Hydrologic and Water Quality Modeling of a CAFO Dairy Lagoon

by

Noah Rudko

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2021 by the
Graduate Supervisory Committee:

Rebecca Muenich, Chair
Margaret Garcia
Tianfang Xu

ARIZONA STATE UNIVERSITY

May 2021

ABSTRACT

In recent decades animal agriculture in the U.S. has moved from small, distributed operations to large, Concentrated Animal Feeding Operations (CAFOs). CAFOs are defined by federal regulations based on animal numbers and confinement criteria. Because of the size of these operations, the excessive amount of manure generated is typically stored in lagoons, pits, or barns prior to field application or transport to other farms. Water quality near CAFOs can be impaired through the overflow of lagoons, storm runoff, or lagoon seepage. Assessing water quality impacts of CAFOs in a modeling framework has been difficult because of data paucity. A CAFO lagoon module was developed to assess lagoon overflow risk, groundwater quality, and ammonia emissions of a dairy lagoon. A groundwater quality assessment of a Dairy Lagoon in Lynden Washington was used to calibrate and validate the groundwater quality model. Groundwater down stream of the lagoon was negatively impaired. The long-term effects of this lagoon on water quality were explored as well as the effectiveness of improving the lagoon lining to reduce seepage. This model can be used to improve understanding of the impacts of CAFO lagoon seepage and develop sustainable management practices at the watershed scale for these key components of the agricultural landscape.

DEDICATION

First and foremost, I have to thank my friends and family for their continued love and support. Thank you for giving me guidance and for the numerous poop jokes while I talked about my manure work.

ACKNOWLEDGMENTS

I would like to thank my mentors, Dr. Rebecca Muenich, Dr. Margaret Garcia, and Dr. Tianfang Xu for their invaluable help and advice. Special thanks to Mr. Zinke for providing a tour of his Dairy CAFO in AZ that proved particularly insightful in helping me better understand the assumptions I built into my model. This work is supported by the USDA National Institute of Food and Agriculture, Capacity Building Projects for Non-Land Grant Colleges of Agriculture project 1017146, grant number 2018-70001-28751.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER 1

INTRODUCTION

Agriculture in the US has undergone changes from small farms to large, Concentrated Animal Feeding Operations (CAFOs) over recent decades (MacDonald et al., 2018). These changes to how agricultural systems are managed in the US can have significant impacts on nearby communities and the environment. Despite regulation by the Environmental Protection Agency (EPA) and state-level environmental departments and incentives from state and federal agricultural programs, there are still serious issues related to nutrient and other pollution from these operations. Manure plays a significant role in these impacts and there is little known about CAFO impacts, especially at a large scale. These operations tend to cluster in space, creating small "cities' of animals and the impacts of this aggregation has not been fully understood. These operation clusters can even generate as much waste on-sit as some cities, and often store the manure in earthen structures. After hurricanes Florence and Matthew hit the east coast of the US, many of the lagoons in North Carolina were inundated demonstrating their susceptibility to extreme events (Schaffer-Smith et al., 2020). While only farms of a specific size are required to obtain a National Pollutant Discharge Elimination System (NPDES) permit (and this can vary by state), AFOs of smaller sizes still have the propensity to degrade waters. For example, the rise of these large but unregulated farms in the Maumee Watershed in northwest Ohio have been linked to harmful algal blooms in Lake Erie (EWG, 2019).Thus, there is a need to characterize the storage infrastructure and manure management practices of these farms to better manage these potential sources of pollution. Furthermore, most watershed modeling approaches cannot fully account for this kind of contribution of these facilities, making it difficult to simulate effective practices to manage these wastes. The lack of publicly available data, such as CAFO locations, animal counts, and manure management practices exacerbates this issue. The development of a water quality module to assess and identify lagoon storage and management practices can be used to reduce risk to the environment.

Figure 1. CAFO in Puget Sound Watershed, Washington (Ecology's CAFO Water Permit Sacrifices Public Health, Drinking Water, Shellfish Beds, 2017).

The EPA regulatory definition of a CAFO needs to be expanded in response to climate change. While discharges that are a result of storms more intense than the 25-year 24-hour storm event are allowed, the increase in intensive storms requires that these lagoons have added redundancies in place. Even if a CAFO is not actively discharging, measures should be put in place to prevent discharges even during the design storm event. Many CAFOs have been able to avoid discharge permits because they only discharge water during this storm event (Copeland, 2010).Thus, there is a need to determine if smaller sized AFOs are at risk for discharging — based on design volumes of the earthen manure structures.

Discharge is not the only mechanism in which CAFOs might interact with the hydrological environment. Leakage from lagoons or overapplication onto spray-fields has the potential to contaminant groundwater. Lagoons constructed prior to 1990 (or those constructed without adequate guidance from NRCS or SCS) assumed that the accumulation of solids at the bottom of the lagoon would provide a seal and reduce leakage rates over time (NRCS, 2009) This is not the case for lagoons constructed on sandy soils with high permeability. While current design methods for preventing seepage from lagoons have significantly improved, their effectiveness is lacking sufficient studies. Moreover, it is well known that CAFOs interact with groundwater and can cause elevated nutrient concentrations at nearby monitoring and drinking wells (Cook et al., 2008, Arnold & Meister, 1999, Harter et al., 2001). This has numerous health implications for people living near these CAFOs.

Additionally, odors around CAFOs are indicative of ammonia emissions (Preece et al., 2012). Ammonia emissions in the air can interact with Volatile Organic Compounds (VOCs) and form PM-2.5, fine particulates that can cause respiratory issues for at-risk individuals in close proximity to these CAFOs (Donham Kelley J. et al., 2007). The contributions of ammonia emissions by a single swine, dairy, beef, or poultry CAFO are enormous (Wilson & Serre, 2007). Current guidelines and regulations for preventing air quality concerns are limited to siting CAFOs away from people and animals. Further, the people living near CAFOs are typically non-white and poor. CAFOs as they exist today are an example of environmental injustice (Son et al., 2021). These neighborhoods that are already lacking in economic resources also lack the political clout to oppose the construction of CAFOs and to demand that existing CAFOs take proper precautions. Where CAFOs have existed as urban areas expanded, they may not have the resources to live elsewhere. Rather than hope that future developments are not constructed near these CAFOs, there should be clear guidance as how to best manage air quality and groundwater quality concerns that tackle the environmental concern at the source.

Through development of a CAFO manure lagoon water quality module that incorporates physical and chemical processes effective management strategies, design, and construction guidelines can be identified that can prevent air quality and groundwater quality contamination. Additionally, tradeoffs between managing the lagoon to prevent overflow, ammonia emissions, and groundwater contamination can be explored through the use of lagoon module. There are many variables that can affect interactions between the environment, from meteorological variables such as precipitation, properties of the lagoon itself such as its volume and surface area, to properties of the CAFO operation such as the animal count and type. All of these variables and assumptions within the model can be altered.

There have been other models to capture different processes surrounding CAFOs, but not many with the goal of capturing water quality impacts. The EPA released a document in December of 2002 titled "Pollutant Loading Reductions for the Revised Effluent Limitations Guidelines for Concentrated Animal Feeding Operations" however they used a highly simplified approach for the nutrient loadings, such as relating the soil type to a yearly average leakage rate for understanding groundwater quality impacts and pollutant loads (Whitman, 2002). The methods used to estimate runoff entering the lagoon made the assumption that equal amounts of precipitation would infiltrate the soil; antecedent moisture conditions or a variable amount of runoff entering the lagoon was not explored. The EPA primarily explored a field-scale model that also incorporated fertilized fields, but the lagoon model could be further improved. This Sample Farm model developed by the EPA to estimate the pollutant loadings of CAFOs served as a suitable building block for this CAFO model. This CAFO model incorporates groundwater quality loads at the monthly-time scale (an improvement over the yearly-scale estimate used by the EPA) and ammonia emissions at the daily scale.

A more complex model, Dairy-CropSyst was developed to assist researchers and managers in their understanding of different manure treatment operations on air quality emissions and nutrient fate within a single dairy system (Khalil et al., 2019). The model includes the transformation of nutrients within different manure storage options, solid-liquid separators, and emissions from all components of a typical Dairy CAFO. While this is an incredibly detailed farm level model, it would not be easily incorporated into a watershed scale model. Additionally, this farm level model was limited to only dairy CAFOs and did not consider swine or poultry operations. While Dairy-CropSyst does estimate seepage losses in the manure lagoon, it does not estimate nutrient fate through the soil liner or in the subsurface. Thus, the main goal is of improving simulations of how manure lagoons interact with the environment. This CAFO modeling effort in this study provides additional focus on modeling lagoon overflow as a result of extreme rainfall events, modeling solute transport in the subsurface as a function of different soil liner constructions, and quantifying nutrient loading such as ammonia emissions as well as potential trade-offs between air and groundwater quality.

CHAPTER 2

METHODS

The lagoon model is modeled similarly to a ponds and wetlands modules in Soil and Water Assessment Tool (SWAT). The key difference being that there are no controlled outflows from the lagoon. The volume of water and nitrogen the lagoon is simulated at a daily time step. At each time step, the manure generated per day is calculated based on the number of animals and the amount of manure each animal produces (**Fig. 2** and **3**).

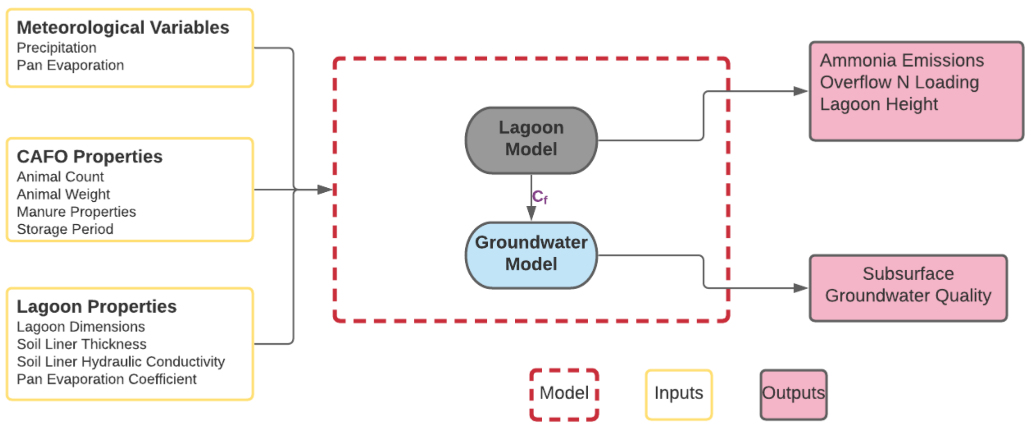


Figure 2. Model Concept Map

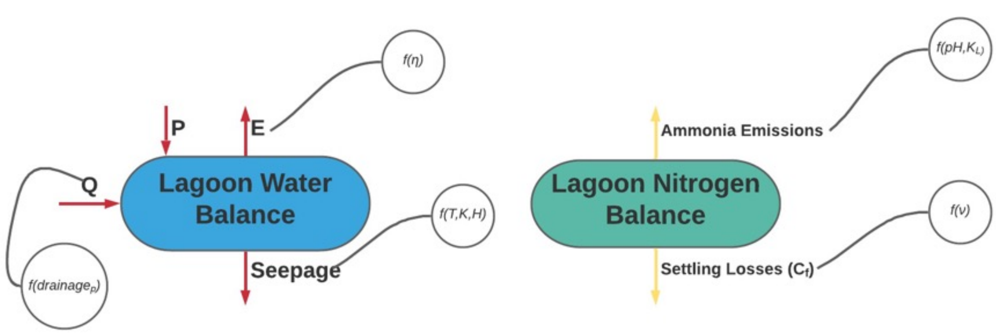


Figure 3. Lagoon Water and Nitrogen Balance

Precipitation. Daily precipitation point measurements from a nearby precipitation gauge are added to the lagoon. While there are no direct precipitation measurements for each CAFO location, it is a suitable estimation for these modeling efforts. The volume of precipitation added to the lagoon is equal to the precipitation depth multiplied by the surface area of the lagoon.

Evaporation. Daily pan evaporation values from the same gauge were used to estimate evaporation. In addition to the simplifications already incorporated into pan evaporation measurements, for manure lagoons, uncertainty exists due to the presence of solid particles on the surface that may inhibit evaporation. The amount of water exiting through evaporation is calculated using the following:

$$E = \eta E_{pan} SA$$

Where η is a pan coefficient (0.69-0.94) and is a correction factor to account for inaccuracy in pan evaporation measurements (Ham, 2004). A value less than 1 indicates that pan evaporation is overestimating the true amount of evaporation. The pan coefficient was estimated by measuring pan evaporation for a pan in the surface of the lagoon.

Runoff. Runoff is calculated using the Soil Conservation Service (SCS) Method.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Where S is the potential maximum retention of the feedlot area.

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

Where *CN* is representative of the soil. It is an indication of the propensity for infiltration to occur — a CN of 100 indicates an impervious area. The curve number can also be modified to reflect the antecedent moisture condition (AMC) of the soil, using the equations in Table 1.

Table 1. AMC Groups for SCS Method

AMC Group	**5-day Antecedent Rainfall (in)**	**Updated CN**
1	< 0.5	$\frac{4.2CN(II)}{10 - 0.058CN(II)}$
2	0.5 – 1.1	
3	> 1.1	$\frac{23CN(II)}{10 + 0.13CN(II)}$

The CN increases as response to increased precipitation. The CN is updated during the model using the measured precipitation depth values from the previous 5 days.

A CN(II) of 91 was used for the feedlot area. Previous studies of runoff from feedlot areas have determined this to be a reasonable value of CN (Andersen, 2016).The volume of runoff that enters the lagoon is obtained by multiplying the direct runoff by the feedlot area.

Seepage. The specific discharge through the soil liner is calculated using Darcy's Law.

$$q = K\frac{dh}{dl},$$

where *K* is the saturated hydraulic conductivity of the soil liner (assumed to be 0.0003 ft/d based on regulations). The hydraulic gradient is calculated using the following:

$$\frac{dh}{dl} = \frac{H + T - GW}{T}$$

Where T is the thickness of the compacted soil liner (assumed to be 1 ft), H is the depth of the lagoon and GW is the depth of the groundwater table above the lagoon bottom. This method of calculating specific discharge through the soil liner is adapted from Glanville et al., 2001. Their measurements of leakage assumed no evaporation in the lagoon, and thus represents the upper limit of leakage. When the depth of the groundwater table is below the lagoon bottom, matric suction is negligible when compared to H or T, and this term is 0. The specific discharge is multiplied by the bottom surface of the lagoon to estimate the amount of water lost due to seepage. The lagoon cross-section is approximated as a trapezoid and the lagoon depth, H, is calculated by calculating the depth associated with the current volume. Evaporation and seepage only occur if there is enough water in the lagoon. The amount of water that leaves the lagoon through seepage is calculated by multiplying the specific discharge, q, by the bottom area of the lagoon.

