

ABSTRACT

ANASTASIOU, CHRISTOS CHARALAMBOU. Development of a Decision Support Methodology for the Design of Animal Waste Management Strategies to Achieve Regional Environmental Objectives. (Under the direction of Dr. S. Ranji Ranjithan and Dr Sarah K. Liehr)

Management of waste from confined animal feeding operations is becoming increasingly important. While anaerobic lagoons and sprayfields are currently used for treatment, recent administrative initiatives call for their replacement. This decision has increased the need for characterization of the cost and treatment effectiveness of alternative technologies. However, due to variations in farm characteristics (e.g., size, location), identification of the most cost-effective combination of treatment technologies to achieve collective environmental goals requires an integrated approach (i.e., all combinations of treatment technology alternatives at all farms in a region must be considered simultaneously). The objective of this research is to develop a regional management decision-support framework to assist policy-makers, planners, and farmers in making cost effective lagoon replacement decisions to achieve desired treatment and public protection goals. A major component of the framework is a cost and treatment efficiency assessment tool to evaluate alternative animal waste treatment technologies for individual farms. Outputs from the assessment tool, together with geospatial data, feed into the regional management component of the framework, which consists of several quantitative techniques to assist in the search for good decisions. Among these techniques are an integer programming-based optimization engine that can be used to find management strategies that meet cost and environmental targets, and a method for efficiently generating alternatives. The management alternatives have similar cost and environmental performance but may behave differently for unmodeled objectives (e.g., risk or equity). Finally, the regional management framework includes an uncertainty analysis component that allows the evaluation of alternatives while considering the uncertainty in model inputs. The decision-support framework was demonstrated through an illustrative example; the regional waste management of swine farms in the Lower Neuse River watershed in eastern North Carolina to achieve a 30% reduction in nitrogen loading. Results show that 1) a regional management approach leads to considerable cost savings, 2) there is significant flexibility in meeting the nitrogen reduction targets with similar cost burden, 3) consideration of uncertainty assists in distinguishing the reliabilities of different solutions, 4) the decision support framework provides input to address a range of animal waste management concerns, including but not limited to cost, risk, equity, and uncertainty.

**Development of a Decision Support Methodology for the
Design of Animal Waste Management Strategies to Achieve
Regional Environmental Objectives**

by

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DEDICATION

TO MY PARENTS

Charalambos and Androulla Anastasiou,

Who with their love, support, and their sacrifices

Helped me reach this point.

My parents, who through their example in life, will always remain

My best teachers!

“Dearest, I only hope that, with all the tools that you have given me, one day I will
achieve all that you have achieved, despite the so many difficulties in your life.

I love you!”

BIOGRAPHY

Christos Charalambous Anastasiou was born on 13 June 1972 in Zodhia, Cyprus. He is a member of a family of five. After the 1974 Turkish military invasion of Cyprus, his family was forced to move to the town of Astromeritis, Cyprus, where he spent most of the years of his life. Christos graduated from The Grammar School secondary educational institution in Nicosia, Cyprus, in June 1990. In July 1990, he joined the Cyprus National Guard, where he served until August 1992. After receiving a Fulbright scholarship for undergraduate studies in the United States, Christos enrolled in the University of Florida pursuant of his bachelor's degree. He majored in environmental engineering and took extensive coursework in water and wastewater treatment. He received his Bachelor of Science degree in May 1996. Christos joined the graduate program in the Department of Environmental Engineering Sciences at the University of Florida. He conducted his master's research work, under the guidance of Dr. Clay Montague, both in the Department of Environmental Engineering Sciences at UF and at the Everglades National Park Ranger Station in Key Largo, Florida. He received his Master of Engineering degree and a Graduate Studies Certificate for Wetland Science and Water Resources in August 1999. Christos joined the Environmental Systems Analysis Doctoral program of the Department of Civil Engineering, at North Carolina State University in August 1999. During his time at NCSU, he held a number of research and teaching positions in the Departments of Civil Engineering, Biological and Agricultural Engineering, and Agricultural and Resource Economics. Christos has a keen interest in the fields of environmental management, policy, environmental systems analysis, and the development of decision support tools for environmental decision-making. He expects to cultivate his interests further through a career in academia.

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CHAPTER 1: Introduction

The purpose of this study is to develop, evaluate, and demonstrate a quantitative framework to assist in *regional* management of animal waste. This framework includes methodologies that allow the exploration of cost-effective allocations of animal waste treatment systems to farms while meeting environmental and social goals, as well as consideration of the effects of uncertainty.

1.1 Background

Waste from animal farms may pose a serious environmental, human health, and aesthetic problem unless appropriate waste management techniques are employed. Animal waste (especially swine waste) is currently managed predominantly through anaerobic lagoons and sprayfields. Runoff from livestock operations enters surface and ground water due to poor maintenance of waste lagoons, improper design of storage structures, improper storage of animal waste, and excessive rainfall that leads to spills and leaks of manure-laden water. Over-application of manure in sprayfields is another source contributing to animal waste runoff.

When livestock manure and other animal waste spills or leaks into surface and groundwater, it can create a threat to water resources and public health. This runoff has nutrients such as nitrogen and phosphorus that in excess can cause algae, and other microorganisms, to reproduce in waterways, creating unsightly and possibly harmful blooms. Explosive algae populations can lower the level of dissolved oxygen, which can harm fish and other aquatic habitats. Spills from ruptured waste lagoons and other faulty storage facilities have contributed to fish kills (Burkholder et al., 1997). Animal waste runoff can also be a threat to the health of people who are exposed to affected waters because of bacteria, protozoa, and viruses in animal waste. Odor is another problem arising from waste lagoons and storage structures, and it not only is an aesthetic issue for people living nearby but also can become a health issue by causing such problems as chronic headaches.

An increase in concentrated animal farming operations in the United States in recent years necessitates better animal waste management practices both at the farm and at a regional level. A national effort to develop alternative animal waste management practices has been recently launched (USEPA, 2000). North Carolina is one of the top producers of swine in the United States. Waste from swine farms and their

current management practices have been a point of public debate for more than a decade. In response to public dissatisfaction with the anaerobic lagoons, the replacement of this treatment system with alternative treatment technologies has been proposed by the State. The upgrading of treatment practices in North Carolina corresponds to the national effort to develop alternative animal waste management practices.

A key goal in this effort is to better characterize new animal waste treatment technologies. Current studies are focused on available treatment technologies and how these can be applied at individual farms. A limited number of treatment technology evaluations have been completed. Parameters evaluated in these studies include nutrient removal, solids produced, ammonia and odor emissions, construction costs and operation costs. Anaerobic lagoons, ambient anaerobic digesters (Cheng, et. al., 1999), sequencing batch reactors (Classen and Bicudo, 1999), upflow aerated biofilters (Westerman, et. al., 1999), and constructed wetlands (Payne Engineering and CH2M Hill, 1997; Hunt et al., 1995; and Szogi and Hunt, 2001) have been evaluated for use with animal waste. Evaluations of 18 more alternative animal waste management technologies and processes are currently in progress at North Carolina State University (Williams, 2002). The information generated in the technology evaluation studies still needs to be made available in an easily accessible format that allows comparison of treatment systems for similar farm characteristics.

While technology evaluation studies provide the critical knowledge base for identifying the cost-effective treatment option for an individual farm, methods to identify a collective management strategy to meet regional environmental goals are lacking. A management strategy requiring the use of the least-cost technology to meet a reduction target (e.g., 30% reduction in nitrogen loading) at each individual farm may not be the most cost effective strategy to meet the same reduction target at a regional level. The most cost-effective solution may not be to require all farming operations to treat to the same level. The development of an appropriate management strategy is affected by many factors, such as economies of scale of waste treatment systems, farm location effects, and farm-specific technical feasibility. The development of collective or regional management strategies regarding lagoon replacement that will cost-effectively meet desired treatment and public protection goals are needed. Regional environmental goals may include, for example, the minimization of nitrogen and phosphorus in effluents, ammonia and odor emissions, and risk of surface or groundwater contamination. Mathematical programming-based optimization techniques easily lend themselves to modeling these problems and to search for efficient regional management strategies.

The use of formal optimization, however, is sometimes criticized because the optimal solution to a mathematical model is rarely the best solution to the real problem, as all the objectives and constraints of the real problem may not be included in the model (Liebman, 1976). This omission may be due to errors,

the un-quantifiable nature of certain issues, or issues that were not identified at the point of model formulation. For example, the problem of swine waste in North Carolina has been an issue of contest for a number of years. A management strategy that may be perceived as unfair (non-equitable) in its implementation will likely draw strong reactions from farmers. The availability of a number of maximally different management alternatives that meet the same environmental goals can be very useful to managers and policy makers in exploring options that allow the consideration of such unmodeled issues. Such alternatives can provide excellent starting points for dialogue among stakeholders and therefore allow easier development of practically more feasible solutions. Maximally different management strategies can be systematically generated using mathematical programming methodologies.

In addition to the challenge of modeling regional environmental management issues, such models have also been criticized for relying on a large number of inputs for which the values are uncertain. Many treatment technologies are in an early development stage and therefore, the values of several descriptive parameters needed for their modeling are not well defined. Therefore, the model outputs such as cost and pollutant discharge will also be uncertain. Consideration of uncertainty may lead to different outcomes than those from deterministic evaluations. Thus, consideration of uncertainty on the performance of alternative strategies is important in evaluating strategies for animal waste management.

1.2 Research Objectives

To address the issues described above, this study focuses on the following specific objectives:

- Develop a technology characterization tool -- This tool structures the data from field evaluations of treatment technologies for use in decision support analysis, calculates nutrients and solids discharge, capital costs, and operating costs for different farm characteristics.
- Develop a regional animal waste management model -- this model utilizes existing geospatial data on farm size and location as well as technology characteristics and identifies cost-effective allocation of treatment technologies to farms to achieve regional environmental goals.
- Develop a procedure to generate cost-effective strategies that utilize alternative technology allocations - - this procedure extends the above regional model to explore maximally different solutions to achieve the same design goals.
- Implement an uncertainty analysis procedure to evaluate and compare the performance of alternative animal waste management strategies under conditions of uncertainty.

- Demonstrate the applicability of this decision support framework through its application to a realistic case study to explore a range of animal waste management strategies.

1.3 Organization and Outline of the Dissertation

The major research activities and results are presented in four chapters, each written in the form of a journal paper:

- Chapter 2: Computer Assisted Waste System Selection Tool.
- Chapter 3: Design of Animal Waste Management Strategies to Achieve Regional Environmental Objectives.
- Chapter 4: Managing Swine Waste in North Carolina: Examination of Alternatives.
- Chapter 5: Consideration of Uncertainty in Swine Waste Management in North Carolina.

Each chapter is summarized below:

1.3.1 Chapter 2: Computer Assisted Waste System Selection Tool.

The first part of the decision-support methodology is a computer-based tool used for comparing different animal waste treatment systems on a site-specific basis. The Computer Assisted Waste System Selection Tool (CAWSST) is designed to help farmers make decisions regarding the technology they would use to treat their animal waste to meet environmental criteria. Alternative animal waste treatment technologies are mathematically described in CAWSST. For each treatment system, the tool estimates, among other parameters, cost, nutrient removal efficiencies, and the land area required by each system. The models describing the treatment systems in this tool are implemented within a spreadsheet. Site-specific inputs to the current version of the tool include the number of swine in a farm and the swine-house cleaning method (flush system or the pit recharge system of waste removal). The format of CAWSST is structured such that it allows expansion to include additional alternative treatment technologies as data become available. Results present a comparison of alternative treatment technologies.

1.3.2 Chapter 3: Design of Animal Waste Management Strategies to Achieve Regional Environmental Objectives.

The second paper takes an integrated approach in examining and searching among technology alternatives at all farms simultaneously. The goal was to identify the most cost-effective solutions that achieve collective target reductions in discharge levels in a region. The treatment technology cost and nutrient removal efficiencies, which are outputs of CAWSST, along with existing geospatial data have been used to group farms according to their size or location (e.g., proximity to flood plains). Cost-effective strategies for accomplishing specified goals for environmental protection and public health have been developed. Environmental objectives such as minimizing nitrogen and phosphorus in effluents are considered. Management strategies examined include the least cost solution and uniform treatment among all farms in the watershed. In other strategies, zones that are defined by such factors as political boundaries, farm size, type of farming operation or proximity to floodplains, include farms that are required to treat their waste to the same level. The decision models based on mixed integer linear programming (MILP) are applied. Standard mathematical programming-based search procedures that are commonly available are used for solving the MILP models. The methodology is demonstrated for a case study involving the swine farms in the Lower Neuse River watershed in Eastern North Carolina.

1.3.3 Chapter 4: Managing Swine Waste in North Carolina: Examination of Alternatives.

In the third paper, the Modeling to Generate Alternative (MGA) technique is used to generate alternative management strategies for the case study considered in Chapter 3. MGA techniques (Brill, 1979; Brill et al., 1990; Chang et al., 1982; Hopkins et al., 1982) use optimization to generate a small set of very different solutions. The alternatives may perform differently with respect to unmodeled or un-quantifiable issues, as well as provide new insights into the problem that may not have otherwise been considered. Techniques used in recent work (Harrell and Ranjithan, 1997; Harrell, 1998; Gillon, 1999; Loughlin and Ranjithan 1997; Loughlin et al., 2000; Solano et al., 2002) have been used to generate a small set of efficient strategies that are maximally different from each other while meeting all the modeled constraints. Examples of unmodeled objectives examined in this study include the risk that each management strategy poses in case of a flood event, and the equity based on cost burden of each strategy.

1.3.4 Chapter 5: Consideration of Uncertainty in Swine Waste Management in North Carolina.

In a fourth paper, the decision support methodology is expanded to include the analysis of management alternatives under conditions of uncertainty. The robustness of the alternative strategies examined in Chapter 4 is estimated by evaluating their performance under conditions of uncertainty in the CAWSST inputs. As significant input uncertainty is prevalent, consideration of the performance of a strategy under uncertainty is important when making decisions about technology choices to meet future environmental goals. The *Monte Carlo* simulation approach, commonly used in uncertainty propagation, with *Latin Hypercube Sampling* (Morgan and Henrion, 1990), was used to examine the effect of uncertain CAWSST inputs on the performance of the alternative waste management strategies. Uncertainty importance (correlation) analysis was employed to determine what input parameters contribute most to the uncertainty in the model outputs. A discussion of how consideration of uncertainty influences decision-making at the farm and at the regional level is included.

CHAPTER 2: Computer Assisted Waste System Selection Tool

Abstract

The Computer Assisted Waste System Selection Tool (CAWSST) is a prototype-software designed to help compare various animal waste treatment systems on a site-specific basis. This tool is designed to help farmers, aided by agricultural specialists, make decisions regarding the technology they would use to treat their animal waste to meet environmental criteria. For different treatment systems, the tool estimates the initial and operational costs, the amount of remaining nitrogen and phosphorus that must be land applied, nutrient removal efficiencies, relative effects on odor generation and ammonia volatilization, and the land area required by a treatment system. The models describing the treatment systems in this tool are implemented within a spreadsheet. The following treatment technologies were included: anaerobic lagoon, constructed wetlands, ambient anaerobic digester, sequencing batch reactor, and upflow aerated biofilter. Site-specific inputs to the current version of the tool include the number of swine in a farm and the swine-house cleaning method (flush system or the pit recharge system of waste removal). The format of CAWSST is structured such that it allows expansion to include additional alternative treatment technologies as data become available. The tool can be used for new installations or renovations of existing facilities where the existing lagoon might be used as part of the new treatment system, by taking the role, for example, of a pretreatment stage or a water storage pond.

2.1. Introduction

The Computer Assisted Waste System Selection Tool (CAWSST) is prototype-software developed to primarily assist farmers in choosing alternative wastewater treatment systems. This tool is designed to provide information that allows users to compare various treatment technologies and evaluate trade-offs for their individual animal farming operations. Currently, CAWSST provides treatment efficiency and cost comparisons of treatment technologies for the swine industry. However, it has been designed with the potential for upgrades that may include technologies that are specific to additional types of agricultural, industrial, and municipal waste.

2.1.1 Background

Contaminants in swine waste are very similar to the components of municipal wastewater. A vast amount of literature exists on simple to highly complex descriptions of municipal treatment processes (Metcalf & Eddy, Inc., 1991; Crites and Tchobanaglou, 1998; Henze et al., 1987, 1995). However, this information requires modification for application to animal waste treatment due to differing waste treatment constraints and waste strength characteristics. Swine waste tends to be one to two orders of magnitude greater in contaminant concentration than municipal waste (Table 2.1). These higher concentrations pose additional challenges to treatment but they also provide greater opportunity for resource recovery. For example, the high level of BOD in swine waste lends itself to possible methane generation and utilization as fuel.

Table 2.1 Characteristics of swine and domestic waste (as they are flushed out of the houses).

Parameter / Contaminant	Units	Municipal Waste	Flushed Swine Waste
Total Solids (TS)	mg/L	720	8650
Volatile Suspend. Solids (VSS)	mg/L	165	6050
BOD ₅	mg/L	220	5200
TOC	mg/L	160	6750
COD	mg/L	500	10350
TKN:	mg/L	40	1050
Ammonia -N	mg/L	25	600
Organic -N	mg/L	15	400
Nitrate, Nitrite	mg/L	negligible	5
TP:	mg/L	8	800
Organic	mg/L	3	250
Inorganic	mg/L	5	550
Chlorides	mg/L	50	500
Alkalinity (as CaCO ₃)	mg/L	100	500
Total Coliform	no/100mL	5E8	5E8
Ratio FC/FS ⁽¹⁾		4.4	0.04

⁽¹⁾ FC/FS = fecal coliform to fecal streptococci ratio

Discharge practices of treated swine waste also differ from those for municipal waste. Specifically, swine waste cannot be discharged into surface waters. All treated waste from animal farming operations must be land applied onto designated sprayfields. Therefore, it is not necessary that swine waste be treated to the low concentrations required for the discharge of municipal wastewater. While this practice allows for a

lower degree of waste treatment, additional considerations in waste management appear. For example, in conjunction to the treatment systems, land of appropriate soil-type and area needs to become available for effluent application.

While cost is a consideration in every environmental operation, farmers can be especially constrained by the cost to build and operate treatment systems. An increase in treatment cost would cause an increase to the price of their product and thus make them less competitive in consumer markets. Most farmers will require relatively inexpensive and easy-to-operate systems. However, unlike many municipalities, farmers can afford to build systems that require larger land area, since most farms are not as land constrained as residential areas.

The performance and cost of various swine waste treatment systems has been examined in a number of technology evaluation studies at North Carolina State University (Williams, 2002). This is an ongoing effort at many research and educational institutions. Evaluation of treatment technologies is complicated by the fact that different farms have different waste characteristics, different sizes, and different operating constraints. Mathematical descriptions of treatment efficiencies and economic characteristics can be useful in generalizing available information to extend to farms of different sizes and characteristics. While modeling may not provide the most accurate estimates for full-scale treatment operations, it will nevertheless allow comparison among various technologies, thus helping farmers and environmental managers to reach the best possible decision in waste management.

2.1.2 Paper Contribution

This paper provides a procedure to examine, compare and contrast the various treatment technologies available for swine waste so that farmers can make better-informed decisions regarding waste treatment for their farms. This procedure was developed into a computer-based tool that is flexible and easy to use. Modeling of the treatment processes and incorporation into such a tool provides a means of making technically and economically sound comparisons of various treatment technologies under uniform conditions. Some of the people who may find the tool useful are farmers who want to examine the alternative technologies that can be implemented at their farms, agricultural extension agents, research scientists, or federal and state environmental agents.

2.1.3 Paper Organization

This paper first introduces the basic structure of CAWSST. In this first section, the inputs, outputs, and the general procedure used to model the treatment processes are described. The second section of the paper introduces each of the five treatment technologies included in the current version of the computer tool. For each technology, a brief introduction to the treatment mechanism is followed by a description of the specific components used in the mathematical modeling. Sample results are then presented. A brief discussion on the ways that one can use the tool as well as suggestions for future expansion of CAWSST concludes the paper.

2.2. CAWSST Structure

CAWSST is intended to be a means for comparing and contrasting different technologies as they apply to farms of different characteristics, such as size or animal house cleaning systems. It is not intended to be a wastewater treatment technology design tool.

This version of CAWSST uses the characteristics of animal waste that were obtained from industrial averages (Barker et al., 1994). It also uses information obtained from published evaluations of the following swine waste treatment technologies: anaerobic lagoons (Barker et al., 1994), ambient anaerobic digesters (Cheng et. al., 1999), sequencing batch reactors (Classen and Bicudo, 1999), upflow aerated biofilters (Westerman et. al., 1999), and constructed wetlands (study conducted at NCSU, reported in Payne Engineering and CH2M Hill, 1997 and Hunt et al., 1995). Most of the data presented in these published papers were collected from pilot-scale systems.

The following steps were used in developing CAWSST: First, the available treatment technologies were identified from the literature. Then the swine waste characteristics were organized, alongside cost and treatment data from treatment technology evaluations completed at North Carolina State University (NCSU), in an accessible database. The specific issues of the swine waste management problem in North Carolina were examined. Suggestions from academic and agricultural extension field faculty at NCSU were incorporated in the formatting of the appropriate output parameters of CAWSST. The performance data of treatment technologies were mathematically described and they were subsequently coupled to the swine waste characteristics database to form an interactive computer-based tool.

2.2.1 CAWSST inputs

CAWSST has two different screens that allow the input of parameters. The first screen calls for basic inputs that are production-specific and that include the number of swine and the type of waste-handling system used in the animal houses. The tool provides a choice between two different swine-house cleaning systems that are in widespread use in North Carolina: a flush system and a pit recharge system. If a flush system is chosen, then the user is asked to provide the number and the holding capacity of each of the flush tanks used in the farm, as well as the flushing schedule (frequency of flushes). If the pit-recharge system is identified, the number and holding capacity of pits in the farm as well as the pit recharge frequency are required as inputs. The second input screen is intended for more advanced users, providing the ability to alter parameters that govern the treatment processes included in the tool. These parameters range from those that mathematically describe the individual treatment technologies (e.g. treatment efficiency and loading rate of each technology component), to parameters describing the capital investment or operational cost of each of these technologies (e.g. cost of electricity per kilowatt-hour, cost of land required by each treatment technology). Default values, which are based on existing technology evaluation literature, are provided. A comprehensive list of the input parameters in the current version of CAWSST, and their description, is provided in Appendix A.

2.2.2 CAWSST outputs

Output parameters for CAWSST include the initial and annual operational costs for each technology, per-pig cost, land area required for installation, volume of effluent water from each technology, as well as the treatment efficiency with respect to nitrogen and phosphorus removal from the wastewater. The amount of solids produced by each technology is also calculated, as well as the amount of nitrogen and phosphorus present in these solids. In addition, qualitative measures of odor emission as well as ammonia volatilization are returned. A list of all the outputs provided by CAWSST is shown in Table 2.2.

2.2.3 Mathematical description of the technologies in CAWSST

CAWSST includes five animal waste treatment processes. Each of these processes has variations in its description. Since anaerobic lagoons are already present on all of the existing swine farms in North Carolina, the structure of the lagoon can be used in any of the alternative technologies. For example, constructed wetlands, sequencing batch reactors and aerated upflow biofilters can be evaluated either as stand-alone systems or with an anaerobic lagoon being used for pretreatment. These systems use an inclined screen solid separator for pretreatment, whenever the existing anaerobic lagoon is not used. The

ambient anaerobic digester technology uses an existing anaerobic lagoon as a storage pond, instead of using it for pre-treatment.

Table 2.2 List of the CAWSST outputs, for each of the included technologies.

<i>Output Parameter</i>	<i>Measurement Units</i>
Total System Annual Cost	\$ / year
Initial Investment	\$
Operation and Management Cost	\$ / year
Per Pig Cost	\$ / pig / year
Per Pig Place Cost	\$ / pig place / year
Total System Area	Acres
Separated Solids	tons / year
TKN in solids	tons / year
TP in solids	tons / year
Volume of Suspended Solids	feet ³ / year
PAN remaining in effluent	tons / year
TKN removal efficiency	%
TP remaining in effluent	tons / year
TP removal efficiency	%
Effluent Volume	Million Gallons / year
Value added products	e.g. methane
Ammonia volatilization (relative)	Low, medium, high
Odor (relative)	Low, medium, high

Wastewater treatment systems are described in CAWSST based on data obtained from pilot or full-scale evaluation studies. The treatment efficiency and the descriptive characteristics (i.e. land required for a system) of each technology are based on mass balances and empirical constants. For example, the fate of nitrogen is tracked within the unit processes of each technology. Each unit process of a technology is described by specific percent removal efficiencies. For example, some percent of nitrogen is removed in pre-treatment, some is removed in the reactor, and another portion could be removed in the storage pond. The percent removals of nutrients are calculated on a mass basis instead of concentration. The recycle

water and the storage pond are modeled for each technology. The sprayfield that is used for land-application of the effluent is excluded from the calculations (Figure 2.1).

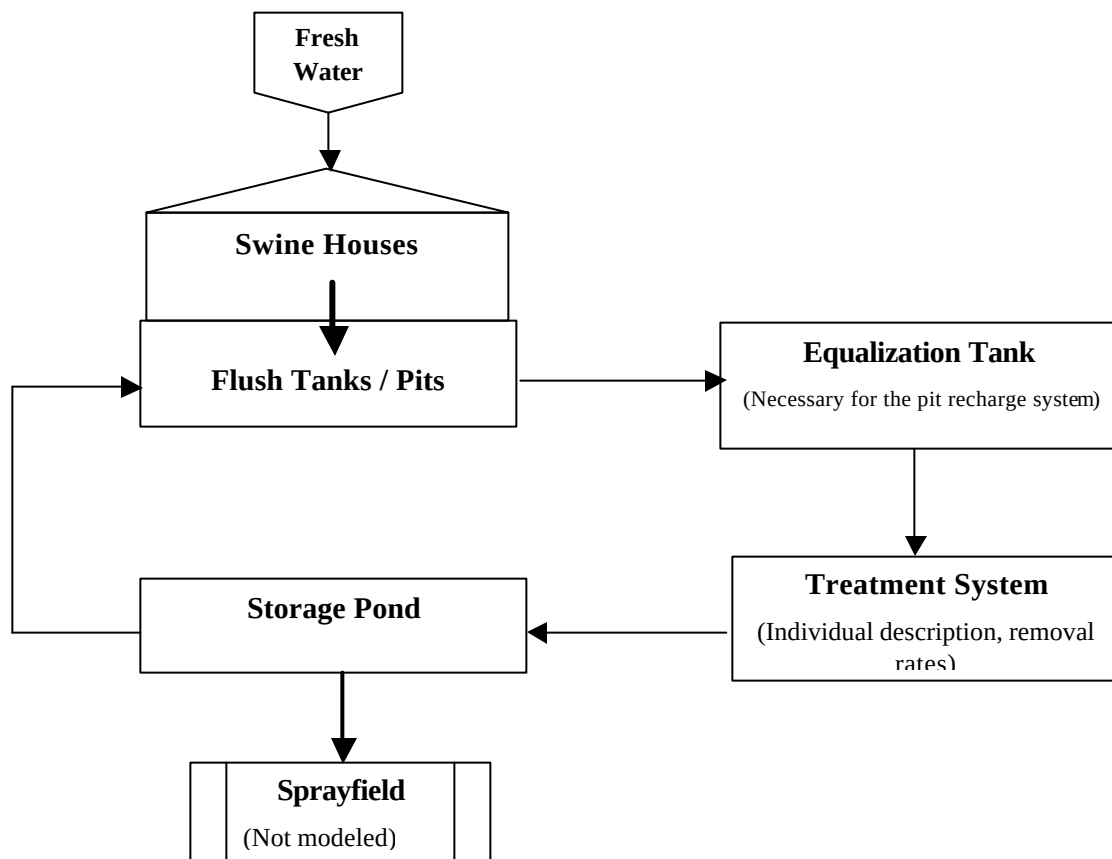


Figure 2.1 Schematic of the interactions among the swine-houses and the treatment system.

Cost calculations are based on a series of empirical constants and assumptions that summarize each unit process of a system. The reason for this approach is the incomplete and largely variable data that characterize the individual components that would be used in the design of a treatment system. For example, in the description of the sequencing batch reactor, the cost of the equalization tank is described in units of dollars per volume. However, in the same system, there is no separate description of the cost involved in piping and pumping of the effluent. These costs are aggregated in the cost of the equalization tank or in the pumping costs.

2.3 Descriptions of Treatment Technologies in CAWSST

Anaerobic lagoons are the most widespread treatment technology in swine farms in North Carolina and elsewhere. A discussion on the modeling of anaerobic lagoons is provided. Furthermore, to demonstrate the calculation procedure and the mass-balances in CAWSST, the constructed wetlands are used as an illustrative example and are then described. The other four alternative technologies that are included in CAWSST are discussed in subsequent subsections.

2.3.1 Modeling of Anaerobic Lagoons in CAWSST

Anaerobic Lagoons are simple and inexpensive systems to design, build, and operate. The main operational and design parameters of anaerobic lagoons are their residence time and size, respectively. They must be large enough to store diluted manure for long enough so that bacteria can decompose it. The total design volume required for an efficient lagoon system is the sum of a minimum specific volume per animal, a waste storage and dilution volume, plus a freeboard and excess rainfall retention space.

The lagoon specific volume is based on a per-kilogram swine weight. The minimum design volume for lagoons, as it is described in CAWSST, is 0.1246 m^3 per kilogram of swine weight. The break-down of this specific volume factor is as follows: 0.0623 m^3 per kilogram swine weight as specific treatment volume of the lagoon, 0.0311 m^3 per kilogram swine weight as specific manure wastewater volume, and 0.0311 m^3 per kilogram swine weight as specific sludge volume. The lagoon volume is thus a function of the minimum design volume factor (0.1246 m^3 per kilogram swine weight), the number of swine in a farm, and the average swine weight (68 kilogram finishing hogs).

The dimensions of the lagoon are based on a combination of the design volume and lagoon depths. A 2.44 m basic structure depth is assumed. An additional 0.61 m of height is included for excess rainfall and runoff, plus safety freeboard. This height adds to the volume and dimensions of the lagoon. The design slope for each face of the lagoon is 3:1. The lagoon length is assumed twice the dimension of its width. A lagoon liner excavation depth of 0.46 m is also assumed. This adds to the area dimensions of the lagoon (due to the slope of the structure), but not to its useful volume.

There are different ways to model the treatment efficiency of anaerobic lagoons, each one with different implications with respect to nutrient removal and area requirements for the system. The following three approaches were mainly explored as possibilities for CAWSST:

In the first approach, a constant concentration of nitrogen and phosphorus in the effluent from the lagoon (Figure 2.2) was assumed. This effluent concentration is obtained from Barker (1994) and it is 550 g/m^3 for nitrogen and 220 g/m^3 for phosphorus. This approach assumes that the treatment efficiency in the anaerobic lagoon *system* is constant. The term ‘system’ is used to describe the interaction among the anaerobic lagoon, the swine-house/pits, and the storage pond/sprayfield. Modeling of the anaerobic lagoon system in CAWSST is based on mass removal rates that do not change with farm size or with different swine house flushing schedules. The system’s treatment efficiency remains the same for all farm sizes, as long as the recycle water (flush water that is used to clean the swine houses) and its nutrient content are not included in the calculation. If the percent treatment efficiency were calculated by performing a mass balance on the influent and the effluent waste mass, it will remain constant irrespective of the recycle schedule. In this first modeling approach the system is treated as a “black box”.

However, under the assumptions of a second modeling approach (Figure 2.3), including the recycle water in the calculations will cause the efficiency of the lagoon unit to be reduced with increasing flushing frequency. Still, it is assumed that the removal efficiency for the system remains constant. The recycle water is considered in the calculations yet it does not affect either the effluent concentration or the removal efficiency of the *system*. A mass balance is performed on the influent manure and the effluent water (to sprayfield). Therefore, the consideration of the recycle does not affect any of the model’s results. The removal efficiency of the lagoon unit process (not the system) is directly proportional to the flushing schedule frequency yet the efficiency of the whole system remains the same.

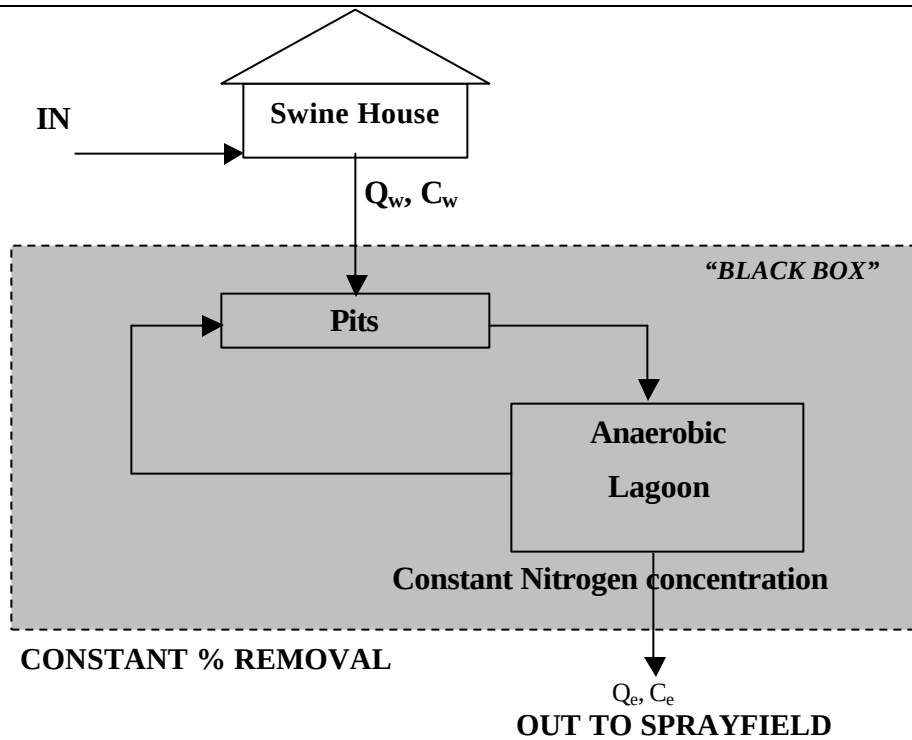


Figure 2.2 First modeling approach for the anaerobic lagoon system.

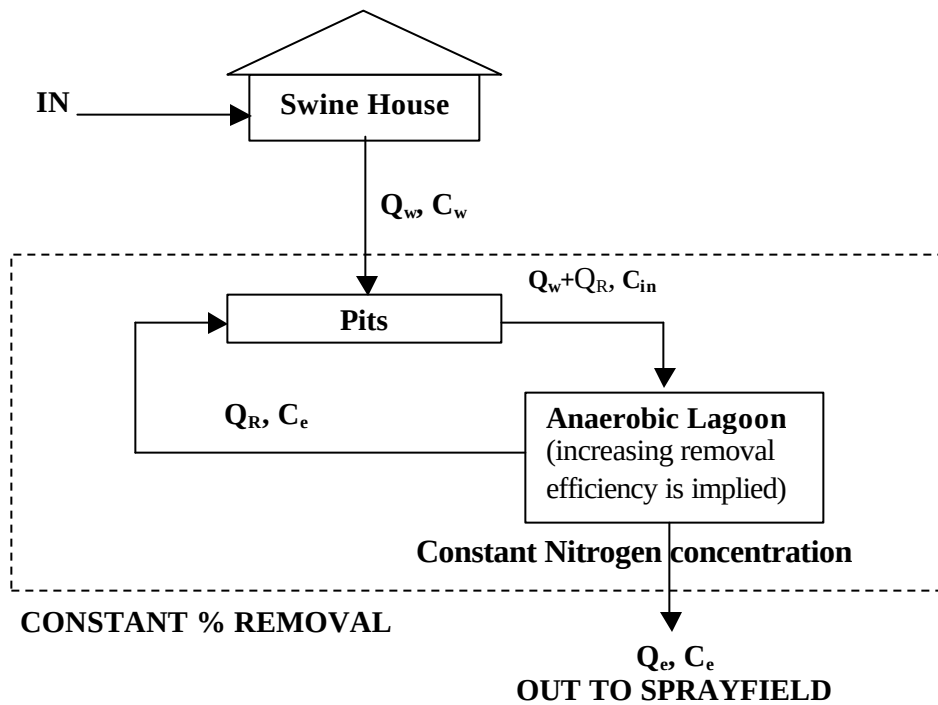


Figure 2.3 Second modeling approach for the anaerobic lagoon system.

The assumption of a third modeling approach (Figure 2.4) is that the anaerobic lagoon unit has constant removal efficiency for nitrogen and phosphorus. The concentration of nutrients in the recycle water is included and therefore, the percent removal efficiency for the *system* changes with a different flushing schedule. After performing a mass balance around the pits in the swine houses and around the lagoon structure (Figure 2.4), the following equation for the effluent concentration is derived (for steady state conditions):

$$C_e = \frac{(1-R)Q_w C_w}{Q_e + Q_R R}$$

where:

C_e = nutrient concentration in effluent and flush water

Q_w = raw manure volume per day

C_w = concentration of nutrients in raw manure

Q_e = effluent volume per day (sent to sprayfield)

Q_R = flush water volume per day

R = percent nutrient removal efficiency of the lagoon unit

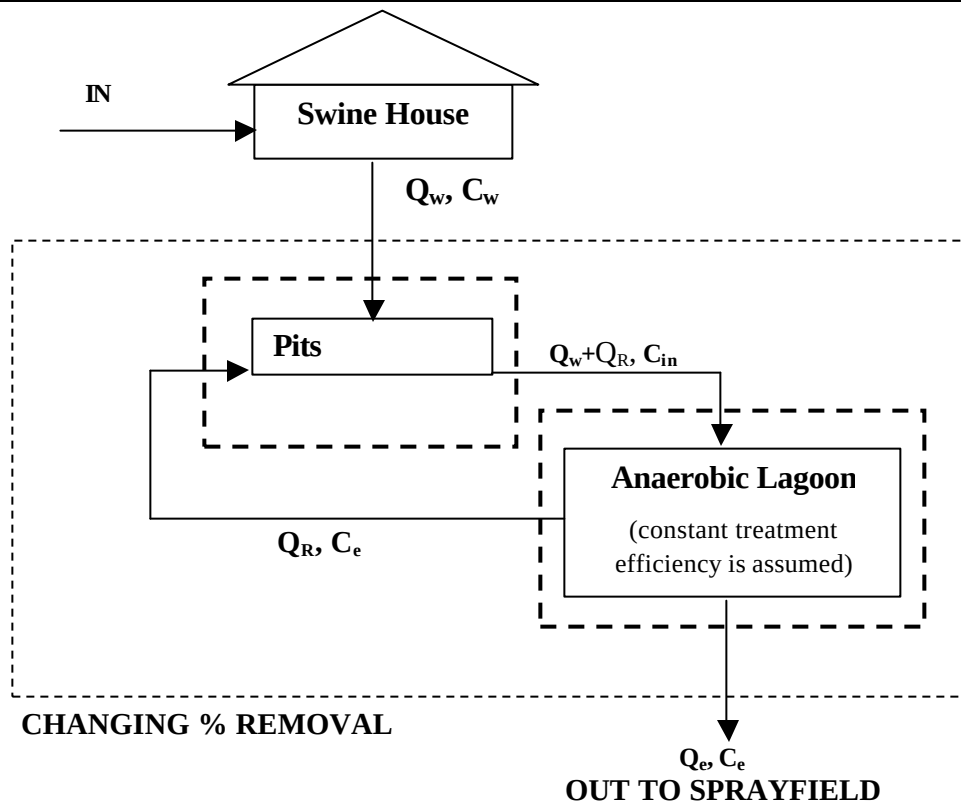


Figure 2.4 Third modeling approach for the anaerobic lagoon system.

This third approach assumes that there is constant treatment efficiency in the anaerobic lagoon *unit*. Similar to the first modeling approach, the flushing schedule does not affect the sizing of the system. Lagoon design is based solely on the animal weight present in the farm. The constant removal rates in the lagoon are 59% and 34% for nitrogen and phosphorus, respectively. These numbers are derived from an 80% and a 65% removal rate on the net influx of nitrogen and phosphorus to the anaerobic lagoon system, respectively (Barker et al., 1994). A change in the flushing schedule at the farm causes the treatment efficiency of the *system* to change. Mass balances around the swine house pits and the anaerobic lagoon unit indicate that the flushing frequency is inversely proportional to the nutrient removal efficiency of the system.

