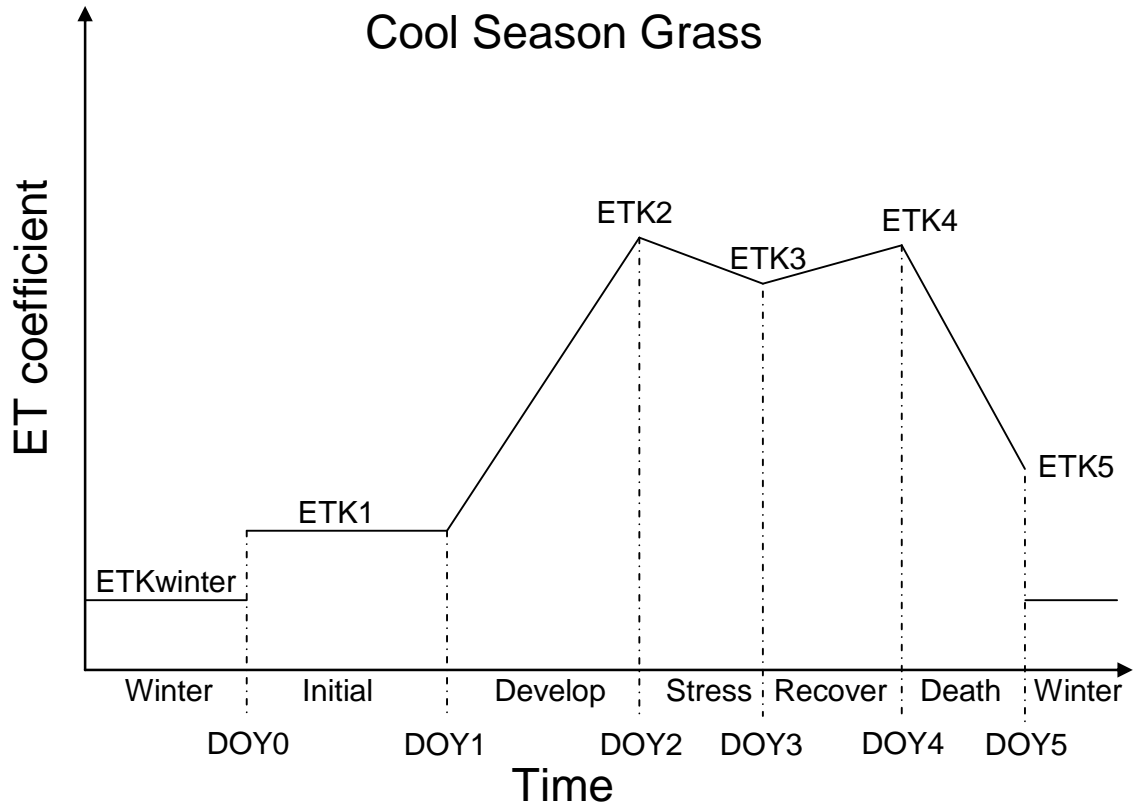


Figure 3.12. ET coefficient model of a cool season grass.

The second ET coefficient model is for a grass harvested four times for hay as shown in Figure 3.13. Here, the ET coefficient starts with a winter period until DOY0 when the initial growth occurs. The ET coefficient for the initial period is ETK1. At DOY1, the ET coefficient begins to increase linearly until DOY2 to ETK2. DOY2 represents a cutting of the plants. The cutting causes the ET coefficient to reset to the ETK1 value for the next day. Figure 3.13 shows the pattern of linear increase and cutting occurs for three more times until DOY5 when the grass enters the winter senescent period again and remains at ETKwinter until DOY the next year.

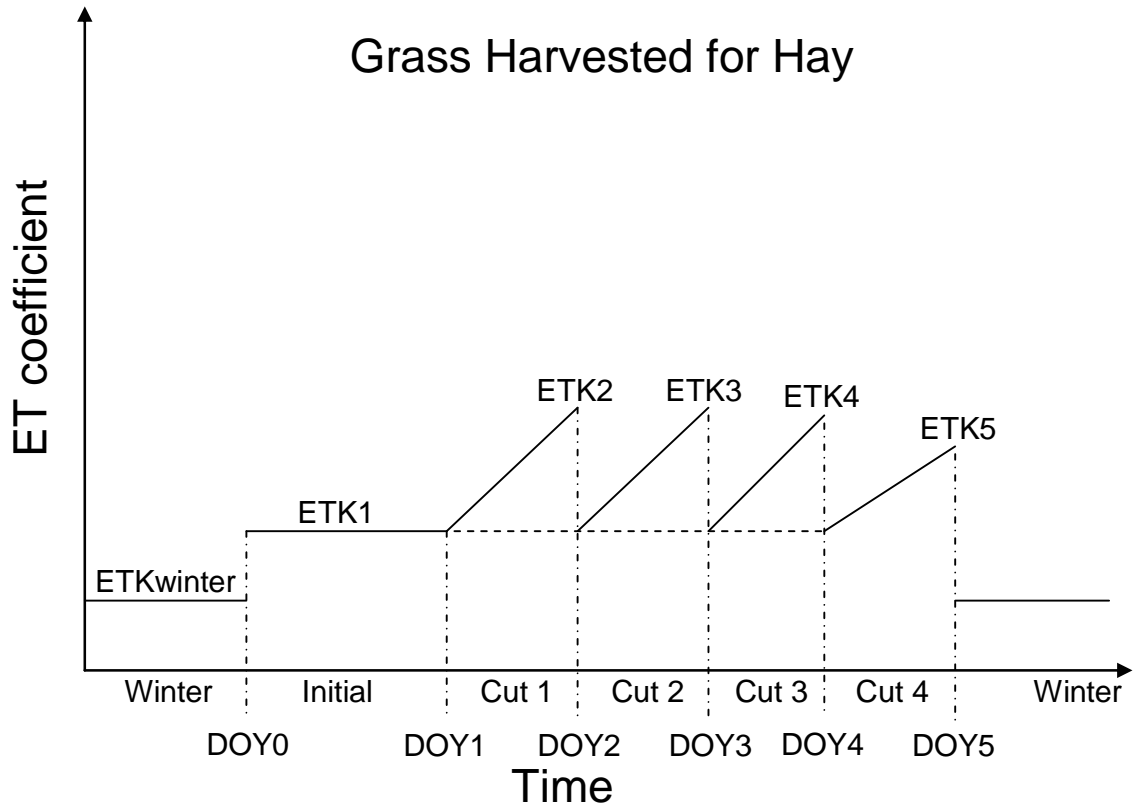


Figure 3.13. ET coefficient model of grass harvested for hay throughout the season.

The third ET model is for a warm season grass. This model can also represent an annual crop, but annual crops are not recommended for a VTA system. Figure 3.14 shows the warm season ET model. Comparing Figure 3.12 and Figure 3.14 shows that the cool and warm season grass models are similar except the stress and recovery periods are exchanged for the mature period and a DOY is removed. The ET coefficient for the mature period is a constant value of ETK2. The other periods follow the same pattern as the cool season grass.

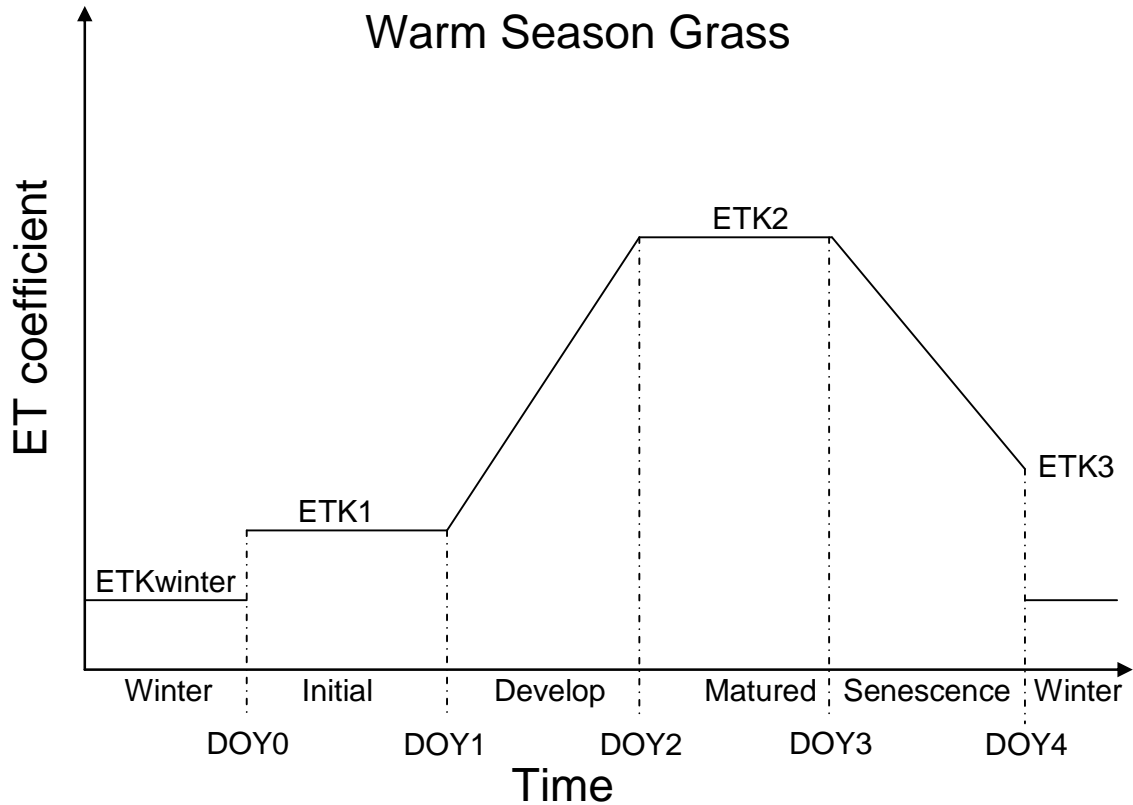


Figure 3.14. ET coefficient model of a warm season grass.

Evapotranspiration removes water from all five of the soil layers at the end of each day. The first layer has water removed as soil evaporation alone. The evaporation rate is the amount of ET remaining from the grass reference ET when the plants ET (Grass Reference ET times ET coefficient) is subtracted. If the water content is below the Readily Evaporative Water (REW) amount, then the amount of water removed is reduced by applying the fraction calculated by Equation 3.67. This reduction simulates the increased energy required to evaporate water from drier soils.

$$f_{evap} = \frac{WC - 0.5WP}{REW - 0.5WP} \quad (3.67)$$

where, f_{evap} is fraction of actual water evaporated

WC is current water content (cm/cm)

WP is wilt point (cm/cm)

REW readily evaporative water (cm/cm)

The other four layers simulate water removal from ET. For the second soil layer, the amount of water removed is 40% of the plants ET (reference ET times the ET coefficient). The third, fourth, and fifth soil layers respectively remove 30%, 20%, 10% of the plant's ET. The smaller percentages for the lower layers are to simulate the plants preference to remove water near the surface first. If the current water content is below the stress point for the soil layer, then water removed is reduced by the ratio of current water content minus wilt point over stress point minus wilt point. The stress point is the water content where the roots in the layer become stressed. The stress point for the second, third, fourth, and fifth layers are respectively 30%, 40%, 50%, and 50% of the available water (field capacity minus wilt point). If a soil layer is stressed, then the water not removed is added to the plants demand for ET in the next lower layer.

Switch between Pooling and Runoff Water Balances

When a spreader system is used with the VTA module, the spreaders can restrict the flow of water. This can allow the water to pool above the spreader and restrict flow upslope from the spreader. The pooled water could cover multiple sections. These sections have a different water balance scheme than normal operations. During normal runoff the water flows downslope and the water balance for each section is calculated progressively downstream. During pooling the sections behave as a single unit and a separate water balance is used. If pooling is occurring in a section, then all sections between this section and the spreader downslope are part of the pooled water balance. To determine when to switch between normal runoff and pooling water balances, two procedures were developed. The first procedure determines when to switch a section to the pooling water balance. The second procedure switches a section back to the normal water balance.

The pooling water balance assumes that the water pooled above the spreader acts as a miniature basin system with a routed water balance. Pooling begins in a section when water backs up into that section. This back up is caused by inflow exceeding outflow at the spreader. This is the primary criterion used in the first procedure. Two other criteria must be met for pooling to occur. The second criteria is, "Does the pooling sections have enough water to fill it to the appropriate depth by the end of the time step?"

The third criteria is "Does the water in the current section have enough time (5 minutes) to reach the previous time step's first downslope pooling section?"

The following procedure checks if all three criteria are met to start pooling water balance. First, the time required to reach the previous pooling sections is calculated by dividing distance between the current section and previous pooling section with Manning's velocity. The velocity is calculated by combining the two parts of the sections. If the time is greater than five minutes, then the procedure stops and pooling does not occur.

Next, the outflow of the system is calculated to determine if inflow exceeds outflow. The outflow for the 5-minute time step is calculated by using the average outflow determined from the spreader stage-discharge curve for the beginning and ending depths. The beginning depth is the depth of the water for the section above the spreader. The ending depth at the spreader is calculated with the inflow's water depth and Equation 3.68. Equation 3.68 calculates the depth at the spreader if a horizontal line is drawn from the inflow depth at the midpoint of the current section. If the volume of inflow plus rainfall is less than the volume of outflow, then the procedure stops and pooling does not occur.

$$d_e = d_m + (0.5 + N)Ls \quad (3.68)$$

where, d_e is ending depth (ft)

d_m is inflow depth (ft)

L is section length (10 ft)

N is number of sections between the spreader and current section

s is VTA slope (ft/ft)

Otherwise, the procedure checks to see if there is enough water to fill the volume needed for pooling. The volume needed for pooling is the volume necessary to allow the water to be level for all sections between the current section and the spreader at the ending depth. It is calculated by taking the area of each section times each section's midway depth calculated with Equation 3.68. The available volume of water is sum of inflow, rainfall, and initial volume at the beginning of the time step minus outflow. If the available volume is less than the volume needed, then the procedure stops and pooling does not occur. Otherwise, the procedure subtracts infiltration from the available

volume. If the new water volume is greater than volume needed for pooling, then pooling occurs in the section. This causes the section to be the start of the pooling water balance.

The second procedure determines when pooling is no longer occurring. After calculating the pooling water balance, the Manning's flow rate at the end of the first pooling section is calculated with a depth from Equation 3.68 ($N=0$). If Manning's flow rate is less than the pooling flow rate, then the section is switched to the runoff water balance. Also, the next downslope section is set as the first pooling section. The section before the spreader never switches out of pooling, because at every time step this section could either use the pooling or section water balance.

Section Inflow

The inflow flow rate and constituent for a section are determined by its position in the VTA. If the section is the first for the VTA, inflow for the effluent part of the section comes from the inflow file, while the rain part is zero. If the section is after a spreader, then inflow for the effluent part is the previous sections outflow for both rain and effluent parts, while rain is zero. For all other sections, the effluent part inflow is the previous section's effluent part outflow and rain part inflow is the previous section's rain part outflow.

Runoff Water Balance

The runoff water balance is performed in a section when the section is not pooled. Each section has a water balance for the rain and effluent parts of the section. The first step is to calculate the velocity and travel time through the section for the inflow water with Manning's Equation (Equation 3.1). Also, the travel time for the water remaining from the last time step is calculated. This travel time is calculated with the velocity from Manning's Equation for the depth of the remaining water. If the inflow is traveling at a faster velocity than the remaining water, then the remaining water velocity is assumed to be the same as the inflow velocity. This causes the remaining water travel time to be recalculated at the faster velocity. This assumes that the inflow water can push the remaining water out of the section. Next, infiltration, as previously described, is

calculated. Outflow and overflow for the section are calculated. Finally, the water balance is performed.

Outflow for the runoff water balance divides the water into two scenarios. The first scenario is that the travel time for the remaining water is greater than five minutes. This means that the remaining water is unable to completely reach the end of the section. Outflow flow rate is then the volume of water that reaches the end of the section divided by five minutes. The volume that reaches the end of the section is equal to the remaining volume times five minutes and divided by the travel time. The second scenario is that the travel time for the remaining volume is less than five minutes. Outflow is the entire volume of remaining water and the amount of water from the inflow that can reach the end of the section. The inflow water that reaches the end of the section is all the inflow water except the volume of water that cannot travel the length of the section in five minutes (inflow travel time multiplied by inflow flow rate). Outflows for the spreaders are handled by having the section upslope always start as being pooled.

Overflow for a section is calculated by combining the section's effluent and rain parts, because the water must spread out over the entire length of the section before water can flow over or through the berms. The two water balances are maintained separate even if overflow is occurring. The combined remaining water and inflow have their velocity and travel times recalculated. These recalculated values are used only in the overflow calculations. The berms act as two broad-crested weirs. Equation 3.2 calculates the amount of overflow with weir length equal to twice the section length because of the two berms and weir depth equal to the depth of inflow or remaining water above the berms. If the overflow volume exceeds the potential overflow volume, then overflow is set to the potential overflow volume. The potential overflow volume for the remaining water is calculated with Equations 3.69a and b. The potential overflow volume is not simply the amount of water above the berm because not all the water is exposed to the overflow of the berms. For water at the end of the section, no water overflows. For water starting at the beginning of the section, all the water can overflow. This means the volume of water that can overflow is dependent on the location within the section. Equation 3.69a shows the volume calculations when travel time is under five minutes. Equation 3.69b is for when the travel time is larger than five minutes. For the

water that leaves the basin within the time step, the volume of water for potential forms a triangle. But the water that remains in the section can be overflow. The overflow for the inflow is calculated with Equations 3.69a and b, except the all remaining water variables are replaced with their inflows counterparts. Equations 3.69a and b is used for the inflow water, because all the inflow that leaves the section can be overflow, but inflow that stays in the section at the end of the time step forms a triangle of the volume of overflow. The beginning of the section cannot overflow, while the end of the section can.

$$V_{pr} = \frac{1}{2} V_r \frac{d_r - d_b}{d_r} \quad \text{for } t_1 < 300 \quad (3.69a)$$

$$V_{pr} = V_r \left(\frac{d_r - d_b}{d_r} \right) \left(\frac{\frac{1}{2}(300) + (t_r - 300)}{t_r} \right) \quad \text{for } t_1 \geq 300 \quad (3.69b)$$

where, V_{pr} is volume of potential overflow for remaining water (ft³)

V_r is volume of remaining water (ft³)

d_r is depth of remaining water (ft)

d_b is depth of berms (ft)

t_r is travel time for remaining water (s)

The runoff water balance is next calculated where water is added and subtracted from the inflow. The runoff water balance is performed in the following steps to the sections water volume:

1. Add inflow that reaches the end of the section
2. Subtract infiltration
3. If overflow volume is greater than water volume above berms
 - a. Then, overflow volume equals water volume and water volume set to zero
 - b. Else subtract overflow
4. If outflow volume is greater than water volume
 - a. Then, outflow volume equals water volume and water volume set to zero
 - b. Else subtract outflow
5. Add in the remainder of the inflow

Infiltration is performed before outflow and overflow because infiltration occurs within the section and the water is exposed to the infiltration process first. The final step for the runoff water balance is to calculate the remaining water depth for the next time step. If

the travel time for the remaining water is less than five minutes, then depth is the remaining volume divided by the section length and effective depth. If the section overflow is greater than five minutes then the depth remains the same. The depth remains the same, because the remaining volume is unable to reach the end of the section within one time step and must be allowed to add to another.