Manure Management. The effects of manure management (removing manure from the lagoon) are a user supplied input based on existing hydrographs of the lagoon. The user specifies the volume of manure removed on a certain date. This portion of the model can be improved by using actual manure management data that discerns the frequency and volume of manure removed from the lagoon. This varies widely by region, animal type, and farmer. In a personal interview with Mr. Zinke, a CAFO manager in Arizona, part of his manure management entailed flushing feedlots after storm events (during the summer monsoon season) when the manure is wet for ease of transport.

Manure Properties. The properties of the manure stored in the lagoon are based on the ASAE 2004 standards, see Table 2. (ASAE, 2004). These are used to estimate the daily production of manure, as well as the nutrient content in the lagoon. Given the data paucity surrounding the chemical composition of the lagoon the degree of nutrient stratification is not known. Stratification of nutrients in the lagoon is not considered — the lagoon is assumed to be well mixed. Nutrient loss in the lagoon is modeled through ammonia volatilization and settling. The nitrogen balance not being closed is due to parameter uncertainty and insufficient lagoon chemistry data.

Table 2. Manure Characteristics

Manure Generated Per Animal	Ammonia-N Concentration	Percent Solids
1.39 ft^3/day	0.079 lb/ft^3	13.95%

Ammonia Volatilization. Ammonia losses to the atmosphere are modeled using the two-film theory for interfacial mass transfer. This model incorporates the pH of the lagoon to determine the amount of free ammonia (ammonia readily available for volatilization) and the bulk concentration of the manure liquid.

$$J_N = K_L\left(FC_T - \frac{P_N}{K_H}\right)$$

Where *F* is the fraction of free ammonia, C_T is the total ammonia species concentration in the bulk liquid, K_H is Henry's constant for ammonia, K_L is an overall liquid-phase mass transfer coefficient, and P_N is the ammonia concentration in the bulk air (K. S. Ro et al., 2008). The fraction of free ammonia is a function of pH and is calculated using the following:

$$F = \left(1 + \frac{10^{-pH}(1 + K_{ads})}{K_{aw}}\right)^{-1}$$

Where K_{ads} is the adsorption of ammonia onto solid particles in the lagoon, K_{aw} is the water dissociation constant adjusted for lagoon water, and pH is the pH of the lagoon. Because the reports focused solely on groundwater there were no measurement of ammonia emissions and thus the concentration of ammonia in the air is assumed to be zero. This is a reasonable assumption given sufficient mixing in the air above the lagoon. The overall liquid-phase mass transfer coefficient incorporates the additivity of the interfacial mass transfer resistances — it is the sum of the gas and liquid-film resistance. The amount of Ammonia-N lost to seepage and volatilization for a ~5-year period is displayed in **Fig. 4**.

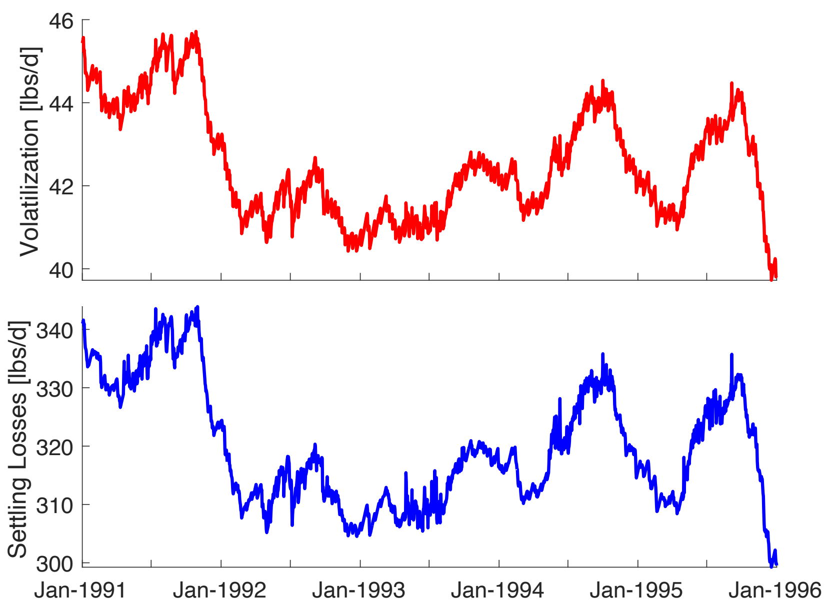


Figure 4. Ammonia-N losses due to volatilization and settling for a 5-year period

The efforts by Ro et al. (2008) developed a process-based model to estimate ammonia fluxes accounting for bubbling enhanced mass transport and varying wind speeds above different lagoons (non-treated, partially treated, and treated) for each season in North Carolina. A K_L value of 1.417 ft/d was incorporated in the model which corresponded to the mean K_L estimation for a non-treated lagoon during the Winter.

Settling Losses. Nutrient settling losses [lb/day] are modeled using the SWAT routine for nutrient settling in wetlands.

$$M_s = \nu C_T A_b$$

Where ν is the apparent settling velocity of the nutrient $\left[\frac{ft}{day}\right]$, C_T is the bulk concentration of ammonia-N in the manure $[\frac{lb}{ft^3}]$, and A_b $[ft^2]$ is the bottom area of the lagoon. This is divided by the volume associated with 1 foot depth at the bottom of the lagoon to represent some degree of nutrient stratification in the lagoon. This is the seepage concentration, C_f.

1D Groundwater Solute Transport. Solute transport through the lagoon liner is modeled using the 1D Analytical Solution to the advection-dispersion equation for a continuous input. Some researchers speculate that lagoons leakage rates of lagoons decrease over time as manure solids settle and reinforce the soil liner and that newly constructed lagoons might behave similarly to an instantaneous point source (Erickson, 1991). Using analytical solutions for continuous input thus represents the upper bound of contaminant transport from manure lagoons (Hunt, 1978).This equation is as follows:

$$\frac{c(x,t) - C_i}{C_f - C_i} = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{x - \bar{v}t}{2\sqrt{Dt}}\right)\right]$$

This solution has an initial condition, C_i, which is the first measurement of ammonia-N in the groundwater reports. C_f is the concentration at the bottom of the lagoon, and x is the vertical distance from the point source, in this case the soil liner thickness, T. The Ogata-Banks solution has the following boundary conditions:

$$\text{BC1: } c(x = 0) = C_f$$

$$\text{BC2: } c(x \rightarrow \infty) = C_i$$

The seepage velocity, $\bar{v}$, is obtained by dividing the specific discharge (*q)* by the porosity of the compacted soil liner. The lagoon sits on top of sand and gravel, but the compacted soil liner is assumed to be clay with a porosity (ϕ) of 0.5. Superposition was applied to simulate the effects of a step-change in the lagoon concentration (ΔC).

2D Groundwater Solute Transport. Solute transport in the subsurface was accomplished using the semi-analytical solution for an instantaneous point source integrated with respect to time (Wexler, 1989). Thus, it has the same initial and boundary conditions as those used for the Ogata-Banks solution.

$$c(x, y, t) = \frac{C_o Q'}{4\pi\sqrt{D_x D_y}} \exp\left[\frac{\bar{v}(x - X_c)}{2D_x}\right] \int_0^t \frac{1}{\tau} \exp\left[-\left(\frac{\bar{v}^2}{4D_x}\right)\tau - \frac{(x - X_c)^2}{4D_x\tau} - \frac{(y - Y_c)^2}{(4D_y\tau)}\right] d\tau$$

The expression in the integrand was solved numerically using Simpson's Rule with 50 segments. C_o represents the concentration outside the lagoon liner obtained from the Ogata-Banks solution, Q' is the discharge per unit thickness of the aquifer, D_x, D_y are the longitudinal and transverse hydrodynamic diffusion coefficients, $\bar{v}$ is the linear seepage velocity in the x-direction, (X_c, Y_c) is the location of the point source, and τ is the dummy variable used for integration. To produce contour plots of the subsurface, the solution is first solved for a specific coordinate over the duration of the simulation, and then this is repeated for a different coordinate.

Coupling the Main Lagoon and Groundwater Model. The complete model is composed of two distinct modules — one for simulating the overall mass balance of the lagoon, ammonia volatilization, and settling losses, and a second for simulating solute transport through the lagoon liner and then solute transport in the subsurface. The main lagoon model provides inputs of the concentration at the lagoon liner to the groundwater model (**Fig. 2**). The model is capable of assessing overflow risk for a particular lagoon level, ammonia volatilization as a function of lagoon pH, settling losses to groundwater, and solute transport in the subsurface. The calibrated model parameter values and the typical range of these values are in Table 3.

Lagoon overflow occurs when the current volume of the lagoon exceeds the capacity, which can be the result of an extreme flood event. To capture the risk of lagoon overflow, Monte Carlo simulations of the primary lagoon model was conducted. The four main uncertain variables explored in the Monte Carlo version of the model were precipitation, drainage quality, animal count, and level of risk. Precipitation was assessed by randomly choosing the daily precipitation events for a single year out of a 30-year period of record for Washington and Arizona. Drainage quality was determined by the general crop progress for each state as poor crop progress can be an indication of poor field drainage. Animal count was sampled based on the distribution for farm sizes according to the NASS census. Dairy farm sizes were used for Washington and beef farm sizes were used for Arizona. Level of risk was sampled from a uniform distribution between 0 and 1. As discussed previously, a level of risk of 1 indicates that the farmer is using 0% of the allocated flood control volume. When the current volume exceeds the specific operating volume, the farmer removes 50% of the current storage. Once these four parameters have been sampled, the model is then run for 1 year. A total of 10,0000 model runs were simulated.

Table 3. Model Parameter Values and Ranges

Parameter	Description	Value	Range	Source
K	Saturated hydraulic conductivity of soil liner	0.0003 ft/d	0.3-0.003 ft/d	(Arnon et al., 2008)
T	Thickness of soil liner	1 ft	0.5-2 ft	(Glanville et al., 2001)
ϕ	Porosity of soil liner	0.5	0.4-0.7	(Fetter, 2001)
η	Pan evaporation coefficient	0.7	0.69-94	(Ham, 2004)
K_L	Overall liquid mass-phase transfer coefficient	1.417 ft/d	1.417-1.559 ft/d	(K. S. Ro et al., 2008)
CN	Curve number for SCS runoff	91	91-99	(Andersen, 2016)
ν	Apparent settling velocity of N	0.095 ft/d	~0.18 ft/d	(Jiao et al., 2014)

CHAPTER 3

ADAPTING THE MODEL TO A DAIRY LAGOON IN WHATCOM, COUNTY WASHINGTON

Whatcom County, Washington. A groundwater report of a dairy lagoon conducted from in 1990 to 1991 in Whatcom County, Washington was used to validate the results of this model. The Edaleen Dairy Lagoon Ground Water Quality Assessment contains measurement values from February 1990 to February 1991 (Erickson, 1991). The report was conducted by the Washington State Department of Ecology as part of the Environmental Investigations and Laboratory Services Program in order to identify if the lagoon leakage was contaminating groundwater. Groundwater monitoring wells were setup downstream and upstream of the lagoon and sampled routinely for water quality parameters such as TDS, COD, TOC, Ammonia-N, and Total Phosphate. The groundwater monitoring wells downstream of the lagoon had elevated concentrations of each of the sampled water quality parameters. The location of available meteorological stations is depicted in **Fig. 5**.

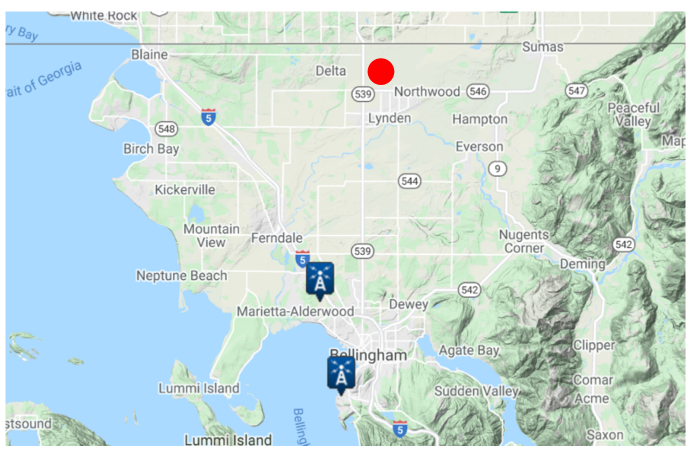


Figure 5. Location of available meteorological gauges near Lynden, Washington. Approximate location of the lagoon indicated by the red dot.

The climate data was obtained from the Global Historical Climate Network which has daily land surface observations around the world and is managed by the National Oceanic and Atmospheric Administration (NOAA). Station GHCND:USC00450587 is located in Bellingham, Washington (48.7177, -122.5113) and is about 15 miles away from the Dairy Lagoon. This station was chosen because its period of record includes the monitoring periods of the groundwater reports and contains daily pan evaporation and precipitation values. Because this is the only station in the region that has precipitation and evaporation measurements for the monitoring period. The monthly average pan evaporation for these gauge stations is zero during the winter; there is insufficient radiation during the winter for pan evaporation to occur and as such is evaporation is set to zero during the winter.

The dairy lagoon is in the Puget Sound watershed, depicted in **Fig. 6**. The region has been characterized by the Washington State Department of Ecology (using land use classification) as having high degradation due to phosphorus, metals, nitrogen, and pathogens while having low export potential (*Watershed Characterization Project - Washington State Department of Ecology*, 2012). This is indicative of "more headwater streams & retention of N." The management action is to restore sinks but reducing sources (manure lagoons) could be another management action.

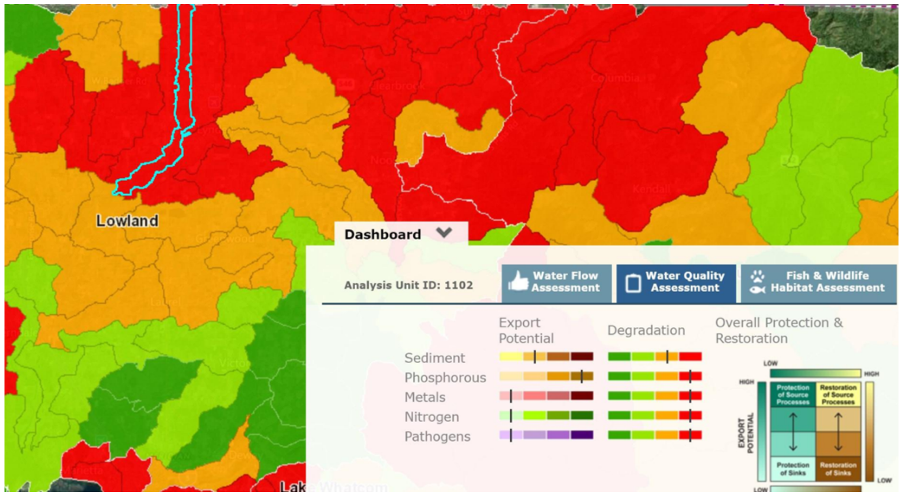


Figure 6. Contemporary Water Quality Assessment of the sub-basin where Edaleen Dairy is Located (Watershed Characterization Project - Washington State Department of Ecology, 2012).