The available monitoring data on the anaerobic lagoon treatment efficiency (Barker et al., 1994) do not include the interaction between the swine houses, the lagoon unit, and the effluent. Therefore, the first modeling approach is used to describe the anaerobic lagoon system in CAWSST. Future data on the process may support a more detailed model in CAWSST.

Anaerobic lagoons are simple treatment systems to design, construct, and operate, in addition to being very inexpensive. Their treatment efficiency with respect to nitrogen and phosphorus is the lowest of all systems, with the exception of the upflow aerated biofiltration system. Anaerobic lagoons provide the basis for comparison among other treatment systems in CAWSST.

2.3.2 Constructed Wetlands

The constructed wetland technology in the tool consists of the following components / unit processes: 1. A single stage anaerobic lagoon is used for pre-treatment. The anaerobic lagoon removes not only many of the solids in the waste but it also removes a 80% of the nitrogen and 65% of the phosphorus in the liquid. The water that is recycled and used in the cleaning of the swine-houses is taken from the anaerobic lagoon. 2. The constructed wetland follows, which is used as the ‘reactor’ for BOD/COD and nutrient (nitrogen) removal. 3. A storage pond is used for storing the treated effluent that comes from the wetland. The water sent for land application is taken from the storage pond. The illustrative example of this section is based on this described configuration and it is shown in Figure 2.5.

The inputs are production-specific and they include the farm’s swine capacity and details on the manure collection system. The tool calculates, among other parameters, the area required for the system, the nitrogen and phosphorus removal, and cost. The constructed wetland model in the tool calculates flow rates

and loading to the wetland using the numbers given in Table 2.3 (Barker et al., 1994; Payne Engineering and CH2M Hill, 1997, Hunt et al., 1995).

Table 2.3. Input parameters needed to calculate flow and loading rates to constructed wetlands (for a finishing operation in CAWSST).

Average weight of a finishing hog ^a	68.18 Kg
Manure volume / hog / day ^a	0.00965 ^{m³} / hog / day
TKN concentration in manure ^a	2900 ^{mg} / L
TKN reduction (of net input) in anaerobic lagoon ^b	80%
Wetland loading rate ^c	25 ^{kg of N} / ha / day
TKN reduction in constructed wetland ^c	87%

^a Barker, et al., 1994.

^b Humenik et al., 1981. This constant is derived from an 80% removal rate on the net influx of TKN in the AL system (in use as of 2001)

^c Hunt et al., 1995.

2.3.2.1 Illustrative example: The Constructed Wetlands model

A description of the model for the constructed wetland treatment system is given in this section. For the illustrative example, a finishing-hog farm of 1000 swine, which employs the flush system for cleaning of the animal houses, was assumed. Two 3.03 m³ flush tanks and a flushing frequency of four times per day were assumed to be in operation. In the following equations, the *italicized* numbers are the constants used (Table 2.3) whereas the use of **bold type** indicates that the calculation of the indicated variables took place in a separate model of the CAWSST software. Figure 2.5 is a flow diagram of the mass balance for the nitrogen in the treatment system, tracking the water flows and the concentration levels for TKN in the unit processes of the system. The example calculations for the flow diagram are given below:

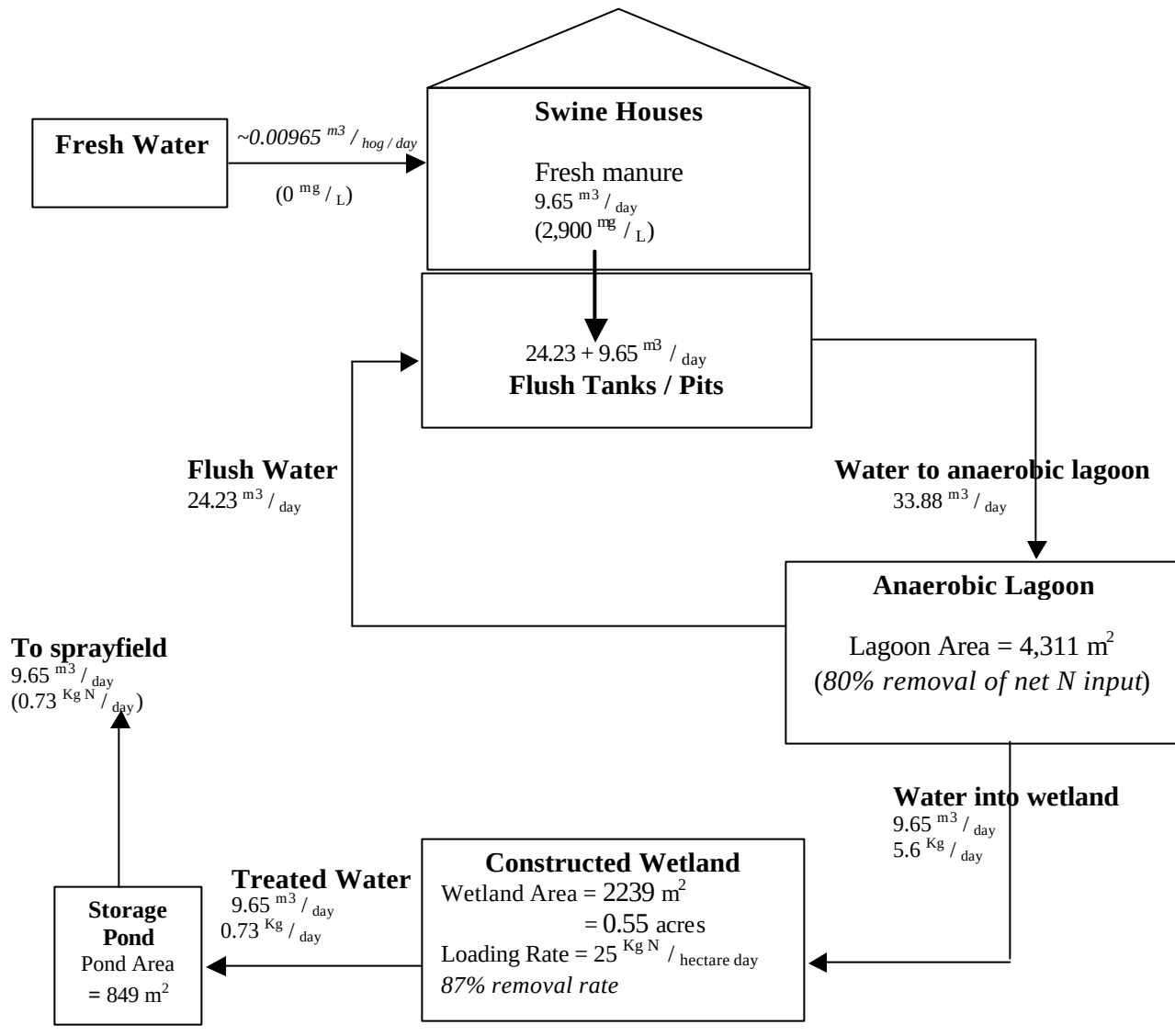


Figure 2.5 Flow diagram of the nitrogen mass balance for a 1000 finishing hog farm.

- Manure volume produced per day = $(0.00965 \text{ m}^3 / \text{hog} / \text{day}) * (1000 \text{ hogs})$
 $= 9.653 \text{ m}^3 / \text{day}$
- Total flush water volume per day = $(2 \text{ flush tanks}) * (3.028 \text{ m}^3 / \text{flush tank}) * (4 \text{ flushes} / \text{day})$
 $= 24.227 \text{ m}^3 / \text{day}$

- Mass of N entering Constructed Wetland (i.e. leaving the anaerobic lagoon)= [(Manure volume produced per day * manure N concentration) * (1 – N removal rate in AL)]

$$= [9.653 \text{ m}^3 / \text{day} * 2900 \text{ g} / \text{m}^3 * (1 - 80\%)]$$

$$= 5.6 \text{ Kg} / \text{day}$$
- Area of the Constructed Wetland = mass of N entering the wetland / nitrogen loading rate by the wetland

$$= (5.6 \text{ Kg} / \text{day}) / (25 \text{ Kg} / \text{hectare day})$$

$$= 0.22 \text{ hectares} = 2239 \text{ m}^2 = 0.55 \text{ acres}$$
- Flow Rate into Wetland = manure volume per day

$$= 9.653 \text{ m}^3 / \text{day}$$
- Total land area required for wetland system = wetland area + anaerobic lagoon area + storage pond area

$$= 2239 \text{ m}^2 + \mathbf{4,311 \text{ m}^2} + \mathbf{849 \text{ m}^2}$$

$$= 7,3995 \text{ m}^2 = 1.83 \text{ acres} = 0.74 \text{ hectares}$$
- TKN remaining in the water after exiting the wetland

$$= (1 - \text{wetland N removal efficiency}) * \text{mass of TKN entering wetland}$$

$$= (1 - 87\%) * 5.6 \text{ Kg} / \text{day}$$

$$= 0.73 \text{ Kg} / \text{day}$$

The cost of the system is based on values obtained from existing pilot plants and the literature. The capital cost includes the excavation, labor, pumps, piping, electrical wiring, and vegetation costs. In this example, the cost of lining the wetland is not included. The operation and maintenance cost is a summation of the labor, electricity, and land rental costs. The annualized and amortized cost is calculated by assuming a 20-year amortization period with an 8% interest rate. The capital and the operation and maintenance costs for a storage pond are included in the system costs. Example cost calculations used to model the constructed wetland system follow:

- Constructed wetland initial cost = [(wetland area * excavation depth) * excavation cost per volume] + cost for labor, wiring and pumps + (vegetation cost per area * wetland area)

$$= [(2239 \text{ m}^2 * 1.22\text{m}) * \$ 2 / \text{m}^3] + (\$500+\$500+\$550) + (\$534 / \text{ha} * 0.22 \text{ ha})$$

$$= \$7,131$$

- Constructed wetland Operation and Maintenance Cost = (maintenance cost per hour * # of hours)+ (electricity cost per kWh * kWh)+ (rent per area * wetland system area)

$$= (\$7 / \text{hour} * 91.25 \text{ hours}) + (\$0.11 / \text{kWh} * 1632 \text{ kWh}) + (\$124 / \text{ha} * 0.74 \text{ ha})$$

$$= \$910 / \text{year}$$
- Constructed wetland annualized and amortized cost = [initial cost * (8% interest rate for 20 year amortization)] + operation and maintenance cost

$$= [\$7,131 * (0.08 * (1 / (1-1.08^{-20}))) + \$910 / \text{year}]$$

$$= \$1,636 / \text{year}$$
- Annual cost for the Constructed Wetland System = annualized cost for (wetland + storage pond + anaerobic lagoon)

$$= \$1,636 / \text{year} + \$ 596 / \text{year} + \$ 214 / \text{year}$$

$$= \$2,446 / \text{year}$$
- Initial cost for the Constructed Wetland System = initial costs for wetland + storage pond

$$= \$7,131 + \$5,231$$

$$= \$12,362$$
- Operation and maintenance cost for the Constructed Wetland System = sum of O & M costs for wetland, anaerobic lagoon, and storage pond

$$= \$910 / \text{year} + \$214 / \text{year} + \$63 / \text{year}$$

$$= \$1,187 / \text{year}$$

The results of the model indicate high nitrogen removal efficiency by constructed wetlands. This is due to the combined removal efficiencies of the anaerobic lagoon and the wetland.

In an alternative description of constructed wetlands in CAWSST an inclined screen solids separator is used as a first stage treatment instead of the anaerobic lagoon (Figure 2.6). In addition, since the anaerobic lagoon is not present, the recycled water used for swine-house flushing is taken from the storage pond. This alteration will cause a change to the economics and the treatment efficiency of the system. The size of the wetland will also be affected, since constructed wetlands are sized based on a maximum daily nitrogen load.

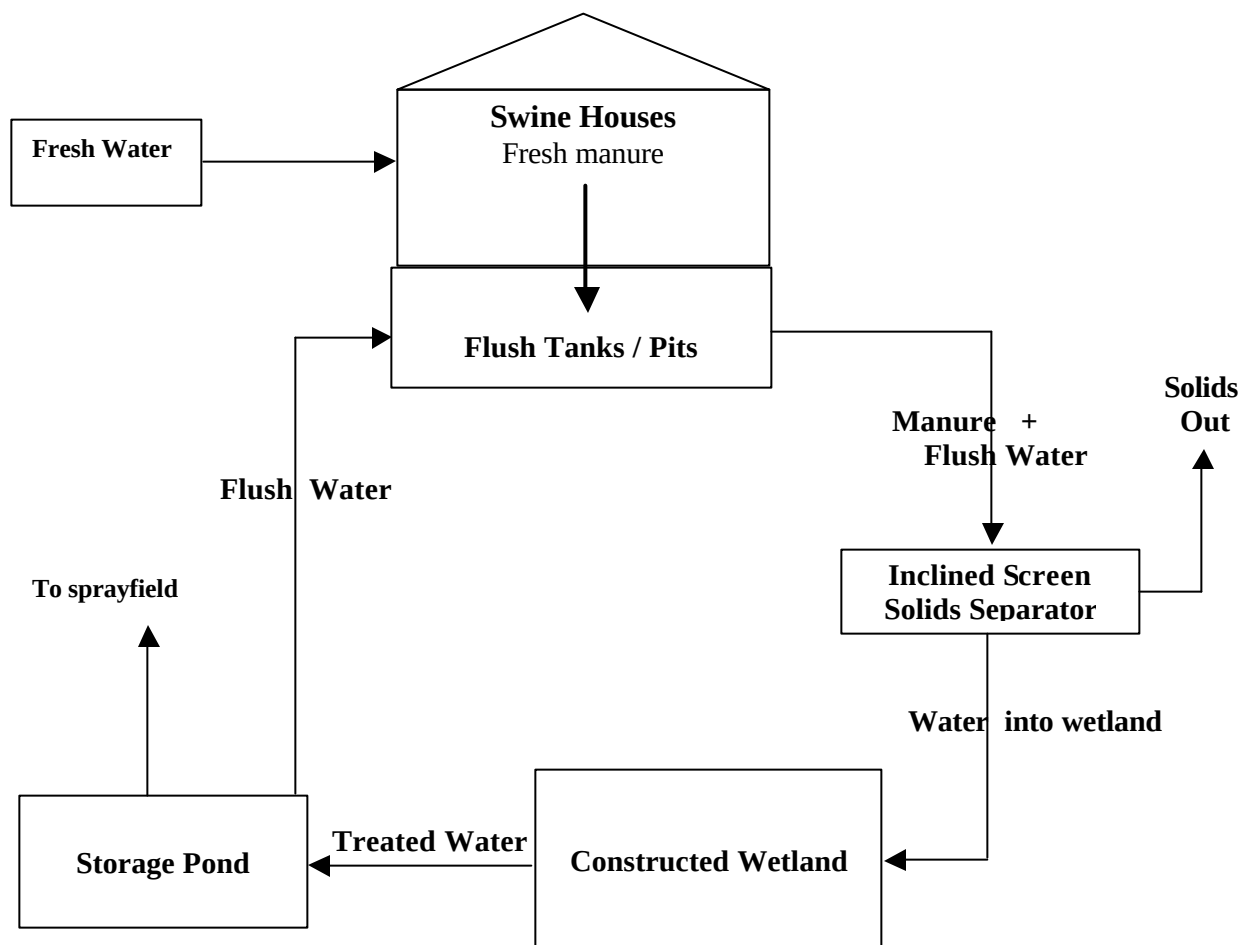


Figure 2.6 Flow Schematic of the Constructed Wetland system that includes a Solids Separator

Also, the amount of solids separated by the inclined screen is modeled in this variation of the constructed wetlands treatment technology. A 50% removal rate, by mass, is assumed for the inclined screen solids separator.

Constructed Wetlands are a medium price-range treatment system. They perform very well with respect to nitrogen removal and, when used in combination with the anaerobic lagoon, they also perform well with respect to phosphorus removal. However, phosphorus removal in constructed wetlands cannot be sustained for a long time. Initially there is a large removal of phosphorus that is bound in the soil or taken-up by plants, however, this removal rate tapers-off when the wetland matures. The main disadvantage of constructed wetlands is the large land area that is needed for their installation.

2.3.3 Sequencing Batch Reactors (SBR)

The sequencing batch reactor (SBR) technology in CAWSST consists of an equalization tank, a reactor tank, a sludge thickener, and a storage pond (Figure 2.7). The equalization tank receives the waste and equalizes flow to the reactor tank. Removal of nutrients and solids takes place in the reactor tank. A storage pond receives the treated water from the reactor. Water for land application and for recycling to the swine houses is also obtained from the storage pond. The description of the system was obtained from a pilot scale study (Bicudo, et al., 1999). This system does not include a solids separation system or an anaerobic lagoon for pre-treatment.

A 96.7% removal of nitrogen and a 77% removal of phosphorus, by mass, are assumed for the system (Bicudo et al., 1999). Both of these removal rates are based on the operating condition of a 24-hour cycle and a 10-day hydraulic retention time.

2.3.3.1 SBR with anaerobic lagoon pre-treatment

In a variation of the SBR technology, an anaerobic lagoon, which may already exist at a farm, is used for pre-treatment of the flushed manure (Figure 2.8). This variation will reduce the operation and management cost for the system and the nutrient removal efficiencies are improved. If flushed waste is pre-treated in a lagoon, much of the solids are removed thus reducing the aeration requirements in the SBR reactor tank.

The sequencing batch reactor technology, without a lagoon pre-treatment, is the most expensive of the CAWSST technologies. Most of the expense for this technology comes from the electricity usage for aeration and pumping of the waste.

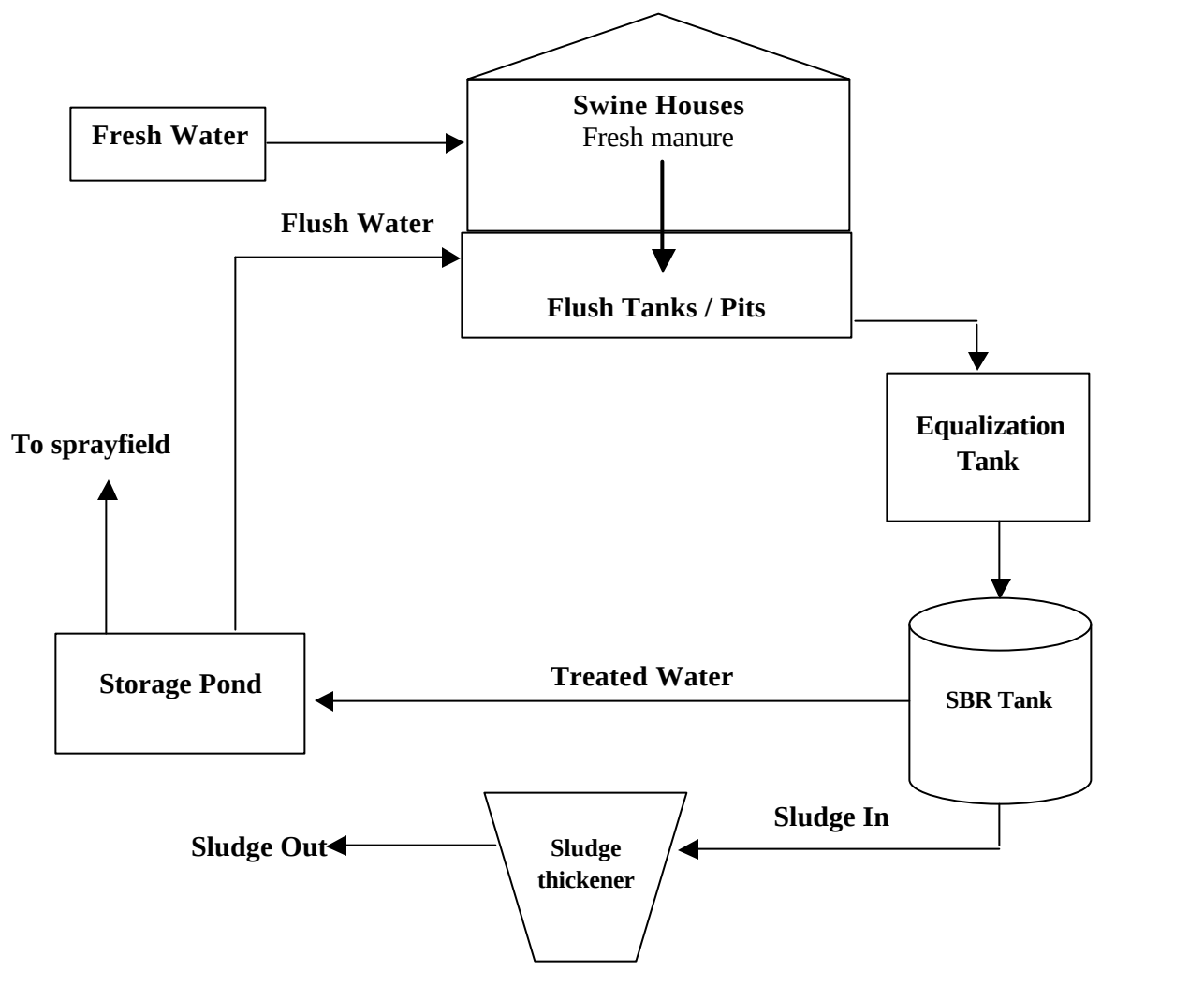


Figure 2.7 Schematic of the Sequencing Batch Reactor system, as described in CAWSST.

The nutrient removal efficiency of the SBR system, when anaerobic lagoon pre-treatment is used, is much improved, over a system that uses a solids separator pretreatment. This is especially true for phosphorus removal. The SBR reactor alone has 77% phosphorus removal efficiency, but when this is combined with the 65% removal of the preceding anaerobic lagoon, the efficiency of the system becomes 93.3% by mass. The analogous numbers for nitrogen removal for this system is 80% for the anaerobic lagoon and 96.4% for the SBR reactor. The combined nitrogen removal efficiency for the system is close to 99%. These removal efficiencies are the highest of all the treatment technologies that are included in CAWSST.

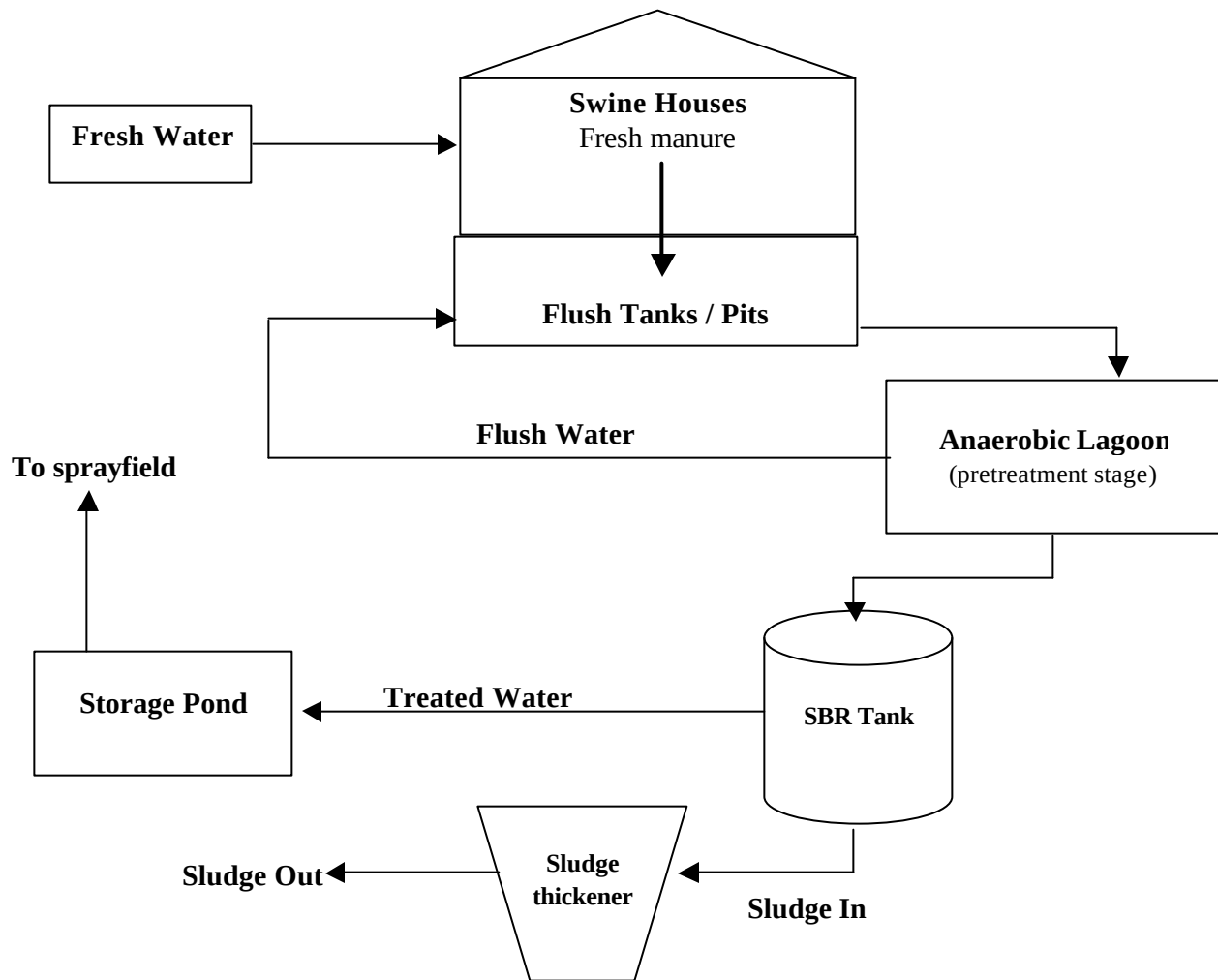


Figure 2.8 Schematic of the Sequencing Batch Reactor with anaerobic lagoon pre-treatment.

2.3.4 Ambient anaerobic digesters

The ambient anaerobic digester technology, as it is described in CAWSST, consists of the digester reactor and a storage pond. The recycle water that is needed for cleaning of the swine-houses is obtained from the storage pond. There are two variations in the description of the anaerobic digester system in CAWSST. For the first variation, it is assumed that the farm already possesses an anaerobic lagoon on site while for the second variation it is assumed that a lagoon is not already present. Despite the two variations of the ambient anaerobic digester system, both treatment processes are identical. Figure 2.9 is a schematic of the ambient anaerobic digester system, indicating that the storage pond could be either a converted anaerobic lagoon or a new structure.

Nitrogen removal in the digester is assumed very low, due to the anaerobic conditions that prevent nitrification from taking place. The digester is primarily used for the digestion of organics (BOD/COD) in the waste. The nitrogen removal efficiency of this system comes from the nitrification / de-nitrification processes that take place in the storage pond and in the swine house pits. A 38% nitrogen removal is attributed to the digester in CAWSST. This removal mostly comes from ammonia volatilization and from the nitrous oxide gas that leaves the system. The phosphorus removal in the digester tank is much higher than the nitrogen removal. The assumption is that most of the 72% phosphorus removal, by mass, comes from processes that bind it in the biosolids.

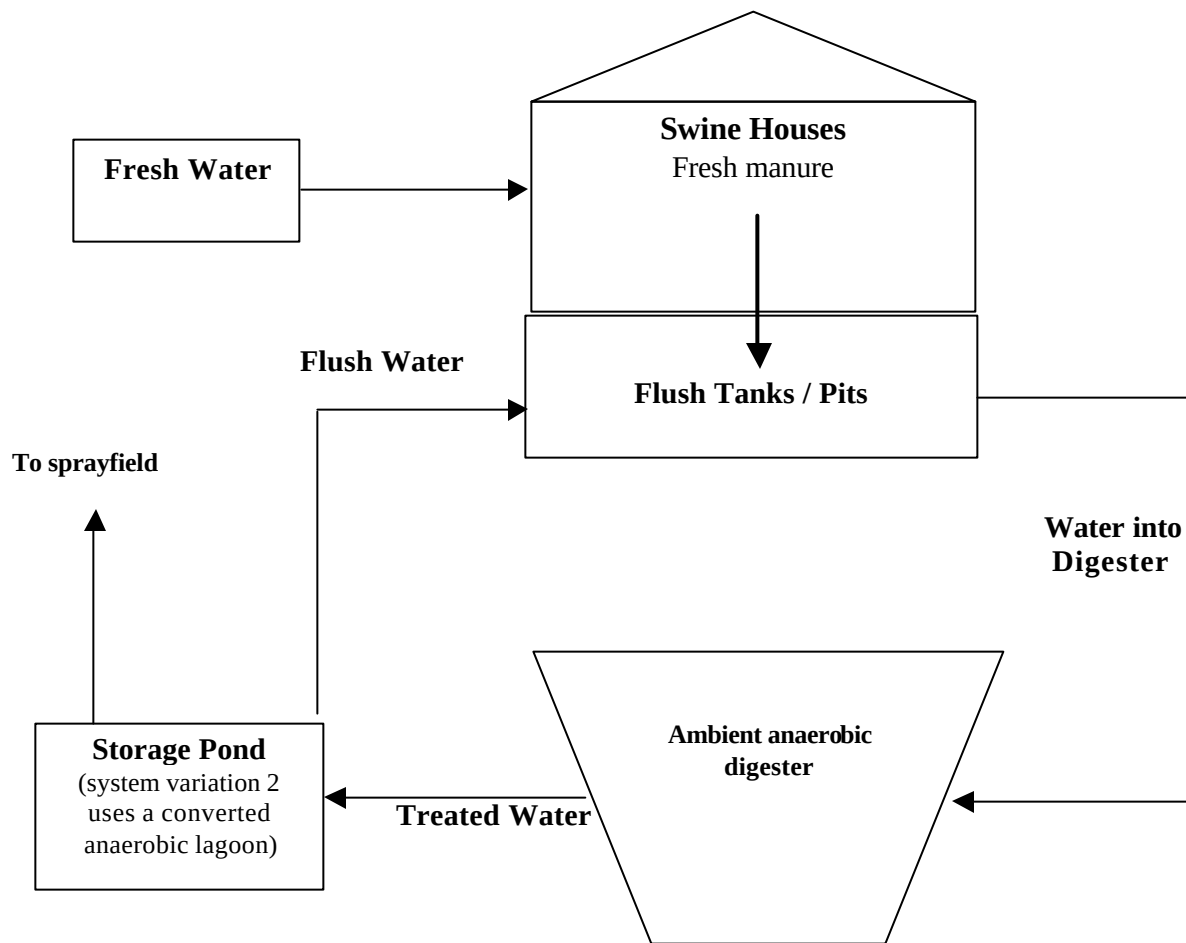


Figure 2.9 Schematic of the ambient anaerobic digester system, as described in CAWSST.

While nutrient removal efficiencies and other treatment specific outputs are identical for the ambient anaerobic digester system variations in CAWSST, the cost calculations differ from one another. In the case when the anaerobic lagoon is already present in the farm, a conversion cost of the anaerobic lagoon to a storage pond is accrued. The lagoon conversion cost, the excavation cost for the digester, the liner cost, and the cover cost sum-up to the capital cost for the system. When a lagoon is assumed not to be already on-site, the cost of constructing a new storage pond replaces the lagoon conversion cost in the calculations.

The ambient anaerobic digester permits little ammonia volatilization and low odor dissipation. In addition, methane (biogas) produced in the system can be collected and used to produce electricity. Qualitative measures of ammonia volatilization and odor release from the system are included in CAWSST; however, the benefit from biogas utilization is not included in the cost calculations. Also, the cost of biosolids-handling is not included.

2.3.5 Upflow Aerated Biofilters

Aerated upflow biofilters are new in the field of animal waste treatment. This technology uses the principle of fixed media biofiltration in waste treatment. Figure 2.10 shows that the system consists of a pre-treatment stage, an equalization tank, two fixed media biofilter towers, a backwash water tank, and a storage pond. Pre-treatment of the waste can be achieved by either an inclined screen solids separator or an anaerobic lagoon (Figure 2.11). Both configurations are considered in CAWSST.

2.3.5.1 Upflow Aerated Biofilter with inclined-screen solids-separator pre-treatment

In the system that uses the inclined screen for solids separation, the waste enters the equalization tank after pre-treatment. Equalization of the influent waste is necessary for controlling the flowrate into the biofiltration towers. After equalization, wastewater is fed to the bottom of a tower packed with plastic media. The microorganisms growing on the media treat the water and thus remove BOD/COD and nutrients. To aid in the growth of the attached microorganisms, the tower is aerated with air diffusers. In the first tower BOD removal is assumed to take place. Then, the water enters the bottom of a second tower where nitrification is to be taking place. Since sludge accumulates over time on the plastic media, regular backwashing of the towers is needed to clean the passage for incoming water. A backwash water tank is necessary to collect the waste dislodged from the filters. After the treated water leaves the biofilters, it enters a storage pond, or a polishing lagoon. The treated effluent is discharged from the storage pond. Recycle water needed for flushing the animal house is also obtained from the storage pond, as is the water needed for backwashing the biofilters.

2.3.5.2 Upflow Aerated Biofilter with anaerobic lagoon pre-treatment

If an upflow aerated biofiltration system is to be implemented at a farm that already utilizes an anaerobic lagoon, both the treatment efficiencies and the cost parameters in the model are affected. An already present anaerobic lagoon replaces a solids separator in pre-treatment of waste (Figure 2.11). The anaerobic lagoon simultaneously functions as an equalization tank. The recycle water that is used for flushing the animal houses is obtained from the anaerobic lagoon, instead of the storage pond.

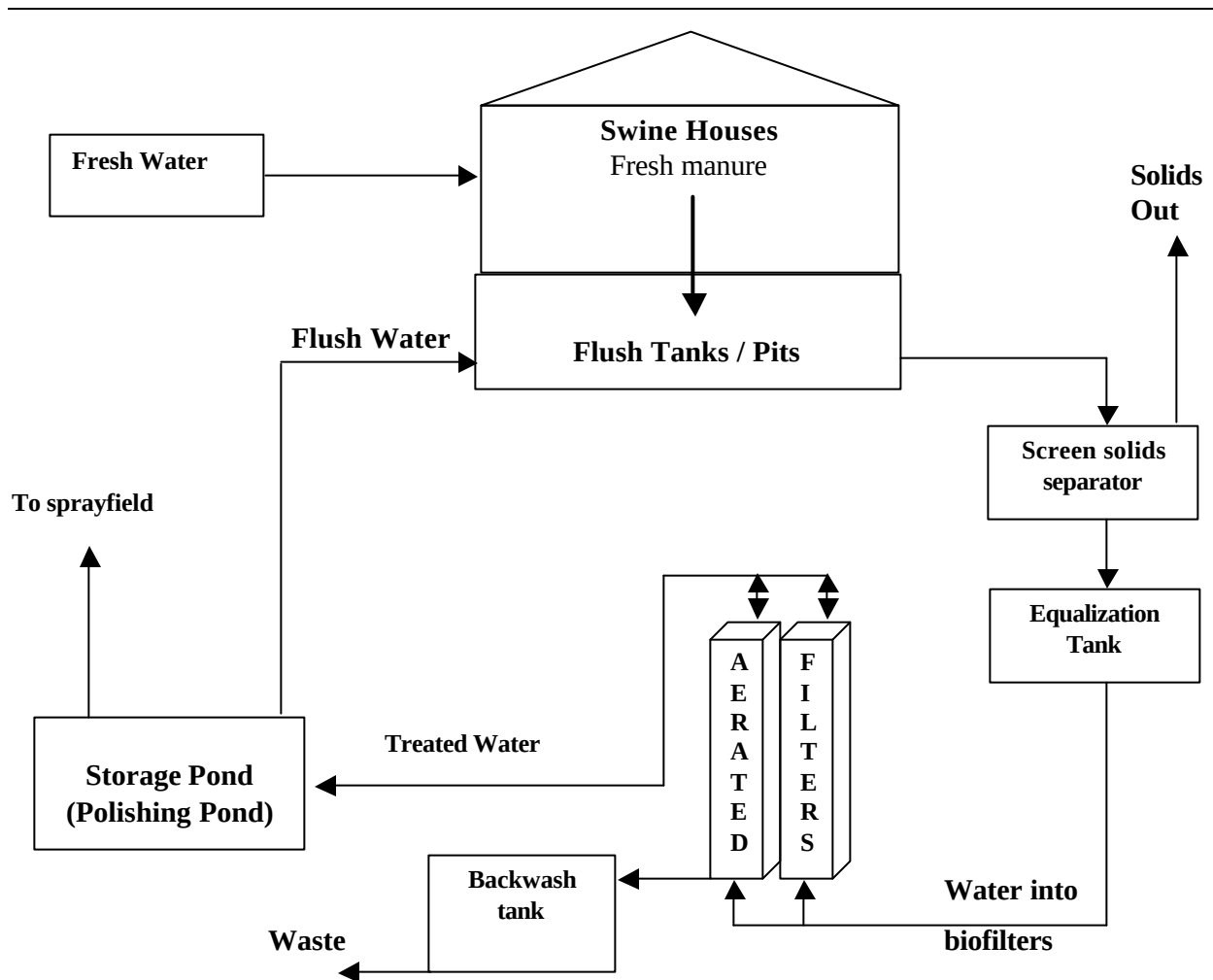


Figure 2.10 Schematic of the Aerated upflow biofilter system, as described in CAWSST.

The presence and use of an anaerobic lagoon greatly affects both the treatment efficiency and the cost of an upflow aerated biofilter system. The combined nutrient removal efficiency of the anaerobic lagoon and the

biofiltration units give the system a combined efficiency of 94% for nitrogen and 75% for phosphorus removal. A biofilter technology with an inclined screen solids separator is only 76% and 48% efficient for nitrogen and phosphorus removal, respectively. The inclined screen solids separator alone is responsible for removing 15% nitrogen and 20% phosphorus. When these treatment efficiencies are examined alongside the cost for each system variation, we see that a system that uses anaerobic lagoon pre-treatment is also 20% cheaper than the alternative (i.e. the variation of the technology).

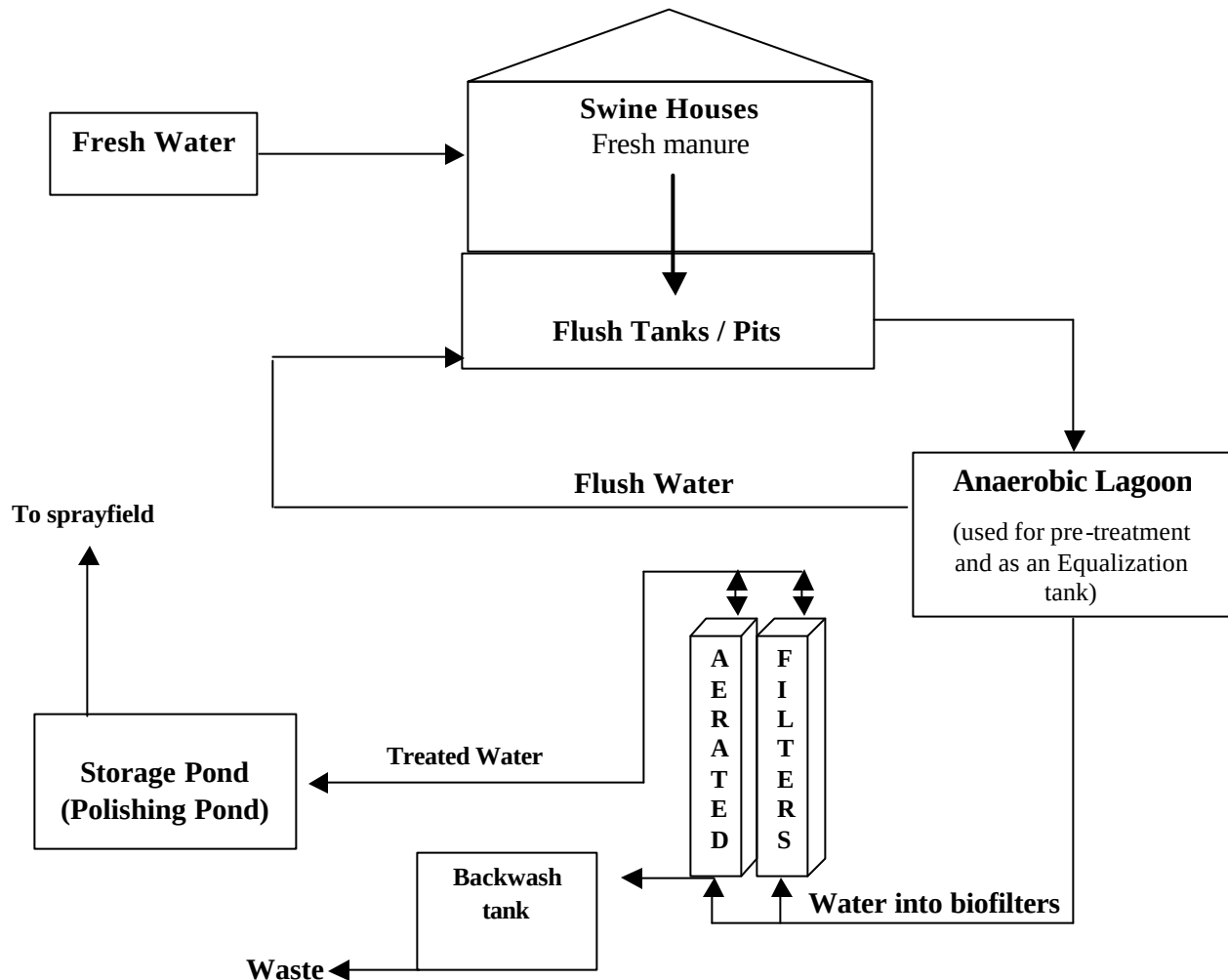


Figure 2.11 Schematic of the Upflow Aerated Biofilter system with pre-existing anaerobic lagoon..

