Blame It On the Weather:

Cost and Design of Manure Management under Extreme Weather Conditions on North Carolina Swine Farms

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Introduction and Background

The purpose of this paper is to assess the effect of manure management system design on manure management costs on North Carolina swine farms under weather extremes.

In 1994, North Carolina became the second largest swine producing state following Iowa. The inventory of hogs rapidly rose from about 2.6 million in 1987 to 9.7 million in 1998. The swine industry also became more concentrated as the number of North Carolina farm operations reporting at least 1 pig fell from 13,500 in 1987 to 3,100 in 2001. The predominant system for managing the manure from these operations is the anaerobic lagoon-sprayfield system. First, the manure is diluted with recycled lagoon liquid and evacuated from swine barns using the flush or pit-recharge systems. The liquid is stored in outdoor earthen cells (lagoons) where anaerobic microorganisms break down volatile solids and reduce the nitrogen content of the effluent. When weather and stage of crop production permit, liquid effluent is irrigated onto the sprayfield for crop fertilization. Although manure management using the lagoon-sprayfield system is relatively simple and economical, it has its limitations. This study concentrates on its sensitivity to weather conditions, specifically excessive rainfall. If the weather is not favorable (particularly through the winter, spring, and early summer as in 2002-2003), the farmer can be forced to use alternative, much costlier methods to manage accumulating liquid. The volume of liquid that has to be managed by more expensive methods is contingent on a set of design variables, a set of farm specific variables, stochastic weather variables, and the constraints imposed by regulations.

An Economic Model of Lagoon and Sprayfield Cost

Farmers are assumed here to minimize costs of manure management subject to a set of constraints. The cost equation includes three components.

(1) Annual Cost = Annualized Lagoon Cost + Irrigation Cost + Cost of Removal of Excess Lagoon Liquid

Among the constraints (described further in following sections) are:

a.) the volume of daily accumulation in the lagoon = manure, urine, spilled water in the barns + precipitation – evaporation from barns and the lagoon – irrigation or other removal of lagoon liquid and sludge,
b.) the volume and depth of the lagoon must satisfy NRCS design criteria,
c.) liquid effluent is irrigated onto hay crops using a traveling gun system,
d.) irrigation rates and timing must comply NC DWQ rules
e.) when liquid level rises into the structural freeboard it must be removed using expensive emergency methods
f.) sprayfield soils become saturated and dry out as described below
g.) lagoon liquid may not be irrigated when lagoon level drops to the minimum treatment level.
h.) Farmers irrigate a specified depth of liquid onto the sprayfield whenever possible,
i.) Cost functions for lagoons, irrigation, and emergency removal are as specified

We vary selected coefficients to simulate the effects on annual cost. Daily manure and spilled water production, irrigation application depth, and lagoon temporary storage volume are among the coefficients varied. Actual daily precipitation amounts over a 10 year period are used to simulate farm costs.

Design of Anaerobic Lagoons

In North Carolina, the design and operation of waste treatment lagoons is regulated by NC Natural Resources Conservation Service (NRCS) standards. According to the NRCS standard 359, a treatment lagoon is defined as an impoundment made by excavation or earthfill for biological treatment of animal or other agricultural waste. Its dimensions are determined by a minimum depth requirement and by the volume necessary for the number and type of pigs it will serve. Lagoon volume is typically characterized by six components (listed from bottom to top of the structure):

1) Sludge storage volume
2) Minimum treatment volume
3) Temporary liquid storage volume
4) Emergency storage for chronic rainfall
5) Emergency storage for a 25-year, 24 hour storm event (precipitation)
6) Structural freeboard (1 foot minimum)

Sludge volume typically accounts for expected sludge accumulation over a five year period. The design treatment volume is a minimum amount of volume and depth necessary for the targeted degree of anaerobic treatment to occur and the lagoon should not be pumped below this level. Sludge storage volume and treatment volume are derived from NRCS estimates of sludge accumulation, volatile solids loading rate, and average hydraulic retention time required for the targeted degree of anaerobic treatment. Temporary storage volume is designed to be consistent with the planned pumping interval included in the waste management plan and the expected daily accumulation of manure, urine, spilled water, and precipitation less evaporation. The NRCS recommendation is that temporary volume should be sufficient to accommodate expected liquid accumulation for a period of 180 days.[1,2]

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[1] NRCS expresses sludge volume and minimum treatment volume in cubic feet per pound of steady state live weight (SSLW) while temporary storage is stated in gallons per day per head or sow (Table 1).
[2] Lagoons can take on a variety of shapes. This model assumes a rectangular trapezoid with a selected depth (NRCS specifications require depth to be greater than 6 feet (NRCSa,b)), a side slope of 1/3 (for every foot of depth the top length increases by 3 feet on each side; NRCS specification require this slope to be less than 1 (NRCSa,b))., and a selected ratio of base length (BL) to base width (BW) of γ (γ = base length/base width). The lagoon total manure volume (sum of design treatment volume, sludge storage, and temporary liquid volume) can be expressed by the following equation:

(2) $MV = \gamma\{BW\}^2(D) + (1+\gamma)(3)\{D^2\}\{BW\} + (12)(D^3)$.

Once the total volume is determined from regulatory standards and lagoon depth D is selected, equation (2) can be solved for base width (BW), γ can be used to solve base length (BL), and top width and length can be found using side slope.