The model was adapted to the dairy lagoon by first determining the geometry of each lagoon. This was based off the given capacity of the lagoon, the surface area, and then by approximating its dimensions for a trapezoid. The lagoon bottom width, side slope, and design depth were estimated based on the surface area and the volume of the lagoon. The summary of these properties is in **Table 4**, and a depiction of the cross-section is in **Fig. 7**.

Table 4. Manure Lagoon dimensions

Dairy Name	Top Width (B)	Bottom Width (b)	Side Slope (z)	Length (L)	Design Depth (d)	Capacity
Edaleen Dairy	275 ft	139.67	4.51 ft	447 ft	15 ft	10.4e6 gal

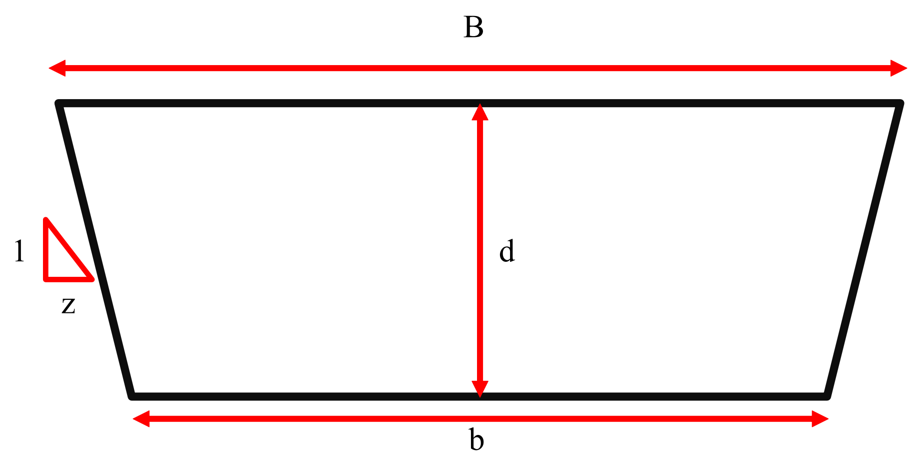


Figure 7. Lagoon cross-section

The Maximum Operating Level (MOL) is the volume of the lagoon allocated for manure. The additional volume is the flood control volume. The MOL for 900 dairy cattle was estimated by assuming a storage period of 2 years for Edaleen Dairy. This corresponds to a MOL depth of 13 ft. Proper manure management requires the farmer to not allow the depth of the lagoon to exceed the MOL. To model risky behavior by the farmer, the *Level of Risk* identifies the point between the MOL and the capacity of the lagoon that the farmer chooses to remove manure. For example, a *Risk* value of 0.4 indicates that the farmer is ignoring 40% of the flood control volume. These scenarios have a higher probability of the lagoon overflowing during a precipitation event.

$$\text{Level} = \text{Risk}\left(V_{cap} - \text{MOL}\right) + \text{MOL}$$

Data Sources. The samples collected in the groundwater quality monitoring report showed elevated levels of ammonia-N in the lagoon and the downstream wells. For this reason, ammonia-N was used as the nutrient of interest in the model. While there were measurements of Nitrate-Nitrite-N (NO3-NO2-N), there were numerous non-detectable samples and the concentration of NO3-NO2-N in the lagoon were only just above the minimal detectable limit for the sampling method used. Total Phosphorus illustrated similar trends as the NO3-NO2-N samples — the measurements were either too low or the well samples showed non-detectable amounts of phosphorous (**Fig. 8**).

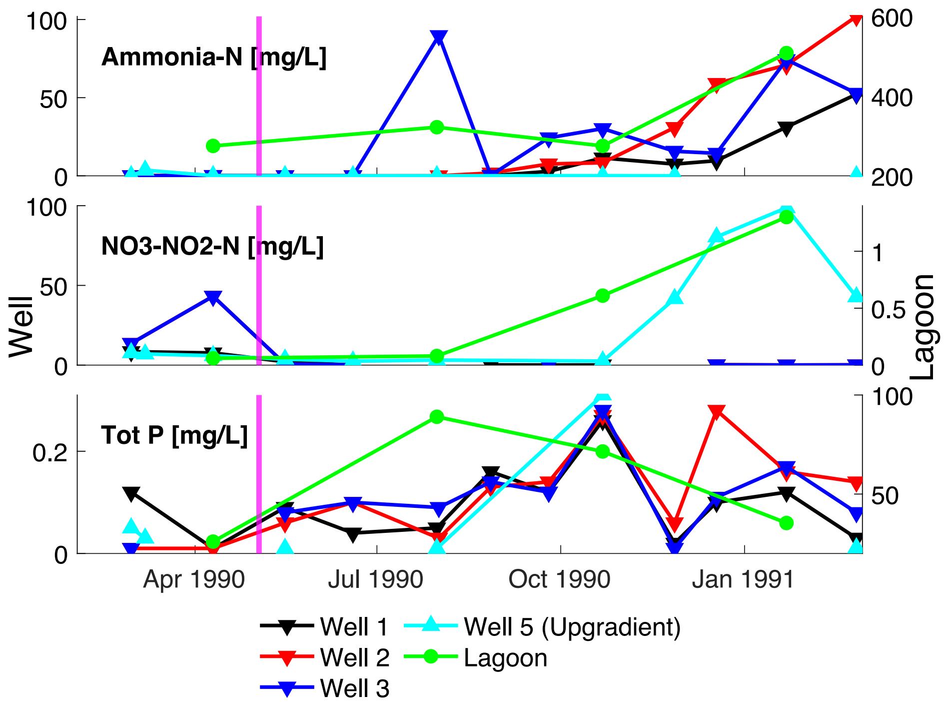


Figure 8. Water quality samples from lagoon and downgradient wells. The pink line indicates the date that the lagoon received waste.

Only Ammonia-N showed trends of solute transport in the subsurface following the addition of waste to the main lagoon. A possible reason for this is that when the groundwater table intersected the bottom of the lagoon in November of 1990 it created aerobic conditions that facilitated the conversion of organic N to inorganic N. The water quality samples of the lagoon and three downgradient wells indicate that the lagoon had an adverse effect on groundwater quality following construction. Because the interactions between the lagoon and the groundwater table increase the complexity of how the lagoon interacts with the subsurface, the 2D transport model was run shortly before this time to justify the assumption of fully saturated flow. A profile view of the lagoon and the location of the monitoring wells is depicted in **Fig. 9.**

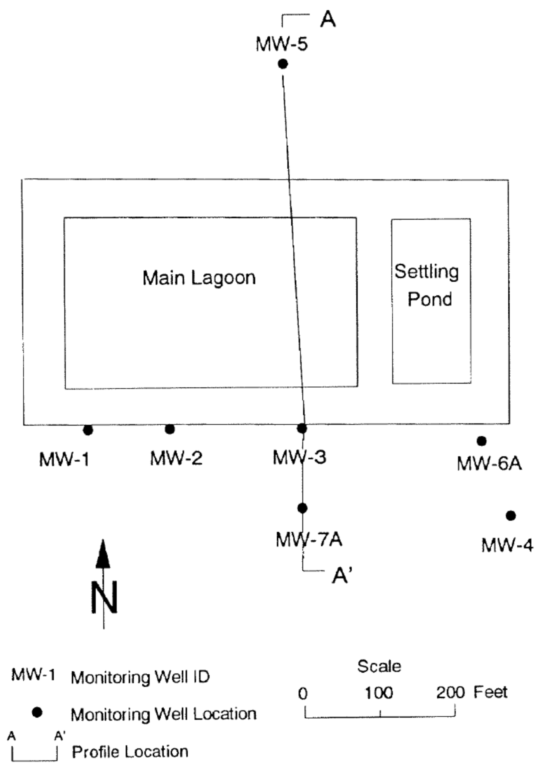


Figure 9. Location of the main lagoon, settling pond, and monitoring wells. (Erickson, 1991)

CHAPTER 4

RESULTS

Results — Lagoon Overflow.

An example 1-year model simulation of the Monte Carlo simulations is depicted in **Fig. 10.** Overflow is a rare phenomenon for both Arizona and Washington. While overflow is more common for the dairy CAFOs in Washington, it still only occurred in 3.17% of the model simulations. By comparison, only 0.83% of the Beef CAFOs in Arizona experienced overflow. Despite the size of the discharge being larger for those farms in Washington, the mean loading rates were smaller because they are normalized to the size of the feedlot area. This is an indication that the distribution of farm sizes in Arizona leans toward smaller farms while the distribution for farms in Washington is more evenly distributed between large and small farms. The model state space (**Fig. 11**) reflects this – overflow (indicated by the red circles) happened for a range of different farm sizes for Washington.

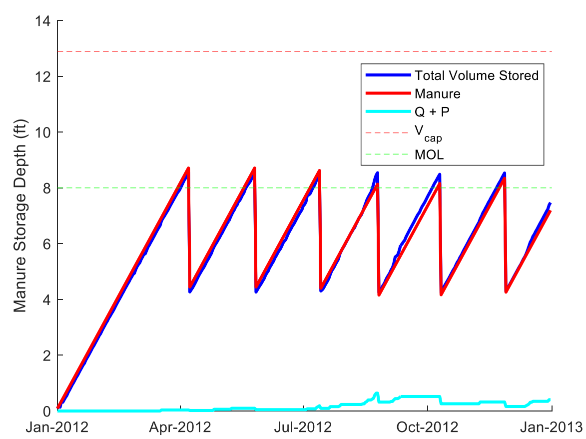
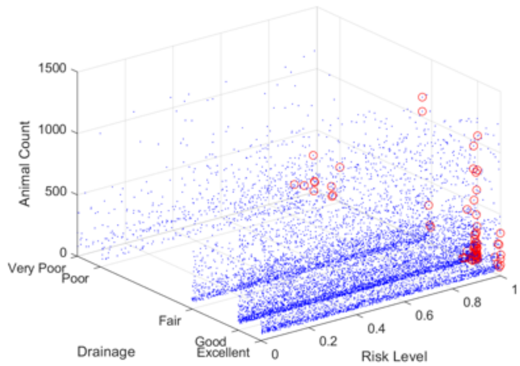


Figure 10. Example 1-year model simulation for Arizona. Animal Count: 1185. Feedlot Area: 296,250 sq. ft. Design Storage Capacity: 180,379 cubic ft. Risk Level: 0.0975. Drainage Quality: 'Fair.'



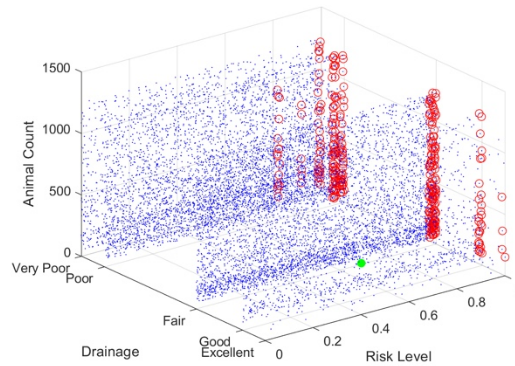


Figure 11. Comparison of model state space for AZ Beef CAFOs (left) and WA Dairy CAFOs (right)

Further, Washington also has worse drainage quality. This is the primary reason that overflow was more common. Overflow also occurred under better management practices, indicated by lower levels of risk. Despite the farmers utilizing more of the allocated flood control volume, the poor drainage quality led to more frequent overflows for the model simulations. It should be noted that this only considered 1-year model simulations. More extensive analysis could entail exploring the risk of overflow for a longer period of time. The nutrient loading results are depicted in Table 5.

Table 5. Monte-Carlo Lagoon Overflow Results

Metric	AZ	WA
Total Overflows	83 (0.83%)	317 (3.17%)
Mean Q Discharge $[\mathbf{ft^3}]$	160.68	391.71
Mean N Loading $\left[\frac{\mathbf{mg-N}}{\mathbf{m^2-yr}}\right]$	11.22	6.98
$\mathbf{q_{05}}$ **N Loading** $\left[\frac{\mathbf{mg-N}}{\mathbf{m^2-yr}}\right]$	0.85	0.22
$\mathbf{q_{95}}$ **N Loading** $\left[\frac{\mathbf{mg-N}}{\mathbf{m^2-yr}}\right]$	44.49	17.81

The lagoon overflow model for Edaleen Dairy was validated using measured lagoon levels. As indicated in **Fig. 12**, the model performs poorly during the end of the monitoring period. Model performance could be improved significantly if manure management data – the frequency and volume of manure entering or exiting the lagoon – was provided. The two simulated decreases in the lagoon level were estimated based off the observed lagoon levels.

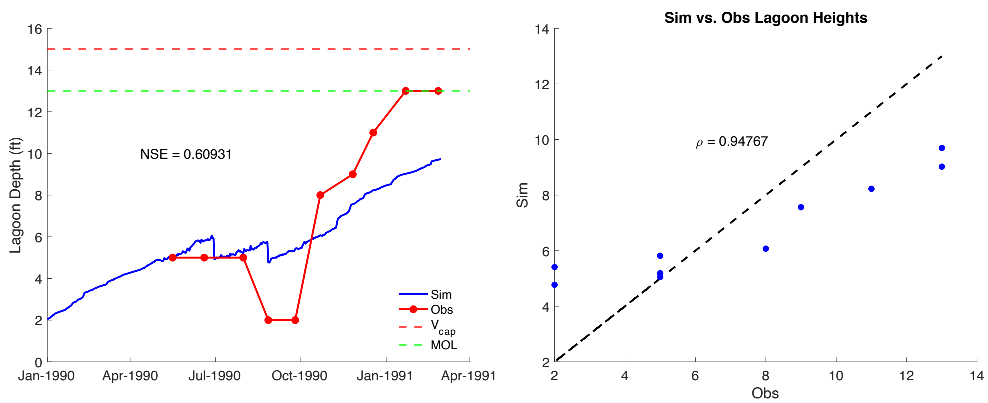


Figure 12. Lagoon overflow model validation results. NSE = 0.60. Model performance can be improved with manure management data.