Pooling Water Balance

The pooling water balance is performed on all sections that are pooled at the same time. The inflows for the effluent and rain parts are combined, because the pooled water begins to mix. The pooling water balance first performs water routing to determine the average outflow, overflow, and remaining volume. Next, the system is checked to see if the section needs to switch back to the runoff water balance. If no switch is needed, then infiltrated water is added to the soil layer, and the volume of water in each section is set to the routed depths. Outflow and overflow are the average for the routing calculations.

Routing of the water for the pooling section is based on Equation 3.70 (McCuen, 2005). The routing inflow is the sum of inflow plus net rainfall. Routing outflow includes both outflow and overflow. Routing is performed in the module by adding the starting volume, rainfall, and inflow together for the routing volume. The volume of infiltration is calculated and subtracted from the routing volume. Finally, half of the initial outflow is subtracted from the routing volume to solve the left-hand of Equation 3.70. Initial outflow is interpolated linearly from the spreader stage-discharge curve for the starting depth at the spreader. Overflow is calculated as weir flow over the spreader with a check of the volume above the overflow amount. The routing volume is the right-hand side of Equation 3.70 converted to a volume. The final depth is solved by iteration, so the final volume, half of the final outflow and overflow are equal to the routing volume within plus or minus 10^{-6} . Final outflow is interpolated linearly from the spreader stage-discharge curve and final depth. Overflow is the average of the overflow based on the broad-crested weir (Equation 3.2). The weir depth is half of the difference between spreader depth and berm depth. Half the depth is used to take into account the slope of the VTA. Weir length is twice the spreader depth above the berms divided by the VTA slope. This is the length along the berm that has water above the berms. The

overflow volume is checked for against the water above the berms to ensure overflow volume does not exceed it. The section's outflow and overflow are an average of the initial and final routing outflow and overflow.

$$\frac{O_2}{2} + \frac{V_2}{T} = \frac{I_1 + I_2}{2} + \frac{V_1}{T} - \frac{O_1}{2} \quad (3.70)$$

where, O is outflow (cfs)

V is volume (ft³)

T is time (300 s)

I is inflow (cfs)

1 and 2 are the initial and final for the time step

Surface Constituent Balance

The surface constituent balance is performed for both the runoff and pooled water balance after each water balance for every time step with water on the surface. First, the constituents in the inflow are added to the constituents in the surface constituents. Next, the percent sediment removed through filtration is computed with the Kentucky Filtration Model for zones C and D (Equation 2.26). The settling velocity is determined by Stoke's Law (3.32a) using the same assumptions as for the settling basin module. The initial particle diameter was assumed to be 2 μm. Constituents are removed from the surface and placed in the soil in proportion to the volume of infiltration to the total water. If the ratio of the amount of sediment removed by filtration to total sediment is greater than ratio of infiltration amount to total water, then sediment, P, organic-N, and COD are removed in proportion to the infiltrated ratio. This makes the assumption that P, organic-N and COD are sediment bound. All constituents are checked so that amounts removed do no exceed amounts in the surface water. After the amounts of constituents removed are subtracted from the surface total, constituents in the outflow and overflow are subtracted from the surface. The amounts of constituents in the outflow and overflow are computed so the concentrations of constituents in the outflow, overflow, and surface at the end of the time are equal.

CHAPTER 4 - Model Sensitivity

Different inputs to the VTA model have different impacts to the amount of outflow from the VTA module. By varying different inputs of the VTA module, the sensitivity to each of those variables can be observed. The area, slope, aspect ratio, soil conductivity, and Manning's roughness number were tested for sensitivity in the VTA module. Also, the concentration of constituents was tested in the VTA and lagoon module.

Methods and Materials

The method for testing the sensitivity was performed by creating a basic design of the feedlot, VTA, and lagoon. The five VTA inputs were each changed separately and simulations were run for a range of values for each input. The inputs were area, aspect ratio, slope, Manning's number, and soil conductivity. Also the inflow concentrations were varied for both the VTA and lagoon. Each variation was simulated with weather data from the Kansas Weather Data Library at Scandia and Ottawa, KS. Scandia is located in the north central part of Kansas, while Ottawa is located in the east central part. Hyetographs for the two sites were generated by the hyetograph module. The sensitivity started with the basic design for the feedlot components and initial values of the parameter evaluated for sensitivity. Table 4.1 shows the basic parameters for the VTA with more information about the plant type and soil type in Appendices A and B, respectively. The feedlot is a square lot with the design values shown in Table 4.2. Table 4.3 shows lagoon's basic design. The lagoon was undersized by about 50% for the Scandia site, so more overflow would occur to give a more robust comparison to the VTA. No settling basin was used because the module was not needed for the sensitivity analysis and to allow higher concentrations in the VTA and the lagoon for comparison.

Only five parameters were selected because of the time required to run the model. The parameters were simulated with between seven and nine changes per site. The two sites modeled required that the VTA module be run about 80 times and required about 40

hours to complete all the simulations. Area was selected because it is a parameter that the user has the most control over. If the VTA system is inappropriate compared to a lagoon, the user can add area to the VTA, if available. Soil properties and slope can be changed but massive reconditioning of the soil or land movement is required. The aspect ratio was analyzed to determine if it has a major effect on the performance of VTA and if it should be considered in the design of the VTA. Manning's number was analyzed because the amount for each plant type given represents the average value. Manning's number for a plant type can vary for the same plant depending of factors such as plant stem density and height. This sensitivity analysis was used to determine if variations in Manning's number should be a concern for the user. Slope and soil conductivity were analyzed for the same reason as Manning's number. Slope for the VTA represents the average slope for the entire area, and it was analyzed to determine if errors in slope measurements could affect the VTA performance. Soil conductivity was chosen to represent the soil properties. Conductivity along with wilt point, field capacity, and porosity are mostly determined from other characteristics of the soil. The most-readily available data comes from NRCS website that usually has one or two samples per county for a particular soil type. Due to soil-heterogeneous nature of soil, the soil properties can vary within the same soil type. All the soil properties are related to each other, but conductivity was chosen because conductivity is not listed on the NRCS website and must be estimated.

The input concentrations for the constituents were changed and compared between the lagoon and VTA to see if concentration could change the results of the design comparison. If the results for the design comparison change, then this would indicate that the method for estimating constituent concentrations in the runoff from the feedlot is important. If little or no change in the results is found, then the concentration of constituents from the feedlot is probably unimportant for the design comparison between two treatment systems.

Table 4.1. Initial values of parameters used in the VTA sensitivity analysis.

Length - ft (m)	1,320 (402)
Width - ft (m)	660 (301)
Slope (%)	2.0
Berms - ft (m)	1.0 (0.30)
Spreaders	None
Soil Type	Silt Loam
Plant Type	Alfalfa

Table 4.2. Basic design of feedlot for sensitivity analysis.

Length - ft (m)	660 (201)
Width - ft (m)	660 (201)
Slope (%)	3.0
Animal Type	Beef
Animal Weight - lbs (kg)	1,000 (454)
Number of Animals	1,000
Scraping Efficiency - %	85.0
Scraping Dates	Jan. 1
	Mar. 31
	June 29
	Sept. 29

Table 4.3. Basic design of lagoon for sensitivity analysis.

Length - ft (m)	120 (37)
Width - ft (m)	120 (37)
Depth - ft (m)	20 (6.1)
Side Slope	3:1
Seepage Rate - in./day (mm/day)	0.01 (0.25)
Pumping Rate - gph (L/s)	10,000 (10.5)
Pumping Time - hr/day	10
Non-Pumping Period	12/01-03/31
Conservation Depth -ft (m)	0 (0)

The area of the VTA was simulated with various relative areas to the original value of 0.50, 0.62, 0.75, 0.87, 1.00, 1.12, 1.25, 1.37, and 1.50. All variations of the VTA were done by changing the length of the VTA. The lengths were rounded to the nearest 10-ft (3-m) section. As area increases the capacity for the VTA to infiltrate water should also increase and outflow should decrease.

The aspect ratio is the length to width ratio of the VTA. Changes in the ratio could affect the convergence of flow and the effective width of the VTA. The different aspect ratios modeled for the VTA were 0.4, 0.5, 0.67, 1.0, 1.5, 2.0, and 2.5. The area of the VTA was maintained with the length rounded to the nearest 10-ft (3-m) interval. The 2.0 aspect ratio represented the basic design of the VTA.

The VTA slope affects the velocity and depth of flow through Manning's equation, which changes the retention time and the infiltration rate of the VTA. As slope increases, the velocity of flow should increase and depth decrease. The retention time and infiltration rate should also be lower. All of these effects should increase outflow. The slope of the VTA was varied from 0.5% to 4.0% in 0.5% intervals. The 2.0% slope is the VTA basic design.

Manning's roughness number affects velocity and depth of flow. As Manning's number increases, the velocity should decrease and depth increase. This will have the opposite effects on the outflow as slope. Manning's values tested ranged from 50% to

200% of the original value. Manning’s numbers tested were 0.12, 0.18, 0.22, 0.24, 0.26, 0.36, and 0.48. The original value was 0.24.

Soil conductivity is one of the parameters of the soil data file. Increasing conductivity should increase the infiltration rate and decrease outflow. With higher conductivities, the soil should be able to infiltrate water at a faster rate. Soil conductivity was the only soil data varied with the others held constant. Although the other soil parameters were simulated as constant, this is not the real case. The soil properties are dependent on one another and changes can affect other soil data. The constant soil parameters were needed to test sensitivity of conductivity. Soil conductivity was simulated at 50% to 200% of the original value for each layer. The original soil conductivities for the first through fifth layers were 0.824 (2.094), 0.540 (1.372), 0.396 (1.006), 0.414 (1.052), and 0.080 in./hr (0.204 cm/hr)

The lagoon and VTA input concentrations of constituents were varied to test the sensitivity of the concentrations to the concentration of constituents in the outflow. All models have a degree of uncertainty and simulated results are only an estimate. For this model, the percent removal and comparison of lagoon to VTA are more important than actual concentrations for the lagoon. By varying the concentrations of input constituents, the sensitivity analysis can show if the percent change and comparison remain the same. The input concentrations were simulated using concentrations of 50%, 75%, 90%, 100%, 110%, 150%, and 200% of the original values. The original weighted mean concentrations from the feedlots are shown in Table 4.4.

Table 4.4. Original inflow weighted mean concentrations (ppm) of constituents for the Scandia and Ottawa, KS tests.

Constituents	Scandia	Ottawa
P	32.7	32.6
Organic-N	214	211.
Ammonium-N	0.491	0.489
COD	3,257	3,229

Results and Discussion

The results of the sensitivity analysis for area, slope, soil conductivity, Manning's number, aspect ratio, and input concentrations are shown in terms of the relative change in the total outflow of water of volume. Also, organic-N, ammonium-N, P, and COD are expressed as the percent change in total mass in the outflow compared to the original total mass outflow.

Figure 4.1 shows that as area increases the volume of outflow decreases. The rate of decrease begins to level off as the size of the VTA increases. Figure 4.2-Figure 4.5 have the same general pattern for ammonium-N, organic-N, P, and COD. Organic-N, P, and COD have a greater relative change for than for the outflow. This is probably due to additional removal of the sediment-bound portion of these constituents. Increasing the area allows for more area for infiltration to occur and the outflow decreases. The decrease in water outflow levels off with larger areas, because of the outflow of runoff that occurs from the precipitation only on the area. The outflow of constituents begins to level off probably because the constituents become more diluted with rain water. This dilution would remove fewer constituents for the same volume of water infiltrated as the water progressed further down the VTA.

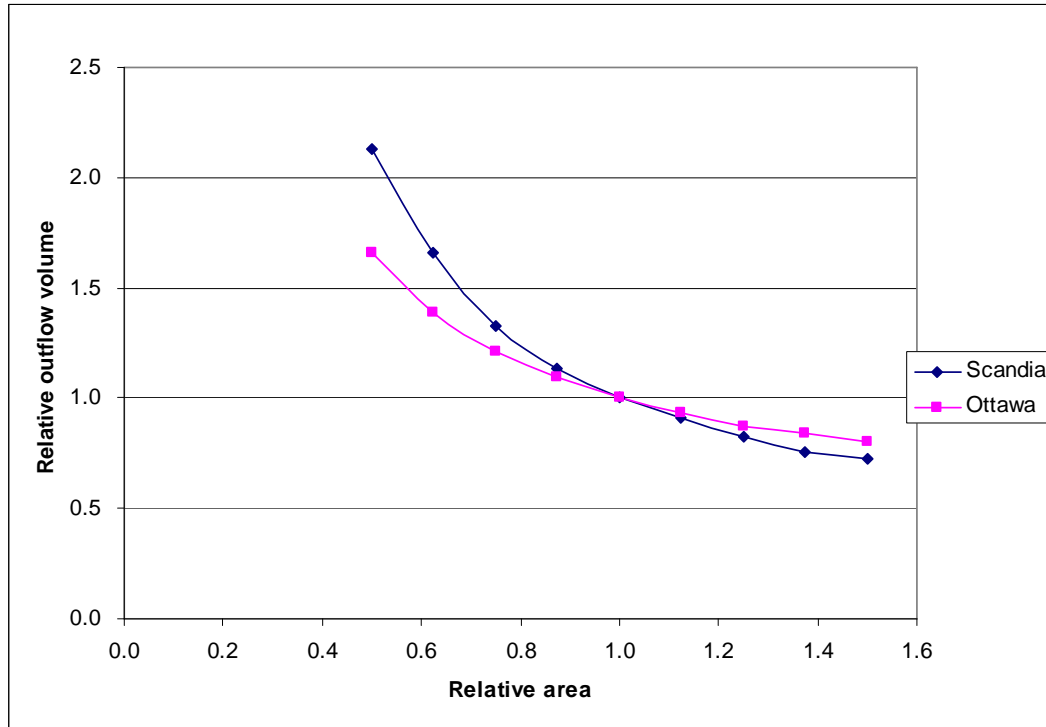


Figure 4.1. Relative outflow volume from the VTA compared to relative area of the VTA.

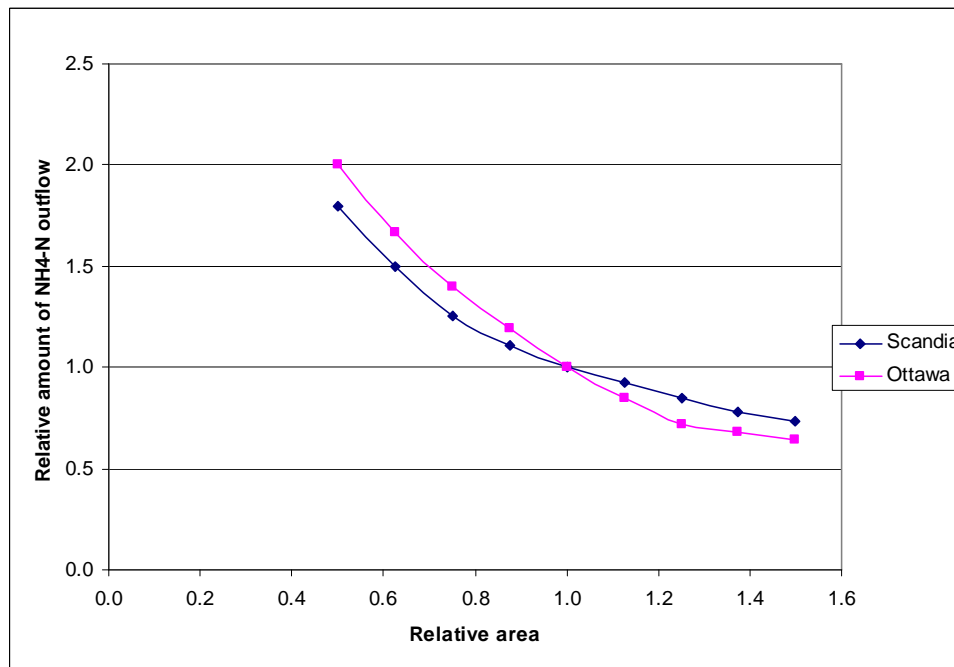


Figure 4.2. Relative amount of ammonium-N outflow from the VTA compared to relative area of the VTA.