Emergency storage depth is added to anaerobic lagoon design to accommodate accumulations during single large storms (the 25 year 24 hour storm) and during longer periods of heavy precipitation (heavy or chronic rainfall). Net precipitation less evaporation varies widely across years and counties. For instance, the average precipitation and evaporation at a monitoring station in Duplin County for the period of 1994-2002 was 52.2 and 49.88 inches and the average net precipitation less evaporation was 2.3 inches indicating that most of the rainfall evaporated. Yearly precipitation minus evaporation measurements ranged from -10.5 inches in 2000 to 23.12 inches in 1999. Schwabe (2001) estimated that the average annual rainfall minus average annual evaporation for North Carolina is approximately 10 inches. NRCS standarads recommend that the heavy or chronic rainfall factor must be at least equal to the 25-year, 24-hour storm depth. In eastern North Carolina 25-year, 24-hour storm is set at seven inches. Following Schwabe (2001), this model incorporates 36 inches of additional depth including 24 inches of emergency storage and 12 inches of structural freeboard. Including additional depth *A*, total lagoon volume *V*, including emergency storage (heavy rainfall and 25 year 24 hour storm) and freeboard volumes can be expressed as:

(3) $V = \gamma\{BW\}^2(D+A) + (1+\gamma)(3)\{[D+A]^2\}\{BW\} + (12)([D+A]^3)$,

where base width (BW) is previously determined from equation (1) and the new top widths and lengths (the length of each lagoon side after additional volume is added) are:

(4) $TTW = BW + (2)(3)[D+A]$ and

(5) $TTL = BL+(2)(3)[D+A]$.

Precipitation and Evaporation

Hog production in North Carolina is mainly concentrated in the eastern part of the state and centered in Sampson and Duplin counties (Figure 1). We collected daily precipitation data from 10 monitoring stations in these counties from 1993 to 2003.[3] Our results are similar for all 10 counties. For expositional simplicity, only results for Duplin County are presented. Daily net addition to the lagoon was calculated as follows,

(6) $$\text{Daily Net Addition} = \text{Daily Discharge} + \text{Daily Precipitation} - \text{Daily Evaporation},$$

where *Daily Discharge* represent the discharge of feces, urine and excess water from the pig barns. *Daily evaporation* was calculated as an arithmetic average of measurements taken in Raleigh, NC and Wilmington, NC monitoring stations (Table 2).

Sprayfield Soil Saturation and 'Acceptable to Spray' Rules

Regulations forbid spraying on saturated or near-saturated fields to prevent ponding and excessive run-off. Sprayfield saturation is calculated daily in the model and it evaluates if the conditions are favorable for irrigation. The saturation level depends on the soil type and its ability to drain water after a rainfall or irrigation. In the model maximum saturation was set at 1.3 inches which is representative of loamy sand, sandy loam and clay loam soil types that are commonly found in Eastern North Carolina.[4] Farmers typically irrigate when the plant available water (PAW) is depleted by 50 percent. Simulation presented in this paper evaluates three scenarios where irrigation levels are set at 0.3, 0.5 and 0.7 inches. This element of the simulation actually represents a set of

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[3] For locations of stations see Figure 2.
[4] Soil saturation is also commonly referred to as plant available water (PAW). The amount of plant-available water is typically measured in inches per foot of soil depth.

constraints faced by farmers.[5] Daily sprayfield saturation (PAW) on day *i* can be expressed as a summation of PAW on the previous day, *i-1*, precipitation that fell on day *i*, and evapotransporation on day *i*:

(7) $$\text{PAW}_i = \text{PAW}_{i-1} + \text{Precipitation}_i - \text{Evapotransporation}_i.$$ [6]

If the plant available water on a given day drops below the (suitable for irrigation) threshold level and there is a suitable crop growing that allows irrigation and the lagoon level is above the minimum treatment volume, the farmer can dispose of *Maximum Saturation-Threshold Level* inches of lagoon effluent. For instance, the simulation shows that on July 22, 2003 PAW for a representative farm located in Duplin County was 0.87 inches. On July 23, 2003 a sprayfield with Bermuda grass removed 0.145 inches of water through evapotranspiration, dropping the PAW level to 0.73. At this time, the farmer could irrigate maximum of 1.3-0.73=0.57 inches of effluent, however, he will only choose to irrigate at his predetermined irrigation level of 0.5 inches. On July 22, 2003 he had to wait for another day to start spraying because his predetermined level of spraying (0.5 inches) was greater than what he was allowed to dispose 1.3-0.87=0.43 inches.

Constraints on Irrigating Only While a Suitable Crop is Growing

The model presented in this paper calculates the level of effluent in the lagoon on a daily basis and assesses if sprayfield irrigation is possible without violating any regulatory

[5] One constraint faced by farmers is that the irrigation pump, reel, and traveling gun they use to irrigate has some minimum application depth that it is capable of applying. Second, their total pumping and irrigation capacity represents a maximum volume and/or area that they can irrigate per hour. Third, they face regulatory constraints on maximum application depth under any conditions and on avoiding ponding and excessive run-off during near saturated conditions. A more complicated representation of these constraints is planned for future versions of this model.

constraints. In addition to soils being below the saturation level that allows sprayfield irrigation, the farmer is required to be growing a suitable crop. In this model we assume that the farmer is growing Bermuda and Rye Grass hay crops. Our model assumes that Bermuda Grass can be used for irrigation from April 1 to October 1 and Rye Grass can be used from January 1 to March 1 and from November 1-December 30. The time periods in March and October when no crops are growing are assumed not suitable for irrigation.

Constraints on Removing Liquid from the Lagoon

If the liquid level rises into emergency storage (heavy rain and storm) volumes, producers are required to inform DWQ about the elevated lagoon level but no immediate action needs to be taken. Producers are typically given 30 days to lower the level in the lagoon and reach levels below heavy rain and storm volumes. On the other hand, if the liquid level rises into the structural freeboard, immediate action needs to be taken. Within three days, producers need to lower the level below the freeboard. This may be done by a variety of means including hauling lagoon liquid off the farm to neighboring properties that can be irrigated and/or by depopulating farms.