The cost of the upflow-aerated-biofilters was not modeled in as much detail as were other technologies in CAWSST. The available data that describe this technology are limited to estimates from pilot scale studies and theoretical design. The biofilter system is the second most expensive system in CAWSST, closely

following the sequencing batch reactor system, whereas its nutrient removal efficiency is the lowest of all treatment systems. Its operation and maintenance costs are high, mainly due to the high electricity requirements for aeration and pumping of water. The obvious advantage of the biofilter system, over other technologies described in CAWSST, is the small land area that it occupies plus its good odor control.

2.4. Sample Results

A prototype of the CAWSST software has been developed. Figure 2.12 shows the inputs screen of the tool. The user is required to choose the type of waste from a pull-down menu, as well as specify the size of the farming operation. The type of cleaning system employed in a farm is also a required input. If a flush system is chosen, the screen option that accommodates that information is activated. Analogous action is needed if the pit-recharge system is chosen.

Computer Assisted Waste System Selection Tool (CAWSST)

Required Inputs

INPUT ITEM	INPUT VALUE	INPUT VALUE	UNITS
Please choose the farming operation:	Hog Farm Waste		
Number of Hogs Present in the Operation	5000		hogs
Is a Flush System available on the farm (yes / no)?	yes		
If YES, please provide the following information:			
Number of available Flush Tanks	12		tanks
Volume of each Flush Tank	800		gallons
Number of Flushes per day	4		flushes / day
If you have a Recharge Pit System available, please provide the following information:			
Number of available Recharge Pits	5		pits
Volume of each Recharge Pit	40000		gallons
Recharge Frequency (per week)	1		recharges / week

Figure 2.12 Example of the user inputs screen for CAWSST.

The results obtained from CAWSST are presented in tables of cost and treatment efficiency for the different technologies modeled (Table 2.2). Figure 2.13 shows a sample outputs screen for data obtained for a 5000-swine farm. A flush system with twelve 800-gallon tanks being operated at a frequency of 4 times per day was assumed for the example presented.

2.4.1 Comparison of treatment technologies in CAWSST

The treatment technologies described in CAWSST exhibit linear relationships in their treatment efficiency of nitrogen and phosphorus versus farm size. However, economies of scale are evident for the different farm sizes (Figure 2.14).

The sequencing batch reactor technology has the highest initial cost for smaller size farms (<5000 swine) whereas the upflow aerated biofilters (without an anaerobic lagoon preceding) have the highest initial cost for larger size farms. The cheapest systems, other than the anaerobic lagoons, are the ambient anaerobic digesters and the constructed wetlands (for farms already having an anaerobic lagoon present). The sequencing batch reactors and the constructed wetlands that use an inclined screen solids separator are the two systems for which economies of scale are most pronounced.

Similar to examining the overall costs for the alternative treatment technologies, one may choose to use CAWSST to compare the capital costs for different size farms. A constructed wetland (with anaerobic lagoon pre-treatment) is the cheapest system to build. For large size farms (>30,000 swine), the second cheapest technology to construct is the ambient anaerobic digester (given that an anaerobic lagoon is already present in the farm).

Operation and maintenance costs do not exhibit economies of scale. Operation cost rankings remain the same for all technologies and farm sizes. The anaerobic lagoon is the cheapest to operate and maintain, whereas the high aeration and pumping costs make the sequencing batch reactor and the upflow aerated biofilters the most expensive.

Anaerobic Lagoon is present

Technology	Total Annual	Initial	O&M Cost	Per Pig	Total System	TKN removal	TP removal	Effluent	Ammonia
	Cost	Investment		Place Cost	Area	Efficiency	Efficiency	Volume	Volatilization
	(\$ / year)	(\$)	(\$ / year)	(\$ / year)	(acres)	(%)	(%)	(Mgal / year)	(relative)
Anaerobic Lagoon	\$607	\$0	\$607	\$0.20	2.68	80.0%	65.1%	3.308	medium
Covered In-ground Digester	\$5,172	\$40,390	\$1,059	\$1.72	3.64	85.3%	88.4%	3.308	low
Constructed Wetland	\$5,708	\$37,900	\$1,848	\$1.90	4.79	97.8%	75.7%	3.715	medium
Sequencing Batch Reactor	\$31,857	\$122,982	\$19,331	\$10.62	2.70	99.1%	93.2%	2.920	medium
Upflow Aerated Biofilter	\$34,189	\$98,375	\$21,135	\$11.40	3.26	94.4%	75.5%	3.420	medium

Anaerobic Lagoon NOT present

Technology	Total Annual	Initial	O&M Cost	Per Pig	Total System	TKN removal	TP removal	Effluent	Ammonia
	Cost	Investment		Place Cost	Area	Efficiency	Efficiency	Volume	Volatilization
	(\$ / year)	(\$)	(\$ / year)	(\$ / year)	(acres)	(%)	(%)	(Mgal / year)	(relative)
Anaerobic Lagoon	\$5,423	\$47,291	\$607	\$1.81	2.68	80.0%	65.1%	3.308	medium
Covered In-ground Digester	\$9,989	\$87,681	\$1,059	\$3.33	3.64	85.3%	88.4%	3.308	low
Constructed Wetland	\$20,872	\$144,807	\$5,821	\$6.96	8.31	95.6%	32.0%	4.391	medium
Sequencing Batch Reactor	\$39,760	\$122,982	\$27,234	\$13.25	0.68	96.4%	77.0%	3.324	low
Upflow Aerated Biofilter	\$37,354	\$118,643	\$21,611	\$12.45	0.62	76.2%	40.8%	2.905	low

Figure 2.13 Example of the CAWSST outputs screen.

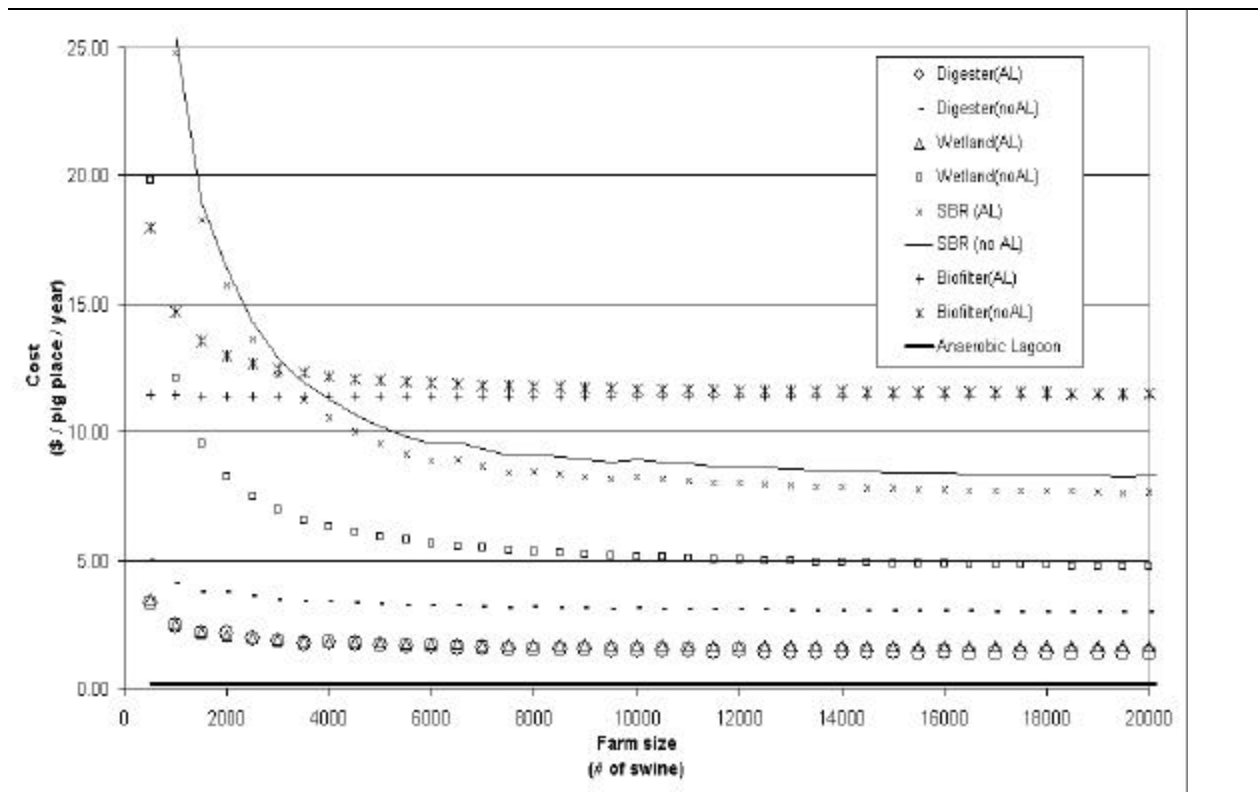


Figure 2.14 Cost of alternative treatment technologies for different size farms.

Despite their high cost, sequencing batch reactors and upflow aerated biofilters are suited for farms where land is limited. These two systems require the least land for implementation. On the other extreme, constructed wetlands require an order of magnitude more land than the most compact technologies.

Unlike cost, the nutrient removal efficiencies of the different technologies remain at constant percentages for all systems, regardless of farm size or flushing schedule of swine houses. The only exceptions are found for constructed wetlands and anaerobic lagoons. The main reason for this model behavior is the fact that treatment technologies were evaluated with respect to their net removal rates. Nutrient removals of individual unit processes constituting each technology were not considered. The sequencing batch reactors have the highest nitrogen removal efficiencies, when used in combination to anaerobic lagoons (used for pre-treatment). Constructed wetlands also perform very well with respect to nitrogen removal, irrespective of the presence of anaerobic lagoon pre-treatment stage. The technology that is best in removing phosphorus are the ambient anaerobic digesters.

2.5. Summary and Conclusions

The design, the development and the utility of a computer-based software have been presented. Data on the animal waste treatment technologies are found in different papers and technical reports. The lack of consistency in the presentation of these data makes them inaccessible to the majority of farmers and decision makers. CAWSST consolidates these data and presents them in a consistent and easy-to-read manner. Furthermore, CAWSST can be invaluable in analyzing and comparing alternative swine waste treatment technologies. An example of this capability was shown (Figure 2.14). The results provided can be used for either making decisions at the farm level or, if combined with other models, for regional environmental management.

CAWSST's structure is flexible to allow the addition of new treatment technology models as new data become available. Since the computer software is organized in a spreadsheet, individual technology descriptions are kept in separate worksheets. New technologies can be easily added. New worksheets can be coupled to the existing structure of the tool with a minimal computer programming effort. CAWSST outputs can be easily presented graphically, and they can easily become inputs for a number of other computer applications and programs, that may range from linear solvers to GIS utilities.

With the completion of more field evaluations of alternative animal waste treatment technologies, CAWSST can be improved and expanded. Future work can develop CAWSST into a tool that can be distributed to farmers, environmental managers, policy-makers, or researchers, through the world-wide-web as an interactive and constantly updateable tool.

CHAPTER 3: Design of Animal Waste Management Strategies to Achieve Regional Environmental Objectives

Abstract

Anaerobic lagoons are commonly used for swine waste management in North Carolina. Their replacement is expected to be expensive. Recent initiatives calling for such actions have increased the need for characterization of the cost and treatment effectiveness of each alternative, which potentially depends on the location and size of the farm. Thus, identification of the most effective solution to achieve collective target reductions in discharge levels needs an integrated approach that examines and searches among these technology alternatives at all farms simultaneously. This chapter presents the development of a procedure to identify collective or regional management strategies that will aid policy makers, planners, and farmers in making cost effective lagoon replacement decisions to achieve desired treatment and public protection goals. A major component of this activity was the implementation of a cost and treatment efficiency assessment tool (CAWSST) to evaluate alternative animal waste treatment technologies (as described in Chapter 2). Building upon the outputs of CAWSST and existing databases, formal optimization techniques to search for good solutions with respect to different goals have been developed. An illustrative example that is used to describe the application of this approach is built upon data for the farms within the Lower Neuse River Watershed. Using farm sizes as inputs to CAWSST, the CAWSST outputs together with GIS data such as farm locations are used in a mixed-integer programming model that helps examine different management scenarios for the region. These management scenarios examine the cost, nutrient release and risk from farms in the watershed when no new open-lagoon-based treatment technologies are allowed, and when the replacement of all lagoon-based treatment options is desired. Technology replacement strategies are identified by optimizing for cost while meeting constraints such as pollutant discharge targets, farm proximity to floodplains, risk levels, or the effect of odor on the area. Example technology allocation strategies under each of the management scenarios include the least cost solution, uniform treatment for the whole watershed area, and uniform treatment within certain zones defined by such factors as political boundaries, farm size, type of farming operation or proximity to floodplains. Results corresponding to a target of 30% reduction in nitrogen for the watershed show large difference in cost and risk for the different management scenarios, as well as indicate considerable flexibility in choosing a technology replacement strategy to meet given cost and regional environmental goals.

3.1 Introduction

According to the 1998 National Water Quality Inventory, approximately 60% of pollution in rivers and streams, and 45% in lakes, comes from agricultural sources. In response to public concern about contamination of rivers, lakes, streams, coastal waters, and groundwater from livestock manure and other animal wastes from livestock operations, US EPA and the USDA developed the Unified National Strategy for Animal Feeding Operations in March 1999, as part of the Clean Water Action Plan. The strategy includes a national goal that requires all animal feeding operations to develop and implement technically sound, economically feasible, and site-specific comprehensive nutrient management plans to minimize impact on water quality and public health (EPA 833-F-00-016, December 2000). To fully achieve these goals one needs to develop and examine collective management strategies that should consider cost efficiency, environmental compliance and practical implementation.

The primary goal of this paper is to describe the development of a modeling approach to address this animal waste management problem at a regional level, and to demonstrate its application through an illustrative case study for a set of swine farms in a North Carolina watershed.

3.1.1 Negative effects of animal waste

Waste from animal farms may pose serious environmental, human health, and aesthetic problems if appropriate waste management techniques are not employed. Animal waste (especially swine waste) is currently managed predominantly through the combination of anaerobic lagoons and sprayfields. Runoff from livestock operations enters natural water bodies due to poor maintenance of waste lagoons, improper design of storage structures, improper storage of animal waste, and excessive rainfall that result in spills and leaks of manure-laden water. Over-application of manure in sprayfields is another source of animal waste runoff. When livestock manure and other animal waste spills or leaks into surface and groundwater, it can create an immediate threat to public health and water resources. This runoff has nutrients such as nitrogen and phosphorus that in excess can cause algae and other microorganisms to reproduce in waterways, creating unsightly and possibly harmful algae blooms. Explosive algae populations can lower the level of dissolved oxygen, which can harm fish and other aquatic habitats. Spills from flooded and ruptured waste lagoons and other faulty storage facilities have killed tens of thousands of fish (Burkholder et al., 1997). Animal waste runoff can also be a threat to the health of people who are exposed to affected waters because of bacteria, protozoa, and viruses in animal waste.

Odor is another problem arising from waste lagoons and storage structures and it not only is an aesthetic issue for people living nearby but also can cause such health problems as chronic headaches.

3.1.2 Current work

Current efforts concerning application of wastewater treatment systems in animal waste management are focused on studying the available alternative technologies and how they can be applied at individual farms. For example, the performance of various treatment systems in terms of nutrient removal and their cost is examined in a number of technology evaluation studies (Williams, 2002). The purpose of these studies is to evaluate the different systems for the treatment of the animal (swine) waste in terms of organic matter (BOD and COD), solids and nutrient removal (N and P), evaluate the characteristics of the separated solids, perform an economic evaluation of the system in terms of both investment and maintenance and operating costs, and evaluate the systems' ability to reduce odors. These systems are studied in either pilot or full-scale plants built in swine farms in North Carolina.

3.1.2.1 Computer Assisted System Selection Tool (CAWSST)

Evaluation of treatment technologies is complicated by the fact that different farms have different waste characteristics, different sizes, and different operating constraints. Mathematical descriptions of treatment efficiencies and economic characteristics can be useful in generalizing available information to farms of different sizes and characteristics, allowing comparison of various technologies for any farm situation. CAWSST was developed to provide a procedure to examine, compare and contrast the various treatment technologies available for animal waste so that farmers can make better-informed decisions regarding the appropriate treatment to implement on their farms (Anastasiou, 2002).

CAWSST is not intended to be a wastewater treatment technology design tool but rather a means for comparing and contrasting different technologies as they apply to farms of different characteristics, such as size or animal house cleaning systems. Farmers who want to examine the alternative technologies to be implemented in their farms, agricultural extension agents, research scientists, or federal and state environmental agents are expected to benefit from the use of this tool.

The basic input parameters required by any user are production-specific and they include the number of swine and the type of cleaning system used in the animal houses. For more advanced users, the ability to alter other parameters that govern the processes in the tool is provided, ranging from those that govern the description of individual treatment technologies (such as treatment efficiencies and loading rates for

different technology components), to parameters describing the capital investment or operational cost of each of these technologies (such as the cost of electricity per kilowatt-hour).

Output parameters for CAWSST include the initial and annual operational costs for each technology, per-pig cost, land area required by each technology, volume of effluent water from each technology, as well as the efficiency of each technology with respect to nitrogen and phosphorus removal from the wastewater. The amount of solids produced by each technology is calculated, as well as the amount of nitrogen and phosphorus present in these solids. Qualitative measures of odor emission as well as ammonia volatilization are also returned.

CAWSST includes the following animal waste treatment technologies: anaerobic lagoon, constructed wetlands, sequencing batch reactor (SBR), ambient anaerobic digester, and upflow aerated biofilter. Constructed wetlands, the SBR and the aerated upflow biofilter can be evaluated with the existing anaerobic lagoon as a form of pretreatment. The alternative pre-treatment for wetlands and the biofilter is an inclined screen solid separator. The ambient anaerobic digester technology has the option of using an existing lagoon as a nitrification/de-nitrification pond. These options are offered since anaerobic lagoons are already present on all of the existing permitted swine farms of North Carolina. The approximate nitrogen and phosphorus removal efficiencies for these treatment systems, as well as their annualized/amortized yearly cost, as they apply to a 3000 finishing hog farm, are given in Table 3.1.

3.1.2.2 Regional waste management

While CAWSST provides the critical knowledgebase for identifying the cost-effective treatment system option for an individual farm, methods to identify a collective management strategy to meet regional environmental goals (e.g., minimizing ammonia and odor emissions, nitrogen and phosphorus in effluents, and risk of surface or groundwater contamination) are lacking. A management strategy requiring the use of the least-cost treatment system to meet a reduction target (e.g., 30% N emissions reduction) at each individual farm may not be the most cost effective and otherwise efficient strategy to meet the same reduction target collectively at a regional level.

Identification of such a strategy is affected by many factors, including economies of scale, farm location effects, or farm-specific technical feasibility. As these improvements can cause tremendous cost burdens for the public as well as the farmers, systematic consideration and examination of such collective management strategies is imperative.

Table 3.1 Summary of approximate performance and cost of treatment technologies as given by CAWSST for a 3000 finishing hog farm.

Technology	Nitrogen Removal	Phosphorus Removal	Cost (\$ / year)	Reference
Anaerobic Lagoon	80.0%	65.1%	\$607	Barker et al., 1994
Ambient Anaerobic Digester	85.3%	88.4%	\$5,172	Cheng et al., 1999
Constructed Wetland (with anaerobic lagoon pretreatment)	97.8%	75.7%	\$5,708	Hunt et al., 1995 Barker et al., 1994
Constructed Wetland (with solids separator pretreatment)	95.7%	32.0%	\$20,872	Hunt et al., 1995
Sequencing Batch Reactor (with anaerobic lagoon pretreatment)	99.1%	93.2%	\$31,857	Bicudo et al., 1999 Barker et al., 1994
Sequencing Batch Reactor (with no pretreatment)	96.4%	77.0%	\$39,760	Bicudo et al., 1999
Upflow Aerated Biofilter (with anaerobic lagoon pretreatment)	94.4%	75.5%	\$34,189	Westerman et al., 1999 Barker et al., 1994
Upflow Aerated Biofilter (with solids separator pretreatment)	76.2%	40.8%	\$37,354	Westerman et al., 1999

Regional treatment facilities have been used as a possible strategy in municipal waste management in the past (Nakamura and Brill, 1977; Fenz et al. 1998). The need for collective actions for animal waste management is reported by Tabachow et al. (2002). Their proposed solutions involve the use of regional treatment facilities that would serve a number of swine farms in North Carolina. However, these solutions are not practically feasible for a number of reasons. For example, the manure, combined with the necessary water needed to flush it out of the swine houses, amounts to a large volume of waste that needs to be transported daily to such a regional treatment facility. The transportation cost of such a large volume of manure would be excessive, whether this was achieved through a network of pipes or using trucks (Tabachow, 2002). Also, if waste treatment does not take place on the farm site, the treated effluent would not be available for use in the flushing/cleaning of the swine houses. Therefore, a continuous and costly supply of fresh water would be required for the proper operation of the farms. If a centralized facility or facilities exist, a single large land plot would be needed to accept the treated effluent. The availability of such a large area is unlikely. Furthermore, large amounts of nutrients

remaining in the effluent water would be concentrated in one single location upon land application. This could magnify nutrient related problems in an area.

3.1.3 Contributions and organization of the paper

In view of the national effort to develop alternative animal waste-management practices, and the consideration for implementation of new emission reduction targets, an approach to develop and examine collective management strategies is needed. These collective management strategies should consider not only cost and environmental compliance but also factors affecting practical implementation.

All of the currently used methods are inadequate in assisting to implement the desired change in animal waste management. A modeling approach to address the animal waste management problem at the regional level is developed. In this paper, the new approach is introduced and its implementation demonstrated through an illustrative case study involving 70 swine farms in the Lower Neuse River watershed in North Carolina.

First, the integrated modeling and solution approach is presented alongside possible ways of investigating regional management issues. The case study area and the waste management problem are subsequently described. Various problem scenarios are then introduced. These scenarios are examined for a number of different strategies that allocate treatment technologies to farms. Based on the results from this case study, this paper concludes by including suggestions for ways in which the modeling methodology could be used to address additional animal waste management concerns.

3.2 Integrated Modeling and Solution Approach

The pollutant removal estimates and the costs computed by CAWSST are integrated into a search procedure to help identify integrated management strategies (Fig. 3.1). As part of this procedure, a decision model is used to identify the most cost-effective allocation of the appropriate wastewater treatment system to each farm to achieve regional environmental goals. This decision model is structured as a mathematical programming model that minimizes cost of treatment for a group of farms while attaining pollutant discharge standards.

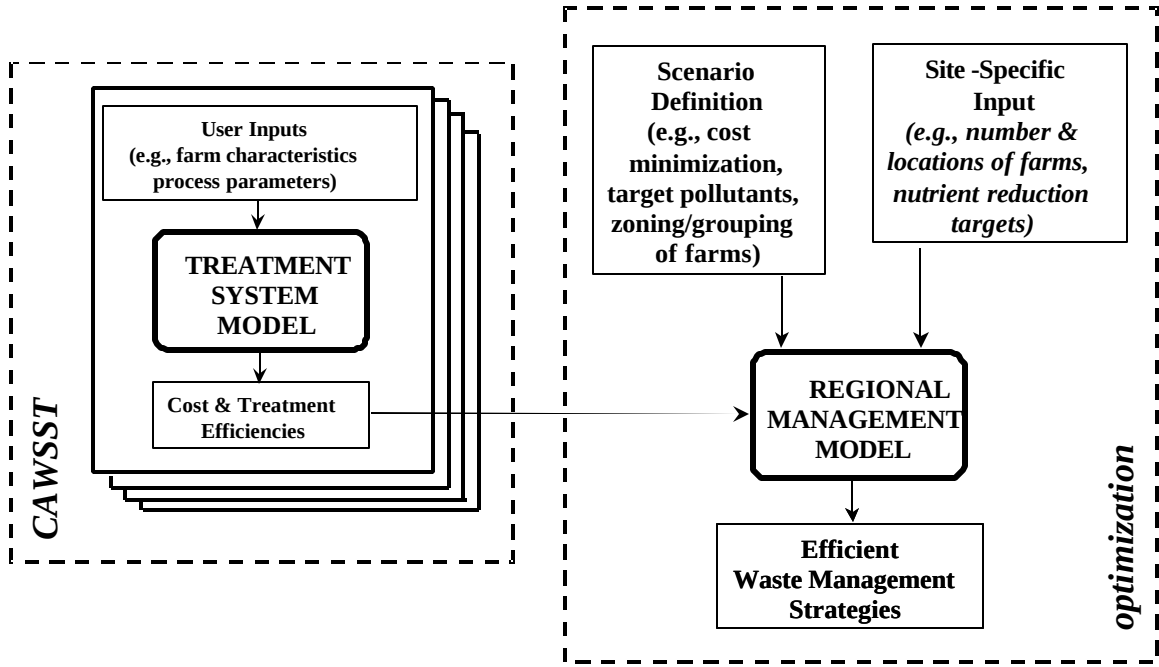


Figure 3.1 Schematic Diagram of the Integrated Modeling Approach

The following is a mathematical formulation of the model:

$$\text{Minimize: } \sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \quad (3.1)$$

Subject to:

$$\sum_{t=1}^n X_{f,t} = 1 \quad \forall f \quad (3.2)$$

$$\sum_{f=1}^N \sum_{t=1}^n [X_{f,t} (100\% - R_t^p) W_f^p] \leq T^p \quad \forall p \quad (3.3)$$

$$X_{f,t} \in \{0,1\} \quad \forall f, \forall t \quad (3.4)$$

where C_{ft} is the cost of using treatment system t at farm f , X_{ft} is a binary variable indicating whether or not treatment system t is used at farm f , R_t^p is the percent removal of pollutant p by technology t , W_f^p is the waste load of pollutant p at farm f , T^p is the collective loading target for pollutant p , n is the number of available alternative technologies, and N is the total number of farms considered in the study area.

Eq. 1 represents the total cost of the waste reduction strategy. Eq. 2 ensures that one and only one treatment system is used at each farm. Eq. 3 ensures that the total release of pollutant p from the collection of farms is within a specified target. Eq. 4 limits the variable X_{ft} to be binary ($X_{ft} = 1$ if treatment system t is allocated to farm f).

This model can be extended to analyze a range of different scenarios. For example, to examine the effect of different pollutant discharge targets on cost, the model can be resolved for different values of the loading target T^p for each pollutant in the pollutant constraint (Eq. 3). These solutions would represent the noninferior tradeoff between cost and allowable loading of a pollutant. By repeating this for different pollutants while constraining the loading from the other pollutants, the effectiveness of a technology allocation strategy in reducing different pollutants simultaneously can be evaluated. This is critical in regions where more than one environmental goal needs to be met at minimum cost.

3.2.1 Uniform Treatment (UT) Strategy

The pollutant target (Eq. 3) in the model, described above, is imposed on the total discharge from all farms. This may yield solutions for which the discharge levels from farms within different regions (e.g. zones categorized by geographic, political boundaries, or watersheds) will be different. Instead, if zone-specific targets are to be imposed, the pollutant target can be specified by including constraint Eq. 3 for the set of farms that form each zone. To impose easier-to-implement pollution control plan, a decision maker may seek strategies that require groups of farms (e.g., those within each pre-specified zone) to use the same type of treatment system. One extreme solution would be for all farms to be required to use the same type of system (a uniform treatment scenario). At the other extreme, a least cost technology allocation strategy may assign different system for each farm, resulting in not necessarily an equitable level of treatment. Depending on the political and practical issues specific to the study area, the constraint Eq. 5 can be added to the model as shown below to incorporate policy-making and management considerations:

$$X_{ft} = U_{kt} \quad \forall f \in \text{Zone } k, \forall t \quad (3.5)$$

where k is the set of farms that belong in the pre-specified zone k , and U_{kt} is a binary variable indicating if technology t is used for zone k . For the *UT Strategy* only one such zone is defined. All farms in the region of interest are required to treat to the same level. Since the different treatment technologies have different treatment efficiencies, all farms in the area would be required to use the same technology.

3.2.2 Zoned Uniform Treatment (ZUT) Strategies

In the example of *ZUT Strategies*, if zone 1 ($k=1$) includes farms 3, and 5, and if zone 2 ($k=2$) includes farms 1, 2, and 4, then $X_{3t}=X_{5t}=U_{1t}$, indicating that farms 3, and 5 treat to the same level (use technology t , in this case). Farms 1, 2, and 4 also use the same technology, which need not be the same as the technology used by farms in zone 1. A set of technology allocation strategies can be defined to represent equal treatment requirements for farms that are within different zones. For our simple example of two zones given above, the following constraints are added:

$$X_{ft} = U_{1t} \quad \forall f \in \text{Zone } 1=\{3, 5\}, \forall t \quad (3.5a)$$

$$X_{ft} = U_{2t} \quad \forall f \in \text{Zone } 2=\{1, 2, 4\}, \forall t \quad (3.5b)$$

3.2.3 Risk associated with floods

Many scenarios may be explored with the proposed management model, thus providing an environmental manager with alternative management options to choose from. Another example in which the model can be used is in examining the risk associated with floods and the treatment technologies in watershed. The following additional scenario is examined to represent an associated planning and management issue.

As the risk of contamination from open lagoons escalates in flood-prone areas, it may be necessary to identify regional management strategies that minimize such risks. This would require a search for cost-effective allocation of treatment technologies to farms such that the overall risk of contamination of open bodies of water from floods is minimized. The proposed management model is applied to examine this scenario.

Using information about the locations of farms and their proximity to floodplains, a surrogate risk index is assigned for treatment technologies that could potentially be used at each farm. For example, use of

anaerobic lagoons in a farm located in a 100-year floodplain has been assigned a higher risk index compared to one that is located in a 500-year floodplain. Similarly, use of a Sequencing Batch Reactor, which has low contamination potential in a flood, has been assigned a lower risk index compared to that of anaerobic lagoons. Separate relative risk indices are assigned to the treatment technologies that could potentially be used at each farm in the watershed.

Using these indices as a basis for comparing the risks of different technologies at every farm, the management model is modified to incorporate a relative measure of risk of a technology allocation strategy as an additional consideration. The model is then employed to explore multiple scenarios to identify alternative technology allocation strategies that are low-risk and cost-effective.

The following is a mathematical formulation of the model:

$$\text{Minimize:} \quad \sum_{f=1}^N \sum_{t=1}^n \text{Risk}_f \text{Risk}_t X_{f,t} \quad (3.6)$$

Subject to:

$$\sum_{t=1}^n X_{f,t} = 1 \quad \forall f \quad (3.7)$$

$$\sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \leq T^C \quad \forall p \quad (3.8)$$

$$\sum_{f=1}^N \sum_{t=1}^n [X_{f,t} (100\% - R_t^p) W_f^p] \leq T^p \quad \forall p \quad (3.9)$$

$$X_{f,t} \in \{0,1\} \quad \forall f, \forall t \quad (3.10)$$

where Risk_t is the relative risk (potential for damage in a flood event) posed by treatment system t and Risk_f is the relative risk (potential for damage in a flood event) posed by the location of farm f in a specific floodplain. C_{ft} is the cost of using treatment system t at farm f , X_{ft} is a binary variable indicating whether or not treatment system t is used at farm f , R_t^p is the percent removal of pollutant p by technology t , W_f^p is the waste load of pollutant p at farm f , T^p is the collective loading target for pollutant p , n is the

number of available alternative technologies, and N is the total number of farms considered in the study area.

Eq. 6 represents the total risk of the waste reduction strategy. Eq. 7 ensures that one and only one treatment system is used at each farm. Eq. 8 ensures that the total cost for the waste reduction technology allocation strategy does not exceed a predetermined target. Eq. 9 ensures that the total release of pollutant p from the collection of farms is within a specified target. Eq. 10 limits the variable $X_{f,t}$ to be binary ($X_{f,t} = 1$ if treatment system t is allocated to farm f).

For realistic problems with large numbers of farms and technology choice, a trial-and-error search for efficient technology allocations by examining the unit costs, removal efficiencies, and relative risks of the treatment technologies would likely be futile. Such an enumeration procedure would be infeasible for a problem where multiple design goals, e.g., finding the cheapest solution that would satisfy both the nutrient removal target as well as the risk objective, are specified. The number of feasible combinations of technology allocations would be sufficiently large that a systematic search using a formal optimization becomes essential.

The models described above are binary linear programming (BLP) models, which are solved commonly using available combinatorial search procedures such as the branch-and-bound algorithm and modern heuristic methods (e.g., genetic algorithms and simulated annealing). The complexity of the search is affected predominantly by the number of binary decision variables that increases proportionally with the number of farms and technologies. Search procedures available within existing software systems (e.g., CPLEX, and What'sBest! for spreadsheet implementations) are so far found to be sufficient to solve the size of problems presented in this study.

3.3 Illustrative Case Study and Scenarios

The applications of this modeling approach to a realistic case study are illustrated in the following sections. An array of management scenarios and technology allocation strategies is defined to demonstrate the different capabilities of the proposed approach and the types of information that could be obtained as outputs. This case study is described for illustrative purposes only, and the analyses and results are not meant to be suggestions for implementation in the watershed.

3.3.1 Background

North Carolina, with a population of 9.6 million swine, is one of the top producers in the swine industry in the United States. The system that is currently used for swine farm waste is a combination of waste digestion in anaerobic lagoons and land application in sprayfields. Despite the fact that this practice meets current federal and state standards, lagoon and sprayfield systems do not have strong public support. The public views the current treatment system as an unsightly, foul odor producing system with a high risk of failure (due to rupture of lagoons) and high ammonia emissions to the atmosphere. In response to public dissatisfaction, the State of NC has developed a plan to replace existing systems with alternative treatment systems. In this plan, the existing facilities will be rated to determine their risks to public health and the environment. Systems posing unacceptable risk will be replaced or closed. The effort to upgrade treatment practices in North Carolina corresponds to a national effort to develop alternative animal waste management practices. As upgrading of swine waste management practices in North Carolina is expected to be costly, evaluation of the costs and technical feasibility of converting animal waste lagoons to environmentally safer waste treatment technologies is a priority.

3.3.1.1 Data Required

The primary set of data required for modeling includes locations of existing farms (including proximity to floodplains or to populated areas); design size (i.e., the land area available to each farm, numbers of animals, etc.) of each farm; the types of waste treatment technologies currently used and historical data on the operation of each farm (for example, history of regulation violations). Existing databases include statewide GIS data layers. Currently, a 1997 database on swine farms in North Carolina has been obtained from the Department of Soil Sciences of North Carolina State University and it has provided the basis for the first implementation of the model. The database includes information on the location of the farms in North Carolina, size (number of swine in each farm), and ownership of the farms. In addition, data regarding watersheds in North Carolina, floodplains, and population distribution in the state was obtained from the USEPA website that contains data for the BASINS project, and from the Q3 Flood database of FEMA. Data from such sources has been compiled into a convenient data structure that supports the proposed modeling approach.

3.3.2 Study area and farm characteristics

The illustrative case study area is based on information on farms in the Lower Neuse River watershed, located in the eastern coast of North Carolina. The Lower Neuse River watershed spans six counties and

it incorporates 70 swine farms of various sizes. Farm size ranges from 250 to 18,000 swine, with the average farm size in the watershed being 3,500 swine. A total of 248,000 swine are grown in these farms, producing 332,000 lbs. of raw waste daily. These farms are located at different distances from the river and main tributaries, and they are located in different floodplains and different population density zones. New Bern is the largest town in the watershed, with a population of 18,000. Two farms, out of the 70 in the study area, are within the 100-year floodplain. Another 23 farms are within the 500-year floodplain. A schematic diagram of the watershed is shown in Fig. 3.2.

3.3.2.1 Environmental Target

In this illustrative study, the environmental goal was set to a 30% reduction in the release of nitrogen from all farms in this study area. Based on preliminary reports, this percentage was chosen from the target for the Neuse River Watershed, where a 30% total reduction in nitrogen load is desired. This reduction target was applied to the collective N production by all swine farms in the study area. This reduction is to be achieved using improvements in the treatment systems at these farms. All farms are assumed to be currently using the anaerobic lagoon for treating their waste.

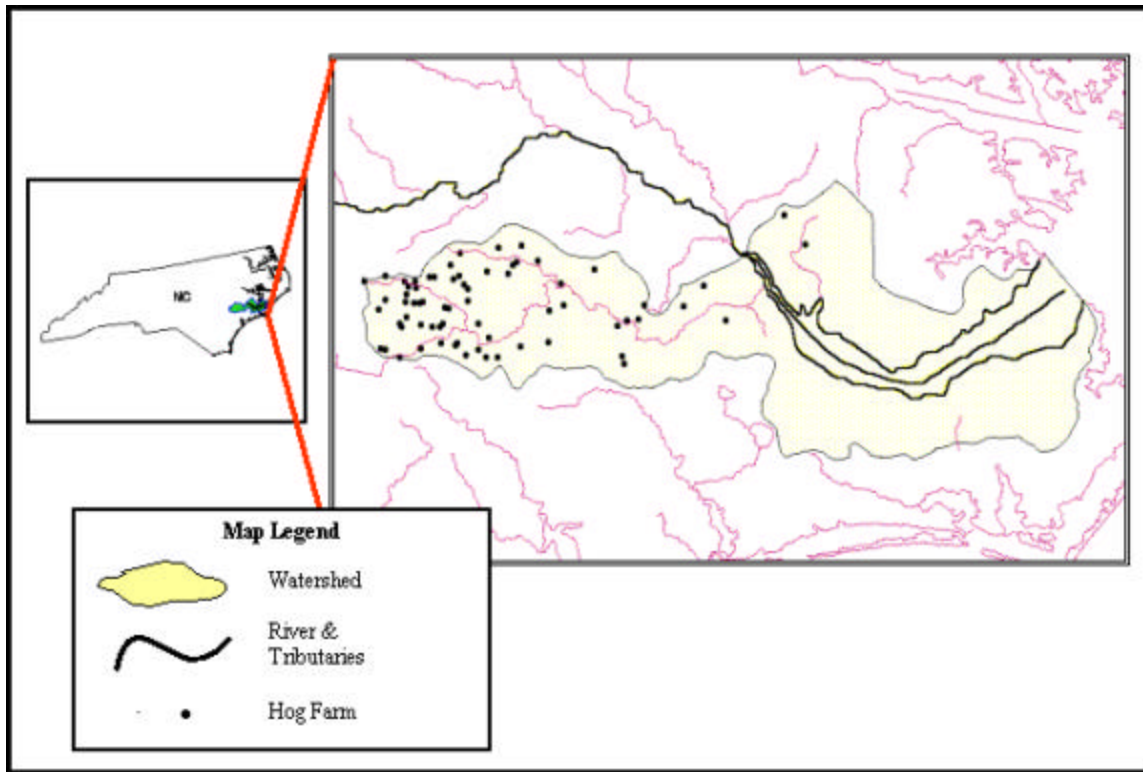


Figure 3.2 Schematic Diagram of Lower Neuse River Watershed indicating swine farms

3.3.2.2 Treatment Technologies Considered

Information regarding the cost and removal efficiencies of five basic treatment systems (with variations) for specific farm sizes was obtained using CAWSST and was included in this study. The basic treatment systems considered are anaerobic lagoons, constructed wetlands, sequencing batch reactors (SBR), ambient anaerobic digesters, and upflow aerated biofilters. The constructed wetland, the sequencing batch reactor, and the upflow aerated biofilter systems are evaluated for two variations. One variation considers the existing anaerobic lagoon being used as pre-treatment for the waste, while the other considers either no pre-treatment (for the case of the SBR), or the use of inclined screen solids separators as a form of pre-treatment. Each of these technologies and their variations has different treatment efficiencies and costs. These treatment technologies exhibit economies of scale, that is the unit cost for the removal of nutrients changes with farm size for each technology.