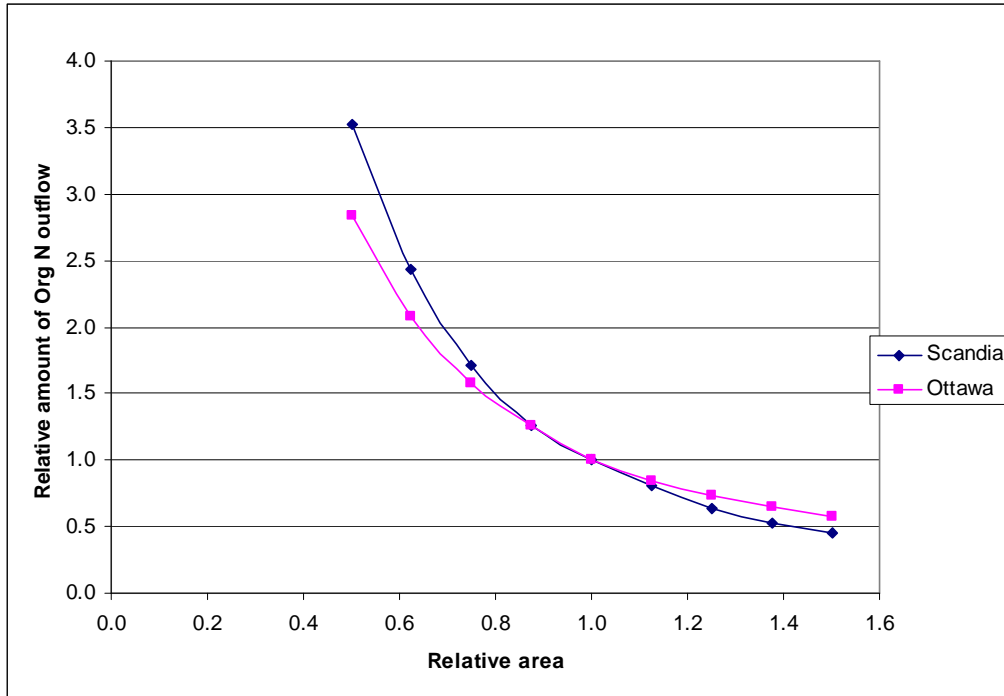


Figure 4.3. Relative amount of organic-N outflow from the VTA compared to relative area of the VTA.

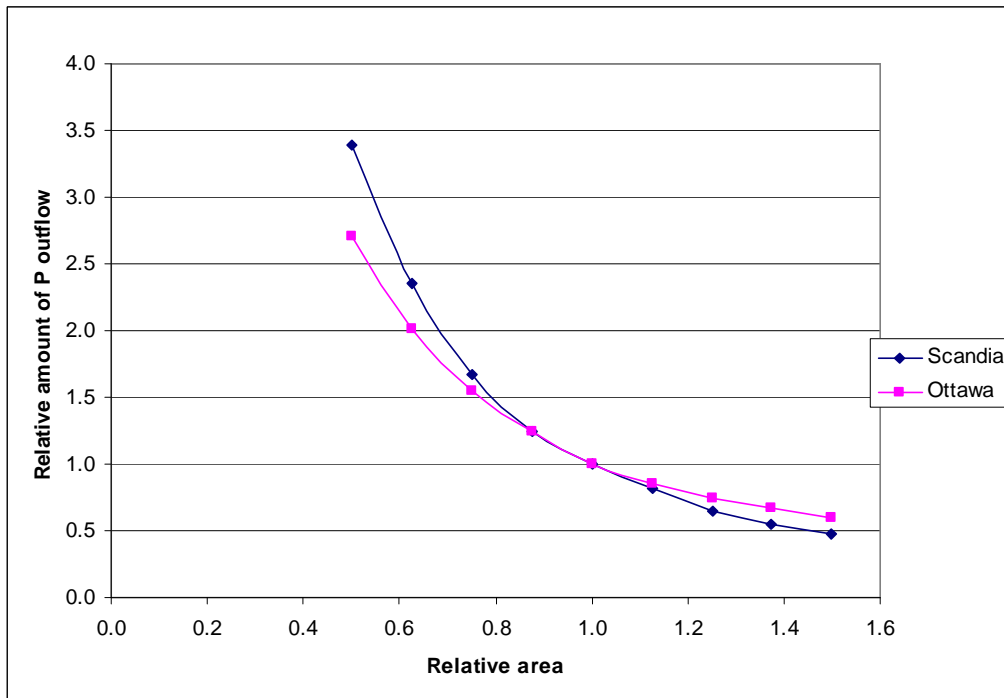


Figure 4.4. Relative amount of P outflow from the VTA compared to relative area of the VTA

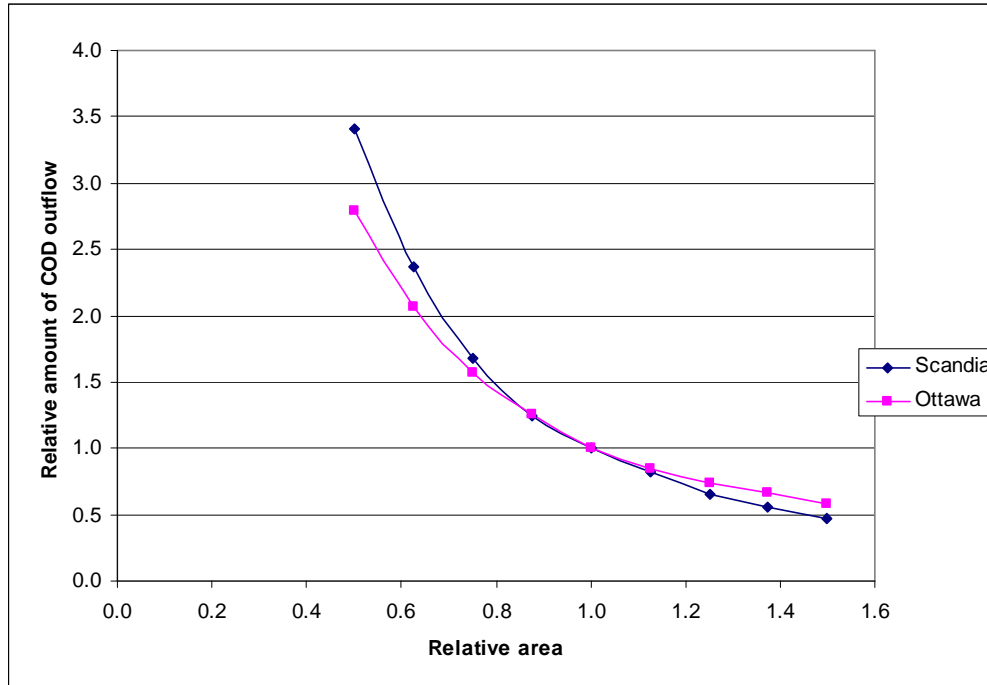


Figure 4.5. Relative amount of COD outflow from the VTA compared to relative area of the VTA

In Figure 4.6, the general trend is for outflow to decrease with increasing soil conductivity. Figure 4.6 also has a diminishing effect on the relative change in outflow with increasing soil conductivity. Higher soil conductivity increases infiltration and decreases outflow. Figure 4.7-Figure 4.10 show that ammonium-N, organic-N, P, and COD have the same general pattern, but with a smaller relative change.

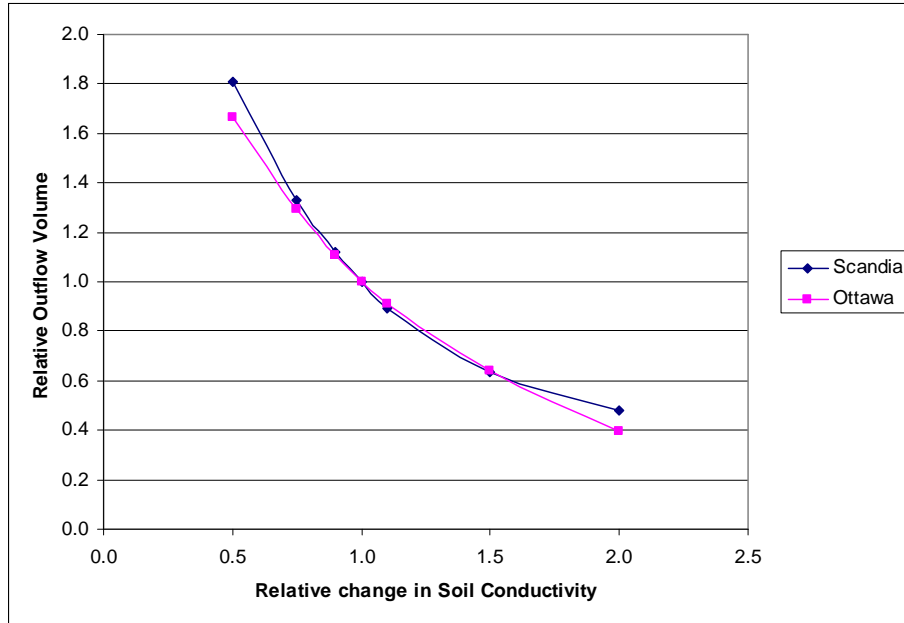


Figure 4.6. Relative change in outflow from the VTA compared to percent relative in soil conductivity.

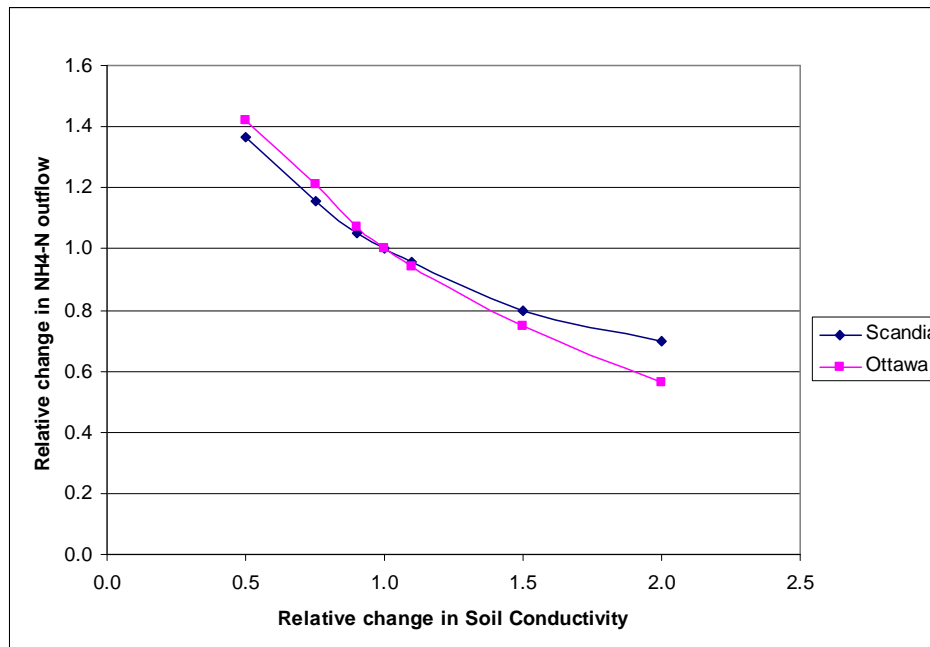


Figure 4.7. Relative change in ammonium-N outflow from the VTA compared to relative change in soil conductivity.

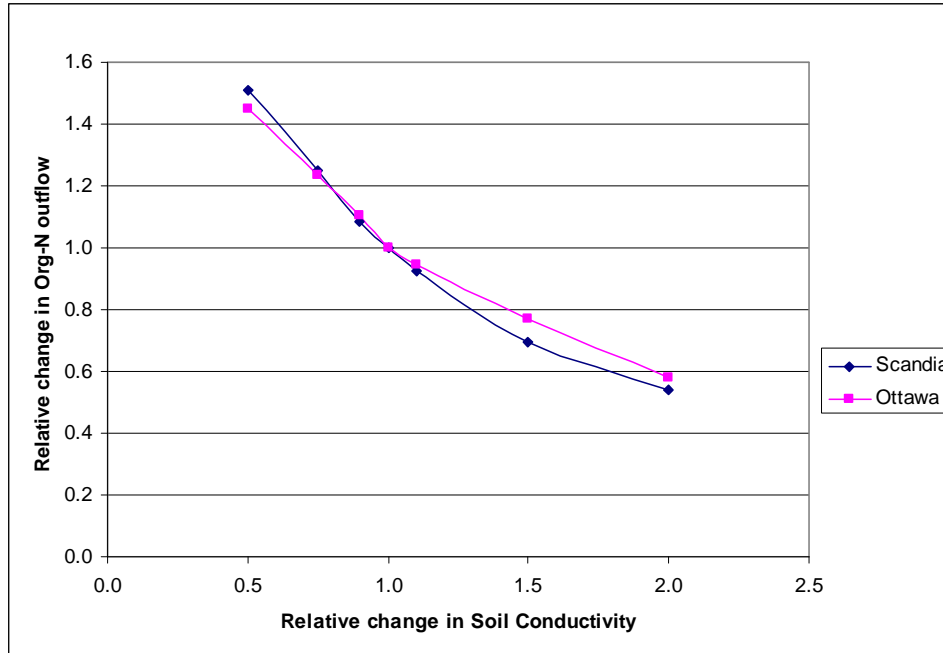


Figure 4.8. Relative change in organic-N outflow from the VTA compared to relative change in soil conductivity.

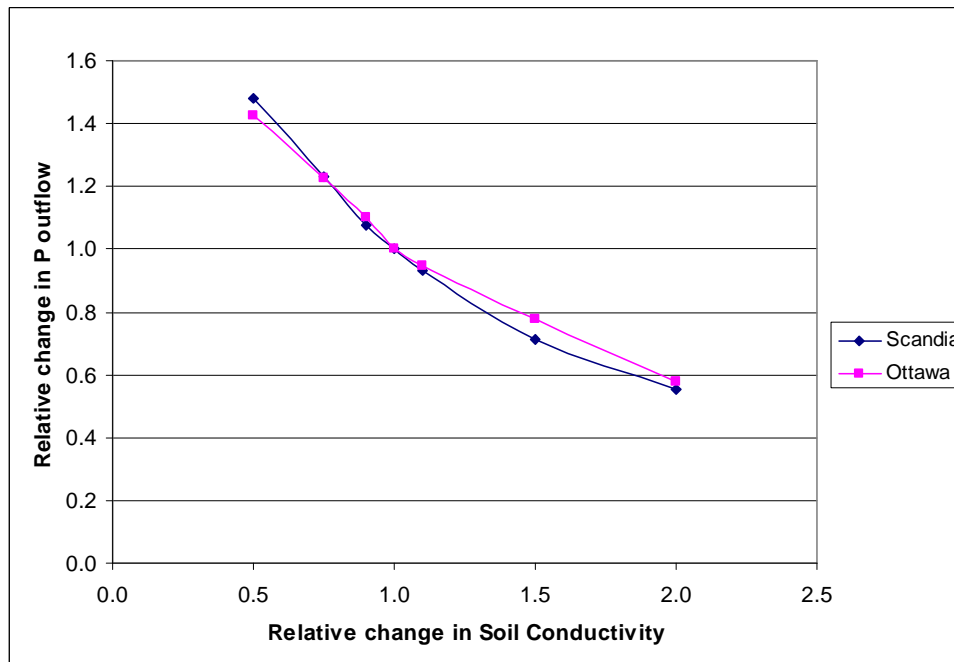


Figure 4.9. Relative change in phosphorous outflow of the VTA compared to relative change in soil conductivity.

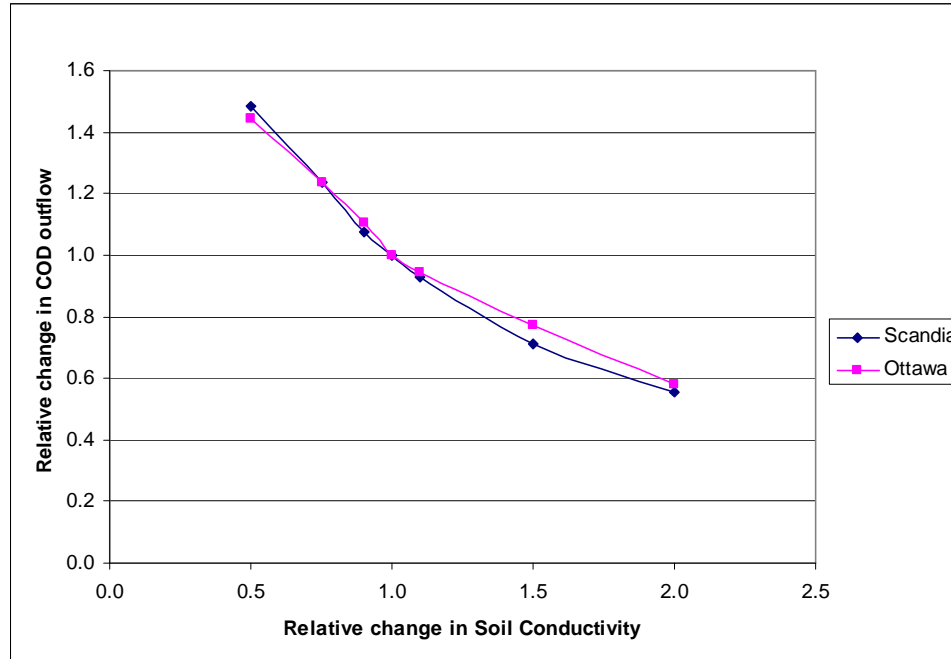


Figure 4.10. Relative change in COD outflow of the VTA compared to relative change in soil conductivity.

As slope increases, the velocity of water within the VTA increases because of Manning's equation (Equation 3.1) as shown in Figure 4.11. The increase in velocity will decrease retention time and allow less time for infiltration to occur. Figure 4.11 and Figure 4.12 show the percent change of water and ammonium-N outflow varies by only a few percent over the entire range of percents. This indicates that outflow and infiltration are influenced only minimally by slope. Figure 4.13-Figure 4.15 reveal that organic-N, P, and COD have greater sensitivity to slope, because these constituents can be removed by sedimentation and velocity is included in the model. Overall, slope has little influence on infiltration, but can influence sediment-bound constituents.