Results

Several scenarios were simulated to explore the relationship between various design and regulatory components and costs. It was argued by many that Spring 2003 in North Carolina was the wettest since precipitation has been recorded (about 100 years). This statement is reinforced by examining data presented in Figure 3 where 2003

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[6] Evapotransporation is defined as a summation of evaporation from the soil and transpiration form plants.

precipitation is represented by the blue line. The spring 2003 monthly values are near to maximums from 1994 to 2003 (purple bars) and summing across months February through July yields cumulative precipitation greatly exceeding the average for the last decade (blue columns). Questions that remain to be addressed by the model are how did the distribution of rain compare to other years and how were sprayfield conditions affected. We addressed these questions using a hypothetical feeder-finish farm with 4,000 animals located in the Duplin County operating under several scenarios.[7] First, the farm was assumed to be discharging manure, urine, and excess water at the NRCS published standard of 2.3 gallons per animal per day. Second, this discharge was increased by 50% and 100% from NRCS recommended values to simulate less efficient water use by producers. Third the farmer is assumed to irrigate every day that the constraints allow as long as the lagoon level does not fall below the minimum treatment depth. Results of this simulation are presented in Figure 4. Three straight lines represent lagoon levels for minimum treatment volume; emergency storage (heavy rain and storm) volumes; and structural freeboard volume. The blue line in Figure 4 (baseline scenario: 180 days storage and irrigating 0.5 inches across the entire sprayfield at each application) represents a farm accumulating effluent at NRCS published rates. The effluent in his lagoon rises into emergency storage in most years in the last decade, but he is able to lower the lagoon level by regular sprayfield irrigation within 30 days. Comparing 2003 to other years, surprisingly, the spring 2003 high precipitation did not cause extraordinary accumulation. As can be seen in Figure 5, the lagoon level starts increasing in mid

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It was calculated as an arithmetic average of measurements taken at Hoffman Forest, NC and Chapel Hill, NC monitoring stations (Table 2).

[7] Predetermined irrigation depth was set at 0.5 inches and the temporary storage volume was set at 180 days of NRCS recommended discharge.

January and reaches maximum in late March when no suitable crop is available for irrigation. As soon as Bermuda grass resumes growing in April, the excess liquid is quickly disposed by irrigation. This scenario suggests that in 2003 the high precipitation did not prevent this hypothetical farm from adequate spraying.[8]

Other scenarios depicting farms with greater daily effluent accumulation are represented by the green and purple lines in the same figure. The graph suggests that their lagoon levels will rise into the emergency storage level regularly and frequently into the structural freeboard which requires an expensive action.

Next, the impact of different predetermined irrigation application levels on the lagoon level was examined. Producers typically irrigate if the plant available water (PAW) is depleted by at least 50%. Assuming that the maximum PAW for the soil type on our representative farm is 1.3 inches, a producer following 50% rule would wait till the plant available water is lowered to about 0.6 inches before starting the irrigation process. As shown in Figure 6 (purple line), this approach seems to increase risk as the lagoon level reaches into the structural freeboard volume regularly. The situation improves greatly if the predetermined irrigation level is lowered to 0.5 inches (green line). If the producer is willing and able to spray 0.3 inches on the entire sprayfield whenever possible (blue line), the lagoon level only enters emergency storage in 1998.

The cost of lagoon construction, sprayfield operation and emergency disposal is depicted in Figures 7, 8 and 9. The construction cost was estimated for a lagoon with a 90, 180 and 270 day temporary storage volume. The calculated total construction cost of

[8] The increase in discharge rates effectively decreases the temporary storage capacity (days) while increasing irrigation volume. For instance, if the actual discharge increases by 100% from the NRCS recommended rate and the lagoon was designed using NRCS standard, the actual temporary storage volume

the lagoon including overhead and contractor and engineering services was annualized to approximate annual cost of the lagoon.[9]

Irrigation costs depend on the volume of lagoon effluent to be applied and the number of acres applied to. Cox and Bosch, Zhu, and Kornegay provide a simple formula for estimating irrigation costs. Inputs to the formula are; A = sprayfield acreage, D = acre-inches applied per acre (depth of total effluent applied), and AI = acre-inches of lagoon effluent. The depth, D, can be calculated by dividing the total acre-inches of lagoon effluent by the number of acres. The formula reports costs in 1992 dollars for traveling irrigation guns, which we multiplied by 1.28 to translate into 2002 dollars.

$$\text{Irrigation Costs} = [7097.44 + 36.05(A) + 403.9(D) - 2546.16(2/[AI]) + 281.44(2/[AI])^2][1.28], \quad (8)$$

Using this equation, the simulated average irrigation cost for a 4,000 head finishing farm is approximately \$2.20 per 1,000 gallons which is consistent with other estimates that were available to us by industry experts.

The cost of emergency disposal varies depending on the method used and the hauling distance to available disposal location. The cost of hauling liquid this spring in North Carolina was reported to be in the range of \$0.02 - \$0.15 per gallon.[10] Here, the cost of emergency disposal is assumed to be \$0.05 per gallon. The volume to be removed by emergency methods was calculated as the maximum volume accumulated above the structural freeboard level during the calendar year.

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becomes only 90 days increasing the probability that the lagoon level will enter the emergency rain, storm and freeboard volumes.

[9] The useful life of the lagoon is assumed to be 20 years. The rectangular lagoon includes a clay liner. The clay was imported to the farm at \$5.5 per cubic yard and the excavation cost was set at \$1.50 per cubic yard. Sludge is assumed to be removed from the lagoon and land applied every 5 years.

In Figure 7, the farm has available 180 days of temporary storage as recommended by NRCS. The cost of lagoon-sprayfield system is evaluated at three different application levels (0.3, 0.5, 0.7 inches) from 1994 to 2003. The annual lagoon cost is constant across years at $22,273.00 (blue bars). Irrigation cost is represented by purple bars and ranges from $14,400 to $15,500 depending on the size of temporary storage volume and annual net rainfall. Emergency disposal cost is represented by yellow bars. The lagoon level never enters the freeboard when the predetermined application level is set to 0.3 inches so emergency disposal cost is zero in all years. When the application level is 0.5 inches, emergency disposal is needed in 1997 and 2000 at a cost of about $7,000 and $11,000. If the effluent is applied when about 50% of PAW water is depleted (0.7 inch application level), lagoon level enters the freeboard in 1998, 1999 and 2000. Cost of emergency disposal ranges from $15,000 to $58,000.