3.3.2.3 Problem Scenarios

Four different management scenarios are examined in this study in an attempt to exhibit the capabilities of the proposed framework.

Management Scenario 1: Inclusion of all treatment technologies in the analysis

In the first scenario, all of the aforementioned available treatment technologies are considered as equal candidates for treating farm waste in the watershed. This scenario includes anaerobic lagoons as well as all technologies that may be based on the use of an open lagoon-like structure. However, since anaerobic lagoons are already receiving such negative publicity, it would be difficult to implement any new technology that may be associated with similar problems as these lagoons.

Management Scenario 2: No new open-lagoon-based technologies

In the second scenario, the data are analyzed under the assumption that the construction of any open lagoon-based technology, other than the already existing anaerobic lagoons, is prohibited. In the second management scenario, constructed wetlands are not included as a possible treatment technology for the farms because of their similarity to anaerobic lagoons (i.e. excavated structure that holds wastewater).

Management Scenario 3: No open-lagoon-based technologies

In a third scenario, and according to the State's plans to replace anaerobic lagoons, all open lagoon-based technologies are excluded from the analysis. Treatment technologies that use the anaerobic lagoon as a pre-treatment stage are also excluded from the analysis in this scenario. The reason for excluding all of the open lagoon-based technologies is that such technologies should pose a high risk in a flood event, and also have similar ammonia volatilization and aesthetic considerations as anaerobic lagoons. If anaerobic lagoons are undesirable due to their nature and operation, then it follows that other similar systems would be equally undesirable. The technologies excluded from the analysis are the anaerobic lagoons, the constructed wetlands, the sequencing batch reactors and the upflow aerated biofilters that use the anaerobic lagoon as pre-treatment. One of the justifications for considering these management scenarios is in finding ways to reduce the use of technologies that pose a high risk in the event of a flood. Logically, eliminating the high-risk technologies from the analysis should also minimize the flood risk in the watershed.

Management Scenario 4: Consideration of Nitrogen in the solids

All of the aforementioned management scenarios only consider the nitrogen in the effluent water from the treatment facilities. However, some of the treatment technologies remove a lot of nitrogen from the wastewater not through the process of nitrification / de-nitrification but instead by removing it in large quantities of separated solids that need to be handled frequently. All technologies produce some solids as part of their treatment cycle. However, in some of these technologies, these solids need be handled only once every 15 years, or only upon closure of the treatment system. In the case of frequent handling of solids, the nitrogen contained in the separated solids needs to be included in the analysis. Since these solids are land applied in areas within the watershed, the goal of nitrogen reduction cannot be realistically achieved. The separated solids need to either be further treated (digested) or considered in the analysis. If the separated solids are ignored from the analysis, one will only manage the re-allocation of nutrients in the watershed. If these solids are not properly disposed of, there is a great potential that this nitrogen will return to the watershed and have certain environmental consequences. Therefore, in a fourth management scenario, the data are analyzed to include all of the nitrogen that remains in the watershed, both in the liquid effluent and in the solids. The assumption is that the nitrogen is contained in the solids and that it has not been removed through the nitrification/de-nitrification cycle is still present in the watershed and is thus included in the analysis.

In all of the management scenarios the 30% reduction in nitrogen in the watershed is set as the environmental goal. The model retains its binary integer character and only one treatment technology is assigned to each farm, based on its treatment efficiency and cost criteria.

3.3.2.4 Technology Allocation Strategies Considered

The following technology allocation strategies were modeled and analyzed for each of the management scenarios considered in this case study.

Least Cost Strategy

Using the modeling approach described above, the following model is formulated for this technology allocation strategy:

$$\text{Minimize: } \sum_{f=1}^{70} \sum_{t=1}^9 C_{f,t} X_{f,t} \quad (3.11)$$

Subject to:

$$\sum_{t=1}^9 X_{f,t} = 1 \quad f = 1, 2, \dots, 70 \quad (3.12)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{\text{nitrogen}}) W_f^{\text{nitrogen}}] \leq 427 \text{ tons nitrogen/year} \quad (3.13)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{\text{phosphorus}}) W_f^{\text{phosphorus}}] \leq 333 \text{ tons phosphorus/year} \quad (3.14)$$

$$X_{f,t}, X_{f',t} \in \{0,1\} \quad f = 1, 2, \dots, 70; t = 1, 2, \dots, 9 \quad (3.15)$$

Uniform Treatment (UT) Strategy

In this technology allocation strategy, all farms are required to use the same treatment system, thus ensuring that all farms are treating their waste at an equal level. Thus, in Eq. 5, there will be one zone ($k=1$) that includes all farms. This scenario characterizes the appropriate technology allocation that imposes the most equitable treatment burden on all farms. The least cost model is modified with the addition of the following equation to represent this technology allocation strategy.

$$X_{ft} = U_{1t} \quad \forall f \in \text{Zone 1} = \{1, 2, \dots, 70\}, \forall t \quad (3.16)$$

Zoned Uniform Treatment (ZUT) Strategies

A set of technology allocation strategies is defined to represent equal treatment requirements for farms that are within different zones. In this case study, the following zonings are considered: by county (6 zones), by farm size (7 zones), by farm type (5 zones), by farm size within county zones, and by farm type within county zones. Again, the least cost model (Eqs. 1-5) is modified as follows to ensure that all farms within a zone treat to the same level. For example, for county zoning:

$$X_{ft} = U_{1t} \quad \forall f \in \text{Zone 1 (Craven County)} = \{1, 2, 3\}, \forall t \quad (3.17)$$

$$X_{ft} = U_{2t} \quad \forall f \in \text{Zone 2 (Duplin County)} = \{4\}, \forall t \quad (3.18)$$

$$X_{ft} = U_{3t} \quad \forall f \in \text{Zone 3 (Jones County)} = \{5, 6, \dots, 43\}, \forall t \quad (3.19)$$

$$X_{ft} = U_{4t} \quad \forall f \in \text{Zone 4 (Lenoir County)}=\{44, 45, \dots, 68\}, \forall t \quad (3.20)$$

$$X_{ft} = U_{5t} \quad \forall f \in \text{Zone 5 (Pamlico County)}=\{68, 69\}, \forall t \quad (3.21)$$

$$X_{ft} = U_{6t} \quad \forall f \in \text{Zone 6 (Sampson County)}=\{70\}, \forall t \quad (3.22)$$

3.3.2.5 Risk Associated with Floods

To incorporate the risk associated with floods the initial model is modified. The objective of the model is to minimize risk in the watershed for a pre-determined budget. The environmental targets remain the same, with a 30% reduction in nitrogen discharged from the farms.

The relative risks associated with floods for farms and for the treatment technologies are developed as follows:

Farms located in the 100-year floodplain are assigned a relative risk index of 100. Farms within the 500-year floodplain have five times less chance of been inundated. In addition, when the 500-year flood event occurs, the water level in the 100-year floodplain is twice that of the 500-year floodplain. Therefore, the relative index for the farms in the 500-year floodplain is 10. Farms located outside of any floodplain still have certain potential of flooding, however small, and thus are assigned a value of 1. A higher risk index indicates a greater risk. In addition, larger size farms also pose a greater risk. Therefore, the relative risk indexes assigned to farm locations are multiplied by the size of the farms to produce the overall risk index for those farms.

Different treatment systems have different risk for releasing pollutants to the environment in flood events. All systems that use open anaerobic lagoons for pre-treatment of waste have the highest risk. The relative index is assigned a value of ten. These systems are the Anaerobic Lagoon, the Constructed Wetland with Anaerobic Lagoon pre-treatment, the Sequencing Batch reactor with anaerobic lagoon pre-treatment, and the Upflow Aerated Biofilter with anaerobic lagoon pre-treatment. Treatment systems that are based on open-lagoon structures have the second highest risk index of eight. One treatment system, the Constructed Wetland with solids separation pre-treatment of waste, falls in this category. Despite the fact that a wetland employs an open, ground level, structure, it is nevertheless shallower. The presence of plants also makes the escape of pollutants to the surrounding environment more difficult during a flood. Ambient anaerobic digesters have the third highest relative risk index of four. A watertight membrane covers the digester. However, the water leaving the digester is still high in nitrogen. This effluent subsequently enters an open-lagoon structure where nitrogen removal takes place. In a flood event, water

rich in nitrogen, but low in organics and phosphorus, can escape to the environment. Finally, systems in which treatment occurs in aboveground structures, such as concrete tanks and enclosed biofilters, have the lowest relative risk index of two. These systems are the Sequencing Batch Reactor and the Upflow Aerated Biofilter with a solids separator. The potential for pollutants escaping to the environment in a flood event is the lowest. Table 3.2 summarizes the relative risk indexes for the farms and the treatment systems.

Table 3.2 Summary of the relative risk indices used in the analysis

<i>Farm Location</i>	<i>Relative Risk Index</i>
Farms within the 100-year floodplain	100
Farms within the 500-year floodplain	10
Farms outside a floodplain	1
<i>Treatment System</i>	<i>Relative Risk Index</i>
Anaerobic Lagoon	10
Sequencing Batch Reactor with anaerobic lagoon pretreatment	10
Constructed Wetland with anaerobic lagoon pretreatment	10
Upflow Aerated Biofilter with anaerobic lagoon pretreatment	10
Constructed Wetland with solids separator pretreatment	8
Ambient Anaerobic Digester	4
Sequencing Batch Reactor	2
Upflow Aerated Biofilter with solids separation preceding	2

The following is the mathematical formulation implemented to analyze the risk associated with floods:

$$\text{Minimize: } \sum_{f=1}^N \sum_{t=1}^n \text{Risk}_f \text{Risk}_t X_{f,t} \quad (3.23)$$

Subject to:

$$\sum_{t=1}^n X_{f,t} = 1 \quad \forall f \quad (3.24)$$

$$\sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \leq T^C \quad \forall p \quad (3.25)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{nitrogen}) W_f^{nitrogen}] \leq 427 \text{ tons nitrogen/year} \quad (3.26)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{phosphorus}) W_f^{phosphorus}] \leq 333 \text{ tons phosphorus/year} \quad (3.27)$$

$$\begin{aligned} Risk_f = 1 & \quad \forall f \in 100\text{-year floodplain} = \\ & \{1 \dots 6, 8 \dots 11, 13, 14, 16, 22 \dots 25, 27, 30, 32, 34, 36 \dots 42, 47, 51, 53 \dots 55, 57 \dots 60, 62, 63, 66, 68 \dots 70\} \end{aligned} \quad (3.28)$$

$$\begin{aligned} Risk_f = 10 & \quad \forall f \in 500\text{-year floodplain} = \\ & \{7, 12, 15, 17 \dots 21, 26, 31, 33, 35, 43 \dots 45, 48 \dots 50, 52, 56, 61, 65, 67\} \end{aligned} \quad (3.29)$$

$$Risk_f = 100 \quad \forall f \in 100\text{-year floodplain} = \{46, 64\} \quad (3.30)$$

$$Risk_t = 10 \quad t = \text{technologies using an anaerobic lagoon (4 tech.)} \quad (3.31)$$

$$Risk_t = 8 \quad t = \text{constructed wetlands (1 technology)} \quad (3.32)$$

$$Risk_t = 4 \quad t = \text{ambient anaerobic digesters (2 technologies)} \quad (3.33)$$

$$Risk_t = 2 \quad t = \text{SBR and biofilters (2 technologies)} \quad (3.34)$$

$$X_{f,t}, X_{f',t} \in \{0,1\} \quad f = 1, 2, \dots, 70; t = 1, 2, \dots, 9 \quad (3.35)$$

The tradeoff curve between cost and risk in the Lower Neuse River watershed is traced for the Least Cost technology allocation strategy of the first management scenario. In this scenario, all available treatment systems are considered in the analysis, and no zoned uniform treatment restrictions are implemented in the analysis. This analysis is indicative of the type of information that can be obtained from using the proposed framework. The tradeoff curve is traced by minimizing risk while constraining cost not to exceed a pre-determined value. All other constraints remain the same. This is repeated for a number of different cost values. The maximum and the minimum possible risk values, with their respective costs, in the watershed are calculated.

3.4 Results and Discussion

The results of the analysis for the four management scenarios examined are presented and discussed here. As expected, the cost of achieving our environmental goals increased with more restriction in the use of alternative treatment technologies. The results presented are the costs of each technology allocation to

farms in the watershed as well as the loading of nitrogen to each of the chosen treatment technologies for each solution strategy.

3.4.1 Management Scenario 1: Inclusion of all technologies in the analysis

Each technology allocation strategy, described above, identifies the allocation of treatment systems to every farm, and estimates the corresponding costs. The costs of the solutions for the least cost, UT, and ZUT technology allocation strategies for each of the management scenarios are summarized in Fig. 3.3. A comparison of these costs leads to the following key observations pertaining to this case study. First, a significant (approximately 165%) increase in cost is incurred when shifting from the least cost solution to the uniform treatment solution. The UT solution uses the variation of the constructed wetland treatment system, which uses an anaerobic lagoon as a pre-treatment stage, for all of the farms in the watershed. The differences in the cost-effectiveness between the treatment system chosen by the UT solution and those selected by the least cost solution contribute to the large increase in cost. The second observation points to the range of zoned uniform treatment solutions with only a marginal increase (approximately 1% - 20%) in cost. Although not as equitable as the UT solution, these ZUT solutions provide a range of alternatives to achieve some degree of equity within reasonable increases in cost, resulting in relatively more cost-effective alternatives that are moderately equitable.

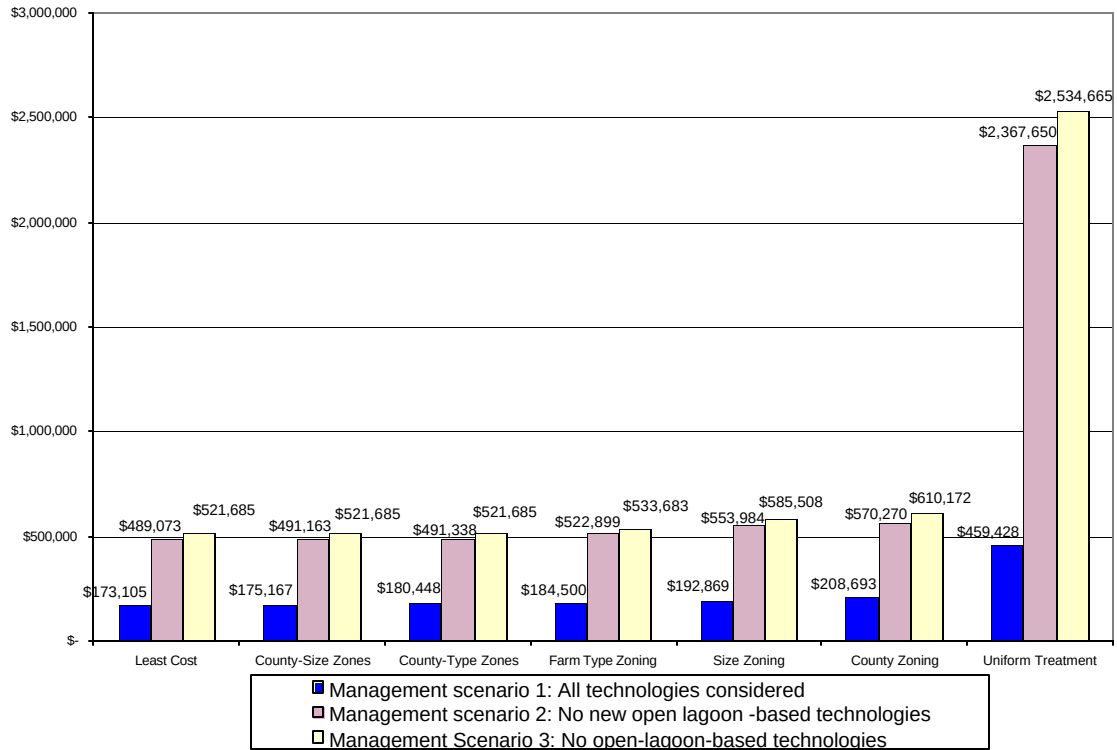


Figure 3.3 Comparison of costs of different technology allocation strategies under different management scenarios

The choices of treatment systems for the least cost, UT, and ZUT alternatives are summarized in Fig. 3.4. The frequency of use of the selected treatment systems by the different alternatives indicated in this figure leads to a few observations. Except for the UT solution, anaerobic lagoons can be used more frequently in the other alternatives and still achieve the collective 30% N reduction target in the watershed modeled in this specific case study. Also, only one other treatment system, the constructed wetlands that use anaerobic lagoon as pre-treatment, is selected from among the potential treatment options. Examining further the farm characteristics with the corresponding choice of treatment systems, more insights are gained. For example, the constructed wetland system is preferred for larger size farms (>5500swine) while smaller size farms are assigned the anaerobic lagoon system. The main reason for this could be the significant economies of scale that are observed with the constructed wetland system in larger size farms. The anaerobic lagoons, which are a significantly cheaper treatment alternative, especially since there are no construction costs incurred under the assumptions of this analysis, have much less noted economies of scale.

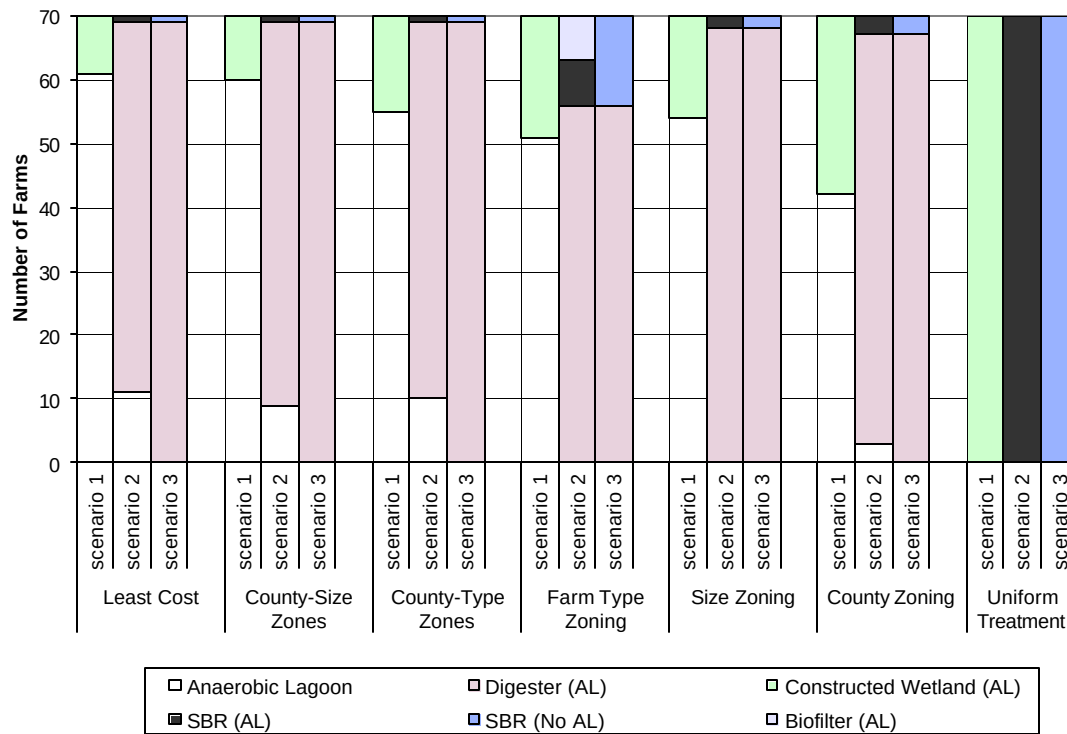


Figure 3.4 Distribution of treatment systems for the different management scenarios

To better capture the nature of the solution obtained through the proposed methods, one must also look at how much waste is treated by each chosen technology. Since the farms in the watershed are of significantly variable size, knowledge of the number of farms that use a certain technology is not adequate to describe the results in a manner that would be useful to an environmental manager. For a 30% reduction of nitrogen from the current levels to be achieved in the watershed, a certain volume of waste needs to be treated by a technology that is more efficient than the anaerobic lagoon. The nitrogen loading is directly proportional to the volume of waste treated by each treatment technology. The total nitrogen contained in the waste produced in all of the swine farms of the watershed (i.e. total nitrogen loading) amounts to 3060 ^{tons}/_{year}. In Fig. 3.5 the loading of nitrogen for each of the chosen technologies is plotted for each given scenario. It is seen that despite different number of farms using a certain technology t, the nitrogen loading for each treatment technology is relatively constant. For the ZUT scenarios of Farm Size and County zones, a larger nitrogen loading exists for the more expensive constructed wetland technology, thus explaining the higher total cost for those management scenarios.

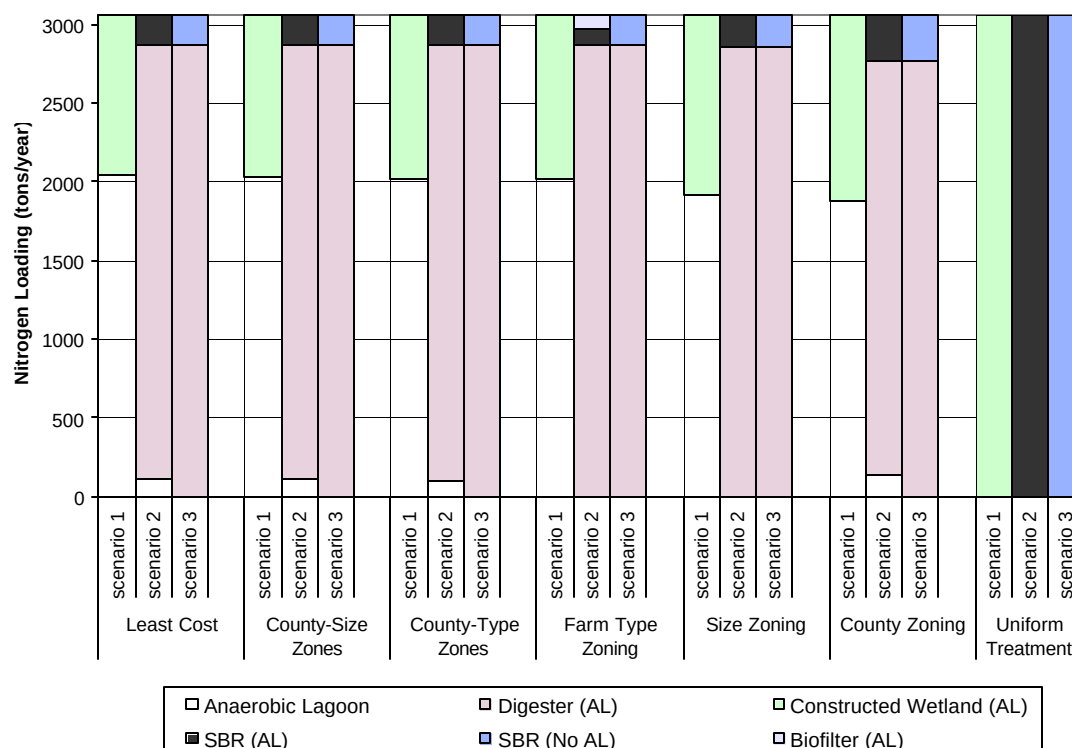


Figure 3.5 Nitrogen loading to the treatment systems for the different management scenarios

3.4.2 Management Scenario 2: No New open-lagoon-based technologies

In management scenario 2, it is assumed that no new open-lagoon-based technologies can be constructed. Therefore, the constructed wetlands are excluded from being a technology that can be allocated to any of the farms in the watershed. As in management scenario 1, where all available technologies are equal candidates for treatment at any of the farms, a significant increase in cost (almost 400%) when shifting from the LC solution to the UT solution is noted (Figure 3.3). ZUT solutions show a marginal increase in cost (1%-10%) for four ZUT scenarios and a 55% cost increase for one of the ZUT scenarios. All cost increases are compared to the total cost of the least cost solution.

Fig. 3.4 summarizes the technology selection for the farms in the watershed. Note the exclusion of constructed wetlands from any of the solutions. The anaerobic lagoons cease to be the predominant technology in farms. Instead, the ambient anaerobic digester, followed by the sequencing batch reactor and the upflow aerated-biofilter, substitutes them. Despite the fact that the use of existing anaerobic lagoons is not restricted, they are allocated to only a few farms in the least cost and three of the ZUT

technology allocation strategies. The reason for this is the fact that for a 30% reduction in nitrogen discharge, from current levels, treatment technologies of higher efficiency need to be used at more farms.

In Fig. 3.5 the loading of nitrogen for each of the chosen technologies is plotted for each technology allocation strategy under the different management scenarios. It is seen that despite different number of farms using a technology t , the nitrogen loading for each treatment technology is relatively constant for all of the technology allocation strategies. This chart can also be used to explain features such as why the County Zoning technology allocation strategy has a higher cost, when compared to the Farm Type Zoning technology allocation strategy. In the Farm Type Zoning technology allocation strategy more farms employ the more expensive treatment systems of SBR and biofilter. However, more nitrogen is treated in a more expensive treatment technology (the SBR) under the County Zoning technology allocation strategy.

This is an example of the type of results obtained, which may not be inherently evident when examining treatment options for farms individually. Anaerobic lagoons are part of the analysis, yet they are not chosen for farms. If they were, the environmental target would not be met. These results also suggest that in the absence of a treatment system such as the constructed wetlands, the complete replacement of all anaerobic lagoons could be a close alternative.

3.4.3 Management Scenario 3: No open-lagoon-based technologies

In Management Scenario 3, all of the technologies that use any form of an open-lagoon-based structure for treatment are excluded from the analysis. The following technologies are thus left as the treatment alternatives: the ambient anaerobic digester, the upflow aerated-biofilter that uses a solids separator for pre-treatment, and the sequencing batch reactor. In the analysis of this scenario, the cost increase of the different technology allocation strategies is small when compared to the solution of management scenario 2 (Figure 3.3). This cost increase is due to the difference in cost between the SBR (preceded by the anaerobic lagoon pre-treatment) and the upflow aerated-biofilter (with a solids separator pre-treatment)(Figure 3.4). The biofilter technology is the most expensive of all the technologies included in the analysis. In the absence of other efficient treatment systems, the sequencing batch reactor technology is selected in the UT solution, despite the large cost that it is associated with.

3.4.4 Management Scenario 4: Consideration of Nitrogen in solids

In the management scenario 4, the nitrogen contained in the separated solids is included in the quantity of the total nitrogen released from the farms into the watershed. The upflow aerated biofilters and the constructed wetlands, both of which use a solids separator, as well as the sequencing batch reactor, are the three technologies that produce a significant amount of separated solids that require regular disposal. Technologies that do not need the frequent handling of solids, or employ a form of solids digestion, are assumed to discharge nitrogen only as part of the treated liquid effluent.

The analysis produced identical results as for the management scenarios 1, 2, and 3. The reason for this is the fact that no technologies that produced a large quantity of solids are assigned by the model to farms in the first place. Therefore, that consideration of nitrogen in the solids did not alter the management scenario costs or the technology assignment to farms. Despite this result, it is still important to consider all of the nitrogen that needs disposal and is found in both the liquid effluent and the separated solids. Only then, a complete accounting of the nitrogen in the watershed would be possible and only then a correct assignment of the appropriate technologies to the farms could be achieved.

3.4.5 Consideration of risk associated with floods

The risk posed under the different technology allocation strategies for the management scenarios was calculated. Each treatment technology at each farm has a certain risk associated with it. The most possible relative risk to the watershed was calculated by assuming that all farms in the watershed use the highest risk technologies (i.e. the technologies that use anaerobic lagoons for treatment or pre-treatment of the raw waste). The highest possible relative risk value is 19,135,780 and it has a cost of \$173,105/year for the least cost technology allocation strategy of the first management scenario. The least possible relative risk value is 3,827,776 for a least cost of \$2,535,120/year in the watershed. These two values define the extreme points of the tradeoff curve between cost and relative risk of management scenario 1 (Fig. 3.6).

Figure 3.6 also indicates that there is only a small improvement in risk for a great cost when the relative risk index falls below 5,000,000 units. On the contrary, the improvement in risk is large for a small cost increase for relative risk values of greater than 10,000,000 units. For example, the relative risk can be reduced by approximately 8,000,000 units for a cost increase of \$144,000 / year for the watershed.

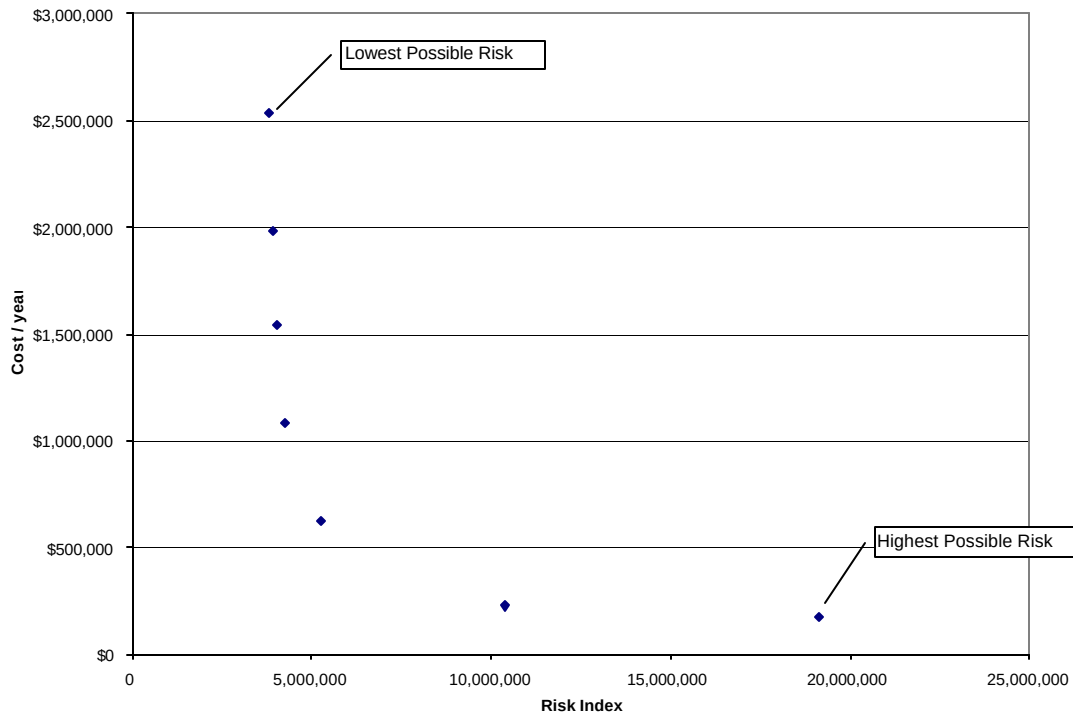


Figure 3.6 Tradeoff curve between cost and risk for the least cost strategy (no zoned uniform treatment restrictions) of the first management scenario (no restriction in the use of the available technologies).

The technology distribution that allows for this improvement in risk is seen in Figure 3.7, on the two rightmost bars in the chart (possible technology allocation strategies 6 and 7). The use of the ambient anaerobic digester for treatment in 10 farms in the watershed causes the big reduction in cost. Each bar in Figure 3.7 represents the technology distribution to swine farms in the Lower Neuse River watershed for a different allowable cost of implementation of the technology allocation strategy. Each technology allocation scheme is independent of the other. For example, if one compares the last two technology allocation strategies, the farms that use the constructed wetlands in technology allocation strategy 6 are not necessarily the same as the ones that use constructed wetlands in technology allocation strategy 7. The vertical axis on the chart shows the number of farms that use a technology under each of the allocation strategies. The horizontal axis shows the relative risk value of each technology allocation strategy.

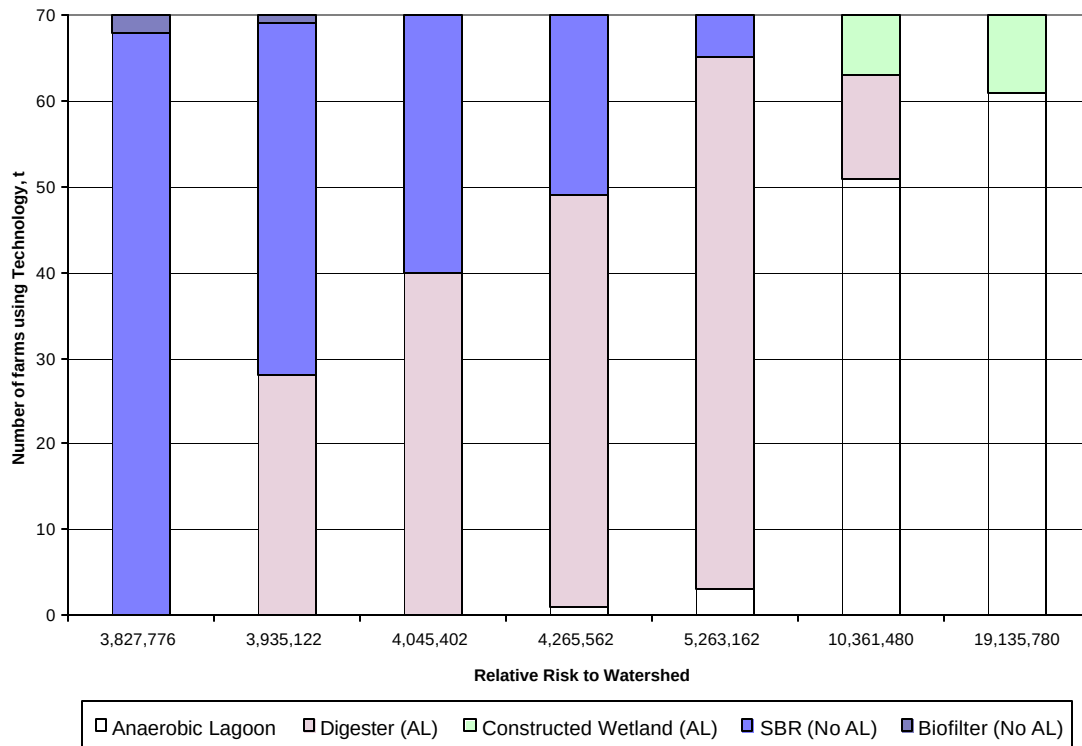


Figure 3.7 Technology allocations for the various solutions of the least cost strategy under management scenario 1.

Additional information can be obtained from risk analysis. One of the main reasons why the replacement of anaerobic lagoons is desired is to reduce the risk in the watershed. If one focuses on the least cost technology allocation strategy under the conditions of management scenarios 1, 2, and 3 (Figs 3.3, 3.4, and 3.5), one can examine whether it is possible to achieve a low risk index for the watershed without excluding anaerobic lagoons as a technology of choice. The cost of the least cost technology allocation strategy under scenario 3 (all open-lagoon-based technologies are excluded from the analysis) is \$521,000/year for the watershed and the relative risk is 7,624,002 units. The cost of the least cost technology allocation strategy under scenario 1 (all available technologies are included in the analysis) is \$173,000/year and the risk is 19,135,780. The difference in cost is thus approximately \$350,000/year. If this extra money is used to find a solution while allowing open-lagoon-based technologies (management scenario 1), the relative risk achieved can be as low as 5,500,000 units. This risk value is 2,000,000 units lower than it is when one excludes open-lagoon-based technologies from the analysis while the cost remains the same.

This result shows that the systematic analysis of risk, using the presented framework, can provide solutions leading to the desired results that would not be obvious to an environmental manager at first. The framework presented is a way for managers to focus on the real issues and interests for an area rather than focusing on positions of how to go about achieving the desired results. There are different solutions for the various environmental concerns in a watershed. Through the presented framework, a tool that a manager can use to find these optimal solutions is provided.

3.5 Future Work and Concluding Remarks

Extensions of the regional management model are currently being investigated to include additional management considerations, such as minimization of odor problems associated with animal waste treatment, minimization of phosphorus discharged to the watershed, and analysis of possible future addition of farms to the watershed. To demonstrate the possibilities offered by the modeling approach presented, these model extensions are briefly discussed below.

3.5.1 Generation of alternative management strategies

The decision support model introduced in this paper may not be able to capture all issues that play a role in decision-making regarding waste treatment improvements in swine farms in North Carolina. For example, the most cost-effective technology allocation may call for treatment technology upgrades that may appear to be inequitable, causing practical and political difficulty in its implementation. To assist in analyzing such issues that are not explicitly modeled, the decision model can be modified incrementally to generate a small set of alternative strategies that use maximally different technology choices. This implementation is based on a standard procedure called Modeling to Generate Alternatives (MGA) (Brill et al., 1990; Chang et al., 1982). Distinctly different choices of treatment technologies are expected to lead to strategies with different characteristics that may perform differently with respect to different unmodeled criteria.

Use of MGA techniques can not only assist in the decision making process in managing animal waste, but also provide valuable insight to the problem at hand. One of the purposes of performing MGA to a real-life problem is to provide decision makers with various ‘starting solutions’ or “benchmark solutions” for further exploration of alternative strategies for managing animal waste in a region.

There are different ways of allocating alternative technologies to replace anaerobic lagoons in specific swine farms to meet a collective environmental target in a region. Generation of alternatives is important in this problem due to the nature of other relevant issues (e.g., the many unmodeled parameters, such as odor, ammonia volatilization/re-deposition and aesthetics) that need to be considered by environmental managers in finding ‘good’ solutions to the problem. Different solutions that include a multitude of unmodeled issues can be generated using MGA techniques. Such solutions can include consideration of equity in the treatment burdens of farms, implementation feasibility, and robustness in performance.

To produce a number of good alternatives to the optimal solution for each of the different management scenarios, a methodical search is required to identify solutions that are maximally different from one another but are still good with respect to the modeled objectives and constraints of the original model. To ensure that an alternative generated is relatively good, a pre-determined relaxation from the optimal solution is allowed. The alternatives are generated by avoiding reassignment of the same technologies to the same farms while ensuring the cost does not exceed a specified relaxation from the optimal value. This cost target is specified based on a percentage deviation from the lowest cost values identified with the models introduced in this paper.

3.5.2 Reduction of odor potential

The odor emitted from animal farm operations is a factor that results in public outcry. The proximity of farms to populated areas may require the use of treatment systems that limit odor emission. The identification of cost-effective management strategies that minimize the effect of odor on communities located in the area of interest may be necessary. The proposed management model can be applied to examine this scenario. Using information about the locations of farms, their proximity to populated areas, the wind profile (wind direction and power density) in the area, and the population in the communities within the area of influence of the odor emitted from the farms, a surrogate odor index will be assigned for treatment technologies that could potentially be used at each farm. The zones of influence of the odor emitted from farm f using technology t will depend on the wind profile for the area. For example, if a community of 50,000 people is located 3 miles south of a farm f , it can be assigned a higher odor index than a community of 50,000 people located 5 miles south of the farm or a community of 5,000 people located 2.5 miles in the same direction.