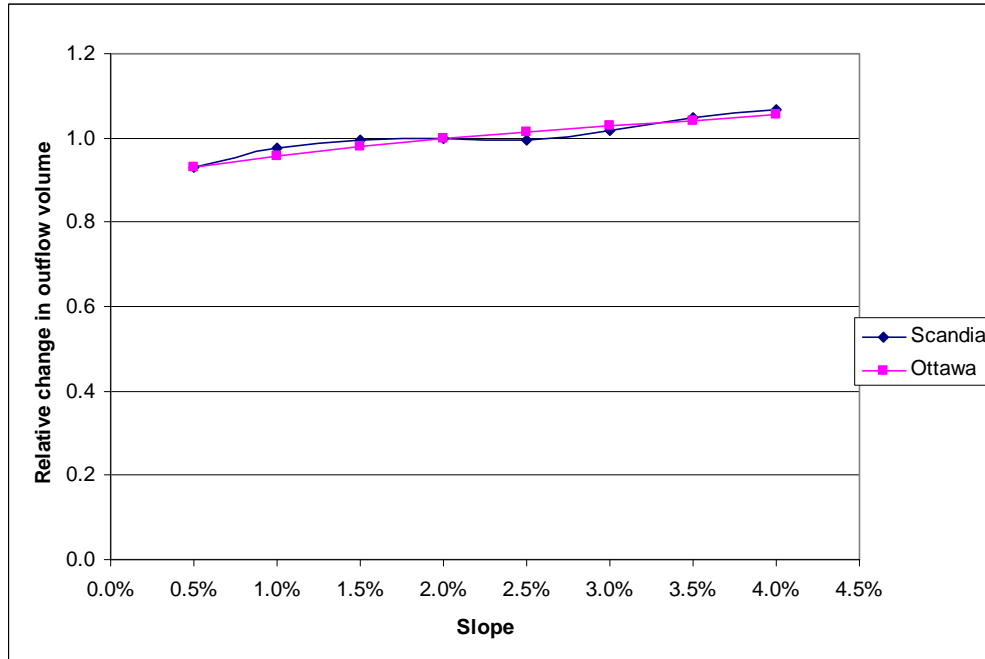


Figure 4.11. Relative change in outflow for different slopes in the VTA.

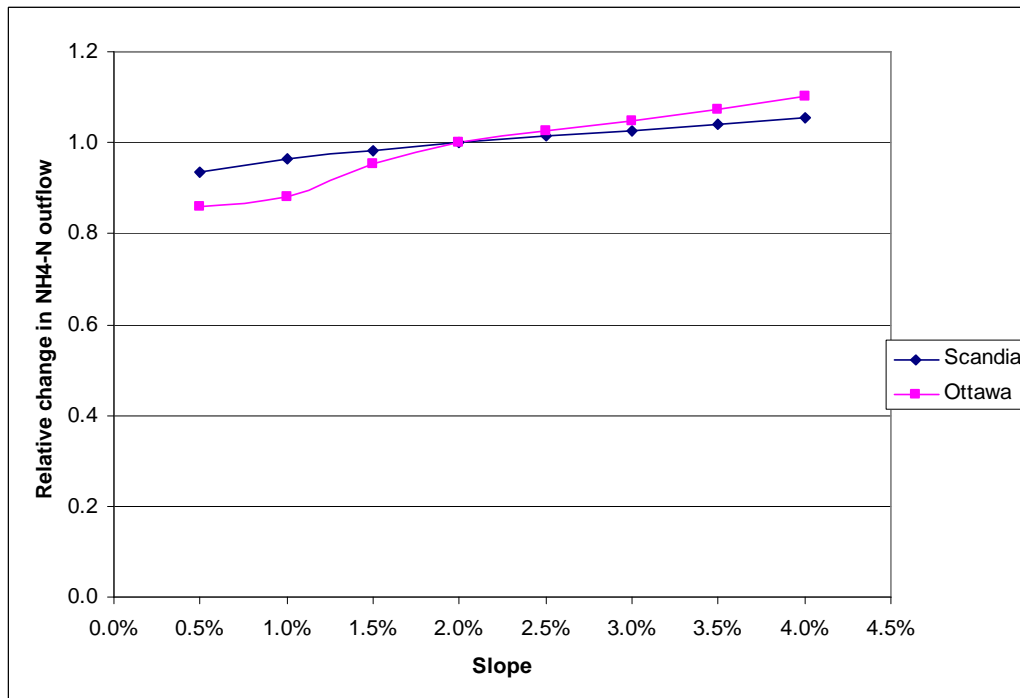


Figure 4.12. Relative change in ammonium N outflow for different slopes in the VTA.

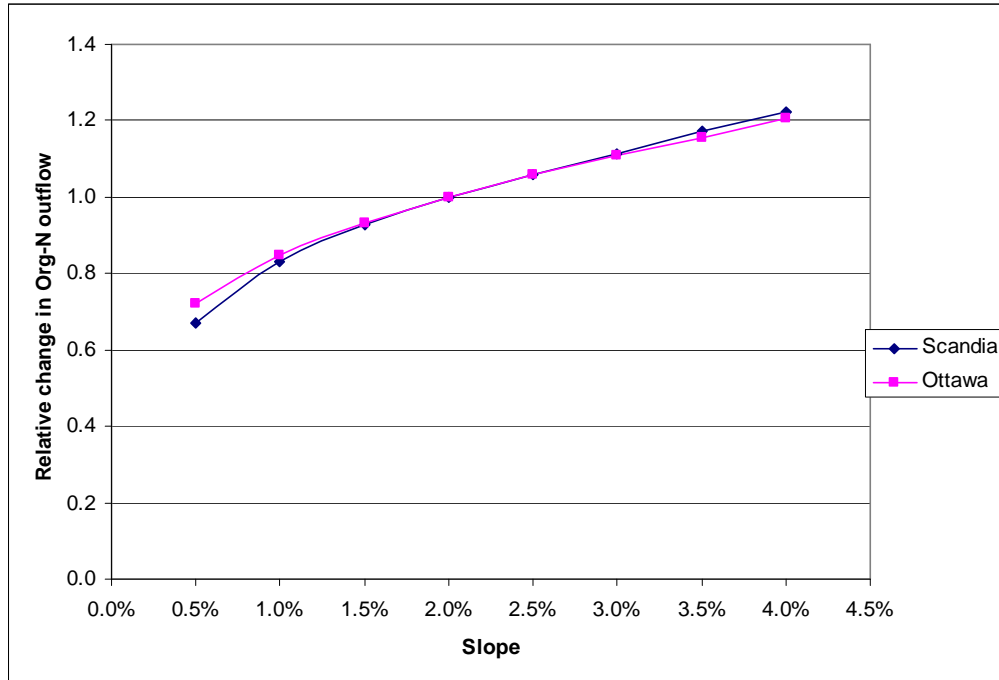


Figure 4.13. Relative change in organic N outflow for different slopes in the VTA.

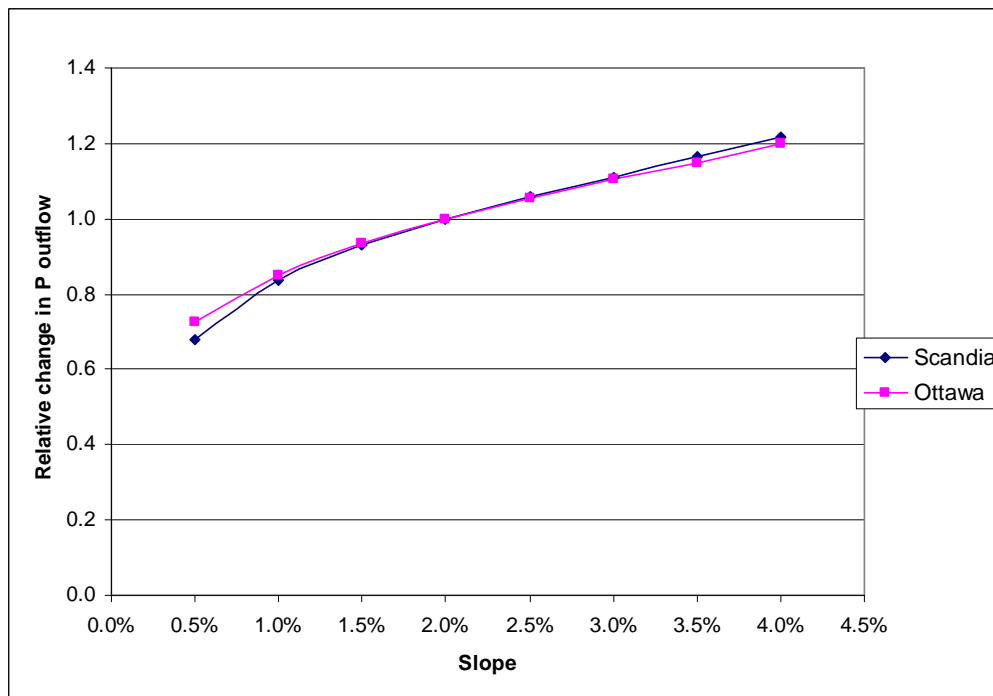


Figure 4.14. Relative change in P outflow for different slopes in the VTA.

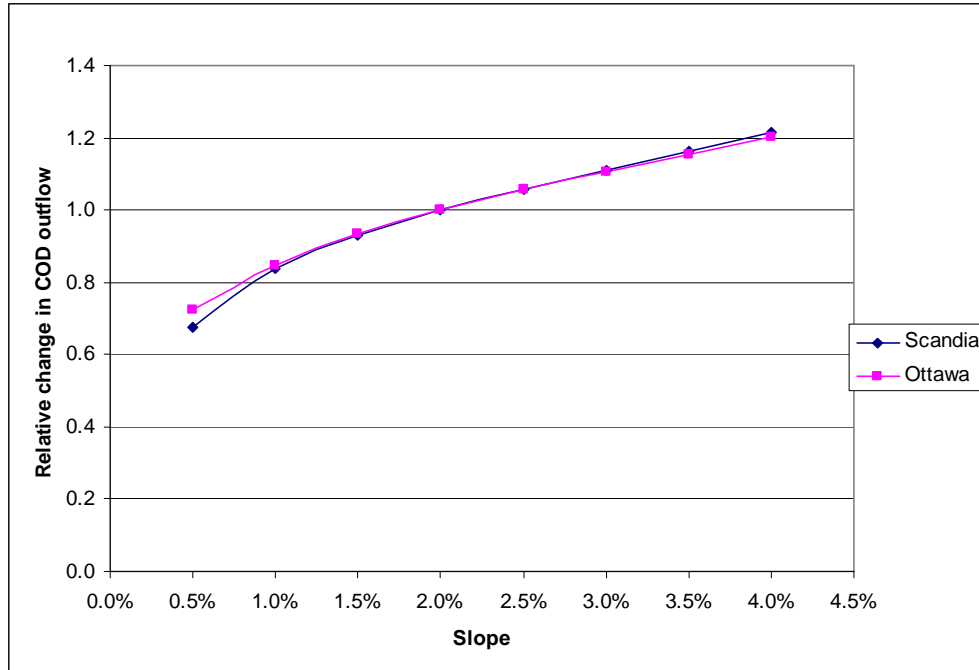


Figure 4.15. Relative change in COD outflow for different slopes in the VTA.

Manning's numbers has the opposite effect of slope. When Manning's number is increased, the velocity decreases. Manning's number has only a slight influence on infiltration and water outflow (Figure 4.16). In Figure 4.17, Manning's number changes the ammonium outflow by less than 10% over the entire range. Both Figure 4.16 and Figure 4.17 have inconsistencies due to the slight differences in the calculations of velocity for inflow and amount of remaining water for a VTA section. Inflow is calculated based on the inflow flow rate and amount of remaining water is calculated by the depth of water covered entirely by the remaining water. This difference can cause slight differences in the calculations over the 35-year simulations and is only noticeable due to the minor changes caused by Manning's number. Organic-N, P, and COD have a greater percent change by Manning's number, but the range is only $\pm 15\%$ from the basic VTA design (Figure 4.18-Figure 4.20). The range of Manning's numbers tested (0.12-0.48) is greater the recommend range of values for alfalfa (0.17-0.30) (Munoz-Carpena and Parsons, 2005). The results of the sensitivity analysis indicate that Manning's number is not a very sensitive parameter. Comparing the results of slope and Manning's number indicates that slope has a greater influence on organic-N, P, and COD, because of the greater range of percent change of constituent outflows.

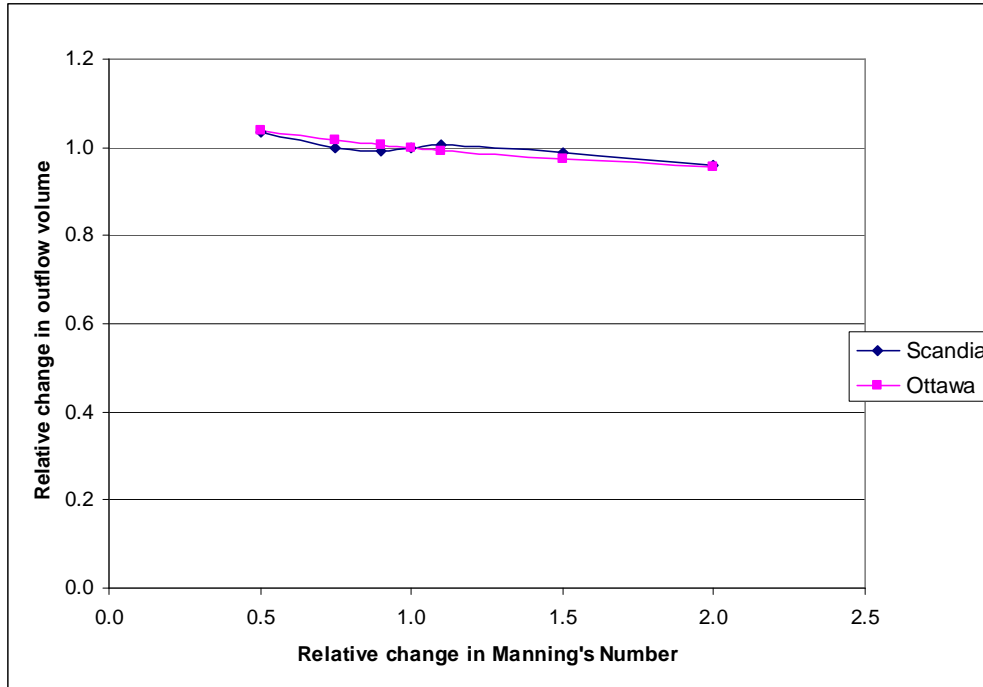


Figure 4.16. Relative change in outflow from the VTA compared to relative change in Manning's number.

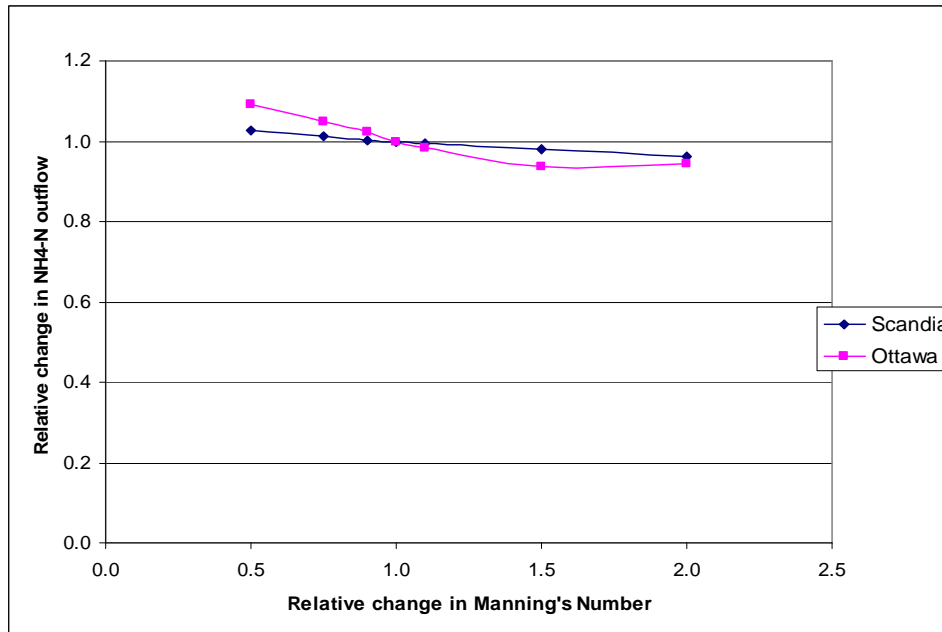


Figure 4.17. Relative change in ammonium-N outflow from the VTA compared to relative change in Manning's number.

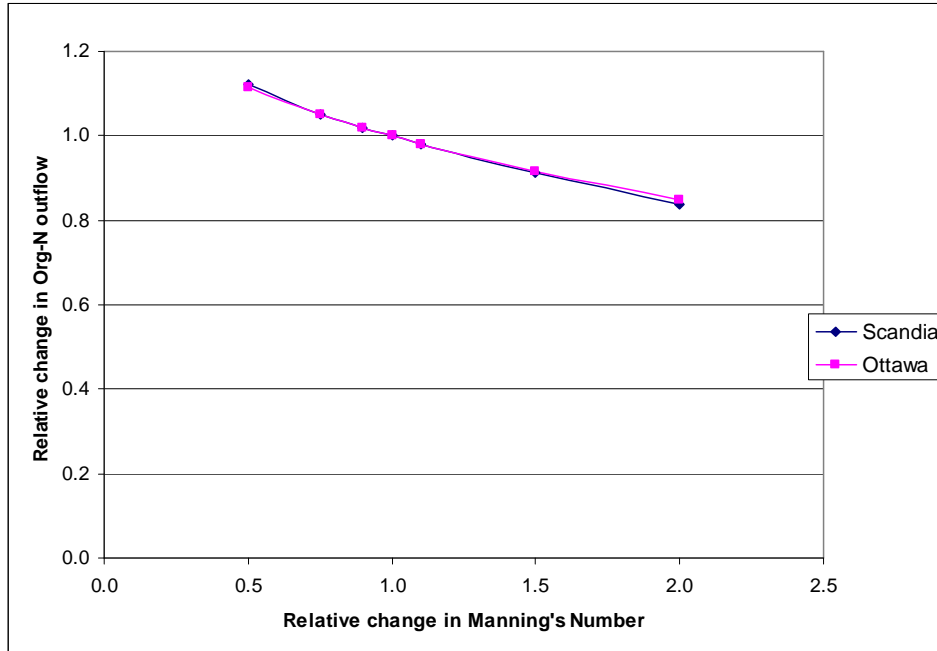


Figure 4.18. Relative change in organic-N outflow from the VTA compared to relative change in Manning's number.