In Figure 8, the temporary storage volume is set at 90 days and the annual lagoon cost is constant at $20,084. Lagoon level rises into the freeboard often with emergency removal costs up to $95,000 when predetermined application depth is 0.7 inches.

The lagoon depicted in Figure 9 has 270 day temporary storage volume. Annual lagoon cost is slightly higher ($24,445) than for the lagoons with less temporary storage volume. The lagoon level only enters the freeboard volume in 2000 where the application rate is 0.7 inches. The increased annual lagoon cost for building additional 90 days of storage is offset by savings on emergency liquid disposal because the lagoon level less frequently rises into emergency volume.

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[10] These estimates only apply to liquid transportation and disposal on neighboring fields. If the only way to stop increasing lagoon levels was depopulation, the cost of emergency waste disposal was much greater.

Discussion

Compliance with regulations governing the anaerobic lagoon and sprayfield system is a contentious topic in North Carolina. The National Weather Service has reported that the 2003 spring has been the wettest on record in North Carolina since record-keeping began over 100 years ago. This spring's rain left North Carolina many lagoons filled to near or into emergency storage capacity in part because sprayfields were so wet that land application of lagoon liquid was not possible or not permitted. In some cases, farmers expended substantial resources for emergency waste disposal to avoid stiff penalties levied by the Division of Water Quality. We believe that our model will provide a useful insight into the cost of emergency waste disposal during high precipitation years and in assessing selected strategies for limiting the cost of compliance with regulations. The cost versus risk trade-off evaluated here is a fundamental economic aspect of engineering design standards.

Several improvements to the model are planned to make it more useful as a management tool. First, the inability of the model to reflect problems faced by many producers in the spring of 2003 suggests that current assumptions about soil drainage and evaporation may be insufficient. Several arbitrary assumptions were made including rates of soil moisture depletion, rates at which farmers can apply effluent to their entire sprayfield, and farmer irrigation rules (i.e. spray every day that it is possible without violating regulatory constraints). The capacity to incorporate individual farm data on lagoon volume and surface area, precipitation, evaporation, soil moisture loss, crop rotation, irrigation capacity, regulatory constraints, and manure and spilled water discharge will greatly improve the accuracy and relevance of the model. Some preliminary insights are provided by the relative effects of lagoon temporary storage capacity, minimum irrigation application depth, and daily manure and spilled water discharge on costs and volume of emergency removal. More work is needed to evaluate the effects of different crop rotations and irrigation methods. For example, row crops may impose fewer days suitable for irrigation and a different expected cost of emergency removal. Similarly, daily irrigation capacity was not included as a specific constraint in this version of the model; instead, it was assumed that the entire sprayfield could and would be irrigated at a constant predetermined depth each time. Despite these limitations, the model presented here provides useful insights into the effects of design factors, regulatory constraints, farm specific factors, and stochastic weather variables on the performance and cost of lagoon-sprayfield systems.

References

Cox, V. N. "A Cost Analysis of Irrigating Swine Waste Effluent." M.S. Thesis. North Carolina State University. Department of Agricultural and Resource Economics. 1993.

Bosch, Darrell J., Minkang Zhu, and E. T. Kornegay. "Returns from Microbial Phytase When Crop Applications of Swine Manure Are Limited by Phosphorus." *Journal of Production Agriculture*. 11:2(1998)157:213.

(NRCSa) National Resource Conservation Service. Natural Resource Conservation Service Practice Standard. Waste Utilization (Acre) Code 633.

(NRCSb) National Resource Conservation Service. Natural Resource Conservation Service Practice Standard. Waste Treatment Lagoon Practice Standard Code 359.

Schwabe, A. Kurt. Assistant Professor of Resource and Environmental Economics. June 2001. Personal Communication.

Figure 1: Location of Permitted Swine Farms in North Carolina

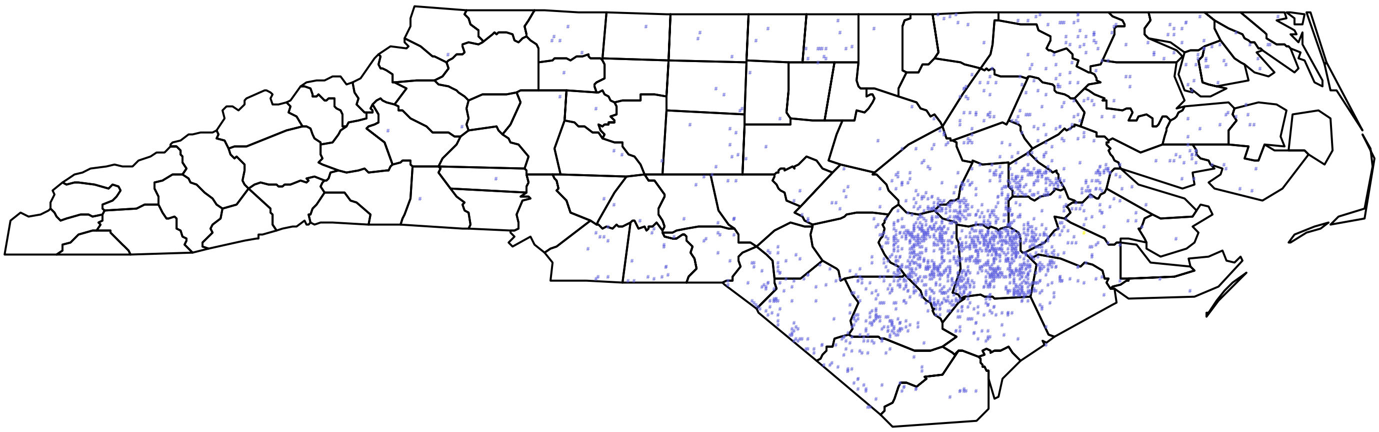


Figure 2: Location of Weather Monitoring Stations in the 10 Counties with the Highest Pig Inventories)