In Figure 3.8, P1 and P2 are communities with different populations, and L1 and L2 are the distances of those communities from farm f that uses technology t. Z_h , Z_m , Z_l are zones pre-specified according to distance from source, that have a high, medium, and low levels of odor influence, respectively

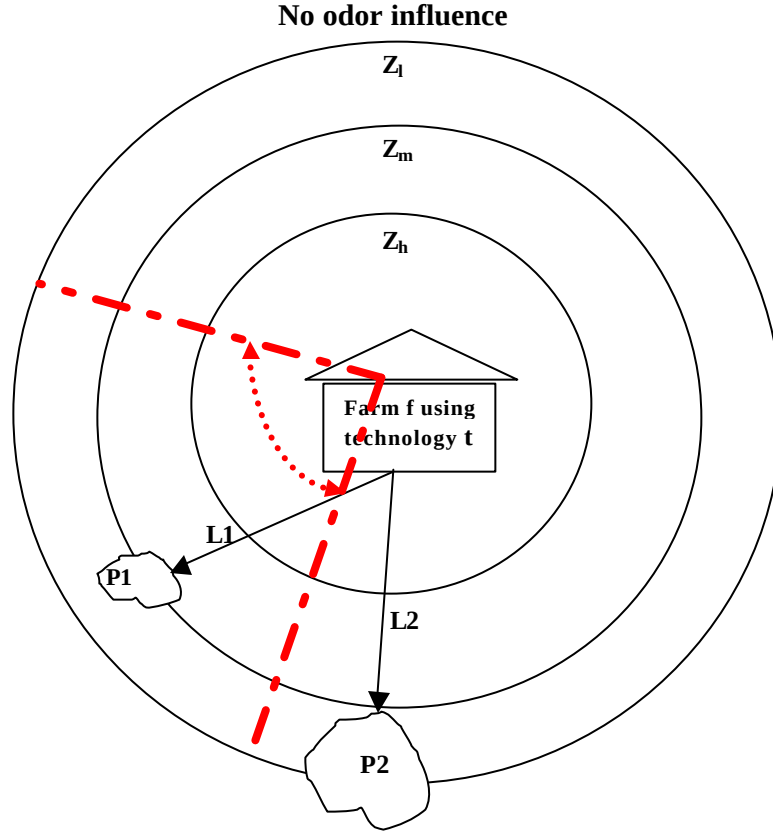


Figure 3.8 Example of odor impact emitted from farms on nearby communities.

from farm f using technology t. Outside of those zones, it is assumed that odor is not a significant problem. The degree of odor problem within each zone can be adjusted depending on the wind direction. For a southwest wind direction, the shaded area in the figure shows the actual zones affected by odor.

The odor measure could attain the form of:

$$F(L_h)P_h + F(L_m)P_m + F(L_l)P_l \quad (3.36)$$

where the relative indexes for each zone of influence are:

$$F(L_h) > F(L_m) > F(L_l) \quad (3.37)$$

P_h , P_m , and P_l are the number of people living within the high, medium, and low zones of odor influence, and L_h , L_m , and L_l , are the distances from the farm to the edge of the high, medium and low zones of influence, respectively.

Using these indices as a basis for comparing the odor emitted from different technologies at each farm, the model can be employed to explore scenarios to identify alternative technology allocation strategies in which neighboring communities are least impacted by odor and are still cost-effective.

3.5.3 Reduction of phosphorus discharge

Revision of nutrient management standard for phosphorus will have an impact in North Carolina. A pending change in Natural Resources Conservation Service standards for designing nutrient management plans for animal waste operations could force some animal producers in North Carolina to look for additional land on which to apply wastes.

Application rates for animal wastes have previously been based on plant needs for nitrogen. However, the unfavorable nitrogen-to-phosphorus ratio in manures has often resulted in an over-application of phosphorus. When more phosphorus than plants can use is applied to land, in the form of animal wastes or fertilizer, phosphorus builds up in the soil. Some of the excess phosphorus may dissolve in soil water and seep out into streams or leach down into groundwater. Some excess phosphorus may bind itself to soil particles and be carried to water-bodies when soil is washed from fields. Over the last decade, research has produced significant evidence that phosphorus can be delivered from some agricultural fields and animal waste application sites to water-bodies in quantities sufficient to cause eutrophication in freshwaters.

In response to the potential water quality impacts of phosphorus, the USDA Natural Resources Conservation Service in 1999 revised its policy on nutrient management to require that plans for animal waste management include consideration of potential phosphorus loss. NRCS in each state was required to revise its nutrient management (590) standard in the Field Office Technical Guide to incorporate measures to address phosphorus loss. The change means that phosphorus will be the rate-determining nutrient on sites with a high or very high potential for phosphorus loss.

Sites that are assessed as medium or low risk for phosphorus loss will still have application rates based on plant needs for nitrogen. If a site has a “high” potential for phosphorus loss, application rates will be limited to phosphorus removed in the harvested crop. If a site has a “very high” risk, then no additional applications of phosphorus in any form can be made. Prohibition or restriction of phosphorus application would have a negative economic impact on animal growers whose land application sites are determined to have a high or very high risk for phosphorus loss. They would either have to purchase more land, which is often not available in areas of high animal concentration, or reduce the number of animals in their operations.

If the management goal is to minimize phosphorus levels in a watershed in a cost-effective manner, different ways to achieve this could be investigated by using the framework presented in this paper. Regional analysis that includes phosphorus could be achieved by modifying the model.

The objective of the model would be to still minimize cost. Zones could be defined for farms that must comply with the nitrogen standard and for farms that must comply with the phosphorus standard. Farms in each zone will be bound by the respective nitrogen and phosphorus target constraints. The farms in these zones can be determined from data that are provided after analyzing the parameters that contribute to area classifications for high phosphorus loss potential. Such soil and hydrologic data are available in GIS format for the state of North Carolina. The optimization procedure would help identify the technologies that could be used at the farms in the area of interest to meet the specified goals.

The possible mathematical formulation of the model follows:

$$\text{Minimize: } \sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \quad (3.38)$$

Subject to:

$$\sum_{t=1}^n X_{f,t} = 1 \quad \forall f \quad (3.39)$$

$$\sum_{f=1}^N \sum_{t=1}^n [X_{f,t} (100\% - R_t^{\text{phosphorus}}) W_f^{\text{phosphorus}}] \leq T^{\text{phosphorus}} \quad \forall f \in \text{P-regulated Zone} = \{1, \dots, k\}, \forall t \quad (3.40)$$

$$\sum_{f=1}^N \sum_{t=1}^n [X_{f,t} (100\% - R_t^{\text{nitrogen}}) W_f^{\text{nitrogen}}] \leq T^{\text{nitrogen}} \quad \forall f \in \text{N-regulated Zone} = \{k, \dots, N\}, \forall t \quad (3.41)$$

$$X_{f,t} \in \{0,1\} \quad \forall f, \forall t \quad (3.42)$$

where C_{ft} is the cost of using treatment system t at farm f , X_{ft} is a binary variable indicating whether or not treatment system t is used at farm f , $R_t^{\text{phosphorus}}$ is the percent removal of phosphorus by technology t , $W_f^{\text{phosphorus}}$ is the waste load of phosphorus at farm f , $T^{\text{phosphorus}}$ is the collective loading target for phosphorus, R_t^{nitrogen} is the percent removal of nitrogen by technology t , W_f^{nitrogen} is the waste load of nitrogen at farm f , T^{nitrogen} is the collective loading target for nitrogen n is the number of available alternative technologies, and N is the total number of farms considered in the study area.

Eq. 38 represents the total cost of the waste reduction strategy. Eq. 39 ensures that one and only one treatment system is used at each farm. Eq. 40 ensures that the total release of phosphorus from the collection of farms in the phosphorus-regulated zone is within a specified target. Eq. 41 ensures that the total release of nitrogen from the nitrogen-regulated farms is within a specified target. Eq. 42 limits the variable X_{ft} to be binary ($X_{ft} = 1$ if treatment system t is allocated to farm f).

3.5.4 Analysis to include new farm development

The presented framework is flexible, facilitating the consideration of a number of interesting questions related to possible expansion of the swine population in a region. For example, the investigation of possible future farm additions to a region can be examined. Despite the fact that currently there is a moratorium on new swine farms in North Carolina, an expansion of the industry can be allowed in the future. In that event, the framework could be used to predict the maximum possible increase in the swine population in a region if certain environmental standards are not to be violated. One way in which this question can be answered is by altering the objective of the management model to be the maximization of the number of swine in the region. The environmental standards will remain as constraints in the model. In this case, the environmental standards cannot be percent reductions from current levels (i.e. as presented in the case study), but instead maximum loadings will have to be defined for the pollutants.

The management framework can also help plan what treatment technologies should be assigned to any new farms. Planning the waste treatment of a proposed farm will be a more cost-effective alternative than later deciding to change an inadequate system. This can be implemented within the framework by including the proposed farms in the model. The new farms will include only the technologies that would be allowed in the future. Then, the framework can be used to investigate cost-efficient technology allocations to all, both existing and new, farms such that future environmental standards are not violated.

3.5.5 Examples of Policy Applications

Aside from the management strategies developed through the proposed framework, alternative management approaches are currently used in other environmental fields. For example, transferable (tradable) permits are an economic policy instrument under which rights to discharge pollutants or exploit resources can be exchanged through either a free or a controlled permit-market. Transferable permits could be excellent instruments to meet regional environmental goals while allowing more freedom to farmers in implementing waste treatment options at their farms, thus addressing equity concerns.

Past implementations showed that transferable permits lead to cost-effective and equitable solutions for regions. However, to avoid additional problems from surfacing, permits must be carefully restricted. For example, in the case of animal waste management, trading permits may result in high pollutant discharge at a single location. If this single location is an ecologically sensitive area of a watershed, the increased concentration of high pollutant loads may create unexpected environmental cost. Tradable permits also ignore risk in a region. Unless explicitly considered, high-risk technologies can be assigned to high-risk farms in a watershed, thus creating various potentially damaging hotspots in a flood event. In addition to the localized problems that need to be addressed in a tradable permit program, social costs must also be considered. For example, under an animal waste management scenario there is a possibility that smaller size farms will be ‘forced’ to shut down. The reason for this could be the fact that it would be economically more beneficial for a small farm to sell all of their rights to discharge than to continue operation. In this way, small, family-oriented farms would be gradually replaced by big operations. Economically, it makes sense that large farms take-over a region, however, the social cost that will result from such a change would be great and would be difficult to quantify before any policy implementation.

Unless explicitly addressed by the zoning of farms, trading of permits can create localized problems. The framework presented in this dissertation can help identify appropriate zones that will constitute trading restrictions. The anticipated distribution of permits after trading can be analyzed for different zones of farms. By using the framework to explicitly examine the risk from flooding to the watershed, policy-makers can find ways to define transferable permits to allow only the use of certain technologies at specific locations.

3.5.6 Summary

In this paper, an integrated modeling approach to identify collective technology allocation strategies to farms for the management of animal farm waste is presented. Using systematic search procedures to solve this management model, cost-effective strategies that meet specified environmental goals can be identified. The modeling approach is flexible to allow examination of strategies that could incorporate consideration of equitable treatment requirements for farms within specified zones. An illustrative case study based on realistic data from North Carolina is used to demonstrate the applicability of this proposed approach.

CHAPTER 4: Managing Swine Waste in North Carolina: Examination of Alternatives

Abstract

There are alternative ways in which appropriate treatment technologies can be allocated to farms in an area. While a number of different possible management scenarios can be defined and analyzed with the use of formal optimization techniques, a number of unmodeled, yet important, factors provide a challenge in finding a practical solution to the animal waste management problem in a region. Implementation of Modeling to Generate Alternatives (MGA) techniques helps explore different alternative solutions that may exist for a given management scenario. MGA helps identify a number of maximally different alternative solutions, which can be good starting points for managers to devise a solution to a waste management problem. Application of this approach also provides insights on any flexibility that is available in solving the problem. This paper introduces an application of MGA techniques to a case study of swine farms in the Lower Neuse River watershed in North Carolina.

4.1 Introduction

A decision support model to assist in the identification of management strategies for swine waste in North Carolina was developed by Anastasiou et al. (Chapter 3). However, the problem of animal waste management is too complex to be fully represented by a mathematical model. The model introduced may not be able to capture all issues that play a role in decision-making regarding waste-treatment improvements in farms. The model suggested by Anastasiou et al. (Chapter 3), is flexible and allows for the addition of a great number of decision objectives. However, some of these criteria may not be easily quantifiable and thus they may not be included in the analysis during the decision-making. For example, the most cost-effective strategy may call for treatment technology upgrades that may appear to be inequitable, causing practical and political difficulty in its implementation. In another example, a cheap and equitable management strategy may include risk-prone treatment technologies in farms that are located in environmentally sensitive areas.

4.1.1 What is Modeling to Generate Alternatives (MGA)?

To assist in analyzing such issues that are not explicitly modeled, the decision model can be modified incrementally to generate a small set of alternative strategies that have farms use maximally different technology choices. This implementation is based on a standard procedure called Modeling to Generate Alternatives (MGA) (Brill et al., 1990; Chang et al., 1982). Manipulating model parameters to generate alternatives has been used in different cases in the past (e.g. Dickey et al., 1973). Using optimization to generate maximally different solutions followed, and several methods for modeling MGA have been developed (Brill, 1979; Church and Huber, 1979; Chang, 1981; Chang et al., 1982; Brill et al. 1990). Distinct choices of treatment technologies across farms are expected to lead to strategies with characteristics that may perform differently with respect to various unmodeled criteria.

4.1.2 Why MGA in animal waste management?

Use of MGA techniques can not only assist in the decision making process in managing animal waste, but also provide valuable insight to a specific problem. One of the purposes of performing MGA to a real-life problem is to provide decision makers with various “starting” or “benchmark solutions” in further exploration of alternative strategies for managing animal waste in a region.

There are different ways of allocating alternative treatment technologies to replace anaerobic lagoons in specific swine farms to meet a collective environmental target in a region. Generation of alternatives is important in this problem due to the nature of other relevant issues that need to be considered by environmental managers in finding ‘good’ solutions to the problem. Unmodeled parameters in the case of swine waste management in North Carolina include the flood risk that technologies used in certain farms may pose, equity of the management strategy, effect of the emitted odor from farms, ammonia volatilization and re-deposition, and aesthetics. In this study different solutions are generated using MGA techniques. The results are examined with respect to risk posed to farms by flood events, equity in treatment burdens and cost to farms, and implementation feasibility.

4.1.3 Organization of Paper

In this paper, the way in which MGA techniques can be employed in swine waste management will be discussed through by using a case study. First, an introduction to the swine waste management problem in North Carolina will be given. The case study area, the Lower Neuse River watershed, will be then

described. The optimization procedure used in examining the least cost management strategy for the farms in the area will be briefly introduced. Subsequently, the MGA methodology used will be introduced, citing the numbers obtained from the study of the Lower Neuse River watershed swine farms. Discussion of the ways in which MGA analysis can assist decision-making will follow. This will be achieved by addressing examples of perspectives of the problem. Introduction to measurements of risk and equity will be part of the concerns expressed by environmental managers and farmers, respectively. Results in both the objective and the decision space will be simultaneously presented. Solutions in the objective space of this problem include the cost of each management alternative and the environmental goals attained under each strategy. Solutions in the decision space of this problem detail the allocation of specific treatment technologies across farms in the study area. Results in the objective space are presented through charts of cost, risk and equity measures for the various management alternatives. Spatial examples of the decision space of the alternative strategies to farms are also presented.

4.2 Illustrative Case Study

To produce a number of good alternatives to the optimal solution for each of the different management scenarios, a methodical search is required. Identified solutions must be maximally different from one another but still good with respect to the modeled objectives and constraints of the original model. To ensure that an alternative generated is relatively good, a pre-determined relaxation from the optimal solution is allowed. In the regional animal waste management example studied in this paper, the alternatives are generated by avoiding reassignment of the same technologies to the same farms while ensuring that the cost does not exceed a specified relaxation value from the optimal value. This cost target is specified based on a percentage deviation from the lowest cost values identified in Anastasiou et al. (Chapter 3).

The applications of ‘Modeling to Generate Alternatives’ to a realistic animal-waste-management case study are illustrated in the subsequent sections. The array of management scenarios and technology allocation strategies developed are based on results from a previous study (Anastasiou et al., Chapter 3). These technology allocation strategies are defined to demonstrate the capabilities of the proposed approach and the types of information that decision-makers could obtain. This case study is described for illustrative purposes only, and the analyses and results are not meant to be suggestions for implementation in the watershed.

4.2.1 Background

North Carolina is the second largest swine producing state in the US with a population of 9.6 million swine. Currently, the swine farms in the state use anaerobic lagoons to treat their waste and they subsequently land-apply the effluent in sprayfields. The public considers the combination of the lagoon and sprayfield waste management as unsightly, malodorous, prone to failure (rupture of lagoons), and as a source of high atmospheric emissions of ammonia. In response to the public dissatisfaction, the State of NC has proposed to replace existing treatment systems with alternatives. Such a treatment system upgrade is expected to be costly.

4.2.1.1 Treatment Technologies

Information regarding the cost and removal efficiencies of five basic treatment systems for specific farm sizes was obtained using a computer based tool, CAWSST (Anastasiou, 2002), and was included in this study. Four of the basic five systems include slight unit process modifications, and thus variations in their treatment and/or cost. Therefore, nine distinct treatment technologies are considered in the analysis. Each of these nine technologies has different treatment efficiencies and costs. The unit cost for each technology changes for the removal of nutrients with farm size (i.e. technologies exhibit economies of scale).

4.2.1.2 Study Area

The swine farms located within the Lower Neuse River watershed were chosen as a case study (Anastasiou et al., Chapter 3). The watershed spans six counties and it includes 70 swine farms of different sizes totaling 248,000 swine. The proximity of farms to flood zones and urban areas is different for each farm.

4.2.1.3 Environmental Targets

The environmental goal specified for the Neuse River watershed in North Carolina calls for a 30% reduction in nitrogen from current levels. Assuming that for this goal to be achieved all point and non-point nitrogen source discharge will have to be reduced by 30% in the watershed, the collective nitrogen release from the swine farms in the area will also have to be reduced by the same percentage. This reduction will come from improvements in the treatment systems at these farms. All farms are assumed

to be currently using the anaerobic lagoon for treating their waste. Approximately 610 tons of nitrogen and 333 tons of phosphorus per year remain in the treated effluent that is land applied.

4.2.2 Least Cost Strategy - Methodology

A decision model to identify the most cost-effective management strategy was developed by Anastasiou et al. (Chapter 3). The allocation of appropriate wastewater treatment system to each farm to achieve environmental goals in a region is called a management strategy. The model is structured as a mathematical programming procedure that minimizes cost of treatment for a group of farms while attaining pollutant discharge standards.

The mathematical formulation to determine a management strategy is as follows:

$$\text{Minimize: } \sum_{f=1}^{70} \sum_{t=1}^9 C_{f,t} X_{f,t} \quad (4.1)$$

Subject to:

$$\sum_{t=1}^9 X_{f,t} = 1 \quad f = 1, 2, \dots, 70 \quad (4.2)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{\text{nitrogen}}) W_f^{\text{nitrogen}}] \leq 427 \text{ tons nitrogen/year} \quad (4.3)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{\text{phosphorus}}) W_f^{\text{phosphorus}}] \leq 333 \text{ tons phosphorus/year} \quad (4.4)$$

$$X_{f,t}, X_{f',t} \in \{0,1\} \quad f = 1, 2, \dots, 70; t = 1, 2, \dots, 9 \quad (4.5)$$

where C_{ft} is the cost of using treatment system t at farm f , X_{ft} is a binary variable indicating whether or not treatment system t is used at farm f , R_t^p is the percent removal of pollutant p by technology t , W_f^p is the waste load of pollutant p at farm f , T^p is the collective loading target for pollutant p , n is the number of available alternative technologies, and N is the total number of farms considered in the study area.

Eq. 1 represents the total cost of the nutrient reduction strategy. Eq. 2 ensures that one and only one treatment system is used at each farm. Eq. 3 ensures that the desired 30% reduction in nitrogen from the current levels released in the watershed is achieved. Equation 4 ensures that the phosphorus released to

the watershed does not exceed the currently released amount. The phosphorus constraint is necessary since some of the alternative treatment technologies do not perform as well as the currently used anaerobic lagoons in removing phosphorus from the waste. Eq. 5 limits the variable $X_{f,t}$ to be binary ($X_{f,t} = 1$ if treatment system t is allocated to farm f).

Solving this model, we obtain an optimum cost of \$173,000/year for the management strategy that meets our environmental goals. Both modeled environmental objectives, of nitrogen and phosphorus, were met. The binding constraint, in this solution, was nitrogen.

4.2.3 Model for Generating Alternatives - Methodology

Several methods for Modeling to Generate Alternatives have been developed (Brill, 1979; Church and Hubert, 1979; Chang, Brill, and Hopkins, 1981; and Chang 1981). The MGA in this paper is implemented using the Hop-Skip-and-Jump (HSJ) approach (Brill, et. al, 1982). The HSJ approach is designed to generate a series of management alternatives that are good with respect to the modeled objectives of cost and environmental targets but maximally different from each other. The objective of the model is to drive-out the technologies that were previously chosen for each farm. HSJ avoids allocating, as much as possible, the same technology to the same farm in new solutions generated. Each alternative is obtained by minimizing the sum of all the variables that are nonzero in any of the previously obtained solutions.

The mathematical representation of the initial MGA model is:

$$\text{Minimize:} \quad \sum_f \sum_t X_{f,t}^1 X_{f,t} \quad (4.6)$$

where $X_{f,t}^1$ is a binary variable that denotes whether technology t was allocated to farm f in the first solution for the scenario. By minimizing the objective function, the difference between the previous and the new solution is maximized. The following constraint limits the generated solutions to good alternatives:

$$\sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \leq C^T \quad \forall j \quad (4.7)$$

where C^T is the cost target, specified based on the least cost value. In this case, C^T is assigned, first, a 10% relaxation and, second, a 20% relaxation over the optimum cost. The optimum cost for the Least Cost technology allocation strategy is \$173,000/year (Anastasiou et al., Chapter 3). Therefore, the objective function for the MGA application (Eqn. 6) for a 10% relaxation over the optimum cost becomes:

$$\sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \leq \$191,000 / year \quad \forall j \quad (4.8a)$$

The alternatives generated are not sufficiently different if the targets of the model are too restrictive. Therefore, the model was reformulated to make it possible to obtain solutions that are even more different by relaxing the conflicting constraint. In this case study, the constraint was cost. Therefore, the cost constraint was relaxed to 20% over the optimum to become:

$$\sum_{f=1}^N \sum_{t=1}^n C_{f,t} X_{f,t} \leq \$208,000 / year \quad \forall j \quad (8b)$$

The environmental constraints that ensure nitrogen release reduction, and that maintain the current phosphorus level, found in the initial model (Eqns. 2, 3, and 4), must be still satisfied.

After more than one additional alternatives for the scenario are generated, the objective function for the HSJ approach (Eqn. 5) will become:

$$\text{Minimize:} \quad \sum_f \sum_t \left(\sum_{a=1}^A X_{f,t}^a \right) X_{f,t} \quad (4.9)$$

where $X_{f,t}^a$ is the binary variable. When $X_{f,t}^a$ takes a value of 1, it denotes that technology t was allocated to farm f in the previously generated alternative solution a. 'A' is the total number of alternatives previously generated.

The environmental target constraint equations (Eqns 10 and 11) remain:

$$\sum_{f=1}^{70} \sum_{t=1}^9 [X_{f,t} (100\% - R_t^{nitrogen}) W_f^{nitrogen}] \leq 427 \text{ tons nitrogen/year} \quad (4.10)$$

$$\sum_{f=1}^{70} \sum_{t=1}^9 (X_{f,t} (100\% - R_t^{phosphorus}) W_f^{phosphorus}) \leq 333 \text{ tons phosphorus/year} \quad (4.11)$$

4.3 Alternatives Generated

The solutions obtained using MGA analysis are different both in objective and in decision space. The results of the analysis performed with a 10% cost relaxation, over the optimal for the least cost technology allocation strategy, are presented.

4.3.1 What are the management alternatives?

Nine different alternatives to the least cost technology allocation strategy were generated. The maximum cost for any one of the alternatives is 10% higher than the optimum cost for the original management strategy. Figure 4.1 shows how many farms in the Lower Neuse River watershed would use a specific technology under each alternative. Each column in the chart represents all 70 farms in the region, for a management alternative. Columns are separated into sections, each section representing the number of farms using a technology t . Anaerobic lagoons (AL), Constructed Wetlands that use anaerobic lagoons for pretreatment (CW(AL)), Ambient Anaerobic Digesters (CAL(AL)), and Upflow Aerated Biofilter that use anaerobic lagoons for pretreatment (UAB(AL)) are the four technologies that are allocated to farms in the generated alternative strategies. Alternatives are arranged in order of increasing cost.

Figure 4.1 shows that certain of the nine possible treatment technologies are not cost-effective enough to be included in any of the management solutions. Specifically, the sequencing batch reactor (SBR) technologies, as well as the Constructed Wetland (CW(noAL)), Ambient Anaerobic Digester(CAL(noAL)), or the Upflow Aerobic Biofilter (UAB) that use an inclined screen solids separator, are never allocated to any farm in any of the cost-effective alternative solutions for the Least Cost management scenario. Instead, the technologies of choice are the anaerobic lagoons (already existing in all swine farms in the state), the constructed wetlands and aerobic biofilters that use the existing lagoons as pretreatment, and the ambient anaerobic digesters.

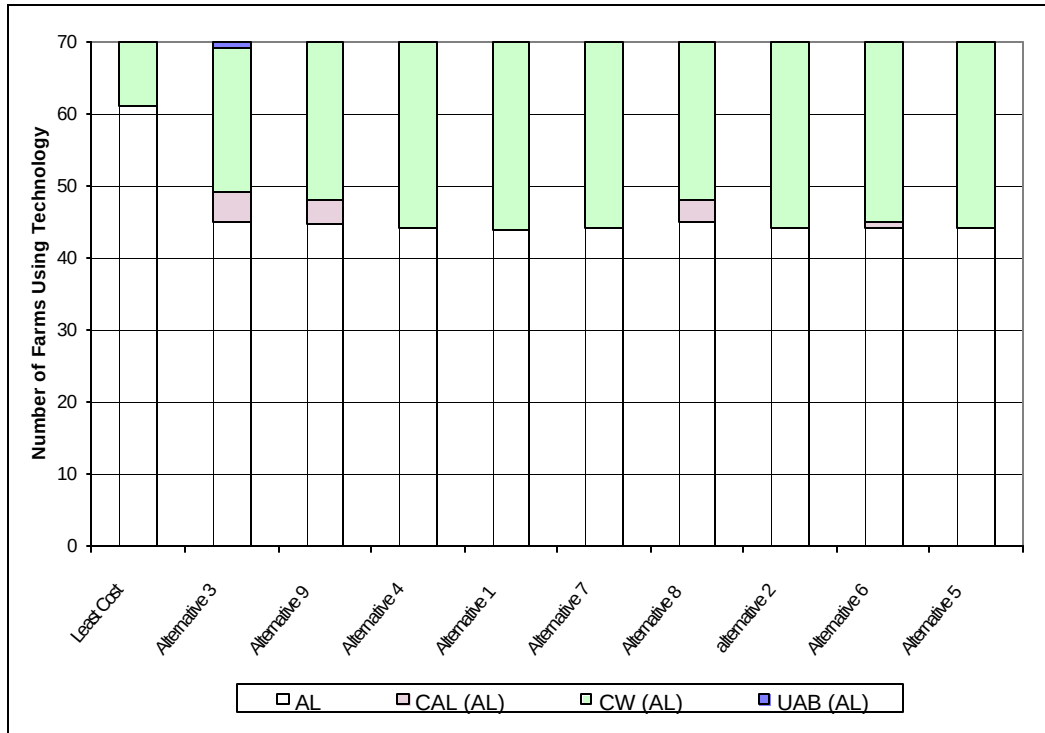


Figure 4.1 Technology allocations in the alternatives for the Least Cost technology allocation strategy, generated with a 10% relaxation on the optimal cost.

Although the number of farms that use the same treatment technology is similar in five of the ten alternative solutions, the locations of these farms are different for each treatment alternative (i.e. alternative technology allocation strategies are different in decision space). The cost values for the alternative solutions allude to this difference (Figure 4.2).

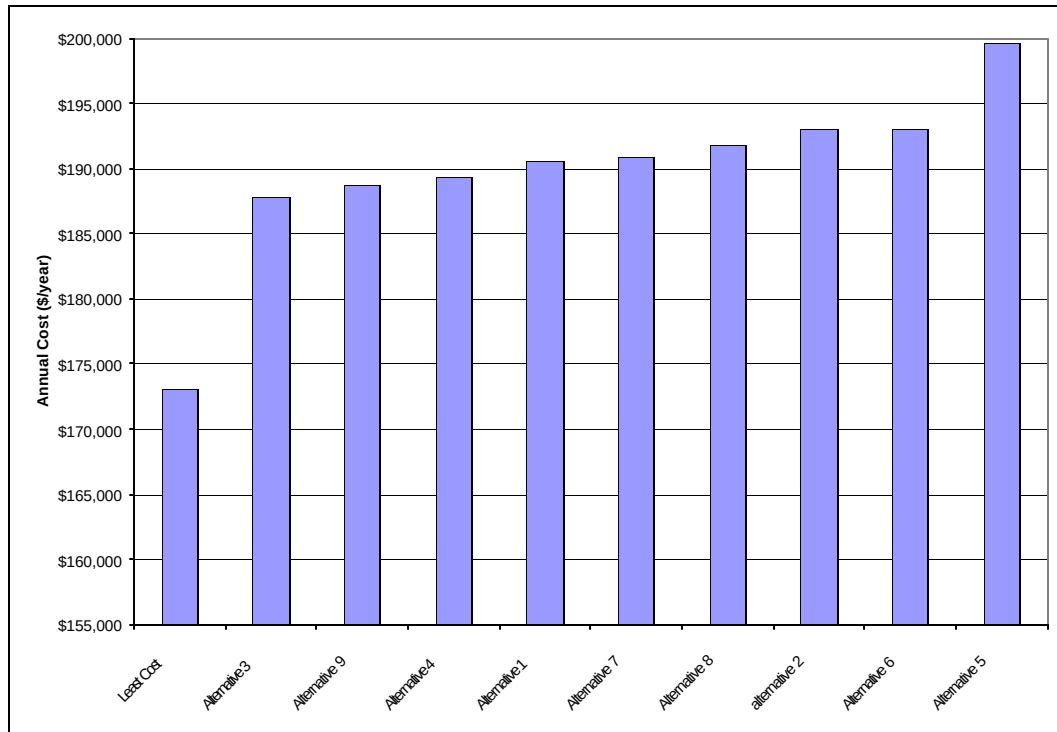


Figure 4.2 Cost of the generated alternatives for the Least Cost technology allocation strategy, generated with a 10% relaxation on the optimal cost.

4.3.2 What do these alternatives really mean?

To best appreciate the results from MGA analysis one must view these solutions in decision space. What we mean by decision space is, in this example, which technology t gets allocated to which farm f . Figures 4.3 and 4.4 show the results for management alternatives 1 and 2, generated from MGA methodology with a 10% relaxation on the optimal cost in decision space.

The cost of alternative 1 (Fig. 4.3) is \$191,000/year and the cost of alternative 2 (Fig. 4.4) is \$193,000/year. Despite the similarity in the annual cost, of each management alternative, the difference between the technology allocations becomes clear by observing the differences in the distribution of symbols on the two maps. Each symbol, on the maps, denotes a different treatment technology used at that specific farm. Anaerobic lagoons are denoted by a triangle and constructed wetlands by a circle. The size of each symbol is a measure of the farm size.

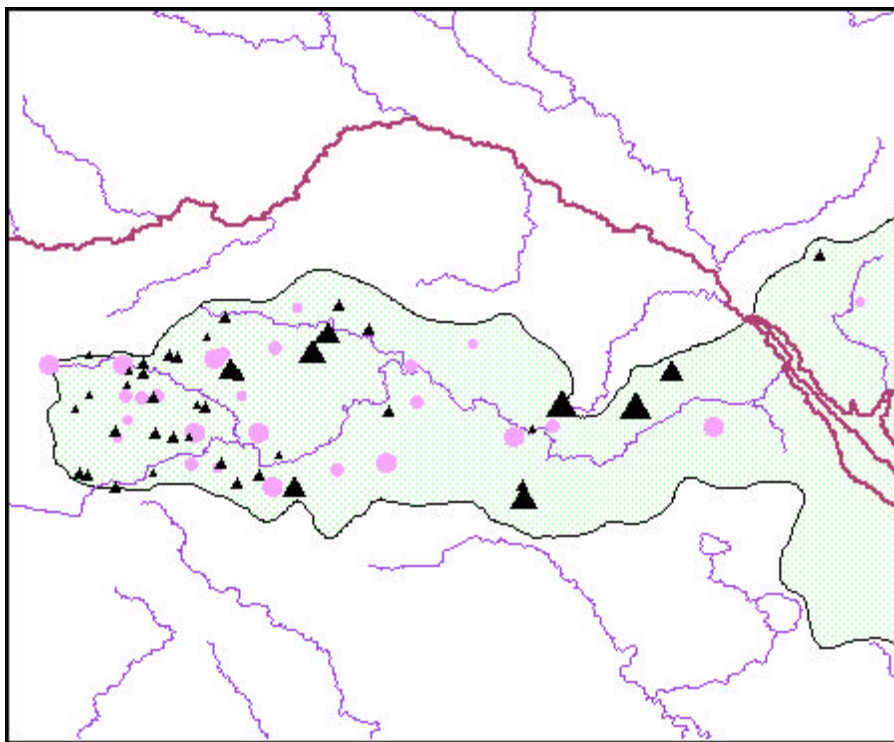


Figure 4.3 Technology allocations to farms for MGA Alternative management strategy # 1, generated with a 10% relaxation on the optimal cost.

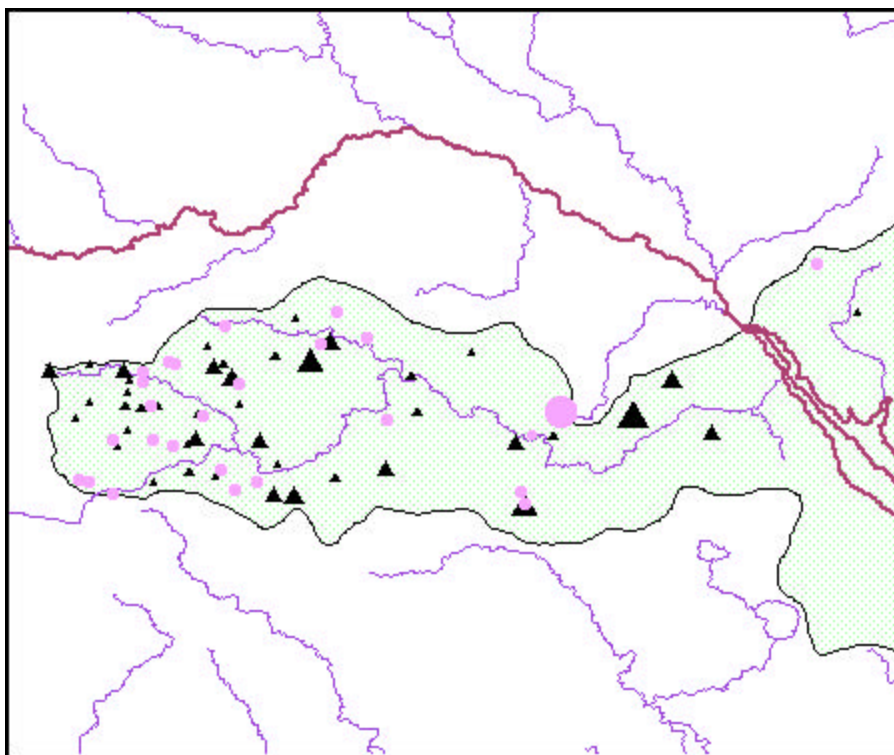


Figure 4.4 Technology allocations to farms for MGA Alternative management strategy # 2, generated with a 10% relaxation on the optimal cost.

In alternative 1, more medium-size farms use the constructed wetland with anaerobic lagoon pretreatment. Conversely, the largest farms use the existing anaerobic lagoons for treatment. In alternative 2, there is a more “balanced” use of the two technologies among the different size farms.

4.4 Use of Alternatives in Management

The problem of swine waste management in North Carolina is complicated. Many issues are involved, pursued by various stakeholders. Environmental managers, swine farmers, environmental activists, and researchers are a few of these stakeholders. In this section, hypothetical questions from each group will be posed and answered, in view of the MGA methodology and results.

4.4.1 Managers: “What about the Risk posed under each management alternative?”

Risk of pollutant release is one of the issues involved in trying to find a solution to the swine waste management problem in North Carolina. Environmental managers have become concerned with minimizing risk of pollutant and nutrient release to the watershed. In addition, anaerobic lagoons have been criticized by the public, as being prone to failure in flood events.

Risk is an objective that has not been included in our optimization model. However, it is still important to consider in reaching a decision regarding treatment technology use in the watershed. Having a number of different management alternatives, already generated by the MGA procedure, allows a management team to examine different starting points for a final implementation. In order to compare the management alternatives, introduced in the previous sections, a measure of risk is needed.

4.4.1.1 How can we define risk?

Relative risk indexes associated with floods for farms and for the treatment technologies were developed for the case study of the Lower Neuse River watershed swine farms by Anastasiou et al. (Chapter 3).

Farms that have a higher probability of being inundated during a flood event were given a higher relative risk index. This relative risk index is multiplied by the size of each farm to produce the overall risk index for each farm. A higher risk index indicates a greater risk to the watershed in the case of a flood. In a similar fashion, different treatment systems have different risk for releasing pollutants to the environment in flood events. The potential for pollutants escaping to the environment in a flood event dictates the

technology relative risk index value. The higher the potential is, the higher the risk index value. Table 4.1 summarizes the relative risk indexes for the farms and the treatment systems. A more detailed description of the relative risk indexes for the farms and the treatment technologies is provided in Anastasiou (2002).

Table 4.1 Summary of the relative risk indices used in the analysis

<i>Farm Location</i>	<i>Relative Risk Index</i>
Farms within the 100-year floodplain	100
Farms within the 500-year floodplain	10
Farms outside a floodplain	1
<i>Treatment System</i>	<i>Relative Risk Index</i>
Anaerobic Lagoon	10
Sequencing Batch Reactor with anaerobic lagoon pretreatment	10
Constructed Wetland with anaerobic lagoon pretreatment	10
Constructed Wetland with solids separator pretreatment	8
Ambient Anaerobic Digester	4
Sequencing Batch Reactor	2
Upflow Aerated Biofilter with anaerobic lagoon pretreatment	10
Upflow Aerated Biofilter with solids separation preceding	2

In this case study, after a technology allocation strategy has been generated using the optimization model, the risk to the watershed in a flood event is calculated for that strategy. This is achieved by multiplying the farm site relative risk index by the farm size and then by the relative risk index of the technology allocated to the farm. The risk calculated for each farm that uses a specific technology is then summed for all the farms in the watershed. This is repeated for all of the alternative strategies generated.

4.4.1.2 Which management alternative is riskier?

In response to the question of risk to the watershed, the results for MGA management alternatives 1 and 2 were spatially plotted in decision space using a GIS utility (Figures 4.5 and 4.6). A smaller size circle in Figs 4.5 and 4.6 denotes a smaller risk posed at a farm site than for large circles. Visual inspection of the maps shows that there is no difference between the two alternatives with respect to risk, neither spatially

nor numerically. A calculation of the total risk in the watershed reconfirms the similarity of this observation.

The manager's question was partially answered. No difference was noted between the two alternatives presented. This may not always be the case though. Other MGA generated alternatives may very well be different with respect to the risk objective. If this is not the case for alternatives generated from a 10% relaxation in the optimal cost, a different percent relaxation will always produce different results.