Farmers typically keep reports of imports and exports of manure at the monthly timescale, but in order to significantly improve model performance this would have to be done at the weekly time scale. A Nash-Sutcliffe Efficiency of 0.60 suggests a satisfactory fit. Precise knowledge of the volume of manure exiting and leaving the lagoon could improve model performance — this highlights the need for these monthly imports and exports should be made publicly available. There is significant correlation between the observed and simulated lagoon heights. While not a perfect fit, this will be suitable to conduct an analysis of lagoon overflow and identify periods of time in which overflow is more common.

A seasonal risk assessment for overflow was performed on Edaleen Dairy. For a given lagoon depth, the probability of overflow occurring was calculated by determining the probability that a rain event of sufficient depth to cause overflow would occur. The exceedance probability for the wet and dry seasons for Washington are depicted in **Fig. 13.** These were constructed by estimating the parameters of the gamma distribution at the monthly scale for the 30-year period of record of precipitation at the weather gauge in Bellingham, Washington.

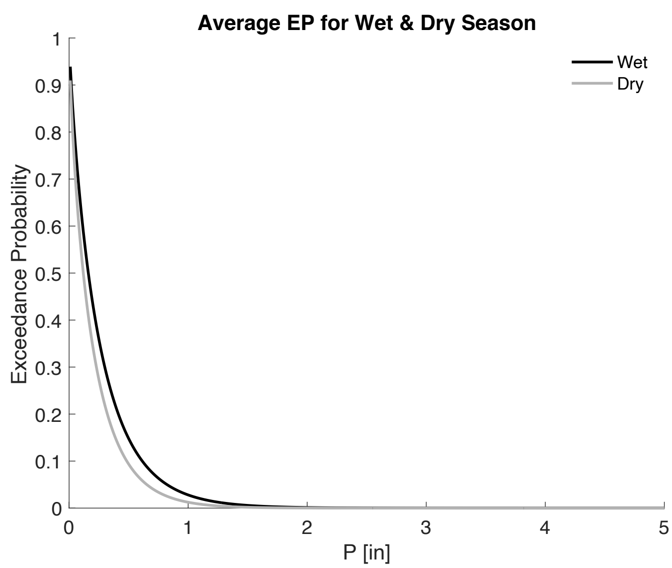


Figure 13. Exceedance probability for wet (Oct-Dec) and dry (Jul-Sep) seasons

Two distinct management and drainage quality scenarios are depicted in **Fig. 14**. This is further indication that lagoon overflow is quite rare. Even when the farmer is only using 10% of the flood control volume, the probability of overflow peaks at 4%.

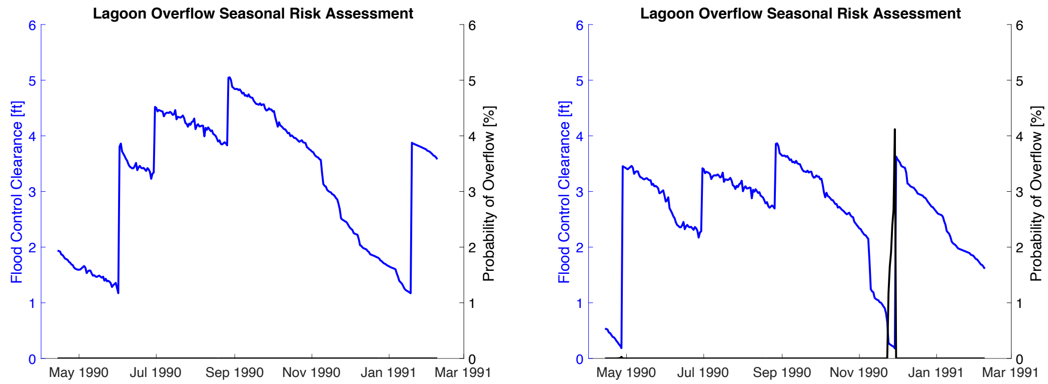


Figure 14. Comparison of different management and drainage quality scenarios. On the left, risk level is 0.4 and no runoff enters the lagoon. On the right, risk level is 0.9 and 100% of runoff enters the lagoon.

However, this information can still be useful by allocating more flood control volume depending on the time of year. Farmers could be instructed to implement a flexible management option for the manure lagoon volume in which they start pumping before the wet season in November. Overflow of these lagoons is a rare phenomenon, but proper management should be taken to reduce the probability of overflow due to the uncertainty surrounding future climate change scenarios on precipitation depth and intensity.

Results — Groundwater Solute Transport. The groundwater model incorporates the concentration at the bottom of the lagoon to simulate 1D transport through the compacted soil liner. The model was run for a period of 2-years to account for the gradual dilution of the concentration in the lagoon due to precipitation. The concentration at the bottom of the lagoon (**Fig. 15)** reaches a constant level in May of 1990 — the date that the main lagoon initially receives waste. Then, this concentration is used as an input to simulate 2D transport in the subsurface.

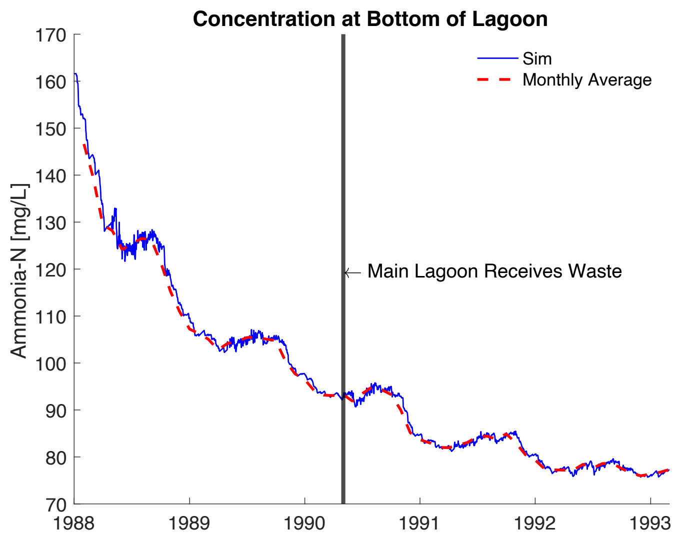


Figure 15. Concentration of Ammonia-N at the bottom of the lagoon. The model was run for 2-years prior to the main lagoon receiving waste to account for gradual dilution of the lagoon due to precipitation.

Because there was no data collected about either the concentration at the bottom lagoon or the concentration just outside the liner, the model was calibrated to the downstream conditions in the monitoring wells approximately 180 feet away from the lagoon. The resulting model calibration is seen in **Fig.** 16.

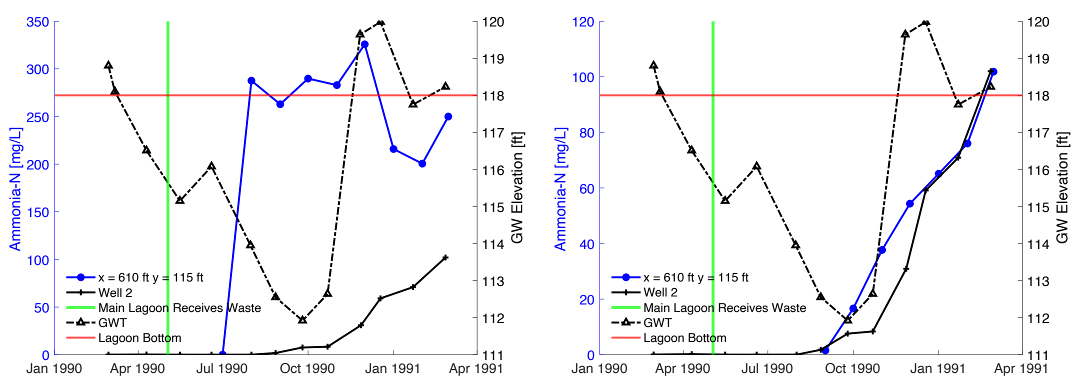


Figure 16. Groundwater model before and after calibration.

Downstream groundwater quality is highly sensitive to the properties of the soil liner. State regulations for specific discharge range from 0.0015 ft/d to 0.021 ft/d. If the state does not have a specific regulation on specific discharge, then a value of 0.015 ft/d is used (NRCS, 2009). The calibrated parameters for the subsurface (regional groundwater flow, subsurface seepage velocity, longitudinal and transverse dispersivity, and the aquifer thickness) remain constant while the soil liner thickness and the soil liner hydraulic conductivity were adjusted to determine its effects on groundwater quality.

The specific discharge for the calibrated model had an average specific discharge of 0.0044 ft/d (**Fig. 17**). A 3-month progression of the contaminant plume (**Fig. 18**) indicates that there is significant transport in the subsurface. The red dot indicates the location of the lagoon, and the black dot is the approximate location of the groundwater table elevation in the downgradient monitoring wells. However, this model does not incorporate the effect that biochemical sealing might have on leakage rates.

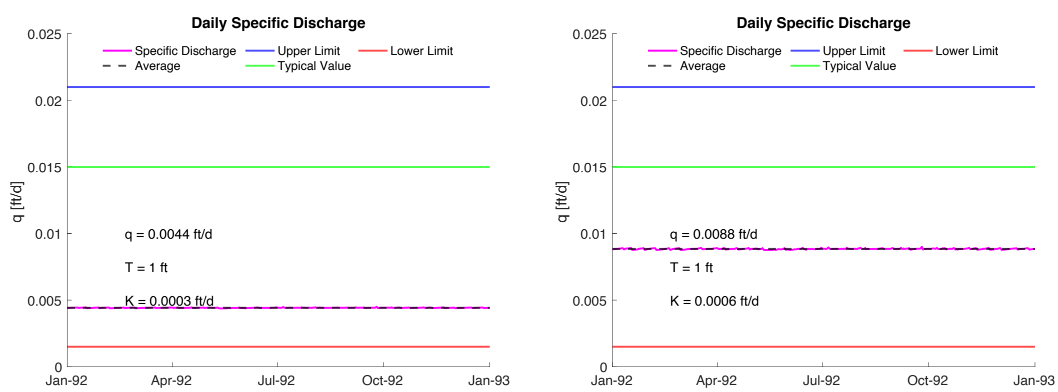


Figure 17. Specific discharge for two soil liner design scenarios. T = 1 ft, K = 0.0003 ft/d (left) and T = 1 ft, K = 0.0006 ft/d (right)

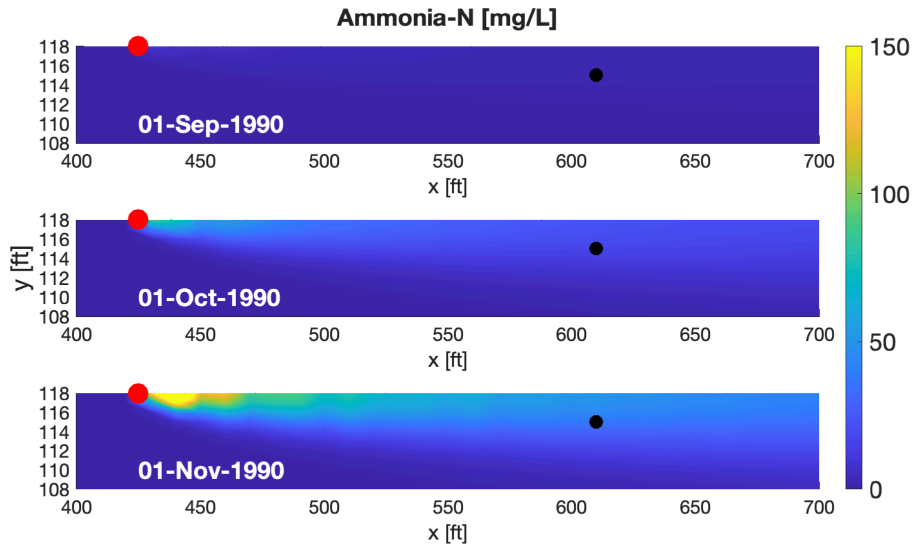


Figure 18. 3-month progression of contaminant plume for calibrated model.

The effects of potential manure sealing rates can be explored by adjusting the hydraulic conductivity. Doubling the hydraulic conductivity of the soil liner has adverse effects on the progression of the contaminant plume. While the initial state is similar for both cases, as time progresses the plume is no longer limited to an area close to the lagoon. A comparison of the concentration outside of the soil liner is depicted in **Fig. 19**.

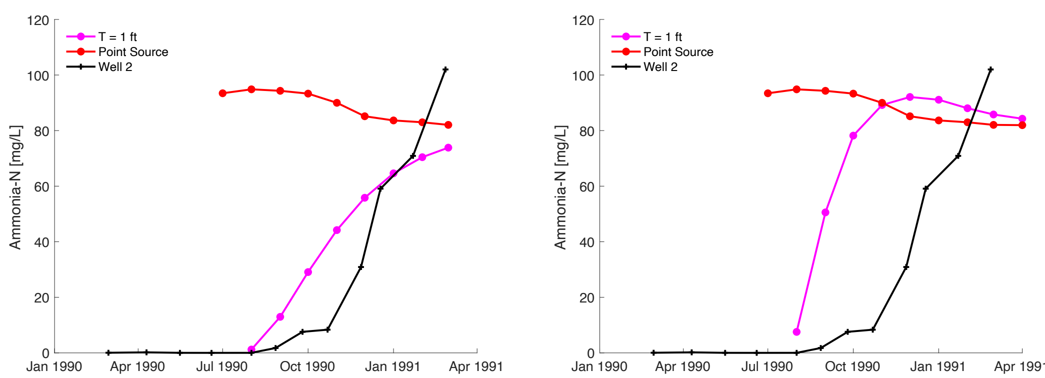


Figure 19. Concentration outside the soil liner. T = 1 ft, K = 0.0003 ft/d (left) and T = 1 ft, K = 0.0006 ft/d (right)

The primary input into the 2D groundwater model is the concentration immediately outside the soil liner. The concentration outside the soil liner is driven primarily by advective processes —a higher specific discharge increases the propensity for nutrients to travel through the soil liner (absent of any biochemical manure sealing effects).