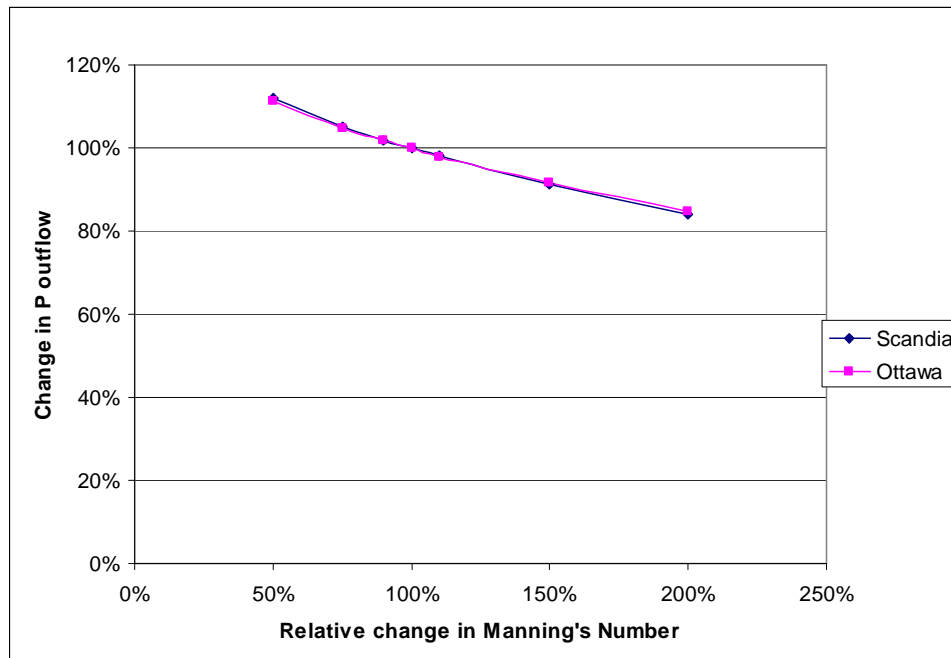


Figure 4.19. Relative change in P outflow from the VTA compared to percent relative in Manning's number.

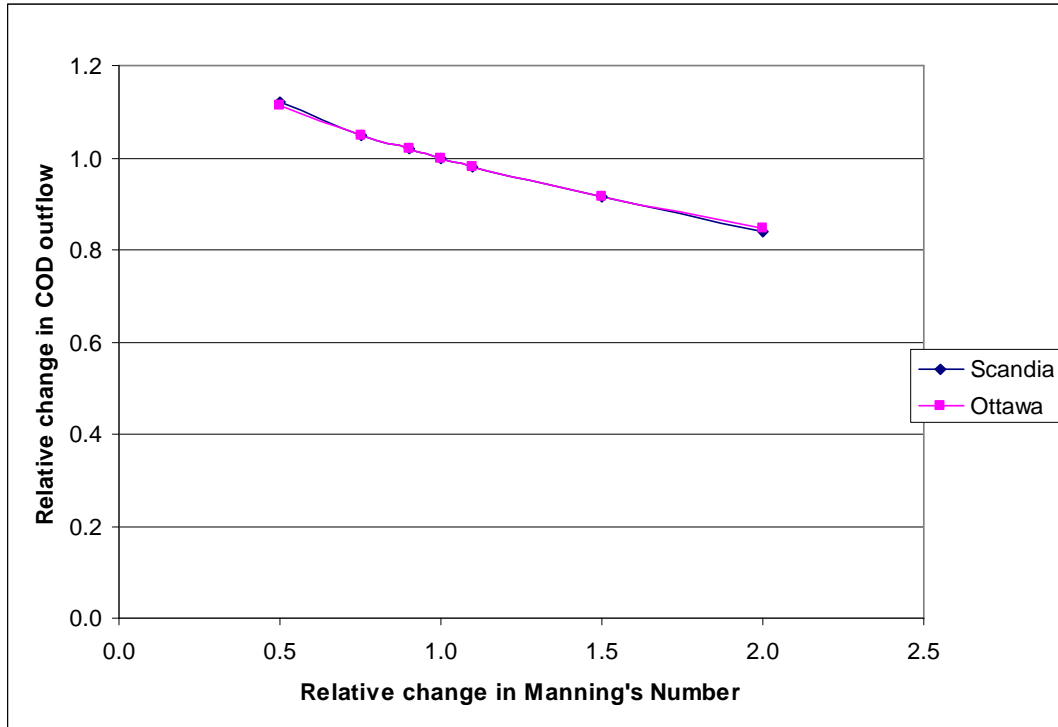


Figure 4.20. Relative change in COD outflow from the VTA compared to percent relative in Manning's number.

Aspect ratio is the ratio of length to width. An aspect ratio of less than one means that the VTA's width is greater than it is long. A larger width will increase the initial infiltration area for the inflow. The larger width also slows down the flow, because the effective width decreases the amount per unit width added which decreases the depth of water added. Similar to slope and Manning's number, the aspect ratio has little influence on the water (Figure 4.21) and ammonium-N (Figure 4.22). In Figure 4.23-Figure 4.25, organic-N, P, and COD removal is greater with smaller aspect ratios, because the increased width slows down velocities and allows more sediment-bound constituents be removed by settling. Comparing slope, Manning's number and aspect ratio graphs for organic-N, P, and COD reveals that aspect ratio falls between slope and Manning's number in its amount of sensitivity.

The smaller aspect ratios with the larger widths remove more constituents according to the model. This is under the assumption that the inflow and any other redistribution system can evenly spread the water across the entire VTA. Also, the

module assumes that slope in the width direction is almost zero. As the VTA gets wider, these assumptions may not hold true. A user must make sure that these and all other assumptions are valid for a particular site.

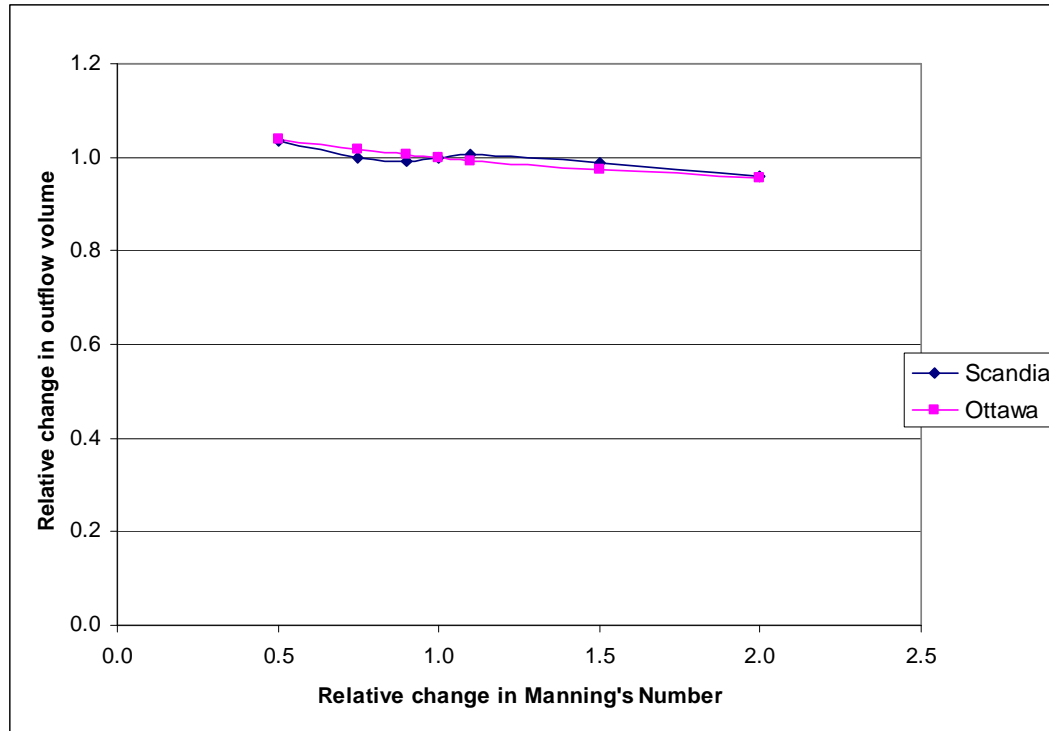


Figure 4.21. Relative change for outflow from VTA for different Aspect Ratios.

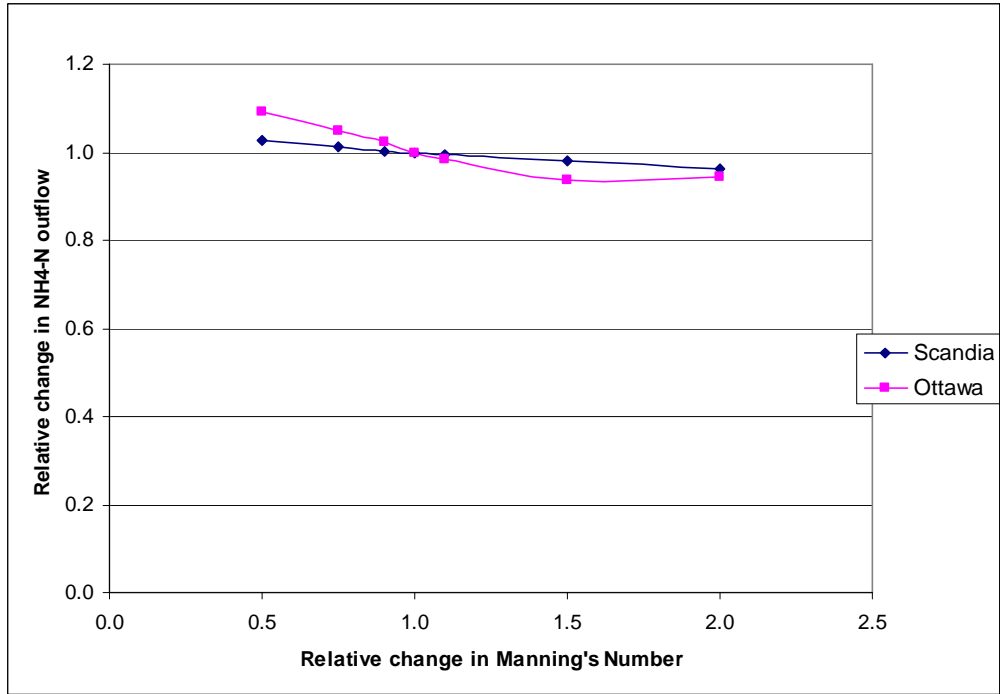


Figure 4.22. Relative change for ammonium-N outflow from VTA for different Aspect Ratios.

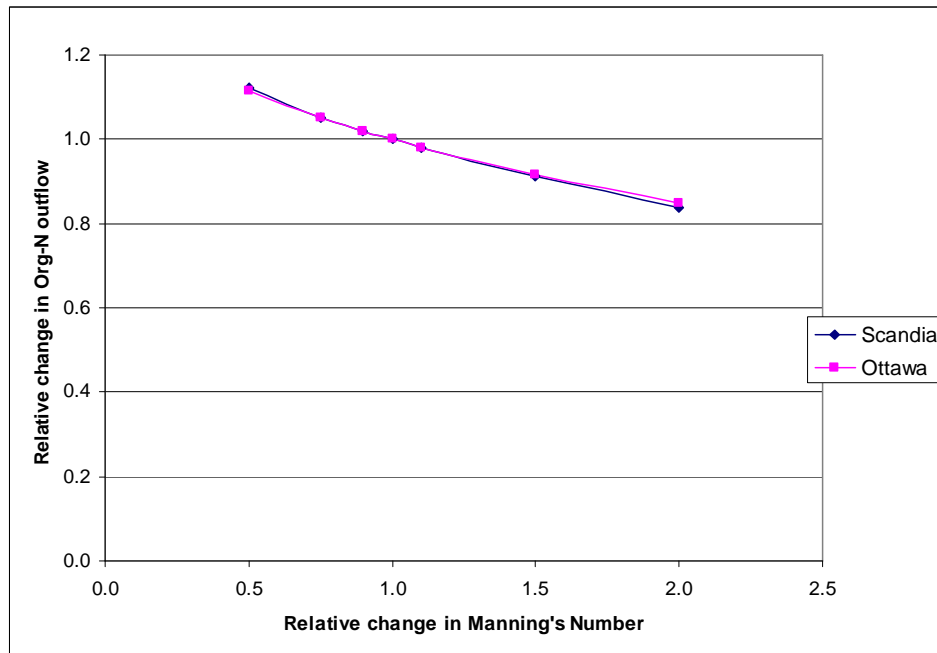


Figure 4.23. Relative change for organic-N outflow from VTA for different Aspect Ratios.

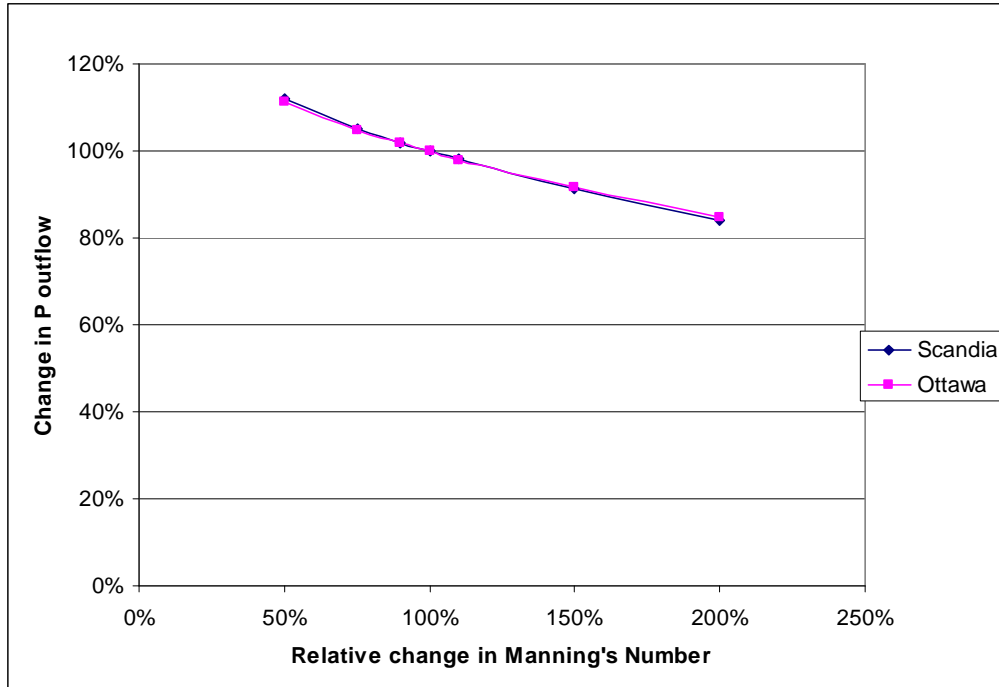


Figure 4.24. Relative change for P outflow from VTA for different Aspect Ratios.

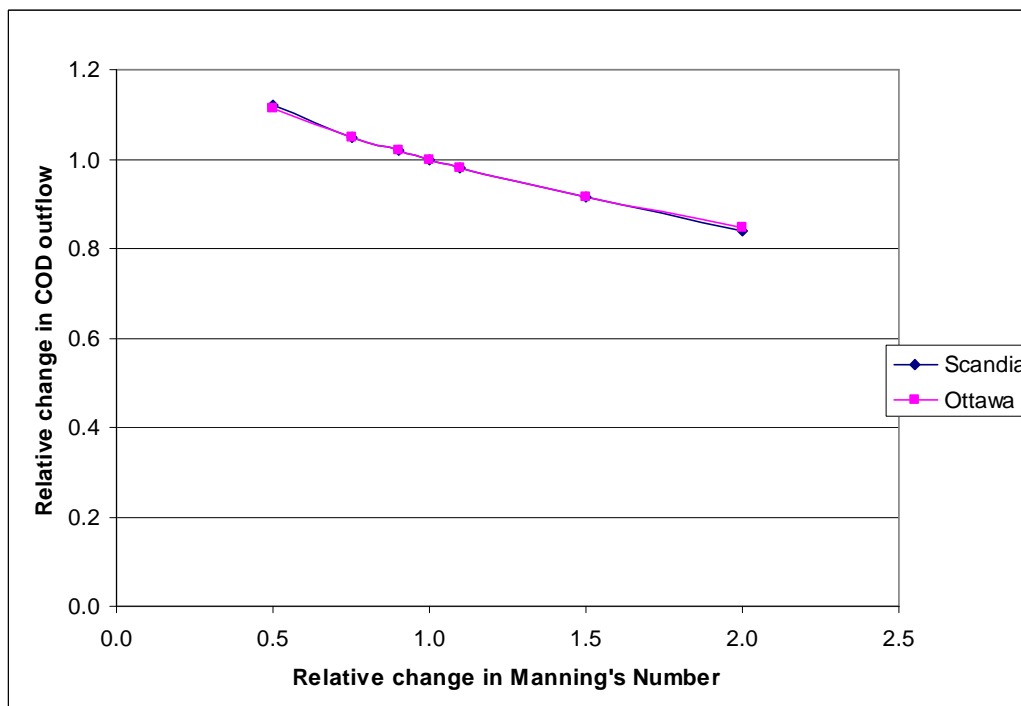


Figure 4.25. Relative change for COD outflow from VTA for different Aspect Ratios.

The concentrations of constituents for the inflow files at the two sites were adjusted by different relative concentration. Table 4.5 shows the relative change in of total outflow of P to the basic design of the VTA and Lagoon module when different relative concentrations of total P in the inflow are used. As Table 4.5 shows, the ratio of inflow and outflow for the VTA are the same, because the VTA removal method for P is calculated based on a percentage of the inflow amount. These same ratios indicated that removal by the VTA is not influenced by inflow concentrations. The Lagoon module relative outflow concentration for P is not equal to the relative change in concentration of the inflow, because the lagoon removes P by precipitation when concentrations are greater than the threshold concentration. With increasing concentrations of P, the lagoon will remove a greater percentage of P and relatively lower amounts of P will flow out. Table 4.6-Table 4.8 are the ratios of outflow to design VTA for different inflows ratios for organic-N, ammonium-N, and COD. Each of these tables has the same pattern as shown for P for the VTA in Table 4.5. All three of these tables indicated that relative removal of organic-N, ammonium-N, and COD are not influenced by different concentrations of constituents in the inflow. Only Lagoon P will be affected, if the feedlot runoff constituents are incorrect.