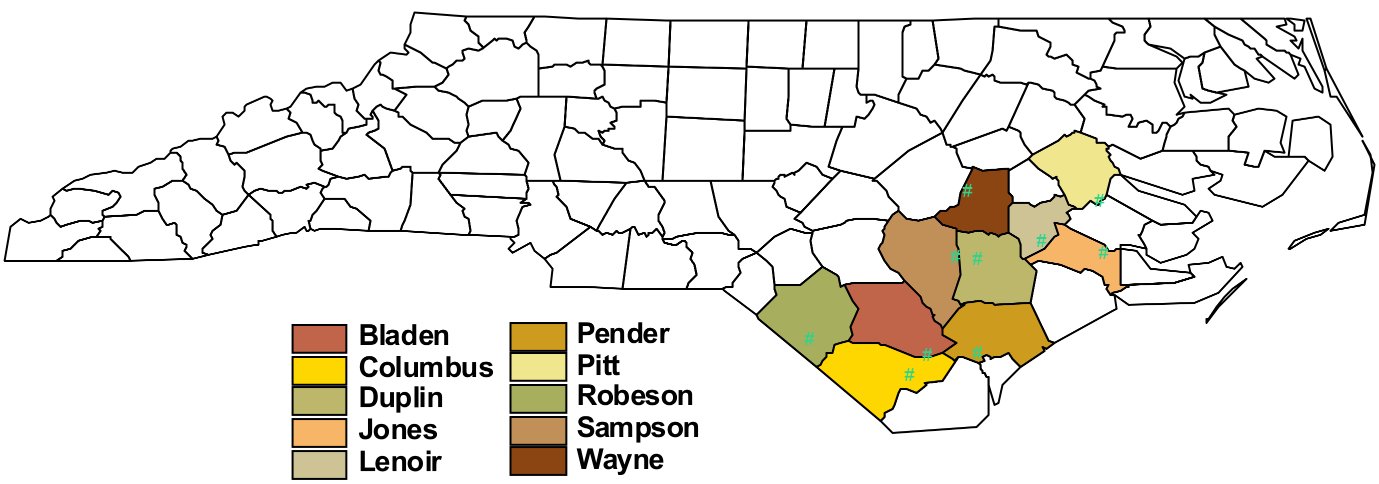


Figure 3: Duplin County Monitoring Station Monthly Precipitation 1993 - 2003

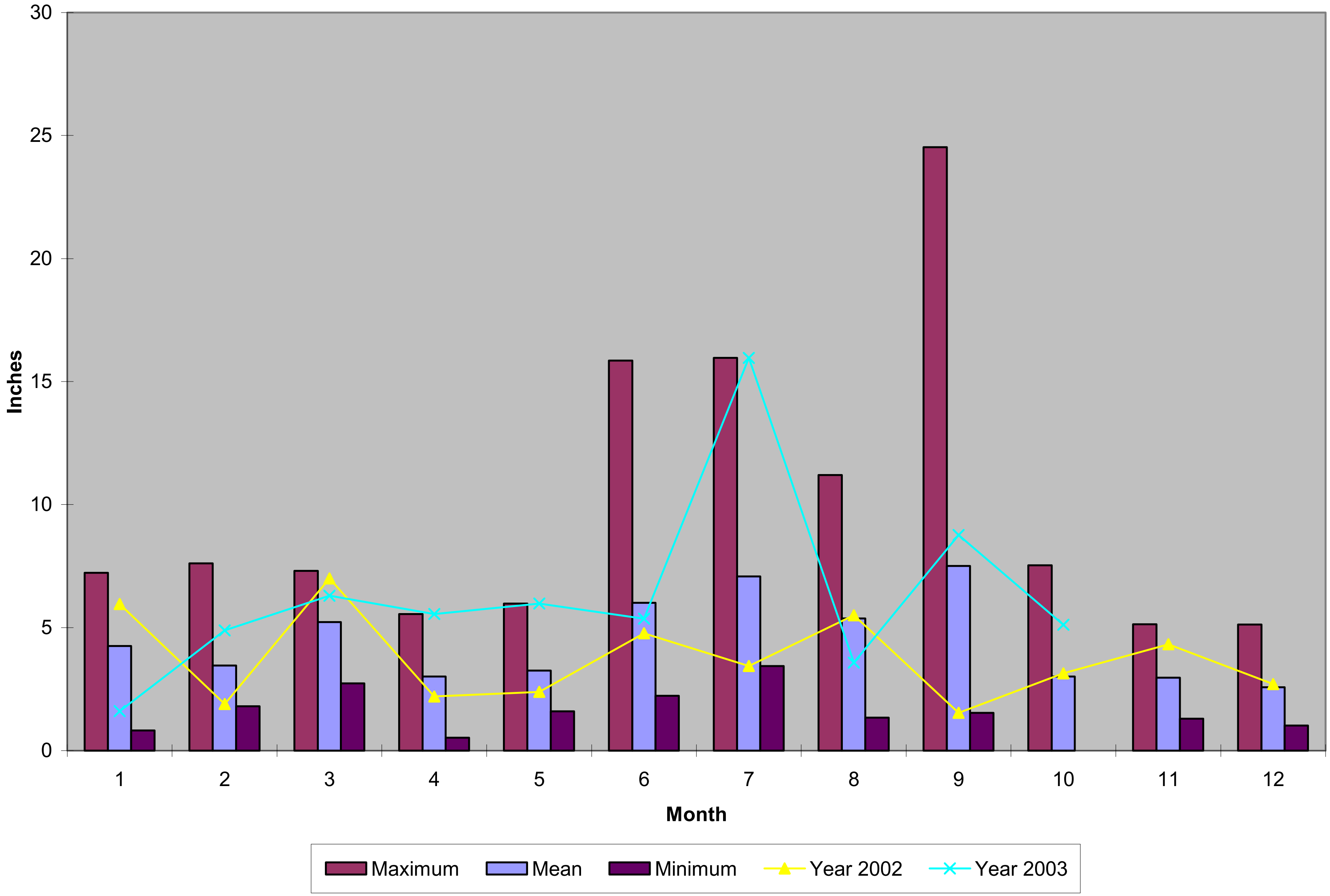
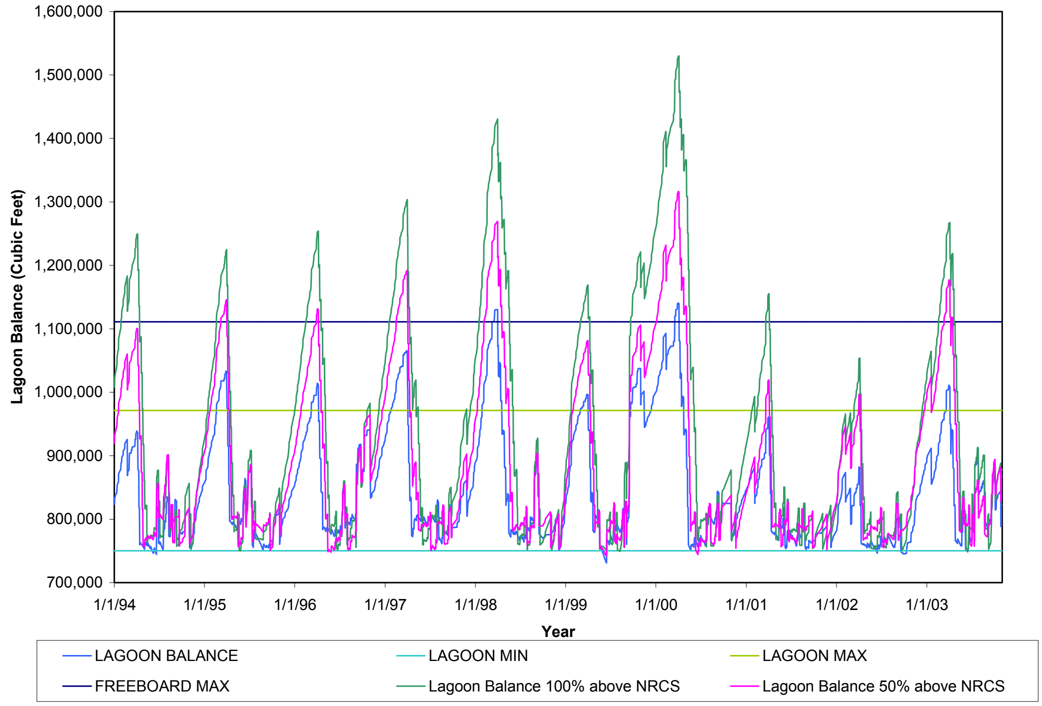