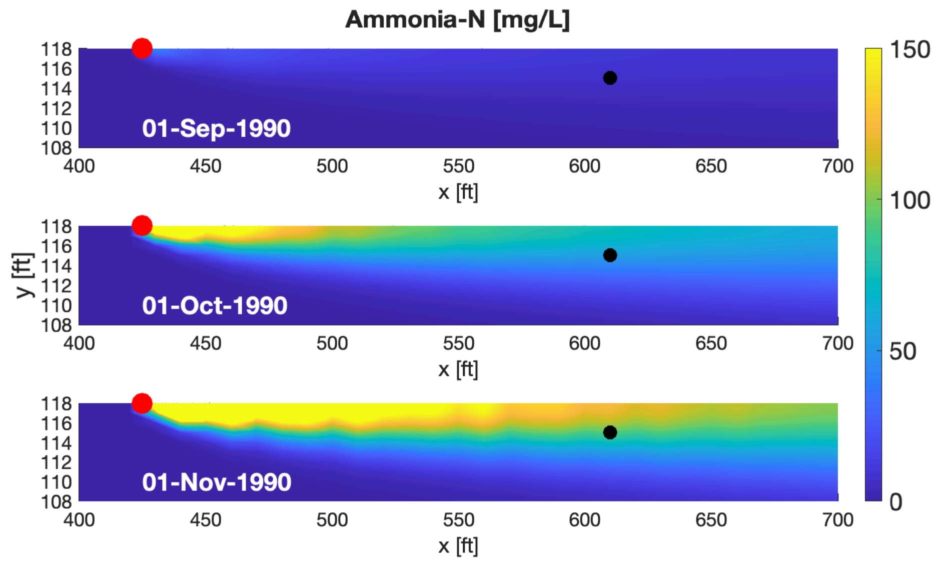


Figure 20. 3-month progression of contaminant plume after doubling the soil liner hydraulic conductivity (K = 0.0006 ft/d)

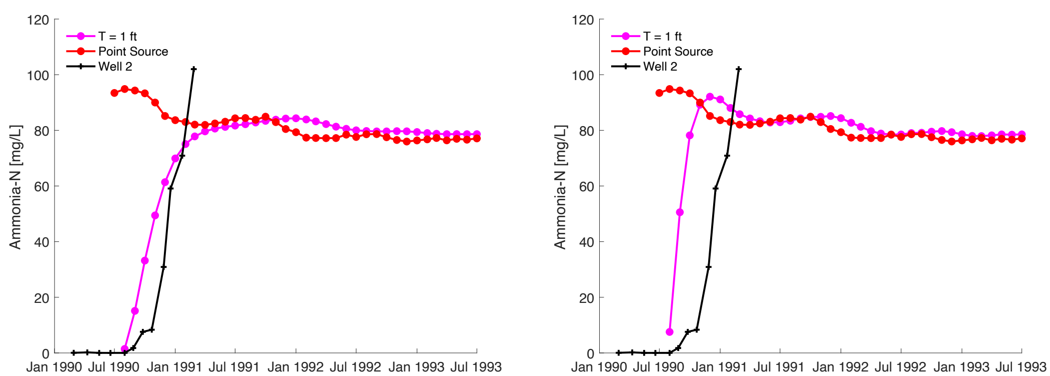


Figure 21. Pseudo-steady state concentration outside the soil liner. T = 1 ft, K = 0.0003 ft/d (left) and T = 1 ft, K = 0.0006 ft/d (right)

Doubling the hydraulic conductivity of the soil liner has the effect of increasing the concentration outside the soil liner by approximately 15%. Additionally, the concentration also increases more rapidly. Further, because the point source concentration is relatively constant for longer model simulations, the concentration outside the lagoon will also approach a constant level. While both soil liner construction methods approach the same pseudo-steady state concentration, delaying the time that this occurs can lead to improved groundwater quality. Thus, designing the soil liner such that there is sufficient time for manure sealing to occur could substantially improve groundwater quality. A 20-month simulation for K = 0.0003 ft/d and 0.00035 ft/d is at x = 475 ft and y = 118 ft is depicted in **Fig. 22**.

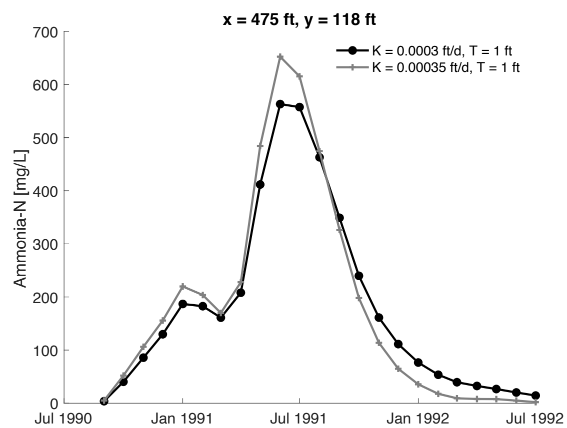


Figure 22. Downstream concentration 50 ft from the point source.

Even small changes in the hydraulic conductivity of the soil liner can have significant effects on downstream groundwater quality. This also indicates that despite the lagoon being modeled as a continuous input, the immediate input of the mass being added to the lagoon behaves similarly to a pulse input, which was initially unexpected. The transport of this contaminant plume in the subsurface (**Fig. 23**) also reflects the small fluctuations in the concentration outside of the lagoon.

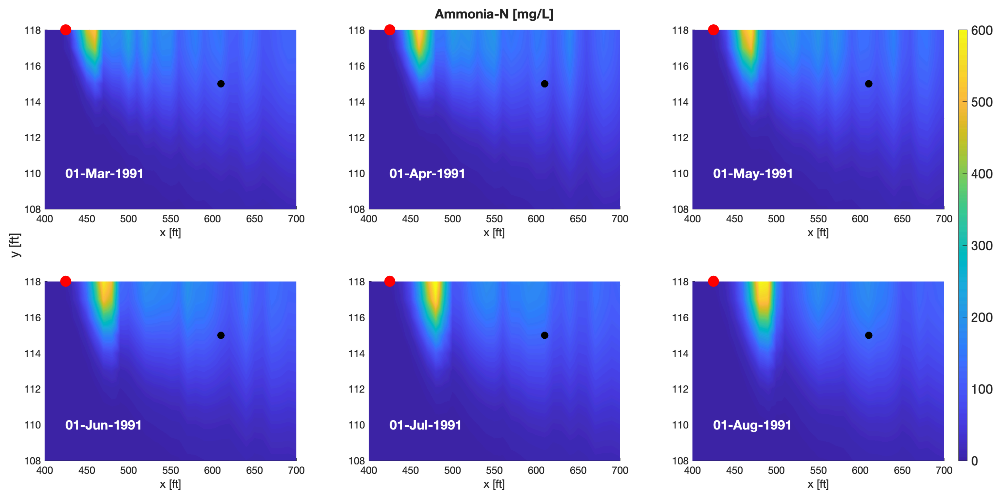


Figure 23. 6-month progression of contaminant plume in the subsurface. (T = 1 ft, K = 0.0003 ft/d)

These small fluctuations outside of the lagoon are a function of the total Ammonia-N concentration in the main lagoon model, which is primarily affected by higher evaporation in the summer. When evaporation is high, the total amount of water in the lagoon decreases and thus the bulk ammonia-N concentration increases. This is seen quite clearly in the summer months (Jun-Aug) where the width of the secondary plumes (150-250 mg/L) are wider than they are in the Spring. This has numerous design and management implications — the first being the timetable of initial construction for these lagoons. Finishing construction in the winter and then adding waste in the early Spring can provide time for potential biochemical manure sealing to occur. This lagoon initially received waste in May of 1990 and these results indicate that (given the regional groundwater flow) it took about a year for peak groundwater quality concentrations to occur before they reached pre-construction concentrations.

Unfortunately, the monitoring at this lagoon did not continue to determine if (and when) concentrations returned to pre-construction levels. However, groundwater quality samples further downstream were further attenuated. Identifying the spatial and time scale that attenuation occurs could provide significant aid in the design and construction of these lagoons.

Increasing the thickness of the soil liner significantly improves groundwater quality (**Fig. 24)**. Not only does it attenuate peak concentrations, but it also delays the time at which the peak concentration occurs.

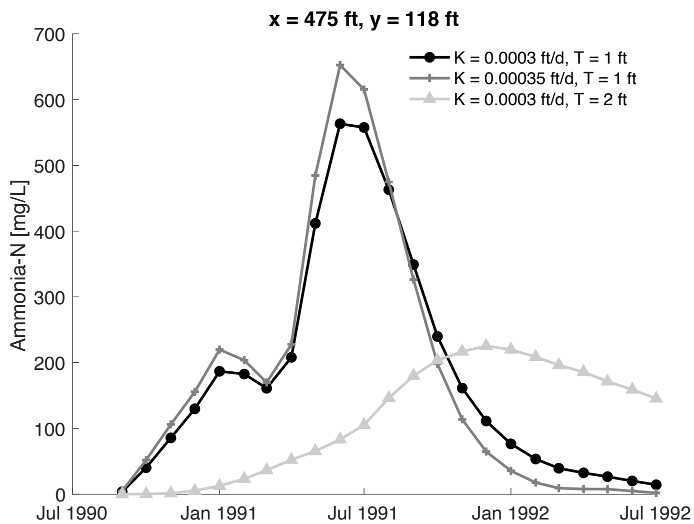


Figure 24. Effect of doubling the soil liner thickness on groundwater quality. Peak concentrations are attenuated and the time to peak concentration is also delayed

The peak concentration is reduced from 563 mg/L to 225 mg/L at a location 50 ft from the lagoon. Doubling the thickness of the soil liner effectively reduces the peak concentration by 2.5. This is significant improvement over halving the hydraulic conductivity of the soil, which may not be a suitable design variable that can be adjusted as easily as increasing the thickness of the soil liner. A 5-year model simulation indicates that the groundwater quality concentrations are further diminished after 3 years (**Fig. 25**).

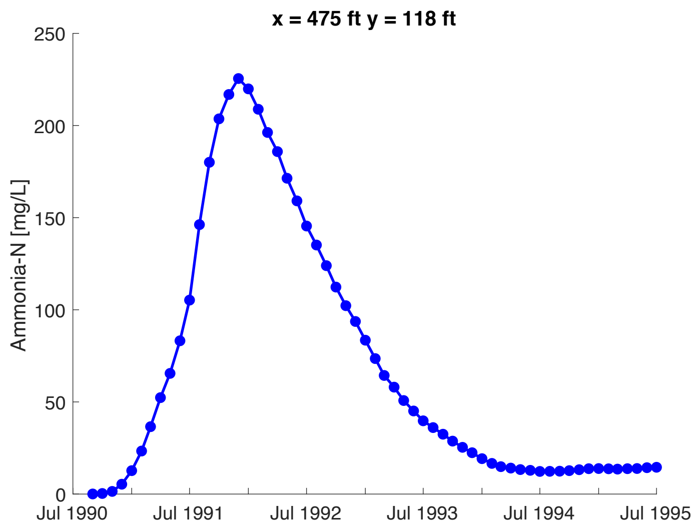


Figure 25. Concentration 50 ft. away from the lagoon after 5-years. (T = 2 ft, K = 0.0003 ft/d)

Results —Ammonia Emissions. Ammonia emissions are a function of the bulk Ammonia-N concentration in the lagoon and the lagoon pH. Farmers are recommended to maintain an operating pH between 7-8 to limit ammonia emissions. The fraction of ammonia in the lagoon available for volatilization increases as pH increases and thus at a higher pH the lagoon volatilizes more ammonia (**Fig. 26**).

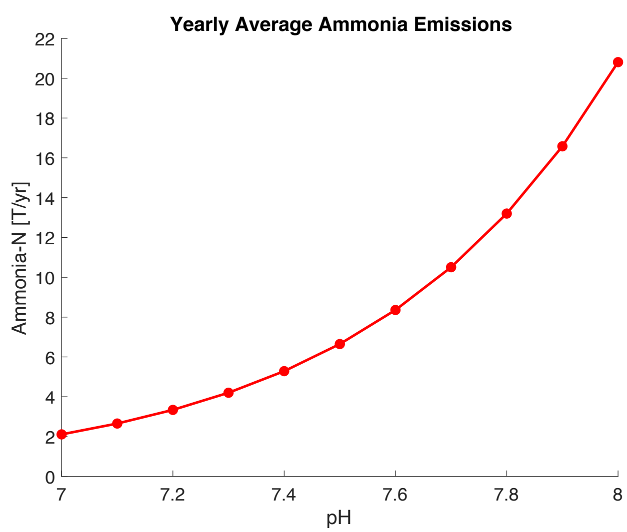


Figure 26. Yearly average ammonia emissions (T/yr) for a 15-year simulation.

Additionally, because the lagoon concentration is sensitive to the amount of water in the lagoon, ammonia emissions increase during the summer because of evaporative losses (**Fig. 27**).

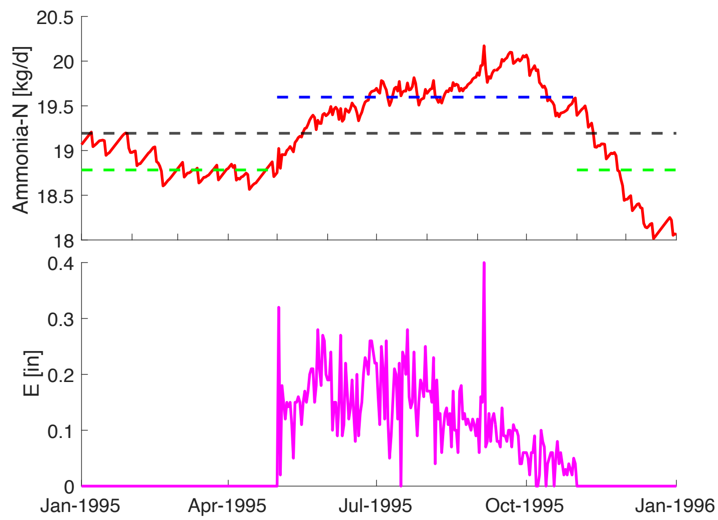


Figure 27. Daily Ammonia-N emissions for 1-year. Daily average for this time period is 19.5 kg/d

Pan evaporation during the winter is difficult to measure because of the cooler temperatures and unavailability of latent heat to facilitate evaporation. From Nov-May, the average ammonia flux is 19.0 kg/d and during the summer (May-Sep) it increases to 19.9 kg/d. This proposes concrete management solutions for farmers such as reducing the pH in the summer by adding lactic acid to the lagoon to reduce emissions (Berg et al., 2006). As indicated by **Fig. 26**, even small fluctuations of pH within the acceptable operating range can greatly affect the ammonia emissions, with the sensitivity of emissions increasing as the pH increases. Reducing the lagoon pH from 7.8 to 7.5 can halve the yearly average emissions.

Proper lagoon construction and management can lead to improved air and groundwater quality. When the soil liner is constructed with a lower hydraulic conductivity or increased thickness, air quality emissions also improve. The less water leaving the lagoon, the lower the bulk concentration of the lagoon liquid. Thus, there are no inherent trade-offs between air and groundwater quality. Because the lagoon is modeled as a massive nitrogen pool, reducing the pH does not lead to increased settling losses because neither process is limited by the amount of nitrogen in the lagoon. Increasing the flux of either (by adjusting the pH or the apparent settling velocity) does not affect either flux. However, the water fluxes (evaporation and seepage) do affect both air and groundwater quality.