Table 4.5. Effect of relative amount of phosphorous inflow (concentration) on relative VTA (total mass) outflow and Lagoon (total mass) overflow from basic designs.

Inflow	Scandia		Ottawa	
	VTA	Lagoon	VTA	Lagoon
0.50	0.50	0.53	0.50	0.54
0.75	0.75	0.78	0.75	0.79
0.90	0.90	0.92	0.90	0.92
1.00	1.00	1.00	1.00	1.00
1.10	1.10	1.08	1.10	1.08
1.50	1.50	1.39	1.50	1.40
2.00	2.00	1.77	2.00	1.78
5.00	5.00	3.62	5.00	3.68

Table 4.6. Effect of relative amount of organic-N inflow (concentration) on relative VTA (total mass) outflow and Lagoon (total mass) overflow from basic designs.

Inflow	Scandia		Ottawa	
	VTA	Lagoon	VTA	Lagoon
0.50	0.50	0.50	0.50	0.50
0.75	0.75	0.75	0.75	0.75
0.90	0.90	0.90	0.90	0.90
1.00	1.00	1.00	1.00	1.00
1.10	1.10	1.10	1.10	1.10
1.50	1.50	1.50	1.50	1.50
2.00	2.00	2.00	2.00	2.00
5.00	5.00	5.00	5.00	5.00

Table 4.7. Effect of relative amount of ammonium-N inflow (concentration) on relative VTA (total mass) outflow and Lagoon (total mass) overflow from basic designs.

Inflow	Scandia		Ottawa	
	VTA	Lagoon	VTA	Lagoon
0.50	0.50	0.50	0.50	0.50
0.75	0.75	0.75	0.75	0.75
0.90	0.90	0.90	0.90	0.90
1.00	1.00	1.00	1.00	1.00
1.10	1.10	1.10	1.10	1.10
1.50	1.50	1.50	1.50	1.50
2.00	2.00	2.00	2.00	2.00
5.00	5.00	5.00	5.00	5.00

Table 4.8. Effect of relative amount of COD inflow (concentration) on relative VTA (total mass) outflow and Lagoon (total mass) overflow from basic designs.

Inflow	Scandia		Ottawa	
	VTA	Lagoon	VTA	Lagoon
0.50	0.50	0.50	0.50	0.50
0.75	0.75	0.75	0.75	0.75
0.90	0.90	0.90	0.90	0.90
1.00	1.00	1.00	1.00	1.00
1.10	1.10	1.10	1.10	1.10
1.50	1.50	1.50	1.50	1.50
2.00	2.00	2.00	2.00	2.00
5.00	5.00	5.00	5.00	5.00

In comparing the five input parameters, the area of the VTA as shown to be the most sensitive. Soil conductivity is next most important. The others in order of sensitivity area slope, aspect ratio and Manning's number. Manning's number is probably not a very sensitive parameter in the VTA module. All other parameters are determined by the design of the VTA and site restrictions. Slope, soil conductivity, and area are parameters that must be obtained on site. Slope can easily be measured when survey is done, also slopes can be estimated from elevation data. Soil conductivity can be difficult to estimate or measure. The NRCS soil lab and soil module can give rough estimates. Whenever possible, site specific data of the soil conductivity should be used.

CHAPTER 5 - VTA Calibration

The VTA module was calibrated with field data from a VTA obtained in April and May of 2002 (Mankin and Okoren, 2003). The VTA was one of three parallel VTAs that drained a 6.7-ac (2.7-ha) feedlot with 300 head of cattle in Miami County, 4 miles (6km) south of Gardner City, KS.. Each VTA was 49.1 ft (15 m) wide and 490 ft (150 m) long with a 2% slope. The sections had 1.6-ft (0.5-m) high steel berms to separate the VTAs. The soil was a Newtonia silt loam with fescue grass planted in 1994. Inflow and outflow were measured every five minutes with two, Model 730 bubbler modules each attached to an ISCO 6700 sampler. Water samples were collected at Time 0, 1, 2, 5, 8, 11, 14, 17, 20, and 23 hours after initial inflow was detected. Each sample was tested for total-P, total-N, ammonium-N, nitrate-N, and total suspended solids and reported to two decimal places in mg/L. The VTA used for the calibration was labeled VTA B.

Methods and Materials

Three storm events that produced water samples were recorded by the ISCO samplers occurring on April 21, May 7, and May 8. The inflow and outflow data were formatted into the outflow data files needed by the model. Nutrient concentrations were assumed to be constant for every five-minute increment until the next water sample was taken. Two water samples in May had no recorded values, so the averages of the water sample before and after were used. Organic-N was assumed to be the total-N minus ammonium-N and nitrate-N. For modeling operations purposes the times of day for storms were shifted by six hours so that each storm event occurred entirely in the same day and are found in Appendix C. The inflow and outflow files are labeled 'calinflow.txt' and 'caloutflow.txt' files for this thesis. The storm total for inflow and outflow are shown in Table 5.1.

Table 5.1. Total daily inflow and outflow for each of the daily ran storms.

	April 21	May 7	May 8
VTA Inflow-m ³	333.	127.	183.
VTA Outflow-m ³	105.	36.7	44.4
Inflow P-kg	0.85	0.26	0.39
Outflow P-kg	0.26	0.04	0.06
Inflow Org-N-kg	9.02	1.45	2.23
Outflow Org-N-kg	2.83	0.03	0.20

The weather data began March 1, 2002 to allow the simulated soil moisture to adjust to conditions prior to the calibration events. The New Century Airport weather station in Olathe, KS, which is 10 miles (15 km) away from the feedlot, provided most of the weather data (NOAA, 2007). The nearest weather station with ET grass reference values was 20 miles (32 km) away near Ottawa, KS. The hyetograph for calibration events was created with rainfall amounts measured with a 0.01-in. (0.025-mm) tipping bucket in five-minute intervals for the beginning in mid-April at the site. For the time before mid-April, the Hyetograph module was used to generate hyetograph. Both files are also in Appendix C. The soil parameters were originally estimated with the Soil module (Appendix B) and NRCS soil lab data (NRCS, 2007).

The calibration of the VTA modules was two-fold. First, the total volume of outflow water for the three storms was used to calibrate soil conductivity. Conductivity was adjusted by a scaling factor until the simulated volume equaled the recorded volume. This calibration was needed because of the sensitive nature of conductivity and the lack of on-site data. The scaling factor was applied to the conductivity of each of the soil layers.

The second part of the calibration of the VTA was done for removal of nutrients. Ammonium-N and nitrate-N are removed by the VTA through infiltration and are dependent on the same parameters as infiltration. Organic-N and total-P can be removed with sedimentation. The only parameters that affect sedimentation and not infiltration are particle diameter and density. Only one of these values can be calibrated with the available data. The particle diameter was chosen. The particle density is assumed to be

2.65 g/cm³. This is the particle density of mineral soil and the actual density could be lower due the high organic content in the soil and manure in the runoff. Both diameter and density have similar effects on sedimentation. The particle diameter was originally assumed to be 2.0 μm. The diameter was adjusted so total measured organic-N and P removal rates simulated agreed with measured removal rates calculated form the field data.

Results and Discussion

The original average soil conductivity calculated with the Soil module was 0.22 in./hr (0.55 cm/hr). This was assigned a scaling factor of one. This average conductivity is similar to the average conductivity of 0.26 in./hr (0.65 cm/hr) for a silt loam soil (Rawls et al., 1983). Figure 5.1 plots different scaling factors of conductivity versus the ratio of simulated to measured total outflow. A ratio of one is when the outflows are the same. The initial soil conductivity values caused the model to overestimate the measured outflow from the VTA by 1.8 times. The outflow from the model was decreased by increasing the soil conductivity by the scaling factor. As Figure 5.1 shows, a larger scaling factor decreases the outflow modeled. A scaling factor of 1.62 was found to allow the predicted outflow to be within 1% of the total outflow. This factor was used for all three storms.

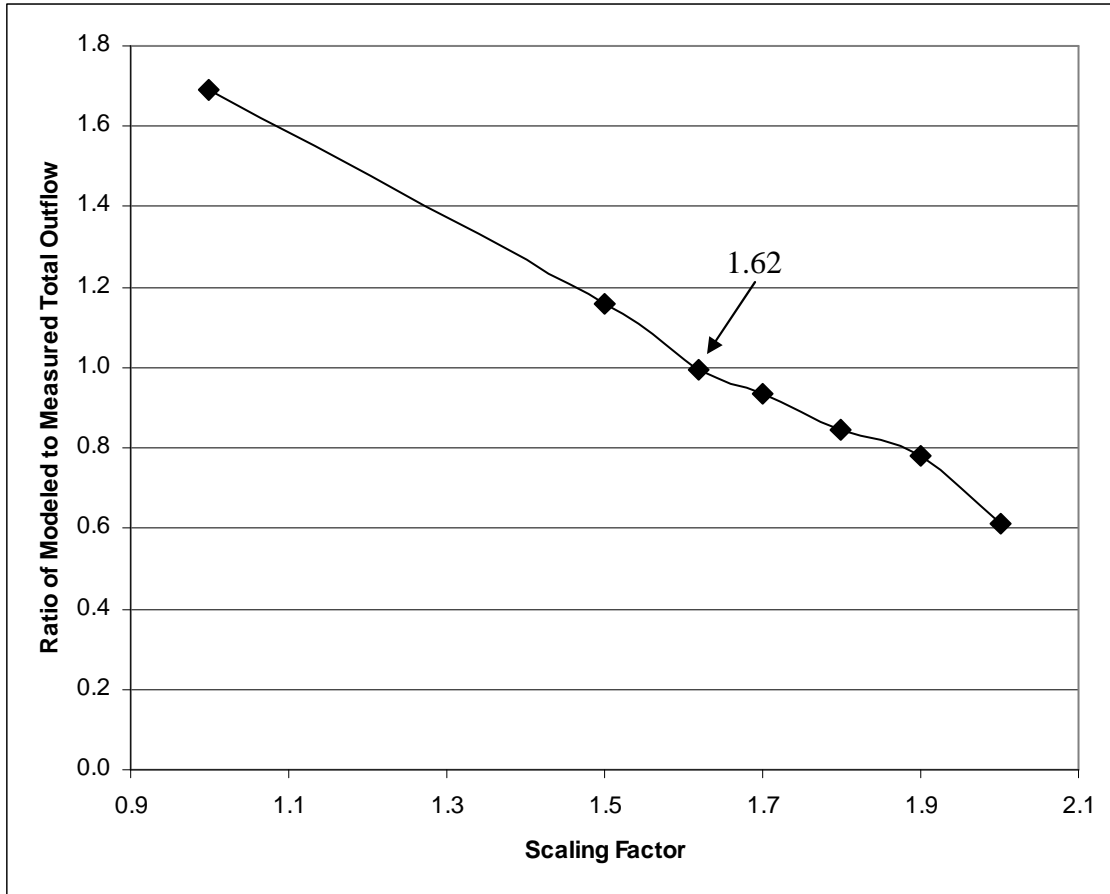


Figure 5.1. Soil conductivity scaling factor versus ratio of modeled to simulated total water outflow.

The nutrient removal was calibrated by changing the particle diameter. The original assumed value was 2.0 μm , which is the upper boundary for clay. Figure 5.2 shows the removal rate for the water runoff, total P, and organic N for the measured outflow of the VTA and the modeled outflow for different particle diameters. In Figure 5.2, the runoff is the same for the modeled values, because particle diameter does not affect infiltration or runoff. The original particle diameter (2.0 μm) overestimates the removal rate of both total-P and organic-N. Several other diameters were modeled and the 1.5- μm diameter had removal rates nearest to the measured total-P and organic-N. The 1.5- μm diameter indicates that the sediment particles removed in the VTA are clay-sized or smaller. In Figure 5.2 the general trend is for larger diameters to have higher

removal rates for total-P and organic-N, because the larger diameters allow more sediment to settle in the VTA.

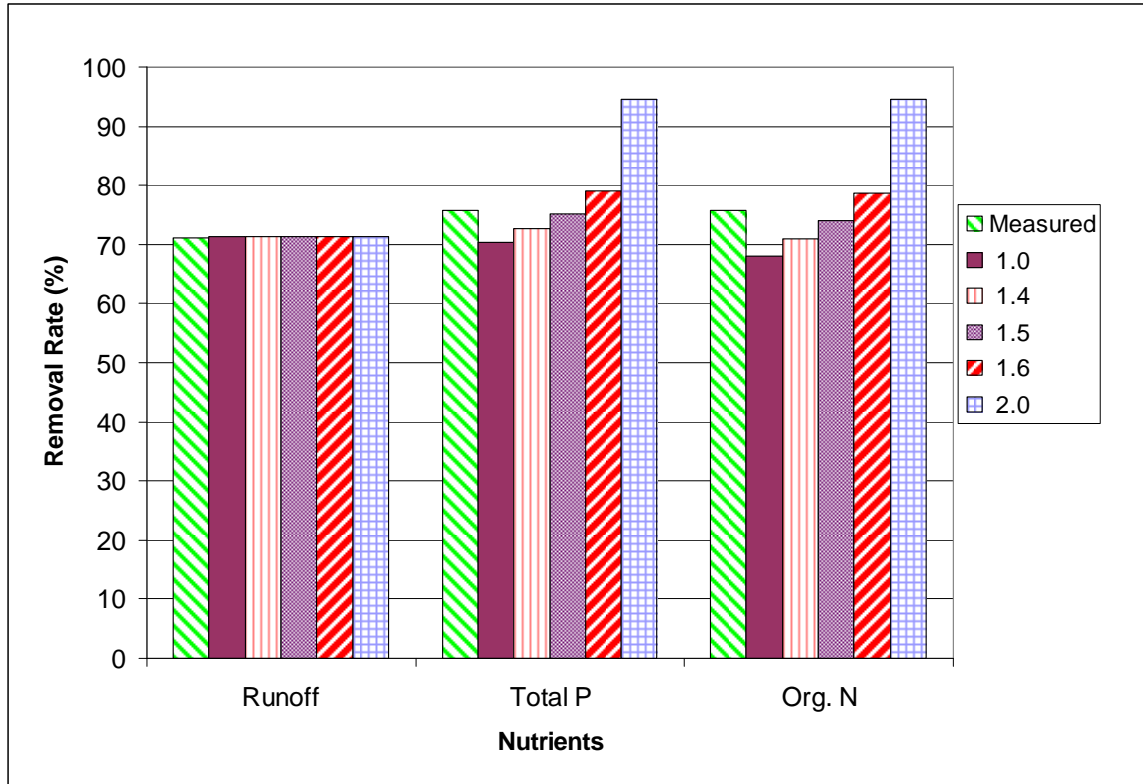


Figure 5.2. Measured and modeled mass removal rates for water, total-P, and organic-N for different particle diameters (μm).

CHAPTER 6 - Comparison Example

Two proposed sites for VTA were selected to be simulated by this model. The first site is a 5.7-acre (2.3-ha) feedlot located one mile (1.6 km) south of Ada, KS in Ottawa County (subsequently called Ada). The second site is a 2.75-acre (1.1-ha) feedlot located in Greenwood County about 6.4 miles (10.3 km) southwest of Toronto, KS (subsequently called Greenwood). The Ada site is in North Central Kansas while the Greenwood site is in Southeast Kansas. The VTAs at the sites were sized by the proposed designs diagrams, while the lagoon and settling bench were sized by several design standards.

Methods and Materials

Table 6.1 shows the dimensions of the feedlots. Both feedlots were assumed to have earthen surfaces. The stocking rate was assumed to be 100 head/ac (247 head/ha) for 1,000-lb (454-kg) beef cattle for both sites. The VTA dimensions for both sites are listed in Table 6.2. The VTAs for each site were also tested at half and double the lengths (Greenwood half length rounded down to 70 ft (21 m)). The soil name was obtained from the Ottawa and Greenwood County Soil Survey books (Atkin and Grinwood, 1980) (Fortner et al., 1982). Soil property data for both sites were downloaded from the NRCS Soil Lab website (NRCS, 2007) with more detailed data shown in Appendix B. The Soil module was used to create the soil property file for the VTA (Appendix B). Weather data used for the Ada site was from Scandia, KS, while the Greenwood site used data from Parsons, KS. Both sites used a berm spreader in the VTA. The spreaders were 0.025 ft (7.6 mm) high and spaced every 50 ft (15 m).

Table 6.1. Feedlot characteristics for Ada and Greenwood sites.

Characteristics	Ada Site	Greenwood Site
Length - ft (m)	1,000 (304.8)	150 (30.7)
Width - ft (m)	250 (76.2)	800 (243.8)
Slope - %	6.67	2.27
Surface type	Earthen	Earthen
Longest Length - ft (m)	1,008 (307)	427 (130)

Table 6.2. VTA characteristics for Ada and Greenwood sites.

Characteristics	Ada Site	Greenwood Site
Length - ft (m)	400 (123)	150 (45)
Width - ft (m)	400 (123)	800 (224)
Slope - %	0.5	2.8
Side Berm – ft (m)	1.0 (0.30)	1.0 (0.30)
Plant	Alfalfa	Alfalfa
Soil Name	Edalgo	Kenoma

The settling basin was 64 ft (22.8 m) long by 32 ft (9.7 m) wide at the top. The basin depth was 6.0 ft (1.8 m) deep with side slopes of 1:1 for both sites. The discharge diameter pipe was 12 in. (30.5 cm). This size allowed for retention times greater than four hours during the 24-hr, 25-yr storm. Also, the outflow rate should not create a depth greater than 0.5 ft (0.15 m) or flow velocity of 1.5 ft/s (0.46 m) on the VTA (KDHE, 2006). Table 6.3 shows the outlet horizontal designs for both sites. The settling basin was modeled after the feedlot for both the VTA and lagoon modeling.

Table 6.3. Outlet characteristics for settling basin of Ada and Greenwood sites.