Figure 4: Simulated Lagoon Liquid Volume at 3 Rates of Manure and Spilled Water Accumulation



Application Rate=0.5 Inches

Figure 5: Duplin County (Year 2003), Application Level=0.5 Inches, Barn Discharge at NRCS recommended level

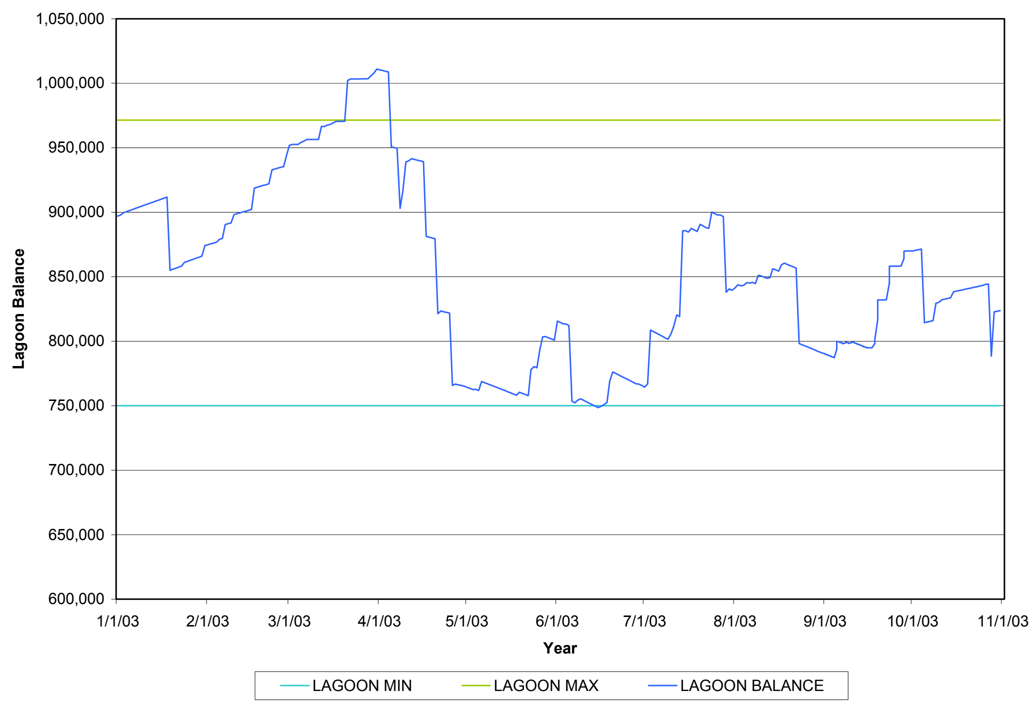


Figure 6: Simulated Lagoon Liquid Volume at 3 Sprayfield Irrigation Application Depths