CHAPTER 5

DISCUSSION

Preventing nutrients from entering the hydrological landscape can be accomplished through adequate design, maintenance, and management of the manure lagoon. Overflow was the initial failure mechanism of manure lagoons explored in the development of this model. However, results indicate that overflow is rare for CAFOs in Washington that receive significant rainfall. Across simulated CAFOs, overflow only occurred approximately 3% of the time. For CAFOs in Arizona, overflow occurred less than 1% of the time. Applying a seasonal risk assessment to Edaleen Dairy indicate that even if only 10% of the flood control volume was utilized and 100% of runoff entered the lagoon the risk of overflow was only 5% during the wet season. While it is not recommended that farmers ignore the portion of the lagoons partitioned for flood control, the risk of overflow is low. The nutrient loading rates during an overflow are also quite low, and the volume of water discharged during a "normal" overflow event is small relative to the size of the farm and the total lagoon volume. Avoiding overflow can be down by berming the sides of the lagoon to prevent clean runoff from entering the lagoon. It should also be noted that these lagoons can be breached when they overflow, and this mechanism is not captured in the model. Even if the farmer only allocates 1 foot freeboard for flood control, it is extremely unlikely that a rainfall event that large occurs in the US outside of hurricanes along the Atlantic coast. If overflow does occur, the discharged volume should be directed toward wetlands. Given limited management options to prevent nutrients from entering the hydrological landscape, farmers should focus primarily on reducing groundwater contamination through seepage and preventing ammonia emissions during the summer.

The results from this modeling effort indicate that groundwater contamination can be prevented through careful construction of the lagoon. This means limiting the specific discharge through the soil liner, which can be accomplished through increasing the thickness of the soil liner or choosing an appropriate soil such that the hydraulic conductivity is low. Increasing the thickness of the soil liner is a more appropriate design choice because the specific discharge is more sensitive to the soil liner thickness than it is the hydraulic conductivity. Further, there may be heterogeneities in the saturated hydraulic conductivity of the soil liner that make this a more difficult parameter to control. This modeling effort simplified complex lagoon chemistry to aid in future model calibration for water quality models. This concentration is then sensitive to small changes in the water stored in the lagoon, increased evaporation during the summer leads to a higher liner concentration. However, over time these minor fluctuations in the liner concentration have little effects on groundwater quality. Because peak concentrations can take a year to occur following the addition of waste in the absence of manure sealing, knowing the timetable that manure sealing is effective could help prevent these peak concentrations entirely. Without manure sealing, it can take several years for concentrations to reach background levels.

Reducing ammonia emissions can be done primarily through reducing the maintenance pH of the lagoon. Adding nitric or lactic acid to the lagoon during the summer when evaporation is high can be a specific management option for farmers. Small reductions in pH in the operating range of 7-8 have the potential to halve ammonia emissions. Emissions can be reduced almost entirely by covering the lagoon, but this might not be suitable a practice in all cases. Because ammonia emissions are also a function of the surface area of the lagoon, farmers have the added benefit of reducing both overflow and ammonia emissions by maintaining a lower lagoon height — the surface area used to calculate ammonia emissions increases as the lagoon height increases because the sides are sloped. A lower design lagoon height also leads to lower specific discharge through the soil liner, which can also prevent groundwater quality issues if the lagoon is already constructed, and it is not economically feasible to perform maintenance on the lagoon liner.

Regulations & Guidance

The Agricultural Waste Management System Component Design Manual provided by NRCS outlines detailed guidelines for designing and maintaining numerous waste management systems for farmers in the US. In regard to preventing overflow, readers are referred to another conservation practice at diverting clean water away from the lagoon. Given that overflow is a rare failure mechanism, this is a suitable design practice. There is also significant detail into different design and construction methods for the soil liner at preventing seepage. It should also be reiterated that lagoons constructed prior to 1990 assumed that the accumulations of solids were sufficient to limit seepage, which is not the case for lagoons constructed on sandy soils (NRCS, 2009).The calibrated lagoon model assumed a highly impervious soil was used for the soil liner, despite the lagoon being constructed without guidance from SCS. And yet, peak ammonia concentrations still occurred several years following the construction of the lagoon. While there might be some degree of solids accumulation that prevents this, there was insufficient data collected to support this. The monitoring should have continued to determine if ammonia concentrations in the downgradient monitoring wells decreased.

The least guidance provided in the design manual is in regard to air quality. Engineers and farmers are instructed to site the lagoons away from livestock and people. This tackles the issue of people from being affected by these emissions in a poor way. This might not be an attainable design choice for the construction of newer lagoons and is not at all useful for the management of existing lagoons. The design manual should provide concrete guidance to reduce emissions from lagoons, not reduce the risk that the emissions are near people. CAFOs in the US are typically located in low-income and nonwhite areas and thus the health effects of the people living near these facilities are negatively affected (Donham Kelley J. et al., 2007).This case of environmental injustice can best be tackled by providing farmers and engineers with adequate guidance to reduce the impact that CAFOs have on the environment.

Several CAFOs in the US are approaching 20-30 years in age and the impacts they had on the environment and neighboring communities might not truly be understood because of insufficient data collection about how these lagoons are managed. Only farms of a certain size are required to obtain a National Pollutant Discharge Elimination System (NPDES) permit, and while farmers are required to collect manure samples under a Comprehensive Nutrient Management Plan (CNMP), this data is not publicly available for most US states. In order to adequately assess the impacts that CAFOs have on the environment, this type of data should be readily available. Knowing the amount of manure generated and exported on-site, as well as the specific management practices of the manure solids and manure liquid can lead to improved environmental assessments of CAFOs, but it can also help CAFO managers refine the way they manage their manure. While the manure lagoon model that was developed provides key insight into how these lagoons might interact with surface and groundwater, this was accomplished through the use of data collected for a groundwater quality monitoring report that was more comprehensive than most data collected for a CAFO. The lack of numerous lagoon samples both temporally and spatially within the lagoon makes it difficult to ascertain the complicated lagoon chemistry. The degree of nutrient stratification in the lagoon can have significant impacts on air and groundwater quality.

To build a complete hydrological model that incorporates lagoon chemistry, a significant amount of data would need to be collected. Water quality samples of the lagoon at several depths in the lagoon would have to be taken frequently to determine the seasonality effects on nutrient stratification. These samples would also provide information about the chemical transformation occurring in the lagoon. Water quality samples would also have to be taken in groundwater monitoring wells upstream and downstream of the lagoon. Air quality emissions will also have to be measured near the lagoon but given that these are often sited near waste application spray-fields it might be difficult to adequately assess the emissions from a single lagoon. To close the water balance, lagoon height measurements will also have to be taken. Analyzing the lagoon height during periods of no precipitation and low evaporation can provide an indication of the degree of seepage in the lagoon, and whether or not sufficient accumulation of solids has led to decreased seepage rates. Measuring evaporation from the lagoon surface would also be necessary to close the water balance. In addition to these water quality samples, and hydrological processes being measured, information on how the lagoon is managed would also need to be recorded. This would entail knowing the frequency and volume of manure entering and leaving the lagoon. While this information might also be garnered from the measured lagoon height, the manure management practices employed by the CAFO manager might change throughout the year.

Lessons Learned.

While this modeling effort does not provide a complete picture of how manure lagoons might interact with the hydrological landscape, a significant amount of information was still gained. The first being the amount of data that would be needed to collect to build a more complete model. However, even incorporating complex nutrient settling processes into simplified empirical equations to estimate the nutrient settling losses that would impact groundwater quality still provided insight into the effectiveness of different soil liner construction designs. A simplified point source model of manure lagoons has the potential of being incorporated into existing water quality models such as SWAT given many of the lagoon equations were adapted from existing pond and wetland modules within SWAT. Even though not all processes in the subsurface might be accounted for (such as vadose zone hydrology or complicated lagoon chemistry) this work aimed to develop a sufficient model for use in watershed models. At the broad watershed management scale, approximating manure lagoons as point sources should improve the performance of water quality models in agricultural watersheds and would be a great next step in research.

The model calibration effort was facilitated by the data collected in the groundwater quality report, but also by previous studies that estimated different processes such as ammonia emissions, pan evaporation, or groundwater seepage. Calibrating the model entailed incorporating these different processes and then adjust the parameters that affected their performance. The understanding of these processes for manure lagoons would all be improved through comprehensive data collection and monitoring of CAFO lagoons. Being able to capture complex sedimentation processes within these lagoons to develop a range of values for the apparent settling velocity of nutrients would be essential to incorporating manure lagoons into existing water quality models.

Calibrating the model also employed the use of several assumptions. Because the groundwater table only intersected the lagoon for a portion of the year, the groundwater model was run shortly before this occurred. This was necessary to satisfy the assumption of fully saturated flow. It is also likely that when the lagoon intersected the groundwater it facilitated aerobic conditions that converted organic N to inorganic N, which could explain the elevated ammonia concentrations in the downgradient wells. Assumptions were also made about the lagoon cross-sectional geometry, which were obtained from the lagoon volume and the surface measurements of the lagoon. Further, the bottom of the lagoon was taken from an approximation within the groundwater quality report. It is possible that the lagoon was deeper (or shallower) than indicated which implicates the assumption of when the lagoon intersects the groundwater table. While the bulk concentration for the simulated lagoon did exceed the measured lagoon samples, these were grab samples taken at the surface of the lagoon. Because the degree of nutrient stratification within this specific lagoon is not known, it is difficult to validate this portion of the model. This means that the simulated ammonia emissions will be higher than expected, but without measured ammonia emissions near the lagoon it is also difficult to validate that process. Given the limited data collected, increasing the complexity of this model is not feasible. As such, the processes explored in the model were limited to what could be validated through the data collected.

The implementation of manure lagoons into water quality models proves difficult because of data availability, however their successful implementation can still be accomplished by simplifying complex lagoon chemistry to simple parameters that are easily calibrated for water quality models. Because manure samples of the entire lagoon profile would be costly to acquire, estimating the apparent settling velocity of nutrients in the lagoon for groundwater quality models can be a suitable way of tackling the uncertainty surrounding the nutrient stratification in the lagoon. Further, while it is not feasible to collect data sufficient to capture complex processes, the data that is already collected as part of their CNMP should be publicly available. This data includes manure samples, soil samples, animal count, and the amount of manure generated and exported. This data would assist in the calibration process, but it would not be necessary. Above all, the location of these manure lagoons should be publicly available.

CHAPTER 6

CONCLUSIONS

Many of the effects that CAFOs have on the environment are well documented, but the specific interactions between the hydrological landscape and manure lagoons are not. Implementing manure lagoons into watershed scale models proves difficult because of data paucity issues, such as states not disclosing the location of regulated or nonregulated operations, let alone data on manure management. Developing a manure lagoon module that incorporates hydrological processes such as precipitation, evaporation, and seepage can improve the performance of water quality models. Because of insufficient data to develop a complex lagoon model, complex lagoon chemical processes were simplified into empirical models to estimate the settling losses in a manure lagoon. The key parameter being the apparent settling velocity of nutrients in the manure lagoon. This value was calibrated to match the peak concentration that occurred downstream during a 1-year monitoring period of a dairy CAFO in Whatcom, County Washington. The long-term effectiveness of the constructed soil liner indicated that it could take several years before groundwater concentrations reached pre-construction levels. Additional monitoring of the dairy lagoon would have assisted in validating these results. Adjusting properties of the soil liner, such as the thickness or the hydraulic conductivity improved groundwater quality. This work highlights the need for better data collection and dissemination of manure characteristics of CAFOs in the US. It is essential that the location of these operations be made publicly available, and that states follow EPA guidelines for regulating these operations. This information could help farmers, researchers, and legislators better manage these key pieces of infrastructure in the agricultural landscape.

REFERENCES

Andersen, D. S. (2016). A Runoff and Sediment Routing Model for Open Lot Beef Feeding Facilities. *Applied Engineering in Agriculture*, *32*(1), 69–78. https://doi.org/10.13031/aea.32.11433

Arnold, S. D., & Meister, E. A. (1999). Dairy Feedlot Contributions to Groundwater Contamination: A Preliminary Study in New Mexico. *Journal of Environmental Health*, *62*(2), 16–19.

Arnon, S., Dahan, O., Elhanany, S., Cohen, K., Pankratov, I., Gross, A., Ronen, Z., Baram, S., & Shore, L. S. (2008). Transport of Testosterone and Estrogen from Dairy-Farm Waste Lagoons to Groundwater. *Environmental Science & Technology*, *42*(15), 5521–5526. https://doi.org/10.1021/es800784m

ASAE. (2004). *Manure Production and Characteristics*. 4.

Berg, W., Türk, M., & Hellebrand, H. J. (2006). *Effects of Acidifying Liquid Cattle Manure with Nitric or Lactic Acid on Gaseous Emissions*. /paper/Effects-of-Acidifying-Liquid-Cattle-Manure-with-or-Berg-T%C3%BCrk/985e8a026a542c1b5e053f4b3bf549c0a6b44cc1

Cook, M. J., Hathaway, J. M., & Evans, R. O. (2008). THE IMPACT OF SWINE LAGOON SEEPAGE ON SHALLOW GROUNDWATER QUALITYā: GROUNDWATER REMEDIATION THROUGH LAGOON CLOSURE AND PUMPING. *TRANSACTIONS OF THE ASABE*, *51*, 10.

Copeland, C. (2010). *Animal Waste and Water Quality: EPA Regulation of Concentrated Animal Feeding Operations (CAFOs)*. 24.

Donham Kelley J., Wing Steven, Osterberg David, Flora Jan L., Hodne Carol, Thu Kendall M., & Thorne Peter S. (2007). Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations. *Environmental Health Perspectives*, *115*(2), 317–320. https://doi.org/10.1289/ehp.8836

Ecology's CAFO water permit sacrifices public health, drinking water, shellfish beds. (2017, January 19). Puget Soundkeeper Alliance. https://pugetsoundkeeper.org/2017/01/19/ecologys-cafo-water-permit-sacrifices-public-health-drinking-water-shellfish-beds/

Erickson, D. (1991). *Edaleen Dairy Lagoon Ground Water Quality Assessment February 1990 to February 1991*.

EWG. (2019). *Interactive Map: Explosion of Unregulated Factory Farms in Maumee Watershed Fuels Lake Erie's Toxic Blooms*. http://www.ewg.org/interactivemaps/2019_maumee/

Fetter, C. W. (2001). *Applied hydrogeology* (4th ed). Prentice Hall.