Characteristics	Ada Site	Greenwood Site
Total Pipe Length - ft (m)	600 (183)	1,100 (335)
Elevation Change - ft (m)	20 (6.1)	10 (3.0)
Irrigated Pipe Length - ft (m)	400 (123)	800 (244)
Irrigated Pipe Slope - %	2.0	0.5
Pipe Type	Corrugated Metal	Corrugated Metal
90° Bends	1	1
45° Bends	0	0
Overflow Length - ft (m)	10 (3.0)	10 (3.0)
Overflow Depth - ft (m)	1.0 (0.30)	0.5 (0.15)

At both sites the lagoons were sized according to the minimum KDHE (2006) design standard. This standard requires that the lagoon to have storage for the following items:

- Sediment accumulation--0.5 acre-in. per acre feedlot (5 mm-ha per ha feedlot) with settling basin
- Processed wastewater--Assumed to be zero
- Net inflow for Dec. 1 to Mar. 31--Rainfall + Runoff - Evaporation
- Storm Water Volume--25-yr, 24-hr storm runoff + rainfall onto the lagoon surface
- Freeboard—2 ft for earthen structures

The processed wastewater was assumed to be zero, because the feedlots were beef cattle operations that should not generate processed water. The 25-yr, 24-hr storm was taken from the map in Herschfield (1961). Dec. 1 to Mar. 31 rainfall was the average rainfall for the weather data files. Runoff for each month was predicted from the NRCS feedlot runoff table (NRCS, 1996). The lagoons were designed with a depth of 10 ft including freeboard. Also, the top length was twice the top width. Data used for the calculations can be found in Appendix D. The lagoon characteristics for both sites are shown in Table 6.4. The seepage rate for both lagoons was assumed to an average rate of 0.043 in./day (1.1 mm/day) for Kansas (Ham, 2002). The lagoons were not allowed to be pumped between Dec. 1 and Mar. 31 to match the net inflow period of the design standards.

Table 6.4. Lagoon characteristics for Ada and Greenwood sites.

Characteristics	Ada site	Greenwood site
Top Length - ft (m)	230 (70.1)	210 (37.6)
Top Width - ft (m)	115 (35.1)	105 (33.8)
Depth - ft (m)	10 (3.0)	10 (3.0)
Side Slopes	3:1	3:1

Results and Discussion

Results for the two sites were obtained by simulating feedlot runoff through the settling basin and into the lagoon or VTAs (0.5, 1.0, and 2.0 times the length). Figure 6.1 shows the volume of water discharged from each of the structures that was modeled. As show in Figure 6.1, both systems had an increase in the volume of water out from the feedlot to the settling basin, because of the extra water that rain on the settling basin. The lagoons discharge less water than the VTA systems. Greenwood site overflows from the lagoon once. The two sites' VTA have different patterns of discharge for the different lengths. Ada VTA discharge decreases with more length, while Greenwood discharge increases. These patterns seem to indicate that Greenwood VTA natural discharges water with its weather pattern, while Ada VTA does not. Although it seems that the lagoon system is better at preventing the discharge of water, the EPA standards is determined by the amount of discharge of N, P, and COD.

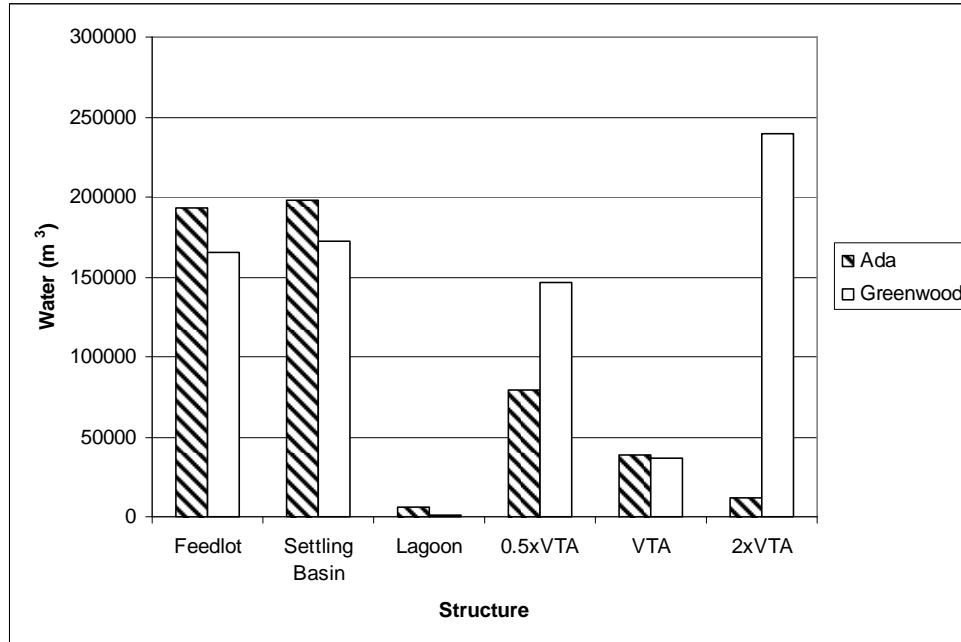


Figure 6.1. Total discharge of water from each structure for 35-year simulations period at Ada and Greenwood sites.

Figure 6.2 and Figure 6.3 show the mass discharge rate of constituents from each system for Greenwood and Ada sites. Because the organic-N can be converted to ammonium-N in the lagoon, the total-N should be used for comparison between the lagoon and VTA. Both figures show that as the length of the VTA increases the discharge rate decreases and less constituents are discharged. Comparing the P, total-N, and COD in Figure 6.2 shows that the lagoon system performs better than the VTA for total amounts of discharge, but the discharge rates for the VTAs were less than 1.5%, 1.3%, and 0.9% for the 0.5-, 1.0-, and 2.0-times the length VTA for all these constituents, respectively. A procedure to determine if the VTA and lagoon are statistically the same has not been developed and the Greenwood lagoon and VTA could be the same statistically. Figure 6.3 shows that the 0.5- and 1.0-times VTA had higher removal rates than the lagoon for P, total-N, and COD. Comparing the 2.0-times VTA and lagoon, the discharge rate of P was 0.4% for the lagoon and 0.5% for the 2.0xVTA. The discharge rates for total-N and COD were 0.3% and 0.2% for the lagoon, and 0.4% and 0.6% for the 2.0xVTA. Although the lagoon performed better than the 2.0xVTA, both discharge rates were similar and a statistical analysis should be developed for the system.

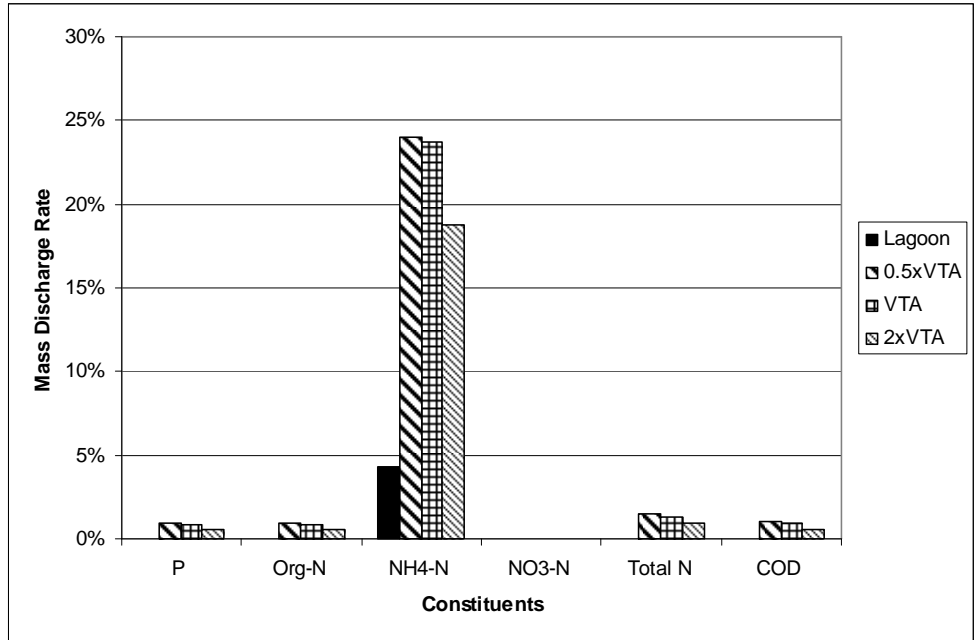


Figure 6.2. Total mass discharge rate in percent of constituents form each treatment system compared to the amount of constituents in the feedlot runoff at Greenwood.

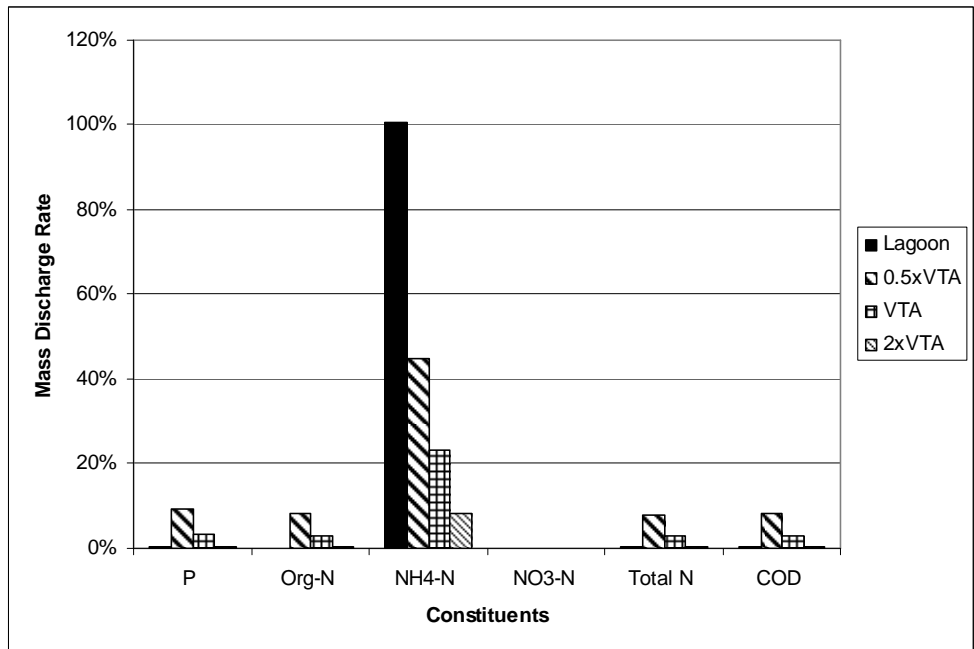


Figure 6.3. Total mass discharge rate in percent of constituents form each treatment system compared to the amount of constituents in the feedlot runoff at Ada.

Table 6.5 and Table 6.6 show the mean and median discharge from the feedlot and each of the treatment system for the Ada site. Table 6.7 and Table 6.8 show the mean and median discharge for the Greenwood site. The EPA final rules developed in 2003 do not state whether mean or median discharge should be used for the comparison of a lagoon and VTA. Table 6.5 and Table 6.6 show that the Ada lagoon performs better for both mean and median measurements for the all three VTA sizes. The Greenwood lagoon performs better than the VTAs by based on mean values (Table 6.7), but the median for the lagoon and VTA are the same for P and COD and there is only 0.01 kg difference between the total-N values.

Table 6.5. Mean discharge in kg for Ada site.

	P	Total N	COD
Feedlot	177	2,570	17,600
Lagoon	0.67	6.84	35.8
0.5xVTA	16.7	210.	1,420
VTA	6.26	75.7	551.
2xVTA	0.95	10.7	98.5

Table 6.6. Median discharge in kg for Ada site.

	P	Total N	COD
Feedlot	177	1,180	17,800
Lagoon	0.00	0.00	0.00
0.5xVTA	16.1	92.0	1,280
VTA	5.08	27.0	445.
2xVTA	0.01	0.08	1.19

Table 6.7. Mean discharge in kg for Greenwood site.

	P	Total N	COD
Feedlot	157	2,250	15,600
Lagoon	0.03	0.42	4.01
0.5xVTA	1.44	22.4	226.
VTA	1.28	20.1	202.
2xVTA	0.92	13.6	140.

Table 6.8. Median discharge in kg for Greenwood site.

	P	Total N	COD
Feedlot	149.	989.	14,900
Lagoon	0.00	0.00	0.00
0.5xVTA	0.00	0.01	0.00
VTA	0.00	0.01	0.00
2xVTA	0.00	0.01	0.00

CHAPTER 7 - Conclusions

The work reported in this thesis has created a computer model that can simulate the release of N, P, and COD from a lagoon or VTA system treating feedlot runoff. The model can run for over 25 years at different sites within the state of Kansas to meet the EPA requirements listed in the CAFO rules for comparing a traditional lagoon system to the alternative VTA system. The feedlot runoff is based on NRCS unit hydrograph method for the water balance and AnnAgNPS for the constituent runoff concentrations. The settling basin is a simple water balance with sediment, organic-N, P, and COD removed with settling of the solids (EPA, 1986). The VTA is designed to calculate infiltration with Green-Ampt Equation and overland flow with Manning's Law. The VTA removes organic-N and P with the Kentucky Filtration Model. The lagoon is derived from Koelliker et al. (1975) water balance and pumping schedule with constituent balance from Miner et al. (1980).

The sensitivity analysis for five different parameters used in the VTA module showed the total area was the most sensitive variable followed by soil conductivity in determining the effectiveness of the VTA system. The calibration of the VTA module showed that soil conductivity estimates can be different from the calibrated values. Also, calibration showed that the effective particle size of constituents should be about 1.5 μm assuming the particle density is 2.65 g/cm^3 .

From both the sensitivity analysis and calibration, soil conductivity has substantial influence on the performance of the VTA system. Unfortunately, the estimation of soil conductivity can vary depending of the equations used. Rawls et al. (1998) and Rawls et al. (1983) provided soil conductivities that were similar and the actual calibrated data was about 1.6 times greater than Rawls et al. (1983). The soil properties reported by the NRCS were estimated from data from a single soil survey sample (NRCS, 2007). The collection of on-site soil data and infiltration testing should yield a more accurate prediction of the VTA performance.

Two sites were evaluated to compare a lagoon and VTA systems. At both of these sites, the lagoon performed better than the VTA according to total and mean values of P, total-N, and COD discharged during the 35-year simulation periods. For the Greenwood site, the lagoon and VTA give the same median values of P and COD of zero. The difference between the lagoon and VTA median discharge of total-N was only 0.01 kg.

Recommendations

Further calibration and validation of the model is recommended. The thesis only calibrated the VTA module for a limited number of storms. The current VTA module is designed with the assumption that management maintains optimal operating conditions with the plants staying alive and any conditions that result in flow concentration in the VTA are minimized. The module may need to be modified to consider management of the system. The addition to the VTA module of a plant die off component may be needed for severe drought conditions. The model makes no considerations for changes of the plant or soil conditions over time. A component could be added that models how plants affect overland flow and infiltration with time. A plant nutrient uptake component should be added to the VTA module to determine if accusations of nutrients in the soils would occur.

Adapting the model to areas outside Kansas may require changing some of the assumptions of the model. Currently, the model assumes shallow groundwater is not important in the VTA. Also, a more robust snowmelt component may be needed if snow melt is a more controlling force affecting the operation of the VTA. Also, the storm hyetographs for areas outside the state of Kansas may not have the same depth-to-duration relationship. The model assumes every storm is a type II storm centered at 12 noon with the duration determined by the depth for a 2-yr storm in Central Kansas. For the feedlot, the concentrations of constituents may be different than the concentrations calculated. Also, the Miner et al. (1980) lagoon constituent balance may be different for other areas. The modular nature of the model should allow making modifications to only those components judged to be inadequate for use in other areas.

Comparison of a VTA system to a lagoon system requires that both systems be properly sized for the feedlot. It is recommended that a standard procedure for sizing the lagoon for the comparison in Kansas be developed, because sizing of the lagoon depth, width, and length may change the performance of the lagoon. The regulating agencies should expand the existing regulations to more fully describe the proper use of the results of the simulations for comparison. Also, clearer definitions should be made to determine whether mean or median is the average measurement used for comparisons.

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Appendix A - Plant Data

Table A.1. Values for different properties for plant types for the VTA (Richard et al., 1997) (Munoz-Carpena and Parsons, 2005),

Property	Alfalfa	Fescue	Bermuda	Corn Silage
ET type	Harvested	Cool-Season	Warm-Season	Warm-Season
ETKwinter	0.40	0.85	0.55	0.25
ETK1	0.40	0.55	0.80	0.25
ETK2	1.20	1.00	0.85	1.10
ETK3	1.20	0.60	0.85	0.60
ETK4	1.20	0.80		
ETK5	1.20	0.85		
DOY0	75	60	121	105
DOY1	105	84	161	125
DOY2	150	161	213	155
DOY3	186	213	253	233
DOY4	248	258	288	303
DOY5	303	305		
Manning's Number	0.24	0.24	0.41	0.15
Retardance Factor	2	2	2	2
Spacing - in. (mm)	1.19 (3.02)	0.541 (1.63)	0.531 (1.35)	9.00 (22.9)

Appendix B - Soils Data

Table B.1. Silt loam soil calculated soil properties for sensitivity analysis.

Layer	Thickness (in.)	Wilt Point	Field Capacity	Saturation	Conductivity (in./s)	Suction (in.)	REW (in.)
1	3.00	0.086	0.286	0.453	6.26×10^{-4}	8.60	0.354
2	14.21	0.086	0.286	0.453	2.88×10^{-4}	10.06	
3	14.21	0.164	0.290	0.314	5.18×10^{-5}	12.45	
4	14.21	0.150	0.206	0.275	8.23×10^{-6}	11.54	
5	14.21	0.150	0.213	0.285	9.37×10^{-6}	11.50	

Table B.2. Newtonia calculated soil properties for VTA module from Miami County, KS.