The purpose of the MGA methodology is not to include an objective in the optimization. Instead, solution alternatives are generated so that when an interested party poses a question different solutions could possibly be more favorable than others with respect to the question (i.e. objective) raised. The different solutions are not necessarily optimal with respect to any specific objective, which may be an afterthought, to the modeling process. Instead, they should be used as "starting points" that can generate discussion, thus aiding decision-making.

4.4.2 Farmers: "How much will I have to pay for treatment? How about other farmers?"

The people that are most directly affected by any management decision regarding swine waste management are the swine farmers themselves. Whether interested in finding an environmentally sound solution, or not, farmers are primarily businessmen and thus interested in their net profits. It is important to them that a cheap solution is found. In addition to a cheap solution, farmers also compete with one another. They are therefore interested in not paying more than their fellow farmers for waste treatment.

Equity is an objective that, like risk, has not been included in our optimization model. For a management solution to be implementable in the real world, it has to be "fair". Different management alternatives generated by the MGA procedure could have different equity values. For management alternatives to be further compared and contrasted, a measure of equity is needed.

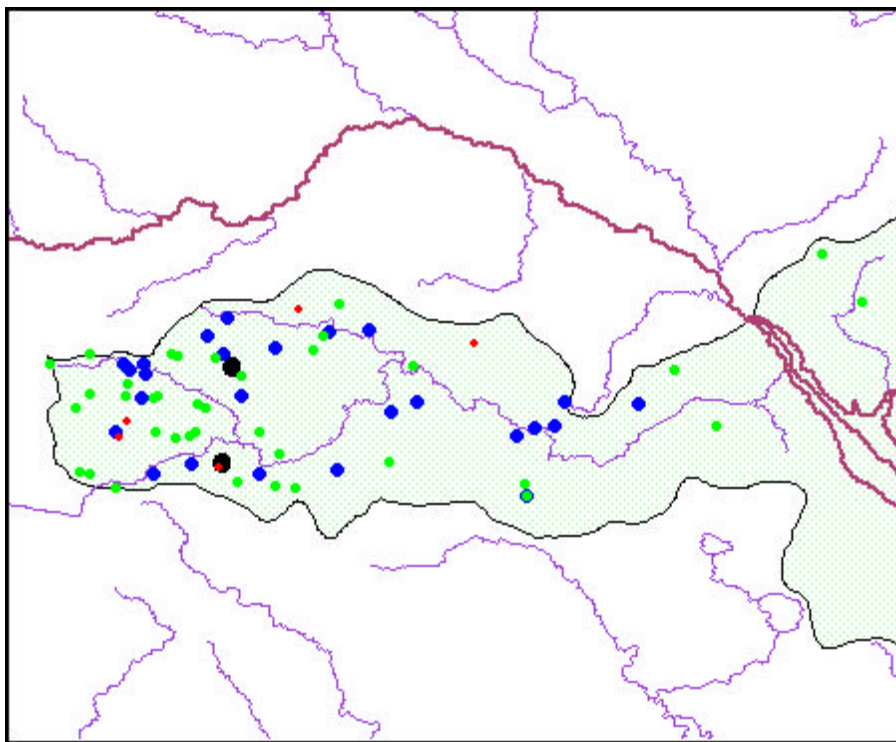


Figure 4.5 Risk posed by each farm site in the watershed, under MGA Alternative management strategy # 1, generated with a 10% relaxation on the optimal cost.

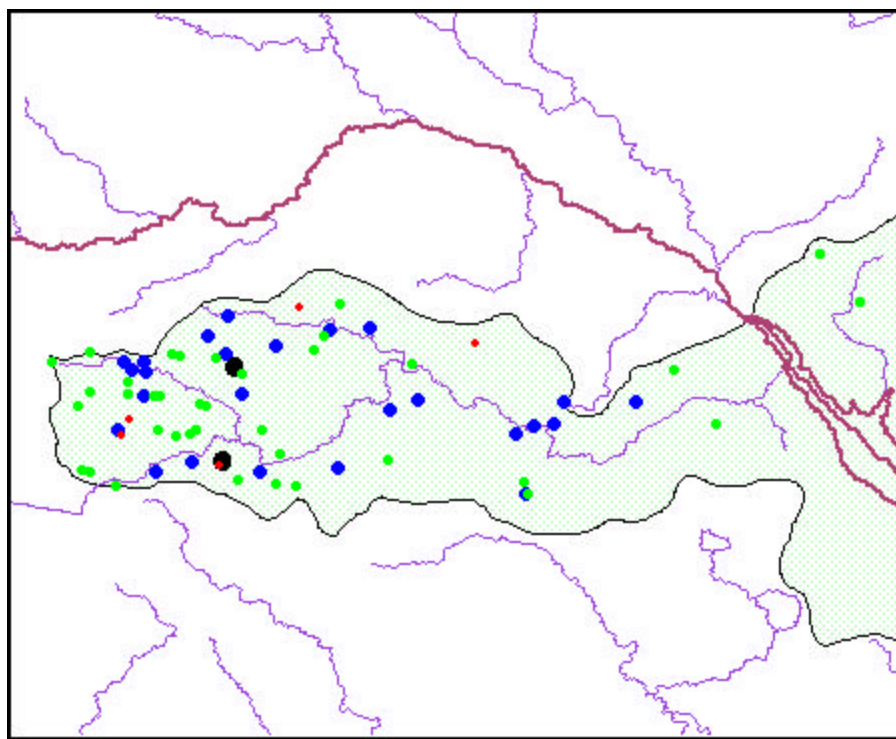


Figure 4.6 Risk posed by each farm site in the watershed, under MGA Alternative management strategy # 2, generated with a 10% relaxation on the optimal cost.

4.4.2.1 Defining equity can be controversial

Equity among waste-treatment-system use in swine farms is a primary planning objective. Equity is necessary in developing acceptable and feasible strategies to implement programs in any environmental management field. Equity can be interpreted as a state of ‘fair’ treatment among farms of similar characteristics, or of equal treatment among all farms.

Finding a good measure for equity can be a challenging task. In the field of water quality management, Johnson (1967) suggested that equals should be treated equally. Johnson’s (1967) suggestion raises the question of defining equality among farms. Depending on the characteristics of these farms considered different groups of ‘equals’ could be defined. One option could be to consider all swine farms as equal. Another could group farms according to their size, and even another according to their geographic location or ownership. Once a fair measure of ‘equals’ is decided on, the question of “equal treatment among equals” arises. For example, in the case of swine waste, the question could be whether farms of similar characteristics should be required to treat to the same level, use the same treatment technology, or pay the same unit price.

Anastasiou et al. (Chapter 3) indirectly addressed the issue of equity through the use of Johnson’s (1967) suggestion. The swine farms in Lower Neuse River watershed were separated into zones. These zones were based on characteristics such as farm size, operation type, or location. In the decision model developed, farms of the same grouping (zone) were required to treat their waste to the same level with respect of nitrogen removal.

However, in this paper, the equity measure used considers the “farmer’s perspective” instead. A ‘fair’ solution is considered the one that has the smallest discrepancy in unit cost of nitrogen removal, for the different farms in the watershed. Therefore, the most equitable solution would be the one in which the technologies allocated to farms cost the same per unit of nitrogen removed from their waste stream.

4.4.2.2 Is any one alternative more equitable than the others?

The unit costs, which each farm has to pay for the removal of nitrogen from the waste, are spatially presented for MGA alternatives 1 and 2 (Fig. 4.7 and 4.8). Smaller circles on the maps denote smaller, and bigger circles higher, unit costs for nitrogen removal at a specific farm. A brief comparative examination of the two maps shows that alternative 2 is obviously more equitable than alternative 1. The variation in the unit costs of farms under management alternative 1 is large. Specifically, two of the

farms in the watershed have to pay a distinctly higher price than the rest. Five more farms have a unit cost that is significantly higher than most others. In contrast, in management alternative 2, all of the farms in the watershed have a very similar unit cost for nitrogen treatment in the waste. Therefore, alternative 2 is a management strategy that farmers could find easier to accept.

The other MGA alternatives may have an even larger difference in equity. Regardless of what the difference may be, the starting points for decision-making have been established. Despite equity not having been one of the modeled objectives, the question posed by the farmers has been addressed.

4.4.2.3 Defining a watershed-wide measure of equity

Two different measures of equity were introduced. The first one is equity defined as equal unit cost of treatment, and the second is defined as equal level of treatment among farms. These two measures can sometimes contradict one another as to which management strategy is equitable. For example, a watershed-wide uniform treatment for farms should be the most equitable according to Johnson's (1967) suggestion. However, due to the economies of scale exhibited by treatment technologies, small farms will be spending much more to treat a unit of nitrogen than large farms. This leads to non-equitable solutions, when equity is measured as variation of unit costs.

Being aware of the possible problems of using unit cost variation as the surrogate for equity, and in the absence of a more universally accepted measure, the methodology is still used in this paper. The *coefficient of variation* on the unit cost of the farms in the watershed was chosen as the measure of equity. Each technology has a different unit cost depending on the farm in which it may be used. The coefficient of variation is the standard deviation of the treatment unit costs divided by the mean of the unit costs for all farms, for a given technology allocation scenario. The technology allocation scenario with the smallest coefficient of variation of unit costs is assumed the most equitable. This measure will be used in Section 4.4, where a comparison of the equitability of each management alternative is presented.

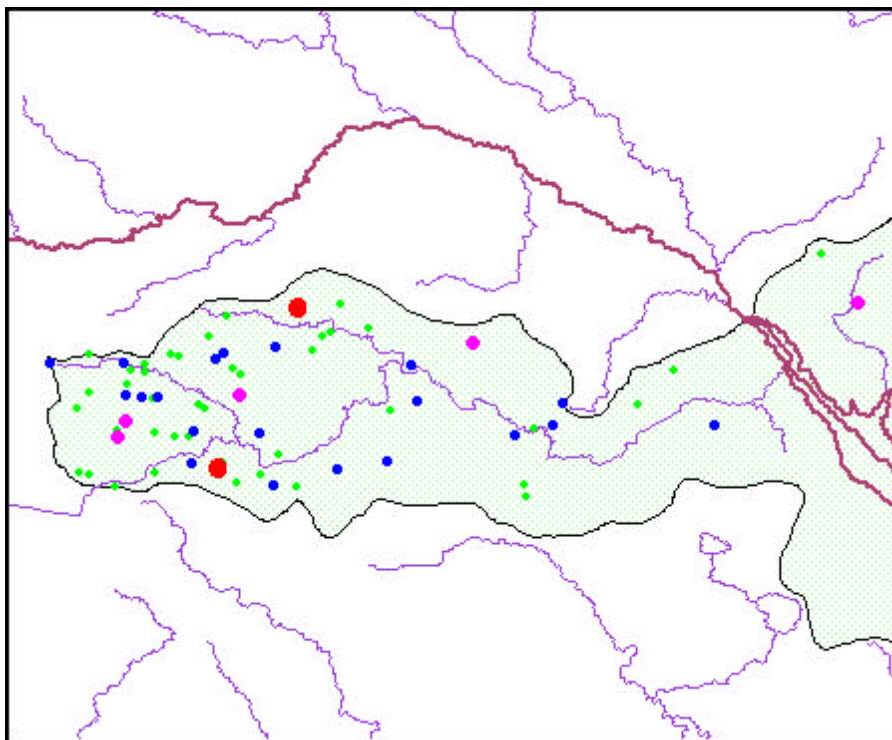


Figure 4.7 Unit Cost of treatment for farms under MGA Alternative management strategy # 1, generated with a 10% relaxation on the optimal cost.

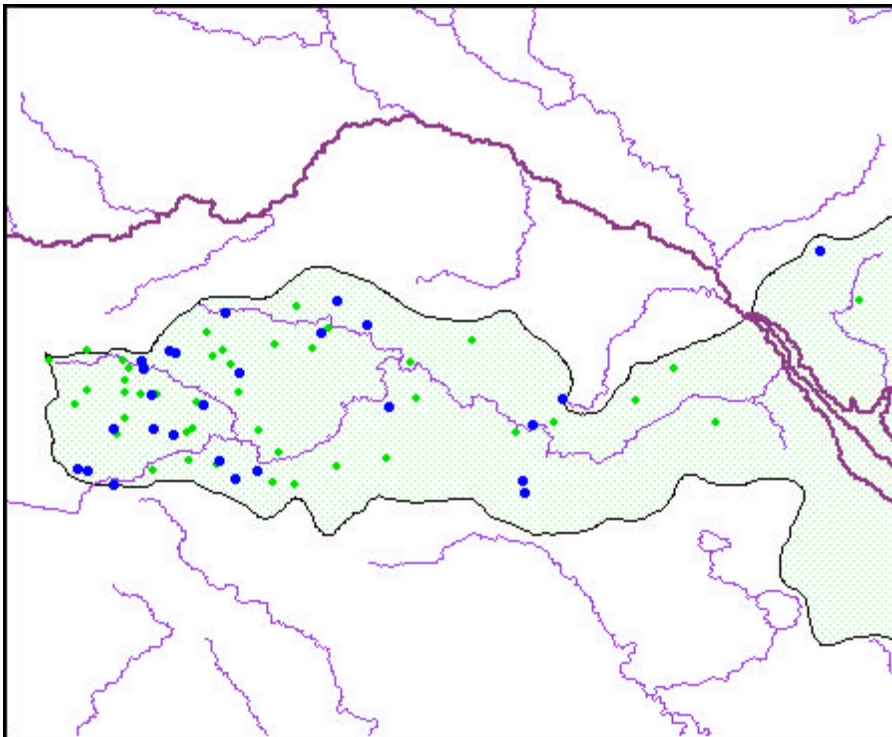


Figure 4.8 Unit Cost of treatment for farms under MGA Alternative management strategy # 2, generated with a 10% relaxation on the optimal cost.

4.4.3 Citizens: “I don’t want a malodorous and unsightly treatment system near my house”

The public of North Carolina has been long dissatisfied with the existing swine waste management practices. One of the reasons for this dissatisfaction has been the odor emitted from animal farming operations. Odor reduces the quality of life for nearby communities. Psychological stress, discomfort, headaches, and therefore lowered property values, are a few of the negative effects of bad odors on a community.

Different waste treatment systems have different efficiencies with respect to limiting odor emission. When farms are located close to populated areas, the use of such odor-limiting technologies would be desirable. The identification of cost-effective management strategies that minimize the effect of odor on communities located in the area of interest may be necessary.

Our management model has not considered the odor criterion in the optimization procedure. Odor could be modeled by using information about the locations of farms, their proximity to populated areas, the wind profile (wind direction and power density) in the area, and the population in the communities within the area of influence of the odor emitted from the farms. However, the lack of hard data on the degree of odor control by each alternative waste treatment technology did not permit the modeling of this objective now.

Since odor is still an important parameter in decision-making, the MGA alternatives become important. The different management alternatives will provide managers with options that will make consideration of odor easier. For example, the results of each MGA solution can be presented in decision space. In Figure 4.9, the technology allocations under MGA alternative 1 are mapped using a GIS utility. Triangles represent the existing anaerobic lagoons, which are to remain, and circles represent the system of constructed wetlands with anaerobic lagoon pretreatment. The size of each symbol is representative of the farm size. On the same map, the population density in the watershed is shown. The lightly shaded area denotes a lower population density. The main towns located in and around the watershed are also mapped (dark colored areas).

Viewing the various management alternatives on maps with similar features can help managers decide on a good solution, with respect to odor as well as possible additional considerations. For example, if a farm is in close proximity to a town, then the factor of aesthetics becomes important. Aesthetics, like odor, can cause emotional strain on nearby residents, cause realtor property values to drop, and in general cause a

community to financially deteriorate. Different treatment technologies have different acceptance by the public. For example, a constructed wetland is a ‘greener’ and more aesthetically pleasing treatment system than an anaerobic lagoon. Viewing management alternatives in decision space can help decision makers identify more issues and implement better strategies.

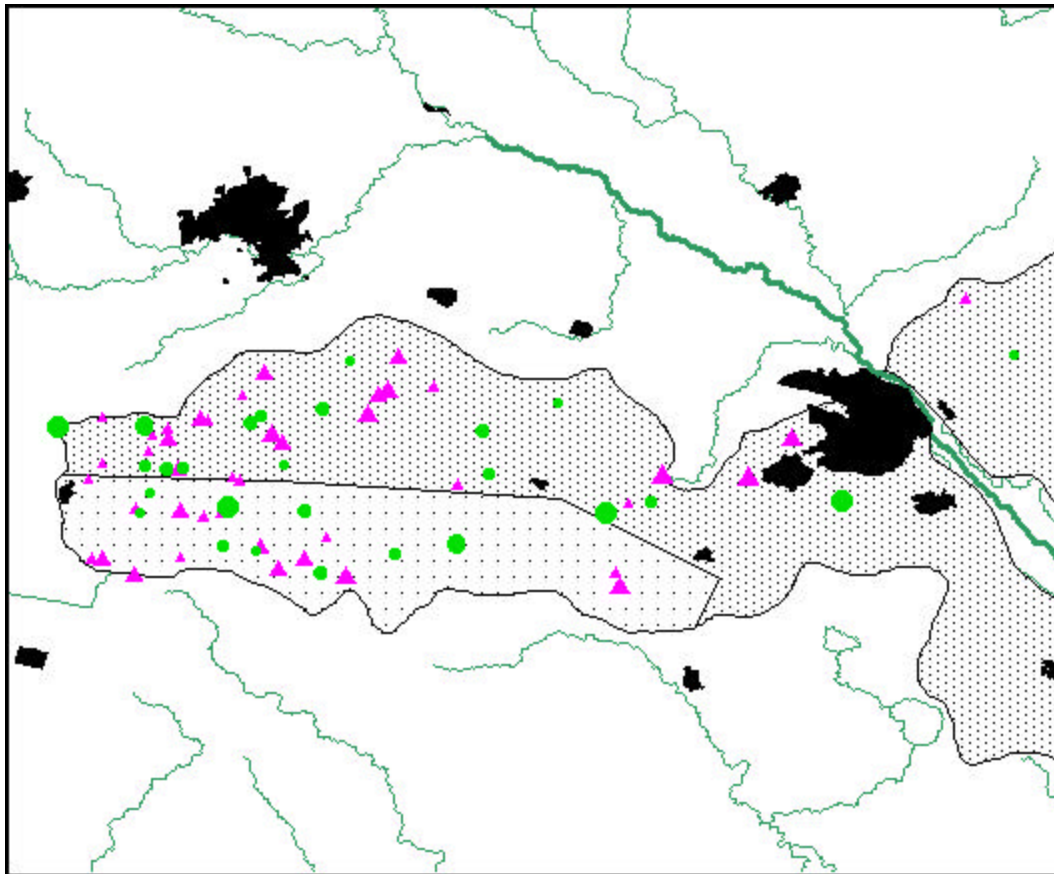


Figure 4.9 Population Density and Towns located in the Lower Neuse River watershed. The farm allocations, for MGA alternative # 1, shown were generated with a 10% relaxation on the optimal cost.

4.4.4 Researchers: “Does MGA tell us anything else about swine waste management?”

Studying the MGA results can provide insight to a problem. The results of the MGA analysis have to be viewed collectively for an understanding of the problem to be gained. For example, by plotting the risk index values and cost of the different MGA alternatives generated (Figure 4.10), we see that the risk is very similar for all the solutions, near the maximum risk possible, for the watershed. In Fig.4.10 the cost of each technology allocation alternative is represented as a bar. The risk to the watershed, under each given alternative technology allocation is denoted by the dotted line. The cost of each alternative is read

on the primary ordinate axis. The risk index values of each alternative are read on the secondary ordinate axis. A higher risk index denotes a higher potential for damage being caused due to nutrient and solids release during a flood event in the watershed.

Observing similar risk indexes in the MGA alternatives does not necessarily mean that we cannot formulate a technology allocation strategy that has a lower risk index for the watershed. If the risk objective is modeled, we get a risk index of 12,706,880 when cost is kept within a 10% increase over the optimal cost of the least cost strategy. This value denotes a 33.6% decrease in risk for a 10% increase in cost. However, the important information that the MGA application provides is that there may not be much flexibility with regards to low risk alternatives under the given cost range.

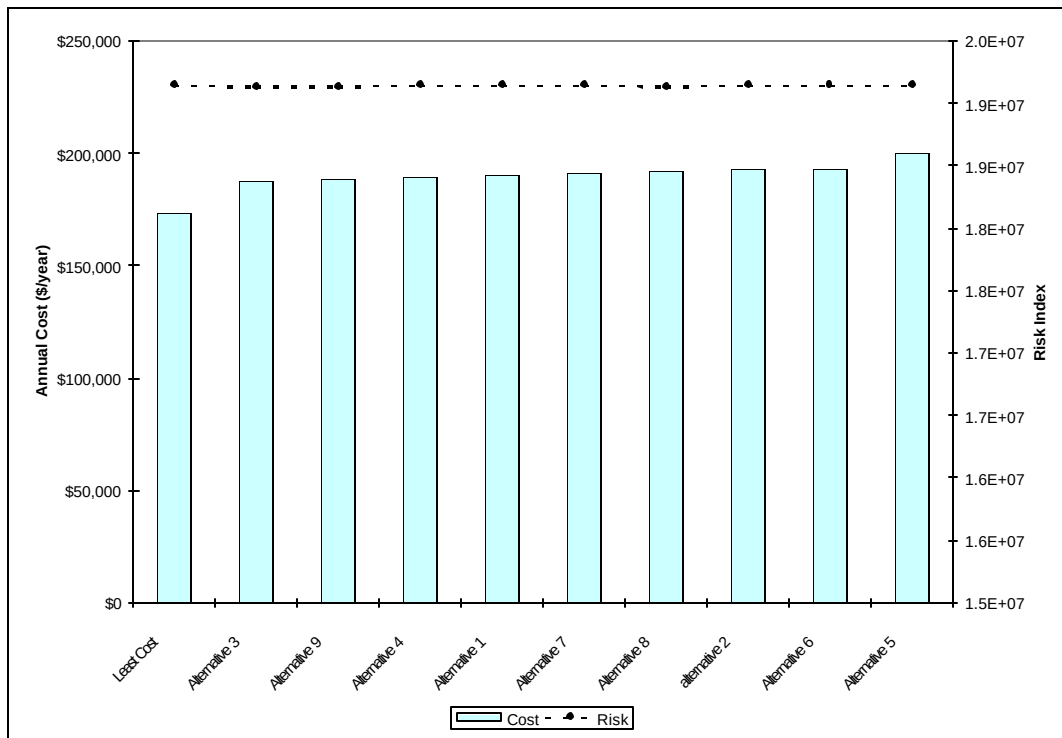


Figure 4.10 Cost and Risk Index values for the MGA alternative management strategies, generated with a 10% relaxation on the optimal cost.

Unlike risk index values, we can see the difference in equity values for the distribution of technologies to different farms for the same management alternatives (Fig.4.11). Again, the bars on the chart represent the cost of each alternative, and cost values are read on the primary ordinate axis. The equity values of each alternative are denoted by the continuous line and are read on the secondary ordinate axis as coefficients of variation for technology allocation strategy. The coefficient of variation in unit cost

for technologies in farms is used as a measure of equity for management strategies. A higher coefficient of variation value denotes a less equitable solution. The differences in equity between certain alternatives are quite significant, although the cost for the alternatives does not differ by much. For example, alternative 2 is 35% more ‘equitable’ than alternative 6, despite the fact that their risk index values are very similar and their cost values are the same. Observing alternatives 4, 1, 7, and 2, we can now see that although the same number of farms use anaerobic lagoons and constructed wetlands for treatment, and although their risk index is the same for a small cost difference, the coefficient of variation is greatly variable.

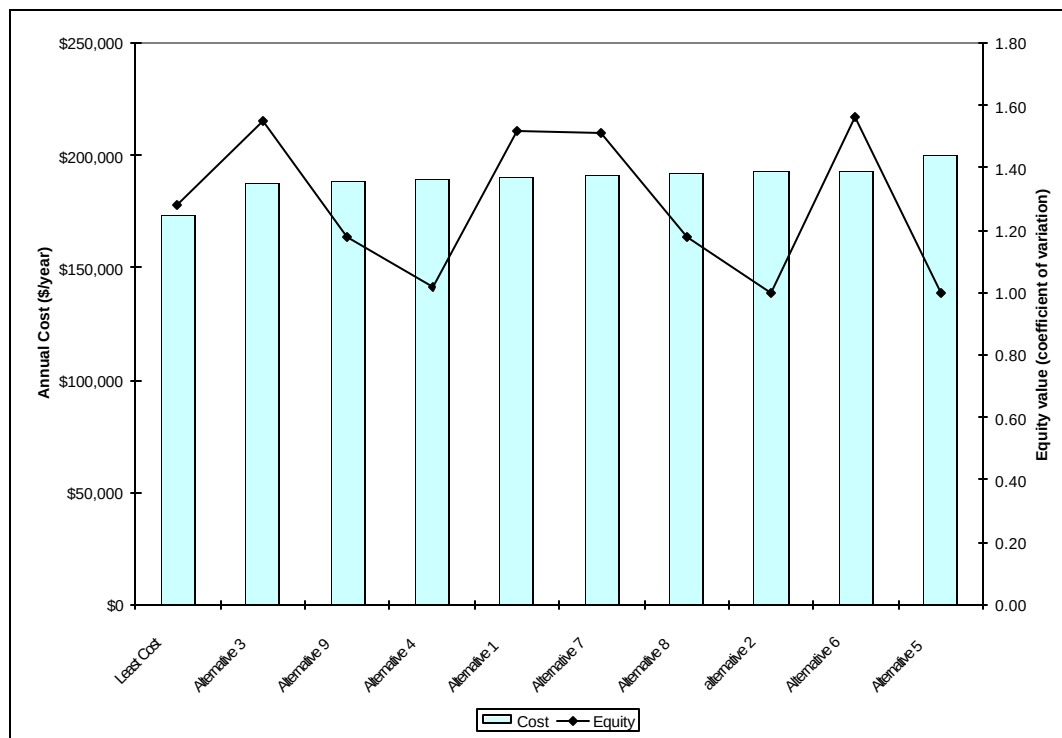


Figure 4.11 Cost and Equity values for the MGA alternative management strategies, generated with a 10% relaxation on the optimal cost.

By repeating this exercise of comparing the different alternatives generated by MGA one can start drawing certain conclusions as to the nature of the problem. Summarizing the suggestions indicated by the results of the analysis introduced, we see that the problem may be inflexible with respect to flooding risk but significantly more flexible with regards to equity.

4.4.4.1 Learning from MGA, and further steps

One might say that the alternatives generated with a 10% relaxation on the optimal cost are not sufficiently different with respect to certain unmodeled objectives. Despite the fact that decision space solutions are different, objectives such as risk have not been shown to be very flexible. This may be due to the fact that the targets of cost and/or nutrient release are too restrictive. Therefore, solutions that are more different were obtained by relaxing the conflicting target of cost.

When MGA is applied to the model for an allowable 20% cost increase, over the optimal value, the risk and equity values are significantly different for the alternative solutions. This becomes immediately evident by observing the distribution of technologies allocated to farms in the watershed (Figure 4.12). The technology distributions for the various alternatives are organized in order of cost of the management strategy, with the cheapest strategies to the left of the chart and the most expensive to the right. It is interesting to see that more of the available alternative treatment technologies are feasible to use in the watershed's farms.

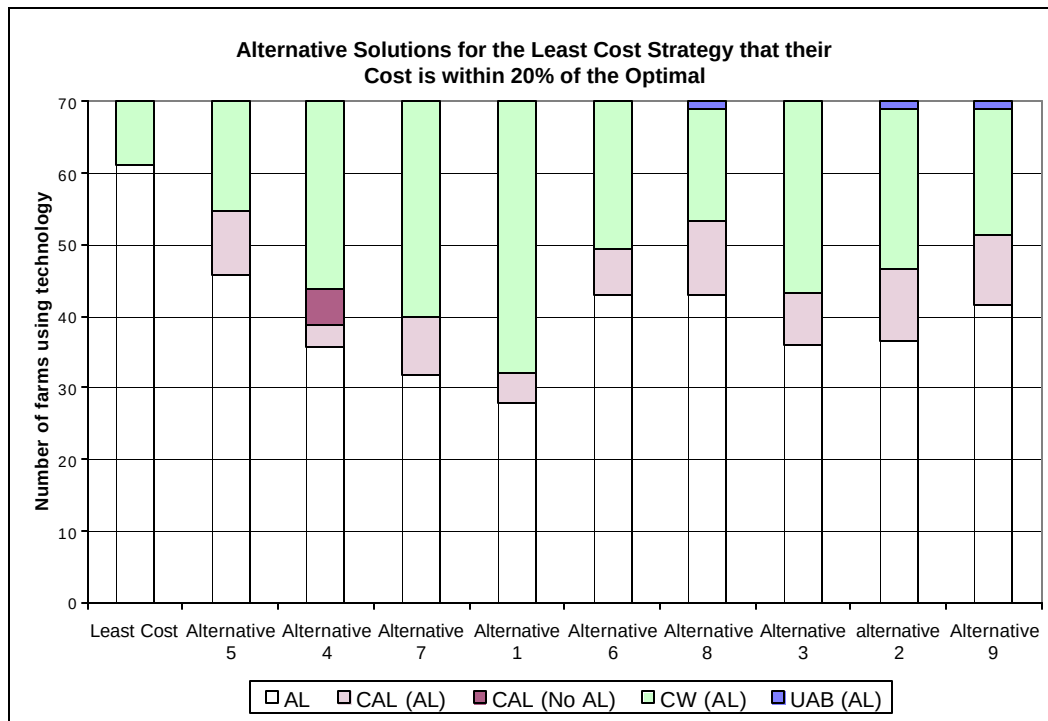


Figure 4.12 Technology allocations in the alternatives for the Least Cost technology allocation strategy, generated with a 20% relaxation on the optimal cost.

The existing anaerobic lagoons (AL), the ambient anaerobic digester (CAL), the constructed wetland with the anaerobic lagoon pretreatment (CW(AL)) and the upflow aerated biofilter with anaerobic lagoon pretreatment of waste (UAB(AL)) are the five, out of the nine, treatment systems that are used at one or another management alternative.

Further differences among the 20%-cost-relaxation alternatives are more evident in the objective space. Figure 4.13 shows the cost and risk index values for these alternatives. We see that by relaxing the cost constraint by an additional 10%, the solutions became evidently more flexible. Similar to the alternatives generated with the 10% cost relaxation, the risk indexes of the solutions do not mean that these would include the lowest value that we can obtain for an allowable cost of \$208,000/year. For the least possible risk under the given cost to be determined, the objective of risk would have to be modeled. However, we see that, for example, MGA alternative 6 poses significantly lower risk to the watershed (approximately 14% than other alternatives). The purpose of MGA is to identify ‘good’ management alternatives that are different with respect to *unmodeled* objectives.

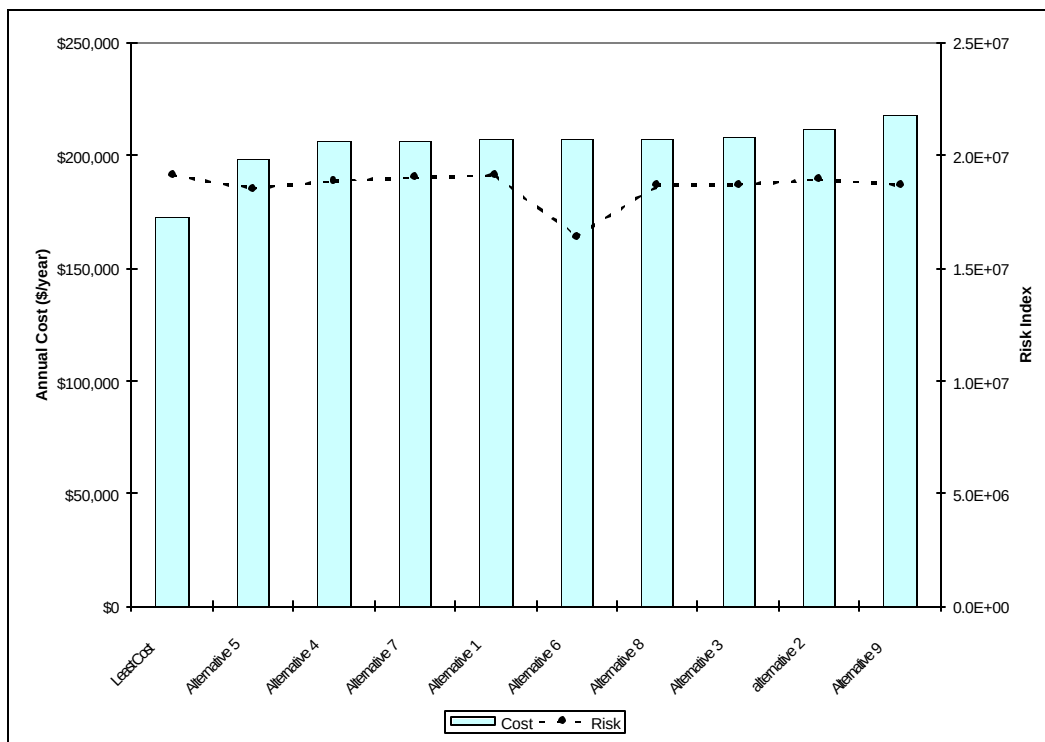


Figure 4.13 Cost and Risk Index values for the MGA alternative management strategies, generated with a 20% relaxation on the optimal cost.

Similarly, the “fairness” of the alternatives is different. An alternative with high risk does not necessarily mean low equity value, and vice versa. In Figure 4.14, the risk index of each alternative is denoted by the dotted line and its value referenced on the primary ordinate axis. The equity of each alternative is given as a measure of the coefficient of variation of the unit costs of technologies allocated to farms in the watershed. That value is referenced in the secondary ordinate axis and is denoted as the solid line for the various alternatives. The risk and equity values, for the MGA alternatives, are arranged from left to right in order of increasing cost for the management alternatives.

No management alternative is clearly superior to the others with respect to both of the unmodeled objectives. Generation of more alternatives, or generation of alternatives under the relaxation of a modeled objective by a different amount may or may not produce a solution that would be markedly better.

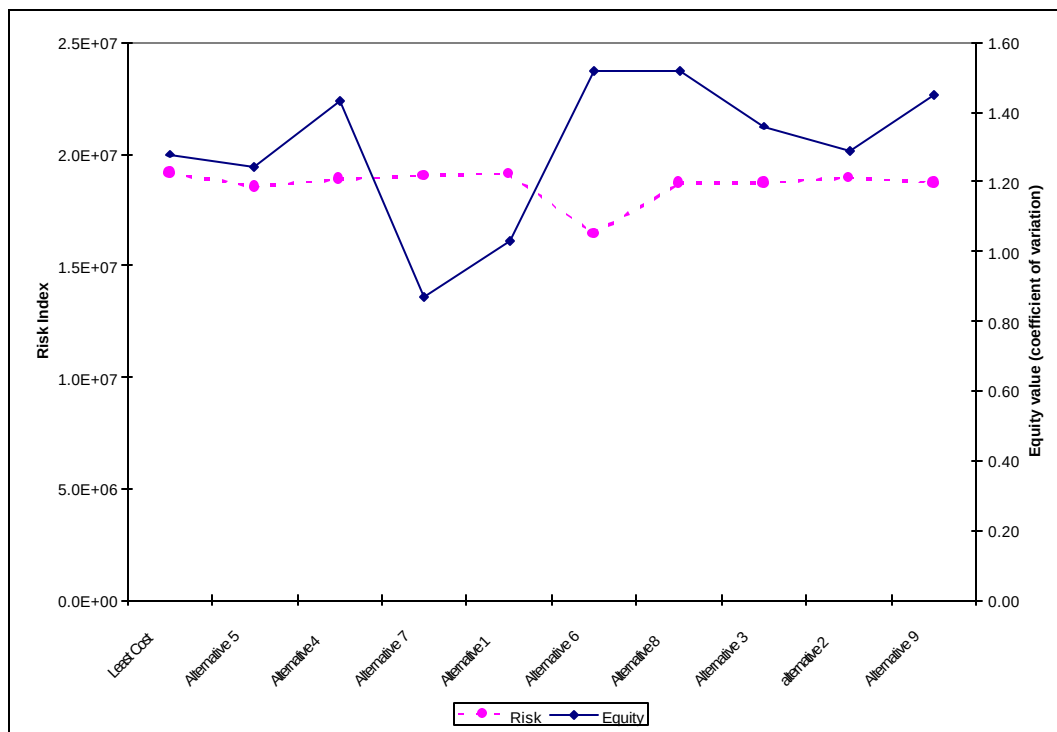


Figure 4.14 Risk and Equity values for the MGA alternative management strategies, generated with a 20% relaxation on the optimal cost.

Comparing the results of the alternatives generated with a 10% and a 20% relaxation on the optimal cost shows the type of analysis that MGA can be used in understanding a problem. Tables 4.2 and 4.3 show the costs, risk, and equity values for the various MGA-generated alternatives under a 10% and a 20%

relaxation of the optimal cost, respectively. Environmental managers, and other stakeholders, should observe these solutions and decide on which modeled objective should be relaxed, and by how much, for feasible ‘good’ alternatives to be generated. What defines a ‘good’ alternative should be determined as part of the decision-making. Comparing such results may indicate whether the given problem is flexible enough so as to allow solutions that significantly differ from one another with respect to some objective.

Table 4.2 Risk and Equity values for the different MGA generated alternatives for a 10% relaxation over the optimal cost value for the least cost strategy.

MGA Solution	Cost (\$/year)	Risk	Equity (coefficient of variation)
Least Cost Strategy	173,105	19,138,880	1.28
Alternative 1	190,647	19,138,880	1.52
Alternative 2	192,980	19,138,880	1.00
Alternative 3	187,847	19,128,770	1.55
Alternative 4	189,368	19,138,880	1.02
Alternative 5	199,690	19,138,880	1.00
Alternative 6	193,044	19,138,880	1.56
Alternative 7	190,858	19,138,880	1.51
Alternative 8	191,749	19,132,130	1.18
Alternative 9	188,694	19,132,130	1.18

Table 4.3 Risk and Equity values for the different MGA generated alternatives for a 20% relaxation over the optimal cost value for the least cost strategy.

MGA Solution	Cost (\$/year)	Risk	Equity (coefficient of variation)
Least Cost Strategy	173,105	19,138,880	1.28
Alternative 1	207,282	19,121,330	1.03
Alternative 2	211,760	18,930,680	1.29
Alternative 3	208,380	18,705,320	1.36
Alternative 4	206,050	18,876,170	1.43
Alternative 5	198,142	18,530,972	1.24
Alternative 6	207,307	16,393,760	1.52
Alternative 7	206,203	19,015,550	0.87
Alternative 8	207,676	18,696,020	1.52
Alternative 9	218,430	18,696,020	1.45

4.4.4.2 Trends in technology allocations indicated by the MGA results

Another way in which MGA results could be used is in finding trends within the solutions. For example, we can separate the watershed’s farms into size categories. We can subsequently determine what

technologies are allocated more frequently to each farm size category (by observing all of the generated alternatives). Such an analysis was performed for results obtained by analysis with both a 10% and a 20% relaxation in the optimal cost of the least cost strategy. The results of the analysis are summarized in Tables 4.4 and 4.5. The number of times that each technology is allocated to a farm of a size category is indicated, alongside the percent of total farms that it represents.

Table 4.4 Frequency of use of each technology by farm size (based on the ten MGA alternatives for the Least Cost strategy, generated with a 10% relaxation on the optimal cost).

Farm Size (swine)	AL	D (w/AL)	D (w/o AL)	CW (w/AL)	CW (w/o AL)	SBR (w/AL)	SBR (w/o AL)	UAB (w/AL)	UAB (w/o AL)	# of Farms in category
0-1999	119 66%	11 6%	0	49 27%	0	0	0	1 1%	0	18
2000-3999	216 64%	0	0	124 36%	0	0	0	0	0	34
4000-5999	70 70%	0	0	30 30%	0	0	0	0	0	10
6000-7999	28 70%	0	0	12 30%	0	0	0	0	0	4
8000-10000	14 70%	0	0	6 30%	0	0	0	0	0	2
>10,000	13 65%	0	0	7 35%	0	0	0	0	0	2
Totals	460	11	0	228	0	0	0	1	0	70

Table 4.5 Frequency of use of each technology by farm size (based on the ten MGA alternatives for the Least Cost strategy, generated with a 20% relaxation on the optimal cost).