Ham, J. M. (2004). *Evaluating Seepage Losses and Liner Performance at Animal Waste Lagoons using Water Balance Methods*. 75–101. https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0336232

Harter, T., Matthews, M. C., & Meyer, R. D. (2001). *Effects of Dairy Manure Nutrient Management on Shallow Groundwater Nitrate: A Case Study*. 2001 ASAE Annual International Meeting, Sacramento, CA. https://doi.org/10.13031/2013.3842

Hunt, B. (1978). Dispersive Sources in Uniform Ground-Water Flow. *Journal of the Hydraulics Division*, *104*(1), 75–85. https://doi.org/10.1061/JYCEAJ.0004925

Jiao, J., Lang, C., Yang, Y., Zheng, J. J., & Yang, J. J. (2014). Apparent settling velocity of nutrients in Banchengzi Reservoir, Beijing. *Shengtai Xuebao/ Acta Ecologica Sinica*, *34*, 4107–4115. https://doi.org/10.5846/stxb201306101627

K. S. Ro, A. A. Szogi, M. B. Vanotti, & K. C. Stone. (2008). Process Model for Ammonia Volatilization from Anaerobic Swine Lagoons Incorporating Varying Wind Speeds and Gas Bubbling. *Transactions of the ASABE*, *51*(1), 259–270. https://doi.org/10.13031/2013.24219

Khalil, T. M., Stöckle, C. O., Carlson, B. R., Uslar-Valle, N., Nelson, R. L., Frear, C. S., Ma, J., Higgins, S. S., Leytem, A. B., & Dungan, R. S. (2019). Dairy-CropSyst: Gaseous emissions and nutrient fate modeling tool. *Computers and Electronics in Agriculture*, *162*, 962–978. https://doi.org/10.1016/j.compag.2019.05.039

MacDonald, J. M., Hoppe, R. A., & Newton, D. (2018). *Three Decades of Consolidation in U.S. Agriculture*. http://www.ers.usda.gov/publications/pub-details/?pubid=88056

NRCS. (2009). *Agricultural Waste Management Field Handbook*.

Preece, S. L. M., Cole, N. A., Todd, R. W., & Auvermann, B. W. (2012). *Ammonia Emissions from Cattle Feeding Operations*. 15.

Schaffer-Smith, D., Myint, S. W., Muenich, R. L., Tong, D., & DeMeester, J. E. (2020). Repeated Hurricanes Reveal Risks and Opportunities for Social-Ecological Resilience to Flooding and Water Quality Problems. *Environmental Science & Technology*, *54*(12), 7194–7204. https://doi.org/10.1021/acs.est.9b07815

Son, J.-Y., Muenich, R. L., Schaffer-Smith, D., Miranda, M. L., & Bell, M. L. (2021). Distribution of environmental justice metrics for exposure to CAFOs in North Carolina, USA. *Environmental Research*, *195*, 110862.

https://doi.org/10.1016/j.envres.2021.110862

Watershed characterization project—Washington State Department of Ecology. (2012, April). https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Watershed-characterization-project

Wexler, E. J. (1989). *Analytical solutions for one-, two-, and three-dimensional solute transport in ground-water systems with uniform flow*. 267.

Whitman, C. T. (2002). *Pollutant Loading Reductions for the Revised Effluent Limitations Guidelines for Concentrated Animal Feeding Operations*. 75.

Wilson, S. M., & Serre, M. L. (2007). Examination of atmospheric ammonia levels near hog CAFOs, homes, and schools in Eastern North Carolina. *Atmospheric Environment*, *41*(23), 4977–4987. https://doi.org/10.1016/j.atmosenv.2006.12.055

APPENDIX A

MAIN LAGOON MODEL

```
%..............................
% CAFO Model - Edaleen Dairy
% Noah Rudko
%
%...............................
clear;clc;

flex = 0; % Set to 1 to implement flexible model
outputs = 0;
empty_lagoon = 0; % set to 1 for farmer to empty lagoon every other
year in july

%...figures
dofig1 = 0; % lagoon height w/ P & E
dofig2 = 0; % lagoon height w/ NSE
dofig3 = 0; % sim vs. obs
dofig4 = 1; % lagoon height w/ P & E


% Read data
% filename = 'USC00450587.txt';
% data = importfile(filename, 3, 2000); %12031
load('Data_Input.mat');
years = 1987:2019;
N_years = length(years); % 1987-2019
year = num2str(1990); % starting year (1988 for 15 year sim)
start_date = str2double(append(year,'01','01')); % convert to double
N_sim = 1; % using 15 year sim
year2 = num2str(str2double(year) + N_sim); % number of years for
simulation
end_date = str2double(append(year2,'03','01'));

num = find(data(:,7) == start_date);
num_end = find(data(:,7) == end_date);
% Choose data corresponding to year

%new_data = data(num:num+N_days+1500,:);
new_data = data(num:num_end,:);



Dates = new_data(:,7); % dates
D = datetime(Dates,'ConvertFrom','yyyymmdd');

% Validation data
obs_dates =
datetime([19900516;19900619;19900731;19900827;19900925;19901022;1990112
6;19901218;19910122;19910226],'ConvertFrom','yyyymmdd');
obs_heights = [5,5,5,2,2,8,9,11,13,13];

idx = ismember(D,obs_dates,'rows'); % index of date array corresponding
to obs data

% Temporal data
t1 = D(1); t2 = D(end);
```

```
time = t1:t2;
X = new_data;
t_start = 1; t_end = length(X);

% Groundwater Elevation Data
MW_dates =
datetime([19900228;19900307;19900410;19900516;19900619;19900731;1990082
7;19900925;19901022;19901126;19901218;19910122;19910226],'ConvertFrom',
'yyyymmdd');
lagoon_bot = 118;
MW3_GW =
[118.8,118.1,116.51,115.15,116.08,113.95,112.55,111.92,112.64,119.64,11
9.98,117.75,118.23];
MW3_GW = MW3_GW - lagoon_bot;
MW3_GW(MW3_GW < 0) = 0;

t_GW = datetime(1990,01,01,0,0,0):datetime(1991,01,01,0,0,0);

GW_depth = interp1(MW_dates,MW3_GW,time,'linear');
GW_depth(isnan(GW_depth)) = 0;

%GW_depth_seasonal = repmat(GW_depth,1,N_sim);



P = X(:,11); % precipitation (in)
ET = X(:,10); % evaporation measurements (in)
P(P < 0) = NaN;
ET(ET < 0) = 0; % No evaporation in wet winter months recorded

eta = 0.7; % evaporation coefficient

%...Farm Information
drainage_p = 0; % Percent of runoff entering lagoon

if drainage_p == 1
    drainage_quality = 'Very poor';
elseif drainage_p == 0.9
    drainage_quality = 'Poor';
elseif drainage_p == 0.5
    drainage_quality = 'Fair';
elseif drainage_p == 0.3
    drainage_quality = 'Good';
else
    drainage_quality = 'Excellent';
end

AC = 900; % Animal Count
AW = 1000; % animal weight
A = 250*AC; % Figure out actual area, but for now assume no runoff
enters lagoon
animal = 'dairy';
T_days = 365*2; % manure storage period (need to verify)
```

```
% Determine change in manure volume per day based on animal type and
weight
switch animal
    case 'dairy'
        dV = 86/62; % ft^3/day
        p_solids = 12/86;
    case 'beef'
        dV = 1.05;
        p_solids = 0.116;
    case 'swine'
        dV = 0.20;
end

% Soil Info
AMC = 1; % initial anticedent moisture class
CN = 91; % CN for feedlot area (Andersen)
Ksat = 0.0019; % saturated hydralic conductivity of soil liner ft/day
T = 1; % Thickness of bottom of lagoon in ft(ranges from 0.5 to 1 ft)
lined = 0;

% Determine CN based on anticedent moisture condition
if AMC == 1
    CNnew = (4.2*CN)/(10-0.058*CN);
elseif AMC == 3
    CNnew = (23*CN)/(10+0.13*CN);
end
S_d = (1000/CNnew) - 10; % maximum design retention

% Sizing of Manure Storage
V_cap = 10.4e6; % Capacity in gallons (aprox)
V_cap = V_cap/7.481; % Capacity in ft^3 (divide gallons by 7.481)
Vmax = V_cap;
L = 447; % Length of lagoon
B = 275; % Top width of lagoon
b = 139.67; % Bottom width of lagoon (aprox as trapezoid)
z = 4.51; % Side slope
depth = 15;


%... N losses (settling & emissions)
nu = 0.095; % ft/d apparent settling velocity of N 0.11

% Ammonia volatilization properties
%KL = 5e-6; % m/s (K. S. Ro et al. 2008)
KL = 1.417; % ft/d
pH = 7.5; % used to calculate amount of free ammonia (7.9)
Kads = 1;
pKa = 9.23;
Kaw = 10^(-9.23)*0.51; % temp of 25 deg C
F = (1+10^-pH*(1+Kads)/Kaw)^(-1); % Corrected amount of free ammonia
available to volatilize

% Lagoon Storage Properties
%MOL = AC*T_days*dV;
MOL = L*get_section_property(13,'trapezoidal',b,z,'A'); % Guess MOL?
y_func = @(y) L*get_section_property(y,'trapezoidal',b,z,'A') - MOL;
```

```
MOL_y = fzero(y_func,5); % Depth corresponding to MOL

Risk = 0.4; % The amount of flood control that the farmer uses to store
additional manure (base = 0.4)

Level = Risk * (V_cap - MOL) + MOL;

parameters =
[eta,drainage_p,AC,AW,T_days,CN,Ksat,T,V_cap,L,B,b,z,depth,nu,KL,pH,MOL
_y,Risk]; % save parameters to file

% Begin timestepping algorithm
% Initialize values
y_start = 2; % starting height of lagoon in ft
V = L*get_section_property(y_start,'trapezoidal',b,z,'A');
Manure = V/(1-p_solids); % Initial amount of solid manure inside lagoon
Q_total = 0; P_total = 0;
S = S_d; % design AMC is initial condition
TotalWater = 0;
j = 0;
i = 0;
N = 0;
yold = MOL_y;
SA = (L*get_section_property(yold,'trapezoidal',b,z,'B')); % Calculate
surface area based on top width
dN = dV*0.079; %  content N lb/ft^3(manure)(ammonia-N) from ASAE
standards
days_since_removal = 0;
removal = 0;
history = zeros(t_end,16);
removal_matrix = zeros(t_end,2);
Overflow_day = 0;
Q_fail = 0; N_fail = 0;
fail_m = zeros(1,2);
for t = t_start:t_end % total amount of days in given year
    % Extract date
    i = i + 1;
    current_date = D(i);
    [curr_year,curr_month,curr_day] = ymd(current_date);

    Pold = P(t); % sample precipitation for given day

    % calculate runoff for storm event
    if Pold > 0 && ~isnan(Pold) == 1
        Q_eff = (Pold - 0.2*S)^2/(Pold+0.8*S); % direct runoff (inches)
        Q_eff = Q_eff * A/12; % runoff in ft^3
        Q_eff = Q_eff*drainage_p; % percent of runoff entering lagoon
        P_eff = Pold * SA/12;  % precip entering lagoon (ft^3)
    elseif ~isnan(Pold) == 1
        Q_eff = 0;
        P_eff = Pold;
    end

        % Determine if lagoon has overflown
    if V > Vmax && Q_eff > 0
        j = j + 1; % days of failure
```

```
        if outputs == 1
            if j > 1
            fprintf('\n   The manure storage facility has overflowed on
day %1.0f',i);
            fprintf('\n   Nitrogen Conc. (mg/l) %1.2f',N/TotalWater *
16018.46337);
            fprintf('\n   Discharge (ft^3) %1.2f',V - Vmax);
            end
        end

        fail_m(j,:) = [V - Vmax,N/TotalWater * 16018.46337];

        if j == 1
            Overflow_day = i; % day that failure occurred

            Q_fail = V - Vmax; % Amount of water that exceed capacity
in ft^3
            N_fail = N/TotalWater * 16018.46337; % mg/l
            if outputs == 1
            fprintf('\n   The manure storage facility has overflowed on
day %1.0f',Overflow_day);
            fprintf('\n   Nitrogen Conc. (mg/l) %1.2f',N_fail);
            fprintf('\n   Discharge (ft^3) %1.2f',Q_fail);
            end


        end
    end

    % Farmer makes decision to remove manure
    if i < 364 % Forecast
    forecast = sum(P(i:i+2));
    else
        forecast = sum(P(i:end));
    end

    if  V >= Level %&& days_since_removal > T_days/2
        type1 = 1;
        if outputs == 1
        fprintf('\n   Farmer has removed manure based on scenario:
%1.0f',type1);
        fprintf('\n   Current date: %s',current_date);
        end
    elseif (V > 0.95*Level && forecast > 0 && removal_matrix(i,1) == 0
&& flex == 1 && t > 166) % Forecast scenario
        type1 = 2;
        fprintf('\n   Farmer has removed manure based on scenario:
%1.0f',type1);
    elseif (curr_month == 8 && curr_day == 27 && curr_year == 1990) ||
(curr_month == 6 && curr_day == 30 && curr_year == 1990)% remove amount
on specific day
        type1 = 3;
        if outputs == 1
        fprintf('\n   Farmer has removed manure based on scenario:
%1.0f',type1);
        fprintf('\n   Current date: %s',current_date);
```

```
        end
    elseif (curr_month == 5 && curr_day == 1 && rem(curr_year,2) == 0
&& curr_year > 1991) && empty_lagoon == 1
        type1 = 4;
        if outputs == 1
        fprintf('\n    Farmer has emptied the lagoon: %1.0f',type1);
        fprintf('\n    Current date: %s',current_date);
        end
    else
        type1 = 0;
    end

    if type1 == 1
        %Manure = Manure * 0.50 + dV*AC; % Remove half
        Manure = Manure - 10*dV*AC; % start pumping, remove manure from
10 animals
        Q_total = (1-10/900) * Q_total; %10/900
        P_total = (1-10/900) * P_total;
        days_since_removal = 0;
        removal = removal + 1;
        removal_matrix(i,:) = [i,removal];
    elseif type1 == 2 % Remove 20% in anticipation of rain
        Manure = Manure * 0.8 + dV*AC;
        Q_total = 0.8 * Q_total; P_total = 0.8 * P_total;
    elseif type1 == 3
        frac = (L*(get_section_property(3,'trapezoidal',b,z,'A') -
get_section_property(2,'trapezoidal',b,z,'A')))/Manure;
        Manure = Manure -
L*(get_section_property(3,'trapezoidal',b,z,'A') -
get_section_property(2,'trapezoidal',b,z,'A'));
        P_total = (1-frac)*P_total;
    elseif type1 == 4
        Manure = 0.2*Manure;
        Q_total = 0.2*Q_total;
        P_total = 0.2*P_total;
    else
        Manure = Manure + dV*AC;
        days_since_removal = days_since_removal + 1;
        Q_total = Q_total + Q_eff; % runoff volume
        P_total = P_total + P_eff; % precipitation volume

    end

    % Is there enough water available for ET and Seepage?
    SeepET = ET(i)*eta*SA + (b*L)*(Ksat*(yold+T/T));
    % Add runoff volume and manure to facility
    if TotalWater > SeepET
        Evapo = ET(i)*eta*SA;
    % Calculate seepage if channel is unlined
        if lined == 0
            Seep = (b*L)*(Ksat*((yold+T-GW_depth(i))/T)); % (b*L) uses
the bottom of the lagoon
        else
            Seep = 0;
        end
    else
```

```
        Evapo = 0;
        Seep = 0;
    end

    ManureLiquid = (1-p_solids)*Manure; % Percent of manure that is
liquid
    ManureSolids = p_solids*Manure;     % Percent of manure that is
solid

    TotalWater = Q_total + P_total + ManureLiquid - Evapo - Seep;
    V = ManureSolids + TotalWater - ManureSolids; % Manure solids are
not stored in the lagoon
    N = ManureLiquid * dN; % dN = lb N/ft^3 manure

    % Calculate depth in lagoon (assume trapezoidal)
    y_func = @(y) (L*get_section_property(y,'trapezoidal',b,z,'A')) -
V;
    ynew = fzero(y_func,5);

    % Calculate surface area
    SA = (L*get_section_property(ynew,'trapezoidal',b,z,'B')); %
multiply length by top width

    % Calculate N losses
    J_N = KL * F * (N/TotalWater); % lb/(ft^2-d)

    Ms = nu * (N/TotalWater)*(b*L); % lb/d settling, (b*L) is bottom of
lagoon
    N = N - Ms - J_N*SA;


    history(i,:) =
[Pold,Q_eff,V,Manure,TotalWater,CNnew,S,Q_total+P_total,N,Evapo,ManureL
iquid,ynew,Seep,Ms,J_N,SA];

    % Adjust AMC
    if i > 6
        if sum(history(i-5:i,1)) < 1.4
            AMC = 1;
        elseif sum(history(i-5:i,1)) >= 1.4 && sum(history(i-5:i,1)) <=
2.1
            AMC = 2;
        else
            AMC = 3;
        end
    end

    % Adjust CN based on AMC
    if AMC == 1
        CNnew = (4.2*CN)/(10-0.058*CN);
    elseif AMC == 3
        CNnew = (23*CN)/(10+0.13*CN);
    else
        CNnew = CN; % default to initial CN
    end
```

```
    Snew = (1000/CNnew)-10;

    % Update values for next time step
    S = Snew;
    yold = ynew;

end
```