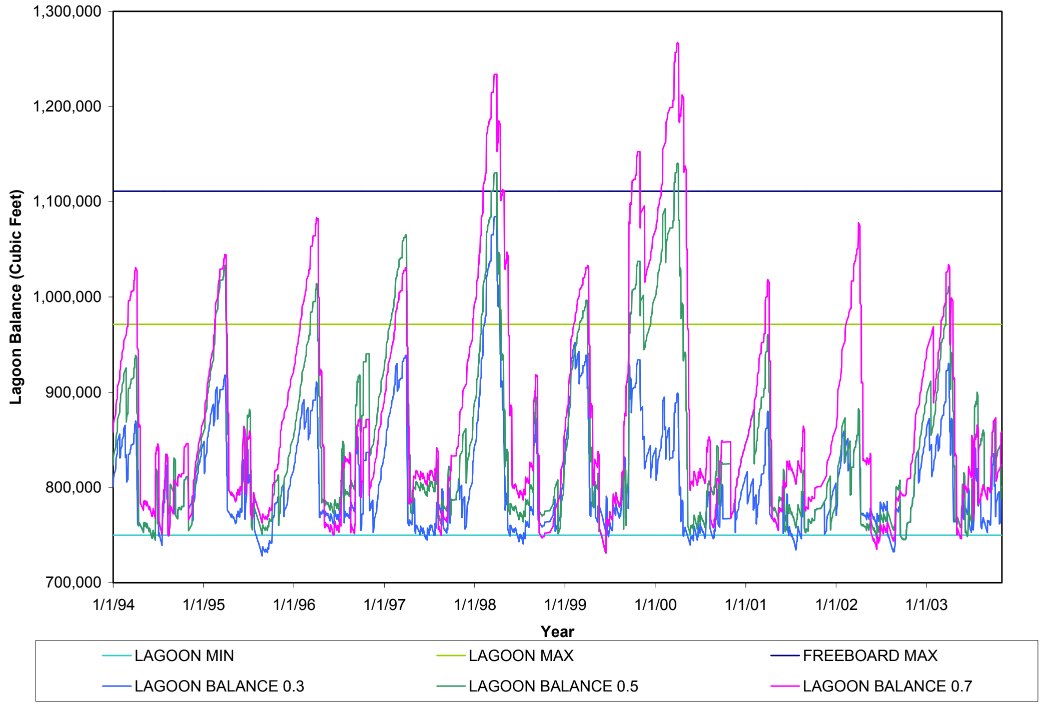


Figure 7: Costs of Lagoon, Irrigation, and Emergency Liquid Removal (180 Day Temp Storage)

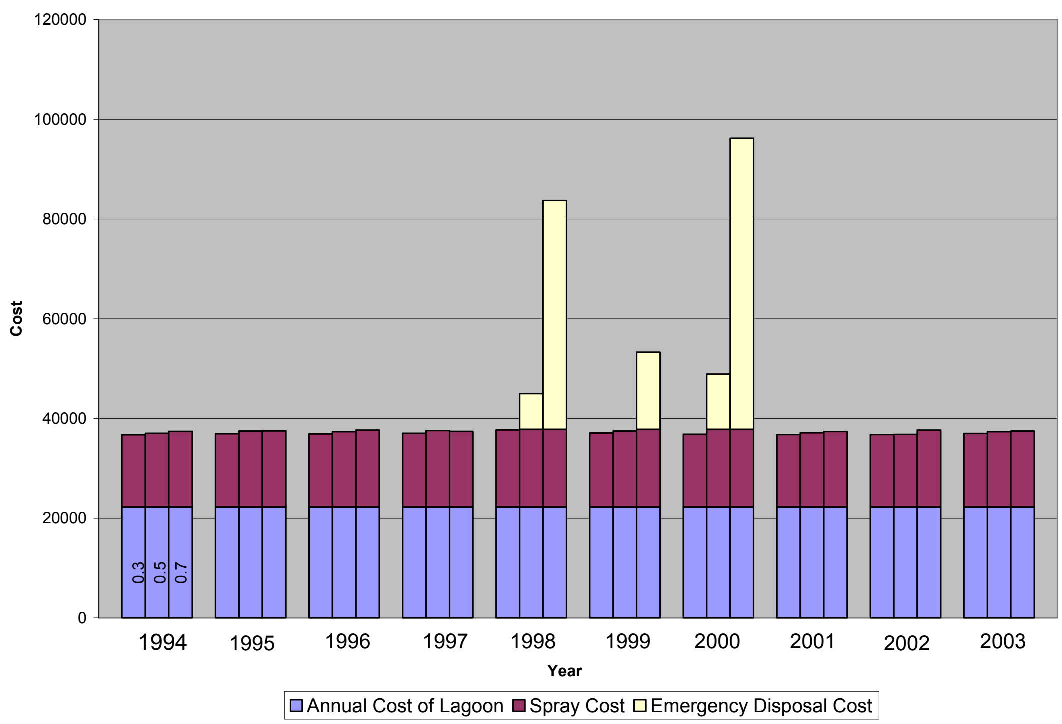


Figure 8: : Costs of Lagoon, Irrigation, and Emergency Liquid Removal (90 Day Temp Storage)