Layer	Thickness (in.)	Wilt Point	Field Capacity	Saturation	Conductivity (in./s)	Suction (in.)	REW (in.)
1	3.00	0.233	0.377	0.503	7.475×10^{-5}	10.75	0.374
2	16.97	0.241	0.374	0.498	6.972×10^{-5}	10.75	
3	16.97	0.251	0.360	0.480	5.565×10^{-5}	11.41	
4	16.97	0.253	0.355	0.473	5.156×10^{-5}	11.50	
5	16.97	0.292	0.363	0.484	5.139×10^{-5}	11.50	

Table B.3. Edalgo calculated soil properties for VTA module from Ottawa County, KS.

Layer	Thickness (in.)	Wilt Point	Field Capacity	Saturation	Conductivity (in./s)	Suction (in.)	REW (in.)
1	3.00	0.125	0.264	0.453	2.370×10^{-4}	8.60	0.354
2	14.21	0.203	0.319	0.445	1.002×10^{-4}	10.07	
3	14.21	0.303	0.355	0.464	3.723×10^{-5}	12.45	
4	14.21	0.247	0.337	0.449	4.343×10^{-5}	11.54	
5	14.21	0.235	0.336	0.448	4.386×10^{-5}	11.50	

Table B.4. Kenoma calculated soil properties for VTA module from Greenwood County, KS.

Layer	Thickness (in.)	Wilt Point	Field Capacity	Saturation	Conductivity (in./s)	Suction (in.)	REW (in.)
1	3.00	0.154	0.398	0.475	2.009×10^{-5}	6.57	0.374
2	21.89	0.240	0.411	0.480	1.536×10^{-5}	10.23	
3	21.89	0.254	0.367	0.434	1.947×10^{-5}	10.90	
4	21.89	0.312	0.397	0.423	6.521×10^{-7}	11.50	
5	21.89	0.290	0.364	0.474	4.462×10^{-5}	12.36	

Appendix C - Calibration Data

Table C.1. Weather data used for calibration of the VTA near Gardner, KS (NOAA, 2007) (Mankin and Okoren, 2003) (Kansas Weather Data Library, 2007).

Year	Month	Day	Temperature (°F)		Rainfall	Windspeed	Solar	Dewpoint	Grass ET
			Max	Min	(in.)	(mph)	(lg/day)	(°F)	(in.)
2002	3	1	43	31	0.10	9.3	88.8	26	0.049
2002	3	2	31	10	0.04	11.2	331.1	10	0.038
2002	3	3	19	4	0.00	11.1	435.2	0	0.032
2002	3	4	42	1	0.00	10.4	441.2	16	0.042
2002	3	5	59	28	0.00	12.8	419.7	27	0.099
2002	3	6	60	36	0.00	12.4	416.8	35	0.099
2002	3	7	65	30	0.00	14.5	139.8	42	0.032
2002	3	8	67	43	0.37	19.9	92.0	54	0.049
2002	3	9	43	18	0.08	16.8	475.2	15	0.094
2002	3	10	50	22	0.00	8.7	451.9	18	0.097
2002	3	11	51	34	0.00	9.8	289.8	27	0.096
2002	3	12	61	27	0.00	5.8	445.6	30	0.076
2002	3	13	74	41	0.00	9.1	457.6	37	0.147
2002	3	14	80	38	0.00	18.9	475.9	39	0.202
2002	3	15	49	33	0.00	12.5	313.7	24	0.062
2002	3	16	45	27	0.00	10.9	240.5	27	0.044
2002	3	17	57	32	0.00	6.2	385.7	34	0.066
2002	3	18	52	39	0.00	9.4	124.5	39	0.031
2002	3	19	55	43	0.00	9.4	73.9	43	0.016
2002	3	20	55	36	0.00	7.4	470.9	29	0.083
2002	3	21	43	17	0.00	17.3	508.4	5	0.101
2002	3	22	40	12	0.00	5.6	507.8	1	0.065
2002	3	23	58	22	0.00	9.4	469.6	21	0.113
2002	3	24	51	37	0.00	15.8	72.3	37	0.041
2002	3	25	37	26	0.00	15.1	65.6	26	0.011
2002	3	26	48	26	0.00	5.8	524.3	23	0.072
2002	3	27	62	27	0.00	12.8	502.3	31	0.138
2002	3	28	68	43	0.27	6.9	524.2	45	0.122
2002	3	29	64	44	0.00	10.3	465.7	40	0.108
2002	3	30	62	42	0.00	7.8	453.0	32	0.099
2002	3	31	57	39	0.00	7.9	483.8	32	0.089
2002	4	1	78	39	0.00	15.7	538.6	41	0.215
2002	4	2	61	34	0.00	17.0	361.8	31	0.112
2002	4	3	43	26	0.00	10.2	567.9	15	0.089
2002	4	4	50	28	0.00	4.9	540.9	18	0.093
2002	4	5	62	31	0.00	4.8	534.5	26	0.116

Year	Month	Day	Temperature (F)		Rainfall (in.)	Windspeed (mph)	Solar (lg/day)	Dewpoint (F)	Grass ET (in.)
			Max	Min					
2002	4	6	68	40	0.01	13.5	337.7	35	0.14
2002	4	7	53	48	0.04	11.4	55.6	46	0.036
2002	4	8	54	46	0.73	8.1	79.1	50	0.017
2002	4	9	64	41	0.00	6.5	578.3	42	0.101
2002	4	10	75	44	0.00	13.3	560.0	46	0.164
2002	4	11	74	52	0.05	13.3	303.6	54	0.112
2002	4	12	63	49	0.00	7.7	282.6	50	0.055
2002	4	13	63	42	0.01	6.3	227.3	50	0.04
2002	4	14	86	51	0.01	12.6	529.8	57	0.154
2002	4	15	85	64	0.00	17.6	583.8	63	0.207
2002	4	16	77	67	0.00	21.3	171.2	63	0.088
2002	4	17	81	65	0.00	12.7	524.2	64	0.17
2002	4	18	81	71	0.00	16.1	363.9	65	0.148
2002	4	19	73	56	0.55	9.1	125.5	56	0.041
2002	4	20	59	51	1.06	11.0	123.3	50	0.034
2002	4	21	60	44	0.79	10.5	424.4	46	0.081
2002	4	22	67	37	0.00	5.8	617.8	45	0.118
2002	4	23	77	50	0.03	9.6	559.5	56	0.134
2002	4	24	70	46	0.00	14.4	380.4	44	0.114
2002	4	25	63	35	0.00	5.2	610.4	30	0.121
2002	4	26	53	47	0.15	11.1	66.3	45	0.016
2002	4	27	77	48	1.07	15.9	270.6	52	0.093
2002	4	28	58	42	0.00	10.6	628.8	39	0.128
2002	4	29	69	45	0.00	5.5	588.9	47	0.118
2002	4	30	76	55	0.00	9.6	175.4	53	0.044
2002	5	1	59	49	0.02	11.3	80.0	53	0.02
2002	5	2	60	43	0.00	7.9	554.9	36	0.104
2002	5	3	67	40	0.00	8.6	534.7	38	0.119
2002	5	4	72	42	0.00	4.9	645.8	49	0.128
2002	5	5	82	51	0.00	11.7	642.1	58	0.184
2002	5	6	77	58	0.78	10.4	407.7	64	0.106
2002	5	7	70	60	0.42	13.5	113.0	59	0.035
2002	5	8	78	54	1.16	16.8	350.4	61	0.085
2002	5	9	63	46	0.00	11.0	676.8	35	0.165
2002	5	10	68	42	0.11	11.5	507.7	41	0.135
2002	5	11	74	53	0.89	12.0	96.6	63	0.026
2002	5	12	74	49	1.16	13.2	90.7	52	0.023
2002	5	13	71	44	0.00	10.0	688.1	43	0.14
2002	5	14	73	48	0.00	5.4	664.4	47	0.149
2002	5	15	74	56	0.00	14.9	614.4	54	0.185
2002	5	16	75	60	0.38	9.9	413.2	60	0.096
2002	5	17	66	48	0.15	12.3	540.1	47	0.136
2002	5	18	65	45	0.00	5.9	694.2	38	0.139
2002	5	19	68	48	0.00	4.5	290.3	44	0.062
2002	5	20	70	46	0.00	5.1	654.2	42	0.154
2002	5	21	68	46	0.00	11.7	654.0	47	0.171

Year	Month	Day	Temperature (°F)		Rainfall (in.)	Windspeed (mph)	Solar (lg/day)	Dewpoint (°F)	Grass ET (in.)
			Max	Min					
2002	5	22	76	56	0.00	18.8	501.5	54	0.197
2002	5	23	70	58	0.35	11.1	118.5	61	0.045
2002	5	24	63	53	1.82	11.1	276.4	52	0.055
2002	5	25	67	49	0.01	6.6	506.0	51	0.102
2002	5	26	74	48	0.00	7.8	687.7	55	0.148
2002	5	27	82	59	0.27	6.2	590.2	63	0.14
2002	5	28	78	62	0.00	6.2	472.0	64	0.113
2002	5	29	81	59	0.00	3.9	676.8	64	0.157
2002	5	30	85	63	0.00	5.3	669.6	65	0.17
2002	5	31	88	69	0.00	7.9	677.6	68	0.193

Table C.1. Hyetograph used during the calibration for the VTA near Gardner, KS.

Year	Month	Day	Hours	Rainfall (in.)	Year	Month	Day	Hours	Rainfall (in.)
2002	3	1	11.83	0.006036	2002	4	27	8.00	0.029722
2002	3	1	11.92	0.009712	2002	4	27	8.08	0.029722
2002	3	1	12.00	0.034252	2002	4	27	8.25	0.029722
2002	3	1	12.08	0.034252	2002	4	27	8.42	0.059444
2002	3	1	12.17	0.009712	2002	4	27	8.50	0.059444
2002	3	1	12.25	0.006036	2002	4	27	8.58	0.059444
2002	3	2	11.83	0.002414	2002	4	27	8.67	0.089167
2002	3	2	11.92	0.003885	2002	4	27	8.75	0.029722
2002	3	2	12.00	0.013701	2002	4	27	8.92	0.059444
2002	3	2	12.08	0.013701	2002	4	27	9.17	0.029722
2002	3	2	12.17	0.003885	2002	4	27	9.25	0.029722
2002	3	2	12.25	0.002414	2002	4	27	9.33	0.029722
2002	3	8	11.83	0.022332	2002	4	27	14.58	0.029722
2002	3	8	11.92	0.035934	2002	5	1	19.58	0.010000
2002	3	8	12.00	0.126734	2002	5	1	20.25	0.010000
2002	3	8	12.08	0.126734	2002	5	6	7.92	0.120000
2002	3	8	12.17	0.035934	2002	5	6	23.50	0.360000
2002	3	8	12.25	0.022332	2002	5	6	23.58	0.300000
2002	3	9	11.83	0.004828	2002	5	7	5.75	0.030000
2002	3	9	11.92	0.007770	2002	5	7	6.08	0.030000
2002	3	9	12.00	0.027402	2002	5	7	17.42	0.030000
2002	3	9	12.08	0.027402	2002	5	7	17.67	0.030000
2002	3	9	12.17	0.007770	2002	5	7	17.92	0.030000
2002	3	9	12.25	0.004828	2002	5	7	18.00	0.030000
2002	3	28	11.83	0.016296	2002	5	7	18.42	0.030000
2002	3	28	11.92	0.026222	2002	5	7	21.08	0.030000
2002	3	28	12.00	0.092482	2002	5	7	21.25	0.030000
2002	3	28	12.08	0.092482	2002	5	7	21.58	0.030000
2002	3	28	12.17	0.026222	2002	5	7	21.75	0.030000
2002	3	28	12.25	0.016296	2002	5	7	22.25	0.030000
2002	4	6	11.83	0.000604	2002	5	7	22.92	0.030000
2002	4	6	11.92	0.000971	2002	5	7	23.50	0.030000

Year	Month	Day	Hours	Rainfall (in.)	Year	Month	Day	Hours	Rainfall (in.)
2002	4	6	12.00	0.003425	2002	5	8	0.58	0.034118
2002	4	6	12.08	0.003425	2002	5	8	0.83	0.034118
2002	4	6	12.17	0.000971	2002	5	8	4.50	0.034118
2002	4	6	12.25	0.000604	2002	5	8	15.83	0.034118
2002	4	7	11.83	0.002414	2002	5	8	18.75	0.068235
2002	4	7	11.92	0.003885	2002	5	8	18.83	0.136471
2002	4	7	12.00	0.013701	2002	5	8	18.92	0.068235
2002	4	7	12.08	0.013701	2002	5	8	19.00	0.034118
2002	4	7	12.17	0.003885	2002	5	8	19.08	0.136471
2002	4	7	12.25	0.002414	2002	5	8	19.17	0.068235
2002	4	8	11.83	0.044060	2002	5	8	19.25	0.068235
2002	4	8	11.92	0.070898	2002	5	8	19.33	0.034118
2002	4	8	12.00	0.250043	2002	5	8	19.42	0.034118
2002	4	8	12.08	0.250043	2002	5	8	19.50	0.034118
2002	4	8	12.17	0.070898	2002	5	8	20.50	0.034118
2002	4	8	12.25	0.044058	2002	5	8	20.58	0.034118
2002	4	11	11.83	0.003018	2002	5	8	21.00	0.034118
2002	4	11	11.92	0.004856	2002	5	8	21.25	0.034118
2002	4	11	12.00	0.017126	2002	5	8	22.58	0.034118
2002	4	11	12.08	0.017126	2002	5	8	22.75	0.034118
2002	4	11	12.17	0.004856	2002	5	8	22.92	0.034118
2002	4	11	12.25	0.003018	2002	5	8	23.00	0.068235
2002	4	13	11.83	0.000604	2002	5	8	23.08	0.034118
2002	4	13	11.92	0.000971	2002	5	10	20.08	0.055000
2002	4	13	12.00	0.003425	2002	5	10	20.17	0.055000
2002	4	13	12.08	0.003425	2002	5	11	0.67	0.148333
2002	4	13	12.17	0.000971	2002	5	11	1.17	0.148333
2002	4	13	12.25	0.000604	2002	5	11	6.67	0.148333
2002	4	14	11.83	0.000604	2002	5	11	15.92	0.148333
2002	4	14	11.92	0.000971	2002	5	11	18.42	0.148333
2002	4	14	12.00	0.003425	2002	5	11	21.08	0.148333
2002	4	14	12.08	0.003425	2002	5	12	2.08	0.072500
2002	4	14	12.17	0.000971	2002	5	12	2.17	0.072500
2002	4	14	12.25	0.000604	2002	5	12	2.42	0.072500
2002	4	19	5.50	0.183333	2002	5	12	2.75	0.217500
2002	4	19	5.75	0.366667	2002	5	12	2.83	0.217500
2002	4	20	16.25	1.060000	2002	5	12	2.92	0.072500
2002	4	21	3.33	0.507857	2002	5	12	6.00	0.072500
2002	4	21	3.42	0.112857	2002	5	12	10.00	0.072500
2002	4	21	3.50	0.056429	2002	5	12	10.83	0.072500
2002	4	21	10.58	0.056429	2002	5	12	11.83	0.072500
2002	4	21	13.08	0.056429	2002	5	12	20.92	0.072500
2002	4	23	5.33	0.030000	2002	5	12	22.00	0.072500
2002	4	26	8.92	0.150000	2002	5	16	4.50	0.126667
2002	4	27	1.08	0.029722	2002	5	16	9.25	0.126667
2002	4	27	2.50	0.029722	2002	5	16	21.08	0.126667
2002	4	27	2.75	0.029722	2002	5	17	7.25	0.075000
2002	4	27	2.92	0.029722	2002	5	17	9.67	0.075000
2002	4	27	3.25	0.029722	2002	5	23	15.67	0.175000

Year	Month	Day	Hours	Rainfall (in.)	Year	Month	Day	Hours	Rainfall (in.)
2002	4	27	3.42	0.029722	2002	5	23	20.25	0.175000
2002	4	27	3.58	0.029722	2002	5	24	3.67	0.364000
2002	4	27	4.42	0.029722	2002	5	24	20.83	0.364000
2002	4	27	4.50	0.029722	2002	5	24	22.25	0.364000
2002	4	27	4.83	0.029722	2002	5	24	23.75	0.364000
2002	4	27	5.00	0.029722	2002	5	24	23.83	0.364000
2002	4	27	5.42	0.029722	2002	5	25	1.58	0.005000
2002	4	27	5.58	0.029722	2002	5	25	1.92	0.005000
2002	4	27	7.08	0.029722	2002	5	27	3.08	0.090000
2002	4	27	7.58	0.029722	2002	5	27	3.33	0.090000
2002	4	27	7.75	0.029722	2002	5	27	3.92	0.090000
2002	4	27	7.83	0.029722					

Appendix D - Data Used for Sizing the Lagoon

Table D.1. Depths and volumes for sizing the lagoon.*

	Ada site	Greenwood site
Drainage Area - ac (ha)	5.74 (2.32)	2.75 (1.11)
Sediment Volume - ft ³ (m ³)	10,417 (295)	4,991 (141)
24-yr, 24-yr Storage - ft ³ (m ³)	93,948 (2,660)	65,275 (1,848)
• Rainfall depth - in. (cm)	5.00 (12.70)	6.41 (16.28)
• Runoff depth - in. (cm)	3.98 (10.11)	5.36 (13.61)
• Rainfall Volume - ft ³ (m ³)	10,988 (311)	11,779 (334)
• Runoff Volume - ft ³ (m ³)	82,960 (2,349)	53,496 (1,515)
Net Inflow - ft ³ (m ³)	19,292 (546)	27,321 (774)
• Rainfall depth - in. (cm)	4.38 (11.13)	8.40 (21.34)
• Runoff depth - in. (cm)	0.48 (1.22)	1.22 (3.10)
• Evaporation depth - in. (cm)	0.28 (0.71)	0.47 (1.20)
• Rainfall Volume - ft ³ (m ³)	9,625 (273)	15,435 (437)
• Runoff Volume - ft ³ (m ³)	9,908 (281)	12,147 (344)
• Evaporation Volume - ft ³ (m ³)	-242 (-6.85)	-268 (-7.59)
Freeboard Volume - ft ³ (m ³)	48,703 (1,379)	48,703 (1,379)

*This table has raw calculations for the lagoon. The numbers were rounded for significant digits at the end of the calculations.