Farm Size (swine)	AL	D (w/AL)	D (w/o AL)	CW (w/AL)	CW (w/o AL)	SBR (w/AL)	SBR (w/o AL)	UAB (w/AL)	UAB (w/o AL)	# of Farms in category
0-1999	79 44%	40 22%	5 3%	53 29%	0	0	0	3 2%	0	18
2000-3999	200 59%	27 8%	0	113 33%	0	0	0	0	0	34
4000-5999	70 70%	0	0	30 30%	0	0	0	0	0	10
6000-7999	26 65%	0	0	14 35%	0	0	0	0	0	4
8000-10000	12 60%	0	0	8 40%	0	0	0	0	0	2
>10,000	15 75%	0	0	5 25%	0	0	0	0	0	2
Totals	405	68	5	224	0	0	0	3	0	70

The results indicated in Table 4.4 do not necessarily show any definite pattern in the allocation of specific technologies to farm of a certain size. A similar percent of farms in each size category are allocated with

the existing anaerobic lagoon technology. This percent ranges from 64-70%. It is obvious, however, that smaller-size farms are more flexible with respect to the type of treatment system they use. The results indicated in Table 4.5, on the other hand, indicate a clear trend of increasing use of anaerobic lagoons in larger size farms. The percentages of use of anaerobic lagoons increase from 44% for smaller size farms to 75% for larger size farms. Also, the flexibility in the use of different treatment technologies by smaller farms is reconfirmed by the data provided in Table 4.5. An additional interesting piece of information that is noted is the similarity in technology distribution for the 4000-5999 swine and the 6000-7999 farm sizes. Approximately 70% of the farms that belong to these size categories use the anaerobic lagoons as the technology of choice.

4.5 Is MGA Useful in Regional Management of Animal Waste?

This paper presented an example of how a decision-making process could proceed and how MGA analysis could be used to assist that process. Questions of risk, equity, odor and aesthetics regarding swine waste management in the Lower Neuse River watershed were raised from viewing MGA results. The way in which these results were used in analyzing the problem as well as initiating a discussion on management possibilities was also shown. It became clear that there are different ways in which swine waste can be managed in North Carolina, without necessarily sacrificing any of our modeled objectives of cost and nutrient reduction in the watershed.

There are many more concerns about swine waste management that one could raise. To give a few more examples, consider the following questions that were generated in a 'brainstorming session': 1. How easy to operate are the chosen treatment technologies? Farmers are concerned about the training that they will have to undergo in order to be able to operate some of the alternative treatment technologies. 2. How much dependence on electricity do these technologies have? The concern here would be that in case of power failure waste will go untreated, thus creating problems in certain environmentally sensitive areas. 3. How about ammonia volatilization and re-deposition that is associated with swine waste treatment systems? This is a much-discussed issue regarding swine waste. It is also one of the main criticisms of anaerobic lagoons. Its quantification has been, however, slow. 4. How does the capital investment compare to the operation and maintenance costs of treatment? Some farmers may not have the financial means to initially construct certain alternative treatment technologies that may be initially costly. These are but a few examples of issues that could be raised about swine waste treatment.

Considering the examples analyzed in this paper, as well as the ones lastly mentioned, one could easily recognize that we cannot possibly model all of the viable concerns and objectives of our management process. It thus becomes evident that having a number of maximally different solutions to a problem can be advantageous to decision-making. MGA is a technique useful to not only manage swine waste in the Lower Neuse River watershed but also to manage animal waste in North Carolina or to make any other decision of regional interest in any area.

CHAPTER 5: Consideration of Uncertainty in Swine Waste Management in North Carolina

Abstract

There are alternative ways in which appropriate treatment technologies can be allocated to farms in an area. A number of different possible management scenarios were identified with the use of formal optimization techniques. However, the uncertainty in the inputs of the decision support models leads to uncertainty in the performance of a management scenarios solution. While a model-driven solution is expected to perform well with respect to the deterministic estimates of cost and other modeled objectives, the performance of that solution is not necessarily reliable when the input parameters are uncertain. This paper shows how uncertainty analysis can help estimate the reliability (or likelihood of success) of a solution. In addition, uncertainty importance analysis (correlation analysis) can help identify the input parameters that contribute the most to the output uncertainty. The use of these techniques in assisting decision-making in the field of animal waste management is demonstrated for a study case of the swine farms in the Lower Neuse River watershed.

5.1 Introduction

Animal waste management is becoming increasingly important in North Carolina and elsewhere in the United States. Poorly managed releases of waste from animal farms may pose a serious environmental, public health, and an aesthetic problem. Swine waste in North Carolina is currently managed predominantly through anaerobic lagoons and sprayfields. In response to public dissatisfaction with these systems, the State of North Carolina has proposed to replace lagoon systems with alternative treatment technologies. Evaluation of the costs and technical feasibility of converting animal waste lagoons to environmentally safer waste treatment technologies is currently under way (Williams, 2002). These studies provide the critical knowledge base for identifying the cost-effective technology option for an individual farm. Predictive models that characterize animal treatment technologies for specific farms have been developed (Anastasiou et al., Chapter 2). In addition, methods to identify collective or regional management strategies that achieve desired treatment, cost, and public protection goals are being examined (Anastasiou et al., Chapter 2 and Chapter 3). Evaluation of these technologies and collective decisions are dependent on many factors, such as economies of scale, farm location, and technical feasibility, etc.

Animal waste treatment technologies have yet to be fully evaluated. Completed evaluation studies and published results are limited. Therefore, many of the factors affecting decisions for the replacement of anaerobic lagoons have a high degree of uncertainty. Sources of uncertainty vary and range from statistical variation to subjective judgment, linguistic imprecision, variability, inherent randomness, disagreement among sources, and approximation (Morgan and Henrion, 1990). In the case of swine waste treatment technologies, most of the input uncertainty can be attributed to incomplete data, disagreement among sources, approximation, and subjective judgment. It is important that the implications of the uncertain inputs on model predictions (management strategies at the farm or in a region) are incorporated in the decision-making.

5.1.1 Contribution

Collective management strategies should consider not only cost and environmental compliance but also practical implementation and reliability of the possible solutions. The primary goal of this paper is to demonstrate how the consideration of uncertainty in the results of predictive and optimization models can lead to better decision-making in animal waste management. The effect of uncertainty on decisions made at the farm level and in a region is examined. This methodology is demonstrated through an illustrative case study of the swine farms of the Lower Neuse River watershed in North Carolina. This watershed was the focus of a previously developed modeling approach that addressed the animal waste management problem at a regional level (Anastasiou et al., Chapter 3, Chapter 4).

5.2 Sources of Uncertainty

Uncertainty is introduced in the decision-making through the incompletely evaluated parameters that characterize alternative animal waste treatment technologies. These parameters provide the basis for the predictive models and the general methodology that assists decision-making. Any uncertainty in these parameters would mean less robust management solutions. An understanding of how these predictive models are structured is helpful.

5.2.1 Computer Assisted System Selection Tool (CAWSST)

CAWSST is a tool that helps examine, compare and contrast various treatment technologies available for animal waste (Anastasiou, Chapter 2). With this tool, farmers can make better-informed decisions

regarding the appropriate treatment technology to implement on their farms. Mathematical descriptions of treatment efficiencies and cost of technologies are useful in generalizing available information on farms of different sizes and operational characteristics.

Anaerobic lagoons, constructed wetlands, sequencing batch reactors, ambient anaerobic digesters, and upflow aerated-biofilters are the five basic treatment processes described in CAWSST (Anastasiou et al., Chapter 2). The latter four processes are evaluated for the case when an anaerobic lagoon is already present at a farm site, and thus it can be included in the treatment system, and for when an anaerobic lagoon is not present. Therefore, there are nine different treatment systems described in CAWSST. Each treatment technology described is based on data obtained from pilot or full-scale evaluation studies. The treatment efficiency and the design characteristics (i.e. land required for a system) of each technology are based on mass balances and empirical constants. For example, the fate of nitrogen in the waste is tracked within the unit processes of each technology. Empirical parameters govern the unit processes of the technologies in the tool. Examples of such parameters are the treatment efficiencies, loading rates, and sizing requirements for each technology, and the cost of electricity used per kilowatt-hour. CAWSST produces outputs for treatment systems for specific farms. These outputs include the capital and annual operational costs for each technology, per-pig cost, land area required by each technology, volume of effluent water from each technology, and the nitrogen and phosphorus removal efficiency of each technology.

Most of CAWSST model parameters were uncertain due to incomplete data, approximation, and subjective judgment. Ninety-four input parameters were considered uncertain and each was described by a mode, and a range of values or a standard deviation (Table 5.1). The probability distributions of the input parameters are independent and non-correlated to one another.

The appropriate probability distributions and the statistical properties for the uncertain inputs were assigned individually using the available literature and engineering judgment. Different distributions were assigned to describe the uncertainty in the inputs. Triangular distributions were most frequently selected; the deterministic value of an input parameter was chosen as the mode, and lower and upper range values were assigned accordingly. Triangular distributions were assigned to parameters for which the mode and the range of values are known from literature or that they were based on engineering assumptions. Uniform distributions were used for the input parameters that have a defined range but for which a mode cannot be clearly identified. This distribution is used for the parameters that are not described in published studies. A normal distribution was assigned to only one parameter (annual excess

rainfall), for which real data were available. The probability distribution of each input parameter of CAWSST is described in Table 5.1.

Table 5.1 Uncertain input parameters in the CAWSST models.

<i>All Systems</i>	<i>Units</i>	<i>Distribution</i>	<i>Range</i>		<i>Std. Dev.</i>	<i>Mode</i>
			<i>low</i>	<i>high</i>		
Average finishing hog weight	lbs	Uniform	135	155	0	150
Manure Volume per Pig	gallons / day / 150 lb pig	Triangular	2.423	2.805	0	2.55
Nitrogen mass in manure	lb N / lb swine / year	Uniform	0.156	0.172	0	0.164
Phosphorus mass in manure	lb P / lb swine / year	Triangular	0.049	0.054	0	0.051
TKN concentration in raw manure	g / m ³	Uniform	3000	3300	0	3175
TP concentration in raw manure	g / m ³	Triangular	940	1040	0	990
Density of Manure	lb / ft ³	Uniform	58	80	0	61
Thickness of the liner used in a lagoon-based systems	feet	Triangular	1.4	1.6	0	1.5
Interest Rate for Amortization	%	Triangular	7.6	8.4	0	8.0
Life period of a treatment system	years	Triangular	18	22	0	20
Basic Storage Lagoon Height	feet	Uniform	7.6	8.8	0	8

Anaerobic Lagoons

Nitrogen removal in lagoon	%	Triangular	72	84	0	80
Phosphorus removal in lagoon	%	Triangular	59	68	0	65
Excavation cost	\$ / yard ³	Uniform	1.8	2.1	0	1.1
Lagoon volume design factor	ft ³ / lb of hog wt.	Triangular	1.9	2.1	0	2.0
Annual excess rainfall	m / year	Normal	N/A	N/A	0.01	0.18
Cost of liner material	\$ / cubic yard	Triangular	1.56	1.80	0	1.64

Constructed Wetlands

Nitrogen Loading Rate	Kg / hectare day	Triangular	24	26	0	25
Retention Time of water	days	Triangular	11	13	0	12
Water Depth	m	Triangular	0.14	0.16	0	0.15
Vegetation area adjustment factor		Triangular	0.68	0.79	0	0.75
Excavation Cost for storage pond	\$ / m ³	Uniform	1.79	2.09	0	1.99
Labor, wiring and pumping costs	\$	Uniform	1000	1150	0	1050
Vegetation cost	\$ / hectare	Uniform	507	587	0	534
Depth to be excavated	m	Triangular	1.16	1.28	0	1.22
Wetland TKN removal Efficiency	%	Triangular	78	91	0	87
Cost of land rental	\$ / hectare	Uniform	120	135	0	124
% Phosphorus removal	%	Triangular	14	17	0	15

Sequencing Batch Reactors

Flush water TKN concentration	g / m ³	Triangular	38	52	0	40
TP concentration in flush water	g / m ³	Triangular	29	39	0	50
Electricity used	KwH / gal of effluent	Triangular	0.011	0.016	0	0.012

Cost of Electricity	\$ / Kwh	Uniform	0.08	0.10	0	0.09
Maintenance and Improvement	%	Uniform	0.025	0.035	0	0.03
Labor rate	\$ / hour	Uniform	9	11	0	10
Cycles (e.g 12 & 24 hr cycles)	hrs / hrs	Triangular	0.95	1.05	0	1
% removal rate of TKN	%	Triangular	86.8	96.6	0	96.4
% removal rate of TP	%	Triangular	69	81	0	77
Hydraulic Retention Time	days	Triangular	9.5	11	0	10
Effluent retention time in holding tank	days	Triangular	128	142	0	135
Solids Retention time	days	Triangular	33	37	0	35
Depth of the equalization tank	feet	Triangular	10	12	0	11
Depth of the reactor tank	feet	Triangular	11	13	0	12
Depth of the Sludge thickening tank	feet	Triangular	9.5	10.5	0	10
Excavation depth to accommodate SBR concrete tanks	feet	Uniform	1.9	2.1	0	2
% of Total-N in separated biosolids	%	Triangular	6.5	7.5	0	7
% of TP in separated biosolids	%	Triangular	3.8	4.2	0	4
Cost for Pumps and Blowers	\$ / gallon of capacity	Triangular	1	1.1	0	1.05
Cost for Process Controls	\$	Triangular	20,000	22,000	0	21,000
Cost for Labor, materials, subcontractors	\$/gallon design volume	Triangular	1.01	1.12	0	1.06
Life period of system	years	Triangular	18	22	0	15

Solids Separator

% Reduction of TP	%	Uniform	19	21	0	20
% Reduction of TKN	%	Uniform	14	16	0	15
Mass removal efficiency	%	Triangular	45	53	0	50

Belt Press

Belt Filter Press Width	m	Triangular	1.8	2.2	0	2
Belt Filter Press Loading Rate	lbs / m / hour	Triangular	570	660	0	600
Belt Filter Press operation time	hours / day	Uniform	7.6	8.4	0	8

Ambient anaerobic digester

% removal rate of TKN	%	Triangular	36	40	0	38
% removal rate of TKN in a storage lagoon	%	Triangular	76	84	0	80
% removal rate of TP	%	Triangular	68	76	0	72
% removal rate of TP in a storage lagoon	%	Triangular	62	68	0	65
Hydraulic Retention Time	days	Triangular	62	68	0	65
Storage capacity of storage lagoon	days	Triangular	170	190	0	180
Height (depth) of Storage Lagoon	feet	Triangular	7.6	8.8	0	8
Slope of the Storage Lagoon sides	proportion : 1	Uniform	1/3	1/2.5	0	1/3
Slope of the Digester	proportion : 1	Uniform	2.5	3	0	3
Cost of the cover	\$ / meter ²	Triangular	4.1	4.5	0	4.3
Basic Digester Height	feet	Triangular	19	21	0	20
Freeboard height	feet	Triangular	1.9	2.1	0	2
Storage Lagoon Basic Height	feet	Triangular	7.6	8.8	0	8
Rainfall and Runoff height	feet	Triangular	1.9	2.1	0	2
Flush water TP concentration	g / m ³	Triangular	38	52	0	30
Flush water TKN concentration	g / m ³	Triangular	29	39	0	30

Upflow Aerated Biofilter

% removal rate of TKN	%	Triangular	68	76	0	72
% removal rate of TP	%	Triangular	23	27	0	26.00%
Plastic Media Specific Surface Area	m ² / m ³ of biofilter volume	Triangular	133	147	0	140
Surface area of Plastic media needed per wastewater volume	m ² / m ³ of wastewater / day	Triangular	27.9	34.1	0	31
Height of Biofilter Towers	feet	Triangular	12	14	0	13
Polishing tank "specific" volume	m ³ of tank volume / m ³ of wastewater	Uniform	0.24	0.26	0	0.25
Height of Polishing Tanks	feet	Uniform	6	8	0	7
Equalization Tank "specific" volume	m ³ of tank volume / m ³ of wastewater	Uniform	3.2	3.7	0	3.3
Height of Equalization / Settling Tank	feet	Triangular	11	13	0	12
Feed Tank "specific" volume	m ³ of tank volume / m ³ of wastewater	Uniform	0.57	0.63	0	0.6
Flush water TP concentration	g / m ³	Triangular	29	39	0	30
Flush water TKN concentration	g / m ³	Triangular	48	65	0	30
Height of Feed Tank	feet	Uniform	6	8	0	7
% of Biofilter Volume Water used in Backwashing	%	Triangular	18	22	0	20
Frequency of biofilter backwashing	per day	Uniform	1.9	2.2	0	2
Hydraulic Residence time of water in backwash storage tank	days	Triangular	2.9	3.3	0	3
Height of Backwash Storage Tank	feet	Uniform	6.3	8.4	0	7
Equalization Tank Cost	\$ / hog capacity	Triangular	2.9	3.3	0	3
Biofilter Cost	\$ / hog capacity	Triangular	23.42	27.12	0	24.65
Design Life of the Biofilters	years	Triangular	11	13	0	12
Electricity Cost	\$ / hog capacity / yr	Triangular	4.92	5.69	0	5.18
Labor Cost	\$ / hog capacity / yr	Triangular	0.79	0.89	0	0.83

5.2.2 Effect of Uncertainty in Technology Models

Many systematic procedures can be used to study the effect that uncertainty in a model's inputs will have on its outputs. Morgan and Henrion (1990) separate these procedures into the following three categories: sensitivity analysis, uncertainty propagation, and uncertainty analysis. Each of these techniques has distinct benefits and drawbacks. Comparative studies for these analysis procedures have been published in the past (e.g. Cox and Baybutt, 1981) with varied conclusions. No-one method is known to be the best for all cases. Instead, the analysis method is case specific.

5.2.2.1 Implementation

To analyze the effect that the uncertainty in the CAWSST inputs will have on the outputs of technology performance and cost, the *Monte Carlo* approach, with *Latin Hypercube Sampling* (LHS) (Morgan and

Henrion, 1990), was used. Monte Carlo sampling is commonly used in uncertainty propagation, where each uncertain input parameter is described with a probability distribution function (PDF). Values are randomly drawn from the PDF of each input parameter. Each set of random values constitutes a realization or input scenario. In the case study presented, CAWSST outputs are calculated for each realization. The model outputs are the cost, and the nitrogen and phosphorus that remains in the effluent, for each management alternative. Figure 5.1 summarizes the steps followed to generate realizations of the outputs under conditions of uncertainty.

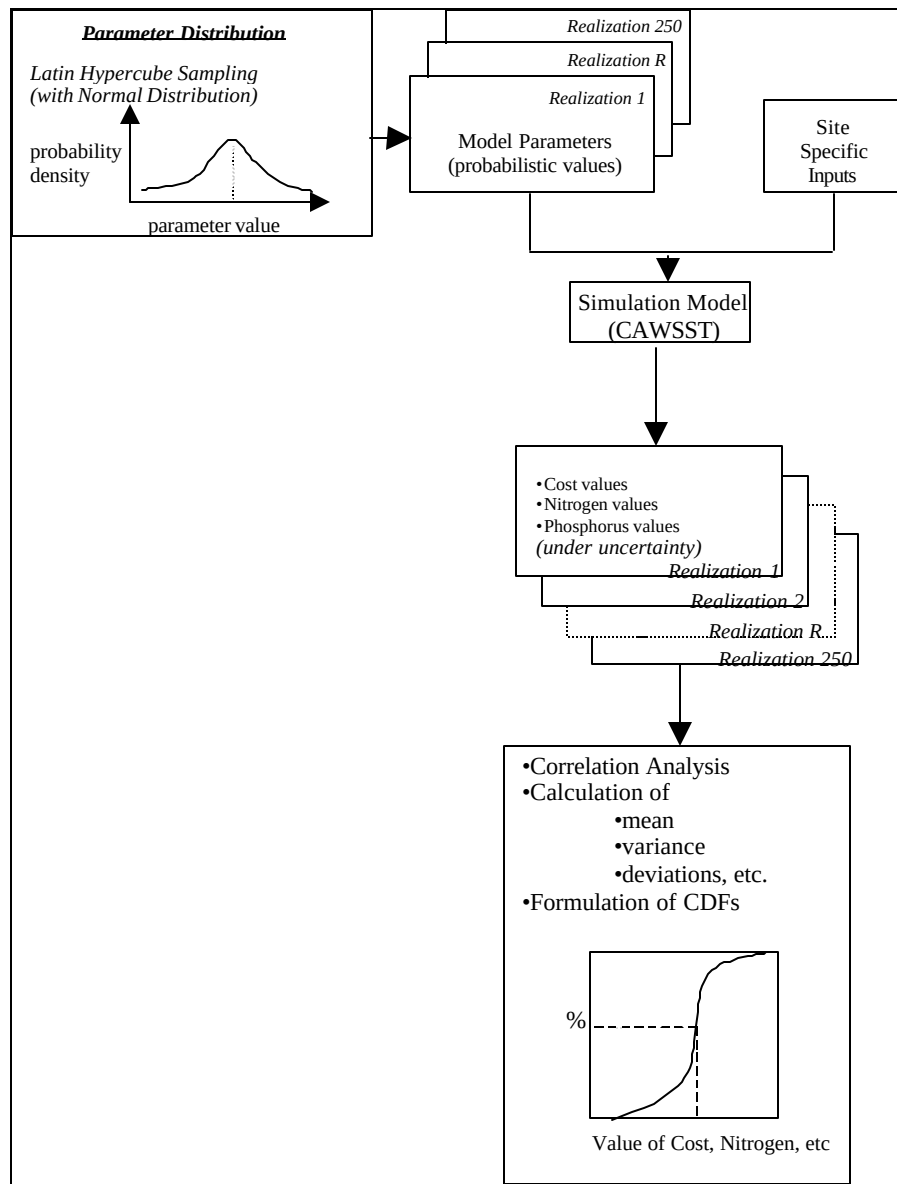


Figure 5.1 Flowchart of the uncertainty analysis in CAWSST.

The LHS method is used to produce a uniformly distributed and stratified sample of points for each input parameter distribution. In LHS, the PDF of each input parameter is divided into equal areas. Sampling occurs uniformly from each of the divisions of the PDF, rather than from the whole distribution space. The use of LHS is more appealing in the example of this paper since it reduces errors caused from sampling noise in the uncertainty analysis.

In the LHS method no one section (fractal) in the probability distribution of each input is accidentally sampled more heavily than another fractal. A smaller number of realizations will provide more accurate results than a simple Monte Carlo approach. The sampling process is repeated N times, resulting in an equal number of independent realizations for each of the model outputs.

5.2.2.3 Generation of CDFs and Correlation Coefficients

For the presented implementation, the probability distribution of each uncertain input was divided into 250 equal intervals. The realizations were then arranged in an increasing order and a cumulative distribution function (CDF) was generated for each output.

CDF curves were generated for the required land, treatment efficiency, and cost of each of the nine CAWSST technologies. An example of the CDF plots is given in Figure 5.2. The nitrogen removal efficiency of the sequencing batch reactor and the constructed wetlands are shown. From the plots, one can obtain information, such as the mean value, the range of values for each output, and the likelihood that the deterministic estimate of that output will be exceeded under conditions of uncertainty. To find the exceedance likelihood we first locate the value of the determinist estimate on the abscissa (this value is indicated by a vertical line in Figure 5.2). We then move vertically upwards until we intercept the CDF curve and then we move horizontally towards the ordinate. The value read on the ordinate is the likelihood that the deterministic estimate will *not* be exceeded.

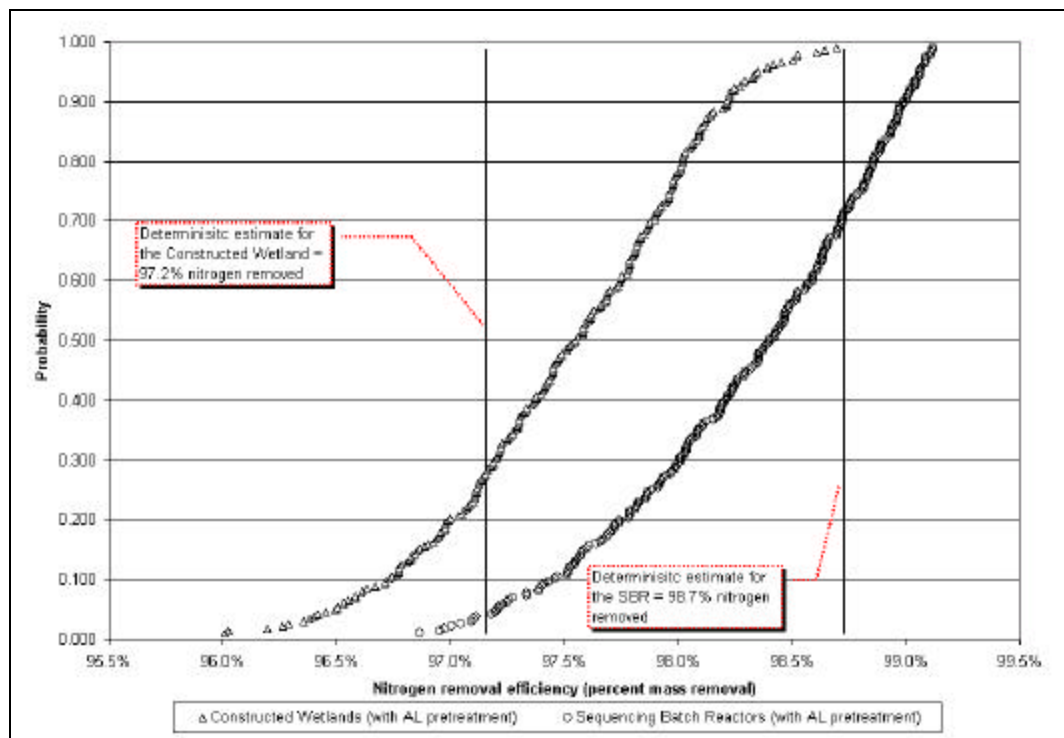


Figure 5.2 CDF curves of the nitrogen removal rates for the sequencing batch reactor and constructed wetlands treatment technologies

Figure 5.2 shows that under conditions of uncertainty, the nitrogen removal efficiency of the constructed wetlands technology ranges from 96% to 98.7% with a standard deviation of 0.6%, and it has an expected value (the mean, or 50th percentile, of the realizations) of 97.5%, whereas the deterministic estimate is 97.2%. The likelihood that the deterministic estimate for nitrogen removal efficiency will be exceeded is 72.2% for the constructed wetlands and 30.5% for the sequencing batch reactor. Therefore, in the case of the sequencing batch reactor, there is a 69.5% likelihood that the nitrogen removal efficiency for the technology will be lower than predicted by the deterministic model. This likelihood is only 27.8% for the constructed wetland. The removal efficiency of the Sequencing Batch Reactor ranges from 96.9% to 99.1%, has a standard deviation of also 0.6%, and its expected value and deterministic estimate are 98.7% and 98.3%, respectively. Tables 5.2 and 5.3 summarize the results obtained from the CDFs, for the technologies that use anaerobic lagoon pre-treatment and for the technologies that do not. Table 5.4 is a summary of the likelihood that the deterministic estimates of the outputs for each CAWSST technology are exceeded when conditions of uncertainty prevail.

Table 5.2 Cost, Nitrogen and Phosphorus release, and land required comparisons for the CAWSST technologies (that use the anaerobic lagoon for pre-treatment) for a 5000 swine farm under conditions of uncertainty.

	Anaer. Lagoon	Digester	Wetland	SBR	Biofilter
Cost per pig place (\$/yr)					
Deterministic Estimate	\$0.20	\$1.58	\$2.00	\$8.71	\$11.67
Expected Value	\$0.20	\$1.57	\$1.81	\$8.91	\$11.54
Minimum Value	\$0.17	\$1.47	\$1.59	\$8.40	\$10.95
Maximum Value	\$0.23	\$1.70	\$2.18	\$9.45	\$12.04
Standard Deviation	\$0.01	\$0.05	\$0.12	\$0.22	\$0.21
Land required (acres)					
Deterministic Estimate	4.37	5.71	8.59	4.40	5.39
Expected Value	4.30	5.60	7.91	4.33	5.26
Minimum Value	3.60	4.89	6.78	3.63	4.60
Maximum Value	5.07	6.43	9.19	5.10	6.09
Standard Deviation	0.29	0.29	0.46	0.29	0.29
TN removal (%)					
Deterministic Estimate	76.7%	83.9%	97.2%	98.7%	93.3%
Expected Value	79.7%	85.4%	97.5%	98.3%	94.3%
Minimum Value	72.7%	82.9%	96.0%	96.9%	92.0%
Maximum Value	85.2%	88.1%	98.7%	99.1%	96.1%
Standard Deviation	2.6%	1.2%	0.6%	0.6%	0.8%
TP removal (%)					
Deterministic Estimate	68.9%	89.5%	74.1%	92.9%	78.5%
Expected Value	65.8%	88.5%	72.1%	92.9%	76.0%
Minimum Value	58.5%	86.2%	66.2%	90.4%	71.1%
Maximum Value	72.3%	90.3%	77.6%	94.8%	80.9%
Standard Deviation	2.8%	0.8%	2.2%	0.9%	1.9%

Table 5.3 Cost, Nitrogen and Phosphorus release, and land required comparisons for the CAWSST technologies (*without* anaerobic lagoon pre-treatment) for a 5000 swine farm under conditions of uncertainty.

	Digester (no AL)	Wetland (no AL)	SBR (no AL)	Biofilter (no AL)
Cost per pig place (\$/year)				
Deterministic Estimate	\$3.10	\$6.20	\$9.44	\$12.26
Expected Value	\$3.15	\$5.97	\$9.61	\$12.16
Minimum Value	\$2.81	\$5.27	\$9.03	\$11.55
Maximum Value	\$3.49	\$6.65	\$10.18	\$12.66
Standard Deviation	\$0.13	\$0.25	\$0.24	\$0.21
Land required (acres)				
Deterministic Estimate	5.71	8.59	4.40	5.39
Expected Value	5.60	7.91	4.33	5.26
Minimum Value	4.89	6.78	3.63	4.60
Maximum Value	6.43	9.19	5.10	6.09
Standard Deviation	0.29	0.46	0.29	0.29
TN removal (%)				
Deterministic Estimate	83.9%	97.2%	98.7%	93.3%
Expected Value	85.4%	97.5%	98.3%	94.3%
Minimum Value	82.9%	96.0%	96.9%	92.0%
Maximum Value	88.1%	98.7%	99.1%	96.1%
Standard Deviation	1.2%	0.6%	0.6%	0.8%
TP removal (%)				
Deterministic Estimate	89.5%	74.1%	92.9%	78.5%
Expected Value	88.5%	72.1%	92.9%	76.0%
Minimum Value	86.2%	66.2%	90.4%	71.1%
Maximum Value	90.3%	77.6%	94.8%	80.9%
Standard Deviation	0.8%	2.2%	0.9%	1.9%

Table 5.4 Likelihood of exceeding deterministic estimates of cost, nutrient removal efficiency, and area requirements for the treatment technologies under conditions of uncertainty.

Technology	Likelihood of exceeding deterministic estimate for:			
	Cost per pig place	Nitrogen Removal efficiency	Phosphorus Removal efficiency	Land required
Anaerobic Lagoon	54.5%	86.4%	14.4%	41.9%
Ambient anaerobic digester (with lagoon)	38.0%	88.0%	11.2%	37.6%
Constructed Wetland (with lagoon)	7.3%	72.2%	19.9%	6.1%
Sequencing Batch Reactor (with lagoon)	77.7%	30.5%	56.9%	43.1%
Upflow Aerated Biofilter (with lagoon)	27.8%	88.4%	9.3%	35.2%
Ambient anaerobic digester (no lagoon)	65.5%	88.0%	11.2%	37.6%
Constructed Wetland (no lagoon)	18.3%	57.7%	90.7%	10.8%
Sequencing Batch Reactor (no lagoon)	71.8%	28.2%	82.9%	13.6%
Upflow Aerated Biofilter (no lagoon)	32.5%	66.3%	49.4%	11.2%

In addition to the CDF for each output, correlation coefficients are calculated for each input to each output coefficient in CAWSST. Correlation analysis (Uncertainty Importance Analysis) results indicate the relative contribution of each model input parameter to the output uncertainty. The correlation coefficients for each input parameter are a measure of their importance to the output parameters. They are obtained by finding the effect of one input over the joint probability distribution function for all other input parameters. The magnitude of each correlation coefficient is a measure of the effect of the uncertainty of an input on the model outputs. The purpose of the uncertainty importance analysis in CAWSST was twofold. First, this analysis helps identify possible inconsistencies and mistakes in the models of the technologies included in CAWSST. Certain inputs may wrongly show up as being important to the outputs of a specific technology. For example, suppose that the depth of the anaerobic digester structure (one of the model inputs) is highly correlated to the area of the anaerobic lagoon. This correlation would indicate a possible mistake in the modeling of the anaerobic lagoon area, since the example input and output should not be correlated in any way. Second, and most important for future research, the uncertainty importance analysis helps identify the areas to which scientists should devote additional time and resources when evaluating alternative treatment technologies. Certain model inputs are found to be of much higher correlation to the model outputs than others. Improving the information on such inputs will result in less uncertain outputs, and thereby better decisions.

The uncertainty importance of the input parameters for each individual waste treatment technology was calculated. Specifically, the correlation between the CAWSST models inputs to the following outputs was calculated: System Area, Annual Cost, Initial Investment, Operation and Management Cost, as well

as the Nitrogen and Phosphorus Remaining in the effluent. The volume of manure produced per pig, the swine weight, and the nitrogen and phosphorus content of raw manure were the inputs that repeatedly contributed the most to the uncertainty for the technology outputs. Whereas changing the CAWSST models to accept better descriptions of the swine farming operations in a region can reduce the uncertainty in the weight of animals, the other inputs need to be studied more carefully in descriptive and evaluation studies. A comprehensive list of the most highly correlated inputs to the technology outputs are presented as examples in Appendix B.

5.3 Effect of Uncertainty on Decisions for a Farm

Considering the uncertainty in the CAWSST parameters can lead to better decisions at a farm, as opposed to only considering the deterministic estimates for each technology. A technology that was deterministically evaluated to perform well with respect to nutrient removal, have a low cost, and have a small land area requirement, is not necessarily the best option for a farm. This section introduces how the results of uncertainty analysis can alter decisions at the farm level.

For a 5000-swine farm, CAWSST gives estimates of the cost, efficiency, and land required, among other outputs, for each of nine treatment systems. Table 5.5 gives a comparative summary of the nine treatment system deterministic outputs.

Table 5.5 Deterministic estimates for the CAWSST treatment technologies for a 5000 swine farm.

Technology	Cost per pig place (\$/year)	Nitrogen Removal (%)	Phosphorus Removal (%)	Area required (acres)
Anaerobic Lagoon	\$0.20	80%	65%	4.4
Ambient anaerobic digester (with lagoon)	\$1.56	85%	88%	5.7
Constructed Wetland (with lagoon)	\$1.77	98%	76%	7.9
Sequencing Batch Reactor (with lagoon)	\$9.43	99%	93%	4.5
Upflow Aerated Biofilter (with lagoon)	\$11.39	94%	76%	5.4
Ambient anaerobic digester (no lagoon)	\$3.16	85%	88%	5.7
Constructed Wetland (no lagoon)	\$5.93	96%	32%	13.8
Sequencing Batch Reactor (no lagoon)	\$12.06	96%	77%	1.1
Upflow Aerated Biofilter (no lagoon)	\$12.01	76%	41%	1.0

Anaerobic lagoons are the lowest cost treatment alternative for a farm. The assumption is that anaerobic lagoons are currently used in all swine operations in North Carolina. When an anaerobic lagoon is used for pretreatment of waste, the digester technology and the constructed wetlands are also low cost treatment alternatives. The most expensive treatment technology is the sequencing batch reactor, followed by the upflow aerated biofilter. All of the treatment technologies exhibit economies of scale for different size farms (Anastasiou et al., Chapter 2).

Sequencing batch reactors are the most efficient in removing nitrogen and phosphorus from the waste. The least efficient of the technologies is the upflow aerated biofilter system that uses a solids separator for nitrogen removal and the constructed wetland system that uses a solids separator for phosphorus removal. The highest level of nutrient removal per dollar cost is achieved by the constructed wetlands.

Despite their high cost, sequencing batch reactors and upflow aerated biofilters are suited for farms that are land constrained. These two systems require the least land space, as opposed to constructed wetlands that require ten times more land.

If a farmer were to choose a treatment technology based on its nitrogen removal rate, irrespective of cost, the sequencing batch reactor would have been a first choice, according to the deterministic estimate of CAWSST. The sequencing batch reactor is predicted to have 98.7% nitrogen removal efficiency. The constructed wetland would have been a second choice, since it removes nitrogen with only 97.2% efficiency. However, when the two technologies are examined under conditions of uncertainty, the constructed wetland may be a better choice for nitrogen removal. From Figure 5.2, and the data of Table 5.2, we see that the expected value of nitrogen removal rate by the SBR is lower than the deterministic estimate. From Table 5.4 we also see that there is 69.5% likelihood that the SBR nitrogen removal efficiency will be lower than the one predicted by the deterministic model, as opposed to 27.8% for the constructed wetlands. Therefore, constructed wetlands are better under conditions of uncertainty (more robust) than sequencing batch reactors.

In a second example of how decisions at the farm level could be affected by the consideration of uncertainty, it is assumed that a farmer cannot exceed a certain budget for the treatment of his waste. If, for example, the farmer can spend up to \$9/yr/pig place to treat his waste, according to the deterministic outputs of CAWSST the anaerobic lagoon, digesters, constructed wetlands, and the sequencing batch reactor (with anaerobic lagoon pretreatment) are feasible technology options. Since the sequencing batch reactor has the highest nitrogen removal rate, among the technologies within the budget, and since it

requires little land to build, the farmer would probably choose this to be the technology he would implement. With the SBR the farmer gets a small system with a high treatment potential. However, if uncertainty is considered, there is almost a 35% chance that the \$9/yr budget that the farmer has will be exceeded by as much as \$0.22/yr/pig place. Under these conditions, the SBR option would not be a feasible or an appealing choice anymore.

5.4 Uncertainty in a Regional Optimization Model

While CAWSST provides the critical knowledge base for identifying the cost-effective treatment system option for an individual farm, methods to identify collective management strategies to meet regional environmental goals are necessary. Identification of such management strategies is affected by various factors. A systematic examination of possibilities is imperative. Anastasiou et al., (Chapter 3) developed a procedure that uses mathematical optimization models. This procedure uses the CAWSST outputs in combination with geospatial data, on the swine farms of North Carolina, as inputs. Figure 5.3 shows how the technology models are coupled with the optimization search. This search identifies cost efficient solutions (objective of the optimization) that meet regional environmental goals (constraints).

Environmental goals such as the reduction in nitrogen and phosphorus emissions in a region were specified. Cost effective waste management strategies that satisfy specified environmental protection goals for a region have been developed (Anastasiou et al., Chapter 3). The decision variables (outputs) of the optimization procedure indicate the allocation of appropriate technologies to the farms of a region.

5.4.1 Case Study

The Lower Neuse River watershed in eastern North Carolina was the focus of previous studies (Anastasiou et al., Chapter 3, Chapter 4). The watershed contains 70 swine farms of various sizes, with an average size of 3,500 swine and a total of 248,000 animals. Farms are located in different floodplains and different population density zones, within the six counties that the watershed spans. The appropriate technologies were allocated to the 70 farms of the Lower Neuse River watershed in a way that the nitrogen loading from the farms would be 30% lower than the present levels. Also, phosphorus loading from farms should not exceed its current levels. All farms in the region are assumed to be currently using anaerobic lagoons to treat their waste. The reduction in nutrient loading was achieved using improvements in the swine waste treatment systems in farms. The optimization model was used to determine the Least Cost (LC) Strategy for achieving the 30% reduction in nitrogen.