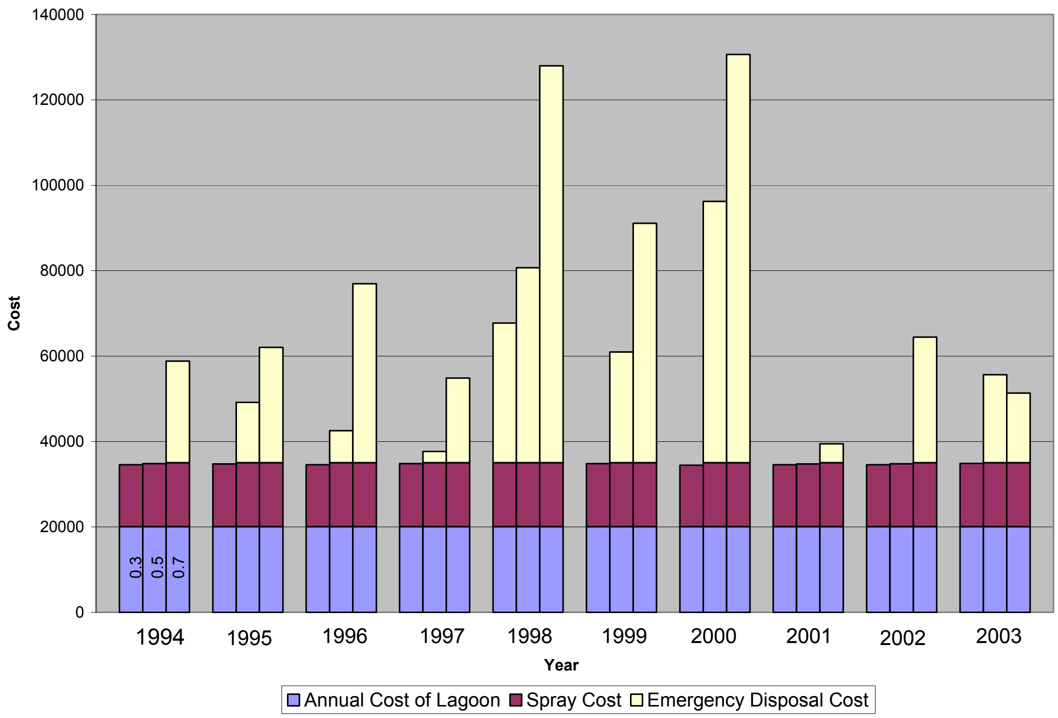


Figure 9: : Costs of Lagoon, Irrigation, and Emergency Liquid Removal (270 Day Temp Storage)

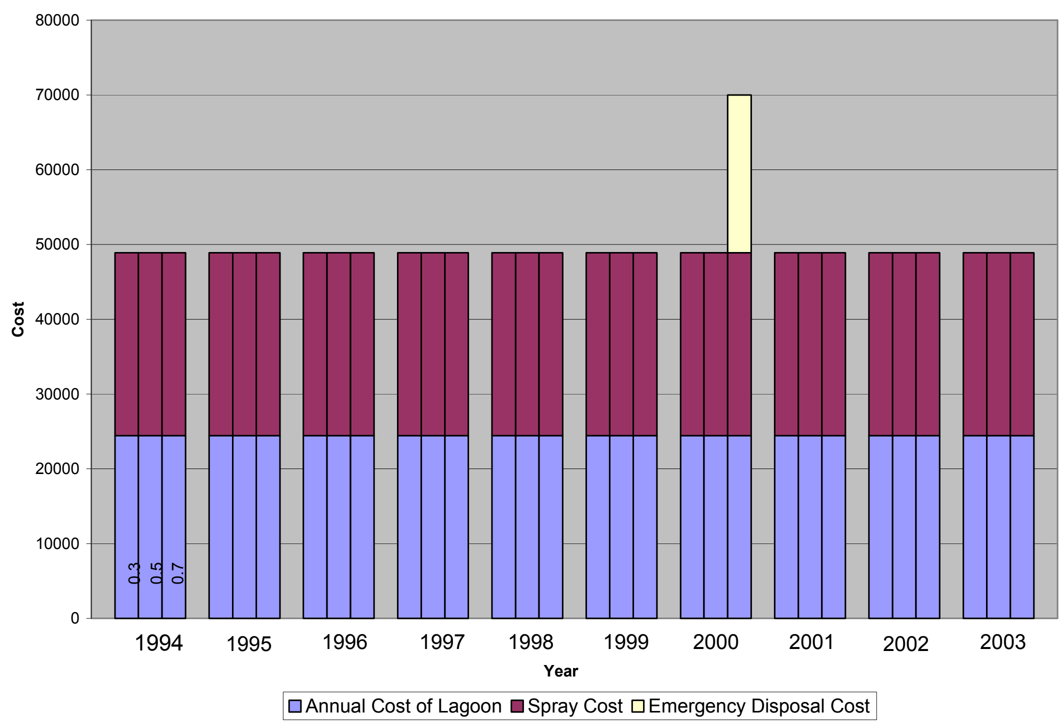


Table 1: Design Treatment, Sludge Storage, and Manure, Urine and Excess Water Lagoon Volumes

Farm Type	Average Live Weight	Design Treatment Volume	Sludge Storage Volume	Manure, Urine, and Excess Water
	lbs	ft^3/lb	ft^3/lb	gallons/day
Farrow-to-Wean	433	0.67	0.17	7.2 per sow
Farrow-to-Feeder	522	0.67	0.17	8.0 per sow
Farrow-to-Finish	1,417	1.00	0.25	23.0 per sow
Wean-to-Feeder	30	1.00	0.25	0.5 per head
Feeder-to-Finish	150[a]	1.00	0.25	2.3 per head

Note: Source is NRCSa

Table 2: Daily Evaporation and Evapotranspiration

Month	**Evaporation***	**Evapotransporation****
	Inches	Inches
January	0.040	0.035
February	0.055	0.055
March	0.115	0.085
April	0.170	0.140
May	0.200	0.155
June	0.225	0.175
July	0.230	0.170
August	0.205	0.145
September	0.160	0.120
October	0.115	0.080
November	0.070	0.045
December	0.050	0.025

*Evaporation rates represent arithmetic averages of measurements taken at Raleigh, NC and Wilmington, NC monitoring stations.

**Evapotransporation rates represent arithmetic averages of measurements taken at Hoffman Forest, NC and Chapel Hill, NC monitoring stations.