APPENDIX B

GROUNDWATER MODEL CODE

```
%.........................................%
% CAFO Groundwater Model
%
% 1D transport through soil liner
% 2D transport through subsurface
%
%.........................................%
clear;clc; %close all;

run('Edaleen_Dairy.m'); clear;clc; %close all;

%...Figures
dofig1 = 0; % Monthly average seepage concentration
dofig2 = 0; % Transport through liner
dofig3 = 0; % 2D transport normalized concentration
dofig4 = 0; % 2D transport in subsurface w/ GWT & lagoon bot
dofig5 = 0; % 2D transport in subsurface contour plots
dofig6 = 0; % 2D transport in subsurface at specific x-y
dofig7 = 1; % 2D transport in subsurface tiled layout
domovie = 0; % plot movie


pulse = 0; % set to 1 to calculate pulse input case

%...Load Data
load('Edaleen_Dairy_Output.mat');
load('Edaleen_Dairy_Dates.mat');
load('Edaleen_Dairy_Param.mat'); % parameters used in model

Ms = history(:,14); % ammonia-N lost due to settling (lbs)
Seep = history(:,13); % discharge through liner (ft^3)
TW = history(:,5);    % total water in lagoon

L = 447;          % Length of lagoon
phi = 0.5;        % porosity of soil liner
b = 139.67;       % Bottom width of lagoon (aprox as trapezoid)
z = 4.51;         % Side slope
K = parameters(7); % soil liner hydraulic conductivity

sldglyr = L*get_section_property(1,'trapezoidal',b,z,'A'); % volume
associated with depth of 1 ft (sludge layer)

N_conc_seep = Ms./sldglyr; % concentration at soil liner interface
(lbs/ft^3)
N_conc_seep = N_conc_seep.*16018.4634; % Converts to mg/l


%...Observation Data
MW = 2; % Set case

if MW == 1
obs_dates_MW =
datetime([19900228;19900410;19900516;19900619;19900731;19900827;1990092
5;19901022;19901127;19901218;19910122;19910226],'ConvertFrom','yyyymmdd
');
```

```
obs_MW = [0.05,0.05,0.04,0.01,NaN,0.02,2.83,11.4,7.5,9.67,31.2,52.2];
Naming = 'Well 1';
elseif MW == 2
obs_dates_MW =
datetime([19900228;19900410;19900516;19900619;19900801;19900827;1990092
5;19901022;19901127;19901218;19910122;19910226],'ConvertFrom','yyyymmdd
');
obs_MW = [0.05,0.2,0.02,0.01, 0.02 ,1.76,7.58,8.35,30.9,59.1,70.9,102];
loop_index = 1:3;
Naming = 'Well 2';
elseif MW == 3
obs_dates_MW =
datetime([19900228;19900410;19900516;19900619;19900801;19900827;1990092
5;19901022;19901127;19901218;19910122;19910226],'ConvertFrom','yyyymmdd
');
obs_MW = [0.03,0.2,0.02,0.01,89.7,0.31,24.3,30.2,15.7,14.4,74.3,52.8];
Naming = 'Well 3';
end

% Groundwater Elevation Data
MW_dates =
datetime([19900228;19900307;19900410;19900516;19900619;19900731;1990082
7;19900925;19901022;19901126;19901218;19910122;19910226],'ConvertFrom',
'yyyymmdd');
lagoon_bot = 118;
MW3_GW =
[118.8,118.1,116.51,115.15,116.08,113.95,112.55,111.92,112.64,119.64,11
9.98,117.75,118.23];
MW3_GW = MW3_GW - lagoon_bot;

% Aggregate Monthly Averages
TT = array2timetable(N_conc_seep,'RowTimes',time');
TT_monthly = retime(TT,'monthly','mean');
TT_monthly(1,:) = [];

if dofig1 == 1
figure(1); clf; hold on;
plot(TT_monthly.Time,TT_monthly.N_conc_seep,'r--','LineWidth',2);
xline(datetime('03-May-1990'),'k','LineWidth',3);
plot(TT.Time,TT.N_conc_seep,'b','LineWidth',1);
legend('Monthly Average','Main Lagoon Receives
Waste','location','northeast'); legend('boxoff');
ylabel('ammonia-N [mg/L]');
title('Concentration at Bottom of Lagoon');
set(gca,'Fontsize',14)
end

%... Choose starting period
N_conc = TT_monthly.N_conc_seep;
start_ind = find(TT_monthly.Time == '01-Jul-1990');
end_ind = find(TT_monthly.Time == '01-Jul-1995');
N_concM = N_conc(start_ind:end_ind);
%N_concM = mean(N_concM)*ones(length(N_concM),1);
t_plot = TT_monthly.Time(start_ind:end_ind); % time values
t_day = days(TT_monthly.Time(end_ind) - TT_monthly.Time(start_ind));
t_lag = 0;
```

```
Ci = 0.05;       % Initial concentration (before construction of
lagoon)


%...Transport through soil liner
% Seepage velocity and flow rate
v = Seep./(b*L); % ft/d
v_bar = v./phi;
v_bar = mean(v_bar); % Use mean value - solution assumes steady state v



% Coordinates
x = parameters(8); % Thickness of soil liner
txt = ['T = ' num2str(x), ' ft'];

% Diffusion Coefficent
% Mechanical DispersionCoefficient
alpha = 6.56e-6; % ft [0.002 mm]
D_mech_x = alpha*v_bar; %ft^2/d
% Diffusion Coefficent
D_star = 0.00186; % diffusion coefficient of nitrogen (ft^2/d)
% Hydrodynamic Diffusion Coefficent
D = D_star + D_mech_x;

solute = zeros(length(t_plot)-1,1);

for j = 1:length(t_plot)-1
    t_day = days(t_plot(j+1) - t_plot(1)); % Initalize t_day
    t = t_day;
    c = 0;
    for i = 1:j
        N_conc = N_concM(1:j); % Extract values for superposition
        if i == 1
            delta_C = N_conc(i) - Ci;
        else
            delta_C = N_conc(i) - N_conc(i-1); % calcultate difference
in concentration
        end

        if i == 1
            c = delta_C*0.5*(erfc((x - v_bar*t)/(2*sqrt(D*t)))) + Ci; %
simplified ogata banks
        else
            t_day = t_day - days(t_plot(i) - t_plot(i-1));
            t = t_day; % t in days
            c = c + delta_C*0.5*(erfc((x - v_bar*t)/(2*sqrt(D*t))))+Ci;
% perform superposition at specific t for step change in C
        end

    end
    solute(j) = c; % store values for plotting
end

%...Plotting
```

```
fprintf('\r%s\n',      '==== Transport Through Soil Liner =========')
fprintf('%s%1.4f%s\n', '    Mean Seepage Velocity   : ',v_bar,' ft/d')
fprintf('%s%1.0f%s\n', '    Soil Liner Thickness    : ',x,' ft')
fprintf('%s%1.5f%s\n', '    Soil Liner K            : ',K,' ft/d')
fprintf('%s%1.5f\n',  '    Hydrodynamic Diffusion Coefficient (Dx)
[ft^2/d] : ',D)
fprintf('%s%1.2f\n',  '    Concentration at end of simulation [mg/L]  :
',solute(end))

if dofig2 == 1
figure(2); clf; hold on;
plot(t_plot(2:end),solute,'mo-
','MarkerFaceColor','magenta','LineWidth',2);
plot(t_plot,N_concM,'ro-','MarkerFaceColor','red','LineWidth',2);
plot(obs_dates_MW,obs_MW,'k+-
','MarkerFaceColor','black','LineWidth',2);
legend(txt,'Point Source',Naming,'Location','northwest');
legend('boxoff');
ylabel('Ammonia-N [mg/L]');
set(gca,'Fontsize',14)
end

%.................2D Transport in
Subsurface...............................
Ci = 0.05;       % Initial concentration (before construction of
lagoon)

% Choose location of interest
Xc = 425; Yc = 118; % center of lagoon

x = 700; y = 118;
txt_loc = ['x = ' num2str(x), ' ft' , ' y = ' num2str(y), ' ft'];

% Seepage velocity calculations
B = 30; % aquifer thickness in ft
v_bar = 10; % mean value from report [ft/d]


Q = 5000/B; % flow rate per unit thickness [ft^2/d]

calc = (x-Xc)^2 - v_bar^2;

%... Estimate diffusion coefficient

% Mechanical Dispersion Coefficient
%alpha = unifrnd(0.042,0.25); % ft [12.7 - 76.2 mm (0.042-0.25 ft) ]
alpha = 0.20;
D_mech_x = alpha*v_bar; %ft^2/d
D_mech_y = D_mech_x/5; % ft^2/d
% Diffusion Coefficent
D_star = 0.00186; % diffusion coefficient of nitrogen (ft^2/d)
% Hydrodynamic Diffusion Coefficent
Dx = D_star + D_mech_x; Dy = D_star + D_mech_y;

% Implement Retardation factor
```

```
R = 1;
Dx = Dx/R; Dy = Dy/R;
v_bar = v_bar/R;

%Dx = 60; Dy = Dx/5; % choose values



solute_2D = zeros(length(t_plot)-2,1);
tmax = zeros(length(t_plot)-2,1);
for j = 1:length(t_plot)-2
    t_day = days(t_plot(j+1) - t_plot(1)); % Initalize t_day
    tmax(j) = t_day;
    t = t_day;
    c_2D = 0;
    for i = 1:j
        N_conc = solute(1:j); % Extract values for superposition
(obtained from 1D transport through liner)
        if i == 1
            delta_C = N_conc(i) - Ci;
        else
            delta_C = N_conc(i) - N_conc(i-1);
        end

        if i == 1
            val = simpsons2D(t,v_bar,Dx,Dy,x,y,Xc,Yc);
            c_2D = delta_C*Q/(4*pi*sqrt(Dx*Dy))*exp((v_bar*(x-
Xc)/(2*Dx)))*val + Ci;
        else
            t_day = t_day - days(t_plot(i) - t_plot(i-1));
            t = t_day; % t in days

            val = simpsons2D(t,v_bar,Dx,Dy,x,y,Xc,Yc);
            c_2D = c_2D + delta_C*Q/(4*pi*sqrt(Dx*Dy))*exp((v_bar*(x-
Xc)/(2*Dx)))*val +  Ci;
        end
    end
    solute_2D(j) = c_2D; % store values for plotting
end

% Calculate normalized concentration
norm_c = zeros(length(solute_2D),1);
for i = 1:length(solute_2D)
    norm_c(i) = solute_2D(i)/solute(i+1);
end

fprintf('\r%s\n',      '==== Transport in Subsurface =========')
fprintf('%s%1.3f\n',  '   Mean seepage velocity [ft/d]       : ',v_bar)
fprintf('%s%1.0f\n',  '   Flow rate per unit width [ft^2/d] : ',Q)
fprintf('%s%1.0f\n',  '   x location [ft]   : ',x)
fprintf('%s%1.0f\n',  '   y location [ft]   : ',y)
if calc > 0
fprintf('%s\n',      '   A meaningful solution can be obtained ');
else
```

```
fprintf('%s\n',      '   WARNING: (x,y) too close to point source for
given v ');
end
fprintf('%s%1.5f\n',  '   Hydrodynamic Diffusion Coefficient (Dx)
[ft^2/d] : ',Dx)
fprintf('%s%1.5f\n',  '   Hydrodynamic Diffusion Coefficient (Dy)
[ft^2/d] : ',Dy)
fprintf('%s%1.3f\n',  '   Concentration at end of simulation [mg/L]  :
',solute_2D(end))

%.............Calculate Concentration at specific t
if dofig5 == 1 || domovie == 1 || dofig7 == 1
num = 0;
minx = 400; dx = 10; maxx = 700;
miny = 108; dy = 1; maxy = 118;
nummax = length(minx:dx:maxx) * length(miny:dy:maxy);

big_storage = zeros(nummax,length(solute)-1);
coord = zeros(nummax,2);
for x = minx:dx:maxx
    for y = miny:dy:maxy
        num = num + 1;
        transport_2D =
transport2D(t_plot,solute,v_bar,Dx,Dy,x,y,Xc,Yc,Q,Ci);
        big_storage(num,:) = transport_2D';
        coord(num,:) = [x,y];
    end
end

end
```