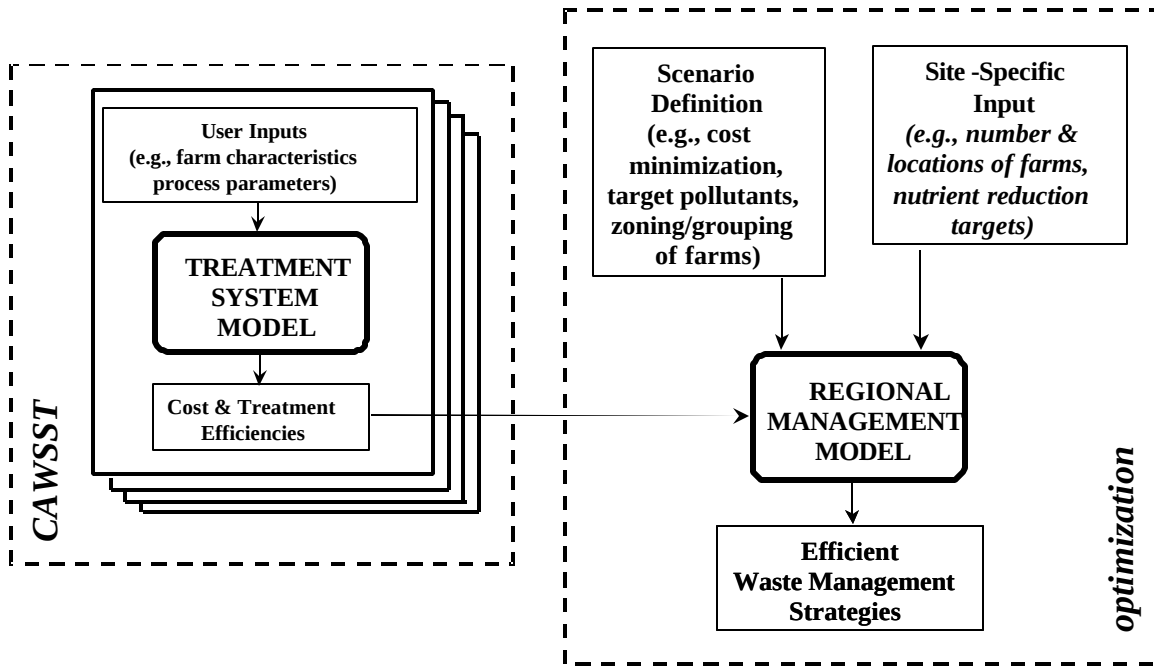


Figure 5.3 Schematic Diagram of an Integrated Modeling Approach (Anastasiou et al., Chapter 3)

The annual cost of implementing the LC strategy was found deterministically to be \$173,000. Under the LC management scenario, approximately 90% of the farms in the watershed should use anaerobic lagoons for treatment and the other 10% should use constructed wetlands (with anaerobic lagoon pretreatment) (Anastasiou et al., Chapter 3).

5.4.2 Implementation of Uncertainty Analysis to the Optimization Model

Uncertainty in the technology models can influence not only the choice of technologies for individual farms but can also influence decisions made for a region. Any uncertainty in the treatment efficiency and cost of either anaerobic lagoons or constructed wetlands, used in the least cost management strategy will carry onto the management strategy values for cost of implementation and for meeting of the environmental targets. To investigate the effect that uncertainty has on regional management strategies, the optimization model results were coupled with the uncertain CAWSST realizations. This procedure is summarized in the flowchart of Figure 5.4.

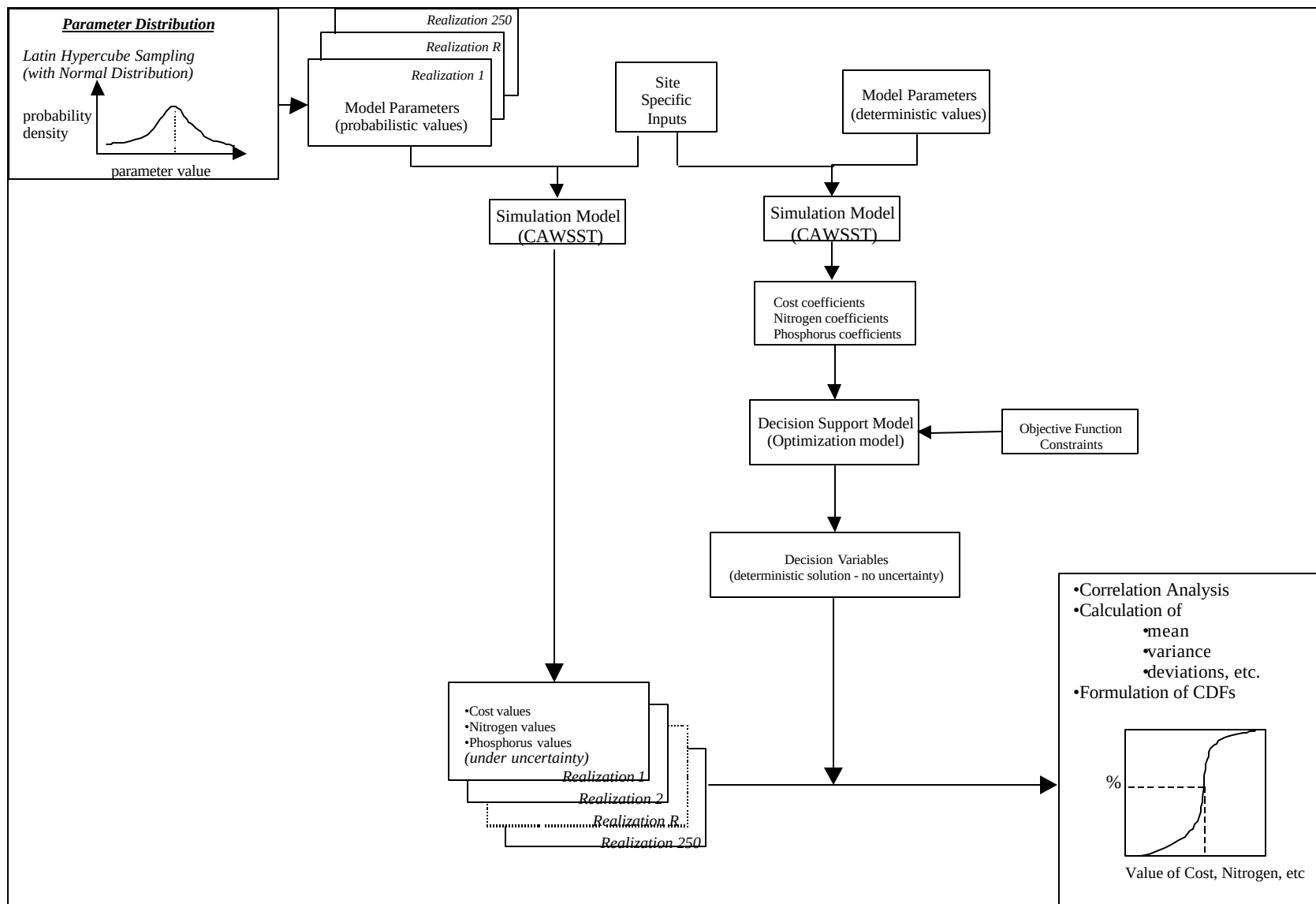


Figure 5.4 Flowchart of the uncertainty analysis procedure

5.4.2.1 The Least Cost Management Scenario

After the CAWSST inputs were treated as uncertain, 250 realizations of the outputs were computed thereby producing the CDF chart, shown in Figure 5.5, for the annual cost. The chart shows that, under conditions of uncertainty, the cost varies between \$154,000 and \$206,000 annually.

The expected cost (i.e. the average value of the 250 realizations) of the LC strategy is \$176,000, and it only slightly exceeds the deterministic value of \$173,000. However, there is a 55.3% likelihood that, under uncertainty, the deterministic value of the model will be exceeded.

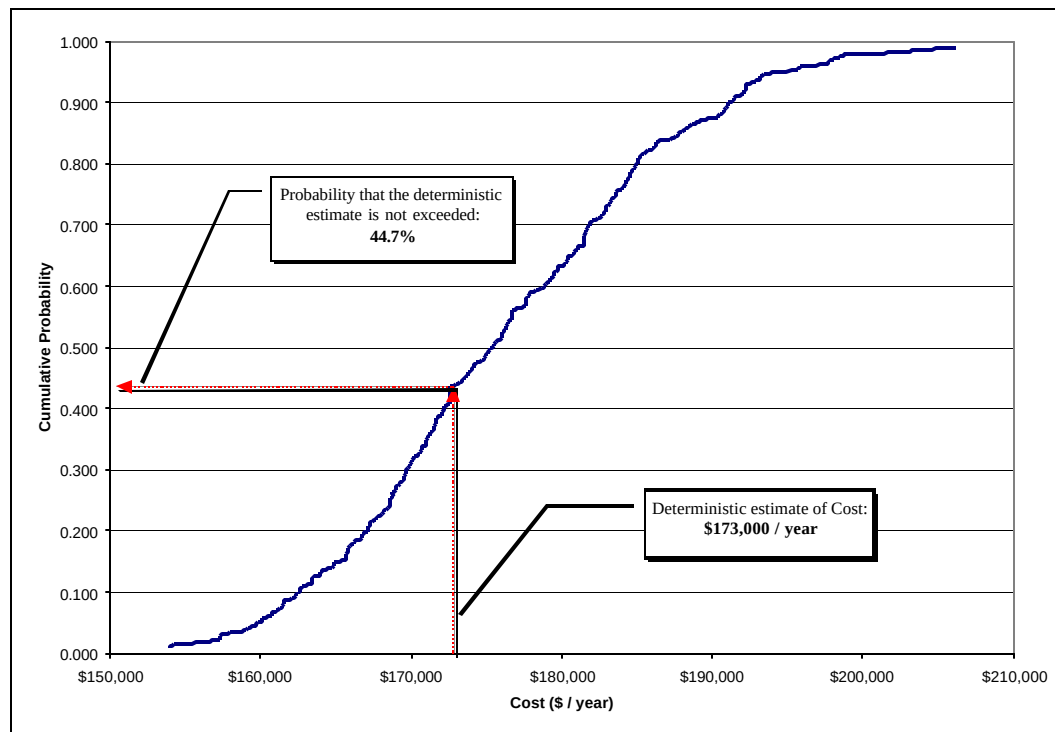


Figure 5.5 CDF curve for the Cost of the Least Cost Strategy

Figures 5.6 and 5.7 respectively show the CDF curves for the nitrogen (TN) and phosphorus (TP) released from farms under the LC strategy. The deterministic TN level is 427 ^{tons} / _{year} whereas the expected TN value is 444 ^{tons} / _{year}. The likelihood that the TN deterministic estimate will be exceeded is 60.4%, and the levels of TN vary from 326 to 601 ^{tons} / _{year}. The TP estimates under uncertainty indicate a range of 257 ^{tons} / _{year} to 371 ^{tons} / _{year}, an expected value of 311 ^{tons} / _{year}, and a likelihood that the deterministic value, of also 311 ^{tons} / _{year}, will be exceeded of 51.5%.

5.4.3 Uncertainty importance analysis / Correlation analysis

In addition to the developed CDFs, uncertainty importance analysis was performed on the regional management strategies, similar to the analysis of the CAWSST outputs. The purpose of the Uncertainty Importance Analysis on the regional management strategies was to determine which input parameters affect each management alternative the most. This analysis is beneficial since the input parameters that need to be improved, if model predictions are to have a higher degree of certainty, are identified.

Table 5.6 shows the uncertain parameters that are strongly and weakly correlated to the cost, nitrogen, and phosphorus release outputs, for the Least Cost Strategy. Although these results would also make intuitive sense, one would not be able to truly find the magnitude and order of importance of input coefficients to the outputs.

Table 5.6 Uncertain Parameters that are strongly/weakly correlated to Cost, Nitrogen, and Phosphorus for the Least Cost strategy.

COST (\$/year)	Correlation Factor
Nitrogen Removal Efficiency of the Anaerobic Lagoon	-0.7354
Nitrogen Removal Efficiency of the Constructed Wetland	0.0063
Excavation Cost of a Lagoon Structure	0.4134
Nitrogen Released (tons/year)	
Nitrogen Removal Efficiency of the Anaerobic Lagoon	-0.9094
Density of the Swine Manure	-9E-05
Average Weight of a Swine	0.3484
Phosphorus Released (tons/year)	
Phosphorus Removal Efficiency of the Anaerobic Lagoon	-0.7940
Slope of the Anaerobic Lagoon Structure	0.0020
Average Weight of a Swine	0.5911

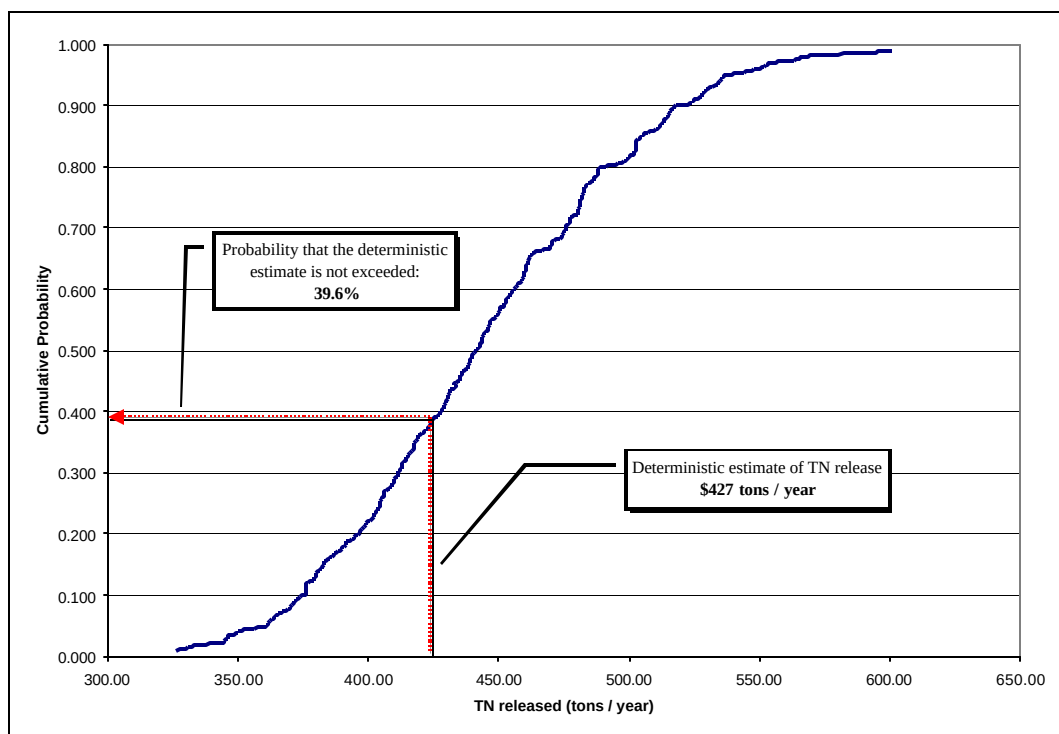


Figure 5.6 CDF curve for the Total Nitrogen released under the Least Cost Strategy

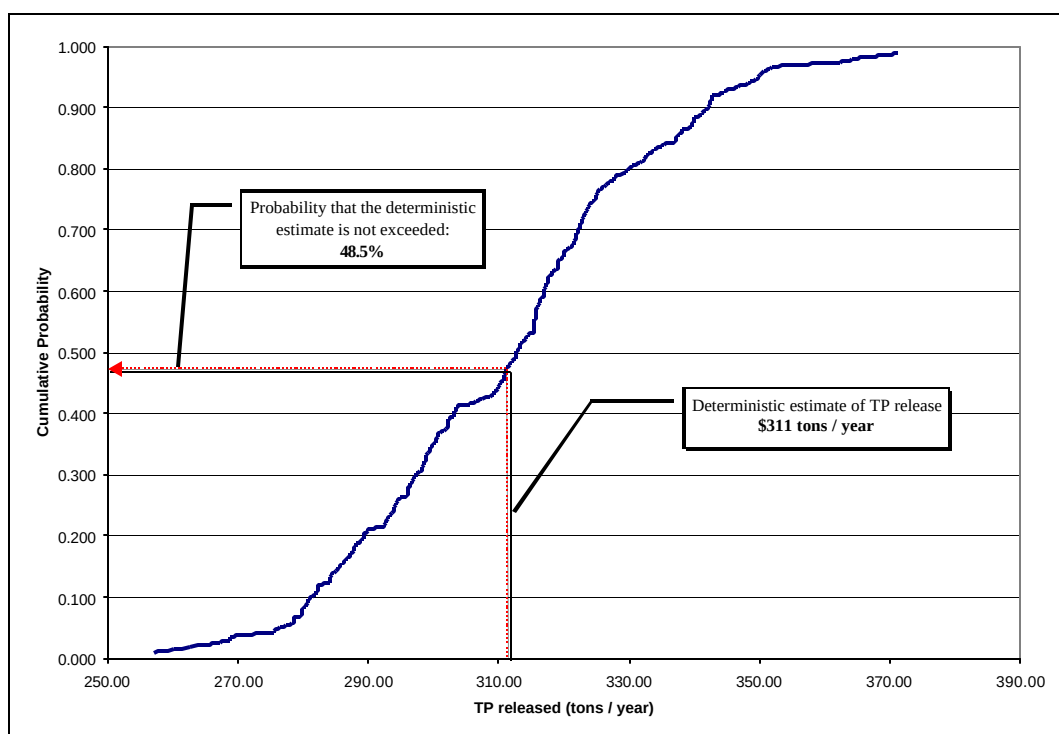


Figure 5.7 CDF curve for the Total Phosphorus released under the Least Cost Strategy

For example, the excavation cost of a lagoon structure is positively correlated to the overall cost of the management alternatives. This means that when the excavation cost increases the overall management strategy cost increases. This is because in all of the management alternatives lagoon structures are used for treatment. Whether the anaerobic lagoon or constructed wetland (with anaerobic lagoon pretreatment) technologies are used, an increase in the excavation cost of a lagoon structure would also mean an increase in the overall cost of the management strategy.

An example of negative correlation between the inputs and outputs is the one between the nitrogen removal efficiency of an anaerobic lagoon and the total nitrogen released under each alternative management strategy. Since in all management alternatives anaerobic lagoons are either used for treatment or used for pre-treatment in combination with other technologies, it follows that an increase in their removal efficiency will result in a lower nitrogen loading.

Uncertainty importance analysis can also identify the correlation between seemingly unrelated inputs to outputs. For example, analysis has shown that the nitrogen removal efficiency of the anaerobic lagoon has a strong negative correlation to the cost of a management strategy. This is because in all management strategies, anaerobic lagoons and the constructed wetlands that use the anaerobic lagoon for pre-treatment of waste are the technologies of choice. If the anaerobic lagoon removes most of the nitrogen from the waste, a subsequent wetland will not need to be as large to achieve the same overall treatment, therefore treatment would be less costly. A smaller treatment system costs less for the following reasons: the area it requires is smaller, the excavation costs would be lower, less piping and pumping costs are incurred. Additional results could also be analyzed in a similar way.

5.5 Effect of Uncertainty on Management Strategies for a Region

The problem of swine waste management is too complex to be fully represented by any mathematical model. Such an optimization model may not be able to capture all issues that are important to decisions for waste-treatment improvements in farms. Such unmodeled parameters include the flood risk that technologies may pose when used in certain farms, equity of each management strategy, effect of the emitted odor from farms, and aesthetics.

To assist in analyzing not-explicitly-modeled issues, the decision model was incrementally modified to generate a small set of alternative strategies that have farms use maximally different technology choices

(Anastasiou et al., Chapter 4). This implementation was based on a procedure called Modeling to Generate Alternatives (MGA) (Brill et al., 1990; Chang et al., 1982). Distinct choices of treatment technologies across farms produced strategies that perform differently with respect to unmodeled criteria.

5.5.1 Deterministic Estimates of Management Strategy Alternatives

The MGA technique was applied to the least cost management strategy and nine alternative solutions were generated for an allowable 20% increase in cost over the optimal solution. The management alternatives obtained are summarized in Table 5.7.

Table 5.7 Deterministic output values for the different MGA alternatives for a 20% relaxation over the optimal cost value for the least cost strategy.

Management Alternative	Cost (\$/year)	Total Nitrogen Release (tons / year)	Total Phosphorus Release (tons / year)
Least Cost Strategy	173,105	427	311
Alternative 1	207,282	427	309
Alternative 2	211,760	427	301
Alternative 3	208,380	427	302
Alternative 4	206,050	427	305
Alternative 5	198,142	427	292
Alternative 6	207,307	427	294
Alternative 7	206,203	427	305
Alternative 8	207,676	427	295
Alternative 9	218,430	427	296

Outputs of the MGA analysis could be used to compare one alternative management strategy to another. For example, results show that the technology allocations to farms for management alternative 6 provide similar tradeoffs between cost, equity, and nutrient removals to management alternative 8. However, many of the key input parameters in the models are uncertain. The cost, environmental estimates for each management alternative do not consider any associated uncertainties. Therefore, even if two management alternatives are similar with respect to cost and environmental objectives (i.e. management alternatives 6 and 8), it would still be impossible for one to know which of the two alternatives is the most reliable (robust) to implement.

5.5.2 Which management alternative can be “trusted” the most?

Evaluation of management alternatives and comparison of their performance under conditions of uncertainty will help identify a relatively more robust decision.

As it was shown in Table 5.7, management alternatives differ in their environmental loads and cost since their technology allocations to farms is different. They also differ with respect to unmodeled objectives, such as risk and equity (Anastasiou et al., Chapter 4). However, with uncertain inputs, each alternative is also uncertain. The results of the uncertainty analysis for the cost, nitrogen, and phosphorus release of each alternative are summarized in Table 5.8. Results were obtained from the CDF curves, shown in Figures 5.8, 5.9, and 5.10, for the annual cost of each management alternative, as well as for the nitrogen and phosphorus loading. The vertical line in Figure 5.9 signifies the deterministic estimate for the nitrogen release of $427 \text{ tons} / \text{year}$, which happens to be the same for all of the management alternatives. For clarity purposes, CDF curves for cost, nitrogen, and phosphorus release are presented for only five, out of the nine, management alternatives. The robustness of each management strategies was compared to one another, through examination of the statistical differences in their CDFs.

Uncertainty analysis shows that reliance upon the deterministic estimates of management alternatives is quite similar for all alternatives, in this case. In almost all of management alternatives, the expected value is lower than the deterministic value for cost, nitrogen, and phosphorus release. The likelihood of exceeding the deterministic estimates for cost is similar for all management alternatives and it ranges between 54% and 56%. However, the nitrogen loading CDF curves show a greater difference among the alternatives. Specifically, the likelihood of exceeding the deterministic estimate for nitrogen ranges between 46% and 68%. Management alternative 9 is the most, and alternative 5 is the least, “robust” under conditions of uncertainty. Finally, the likelihood of exceeding the deterministic estimate for phosphorus release, like cost ranges between 46% and 54%.

If one were to choose one of the management alternatives based on the accuracy of the model predictions, the deterministic value of alternative 9 would be most trustworthy. However, from Table 5.7, it is obvious that alternative 9 was not the best with respect to cost, nitrogen, or phosphorus. An environmental manager could consider these results before implementing a new policy, or before adopting an appropriate strategy for swine waste management in the Lower Neuse River watershed. One may prefer a more expensive but more reliable alternative to another, which could be cheaper but would have a higher chance of exceeding the initially predicted deterministic cost.

Table 5.8 Cost, Nitrogen and Phosphorus release comparisons for the Least Cost (LC) management strategy and alternatives under conditions of uncertainty.

	LC	Alt. 1	Alt. 4	Alt. 5	Alt. 8	Alt. 9
Cost (\$/yr)						
Deterministic Estimate	\$173,105	\$207,282	\$206,050	\$198,142	\$207,676	\$218,430
Expected Value	\$176,183	\$210,460	\$208,994	\$200,683	\$210,548	\$221,577
Standard Deviation	\$10,396	\$10,424	\$10,364	\$9,334	\$10,249	\$10,943
TN released (tons/yr)						
Deterministic Estimate	427.0	427.0	427.0	427.0	427.0	427.0
Expected Value	444.4	443.1	444.4	456.0	439.3	425.1
Standard Deviation	54.3	53.6	53.0	51.6	50.5	48.8
TP released (tons/yr)						
Deterministic Estimate	311.0	309.0	305.0	292.0	295.0	296.0
Expected Value	311.1	308.4	304.6	292.2	294.7	293.1
Standard Deviation	22.4	22.1	21.8	20.6	20.9	20.7

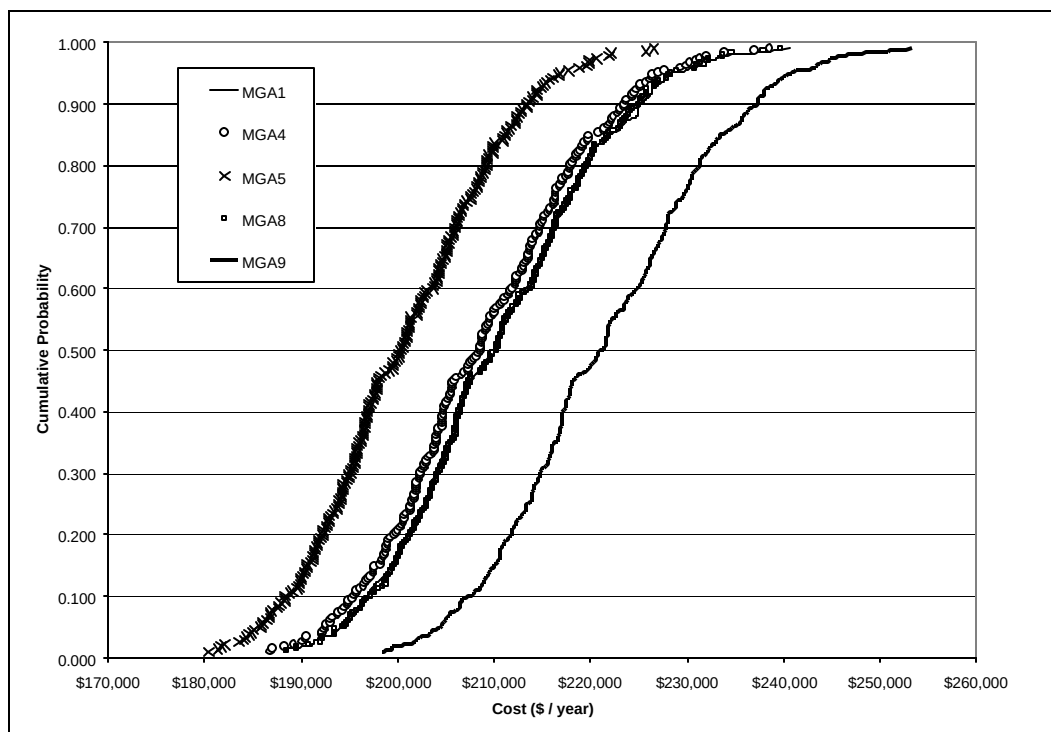


Figure 5.8 CDF curves for the Cost of management alternatives 1, 4, 5, 8, and 9.

5.5.3 With what Reliability do management alternatives fall within a certain budget?

Environmental managers do not only want to find the cheapest solution to a problem but they many times work within the bounds of specific budgets. Although the management alternatives may have similar deterministic estimates of cost, under conditions of uncertainty the likelihood of exceeding a budget needs to be quantified.

The deterministic estimates of the cost for the management alternatives (Table 5.7) range between \$198,000 / year to \$218,000 / year. Therefore, suppose, for example, that a budget of \$210,000 / year exists. Uncertainty analysis can indicate the chances that this budget will be exceeded by a management alternative that the deterministic analysis indicated as feasible.

Figure 5.8 indicates that the cost of alternative 9 exceeds the budget of \$210,000 / year by a probability of almost 85% and by an amount of more than \$40,000 / year. This is quite different from alternative 5, for which the budget has only a 16% probability to be exceeded, and if so, by only \$15,000 / year. A manager would most probably find such information extremely useful when making a decision.

Information obtained from uncertainty analysis can provide quantitative comparisons of management alternatives. A deterministic estimate is a single value whereas uncertainty analysis provides information as to the possible range of answers that any management strategy could end-up having.

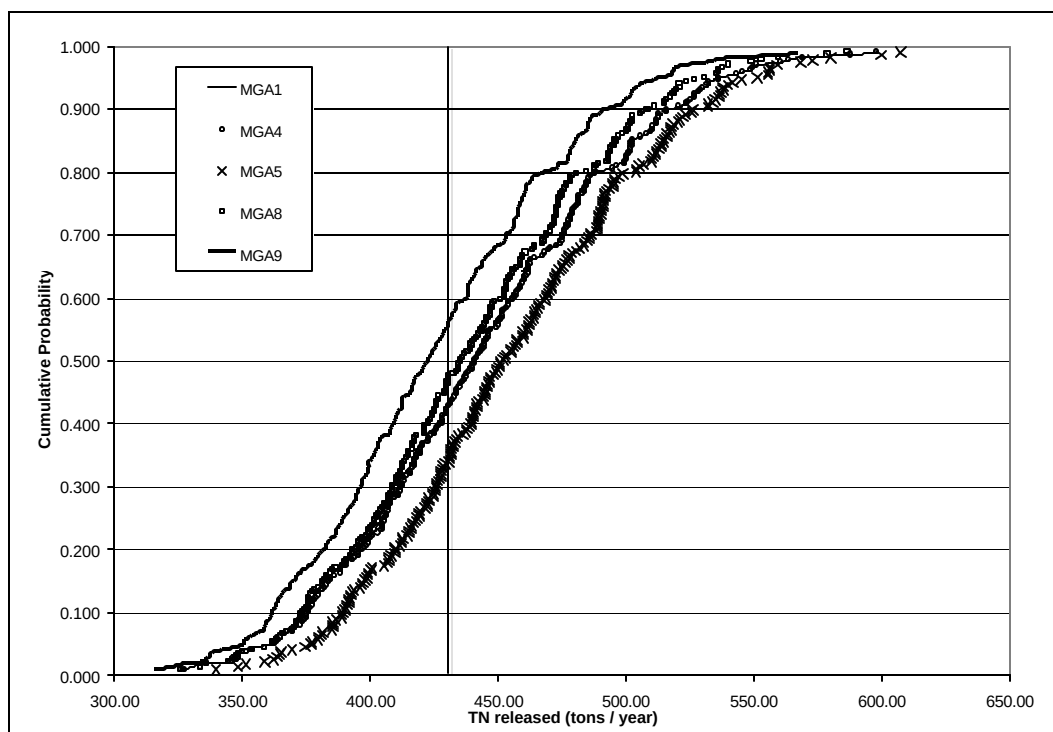


Figure 5.9 CDF curves for the TN released in management alternatives 1, 4, 5, 8, and 9.

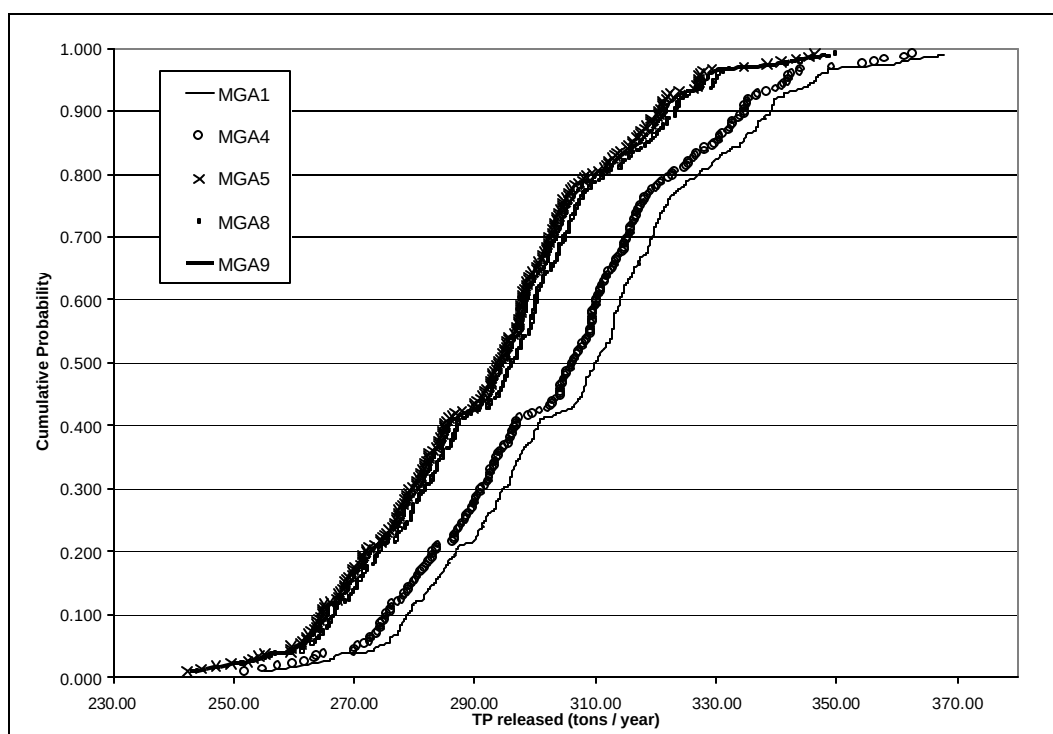


Figure 5.10 CDF curves for the TP released in management alternatives 1, 4, 5, 8, and 9.

5.5.4 How do the performances of management alternatives compare to one another?

In the previous sections, information on ways that different management alternatives can be compared to one another was presented. However, that comparison does not provide any statistical characterization. The results presented in the previous sections do not consider the difference between each of the realizations that result in CDF curves for cost, nitrogen or phosphorus. To achieve such a comparison, the difference between the output realizations for pairs of alternatives was calculated. Specifically, the differences between the base solution of the Least Cost Strategy and each of the management alternatives were calculated and the CDFs were generated. The resulting curves are plotted in Figures 5.11, 5.12, and 5.13, for cost, nitrogen, and phosphorus respectively. The CDFs for the “Alternative# – LC” were generated by subtracting the realizations of the Least Cost Strategy from the realizations for each MGA management alternative.

Observing the CDFs of the output realization differences provides a number of insights. For example, it can be seen that alternative 5 is the cheapest of the management alternatives, and only \$25,000/year more expensive than the LC strategy. However, alternative 5 allows up to 30 tons of nitrogen per year more than the LC strategy to be released to the environment. Also, the variability of the nitrogen release for alternative 5 is quite high. It is therefore a clearly worse management alternative than any of the other strategies with respect to nitrogen release but better with respect to phosphorus release. When alternative 1 is compared to the LC strategy it becomes obvious that the variability of all of the outputs considered (i.e. cost, nitrogen and phosphorus release) is very low. With respect to nitrogen loading, management alternative 1 is almost always better (95%) than the LC solution. In addition, for the 5% of the times that alternative 1 performs worse than the LC solution its nitrogen loading exceeds the LC solution's loading by less than one ton/year.

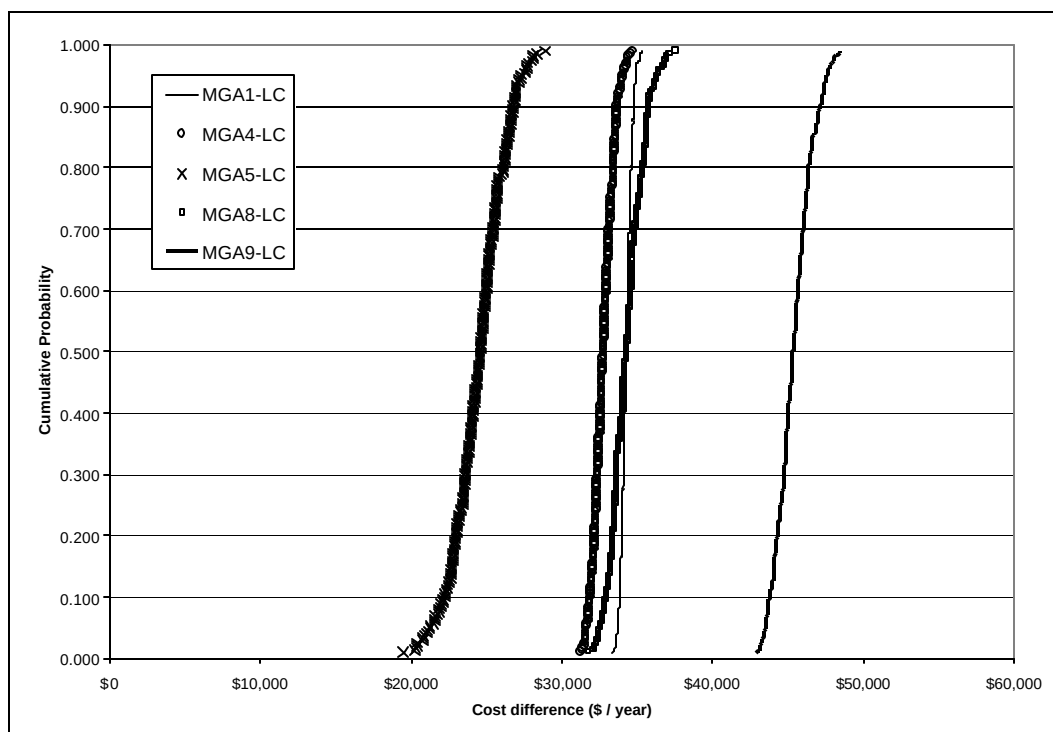


Figure 5.11 CDF curves of the differences in cost of alternatives 1, 4, 5, 8, and 9 and of the Least-Cost strategy.

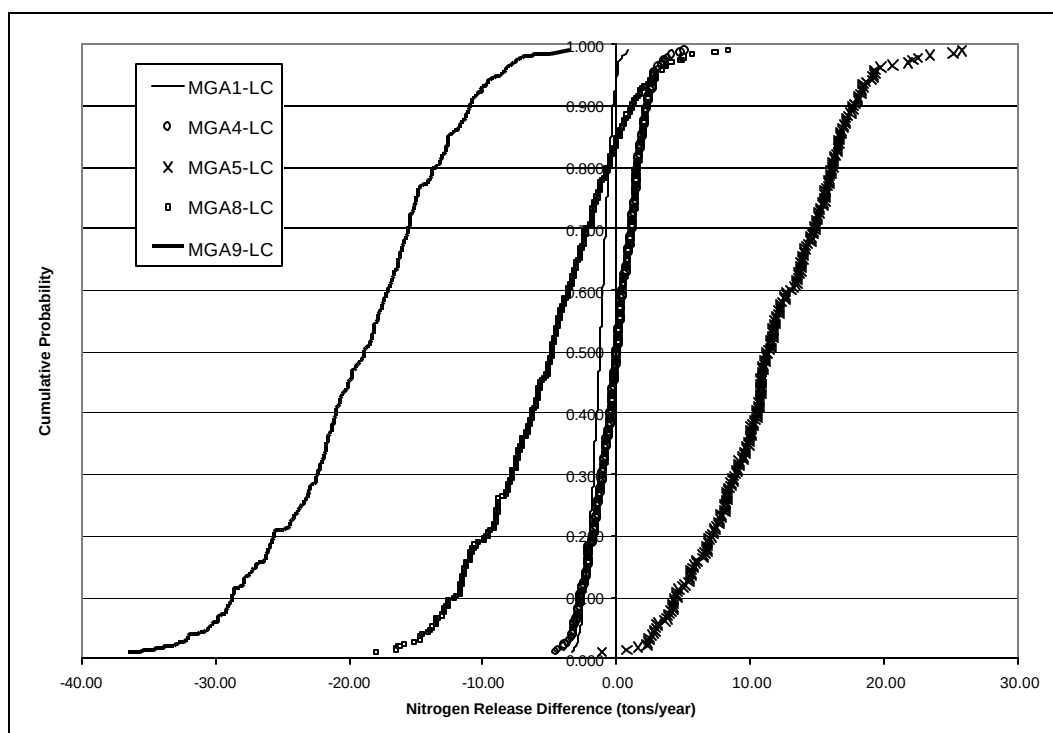


Figure 5.12 CDF curves of the differences in nitrogen release in alternatives 1, 4, 5, 8, and 9 and in the Least-Cost strategy.

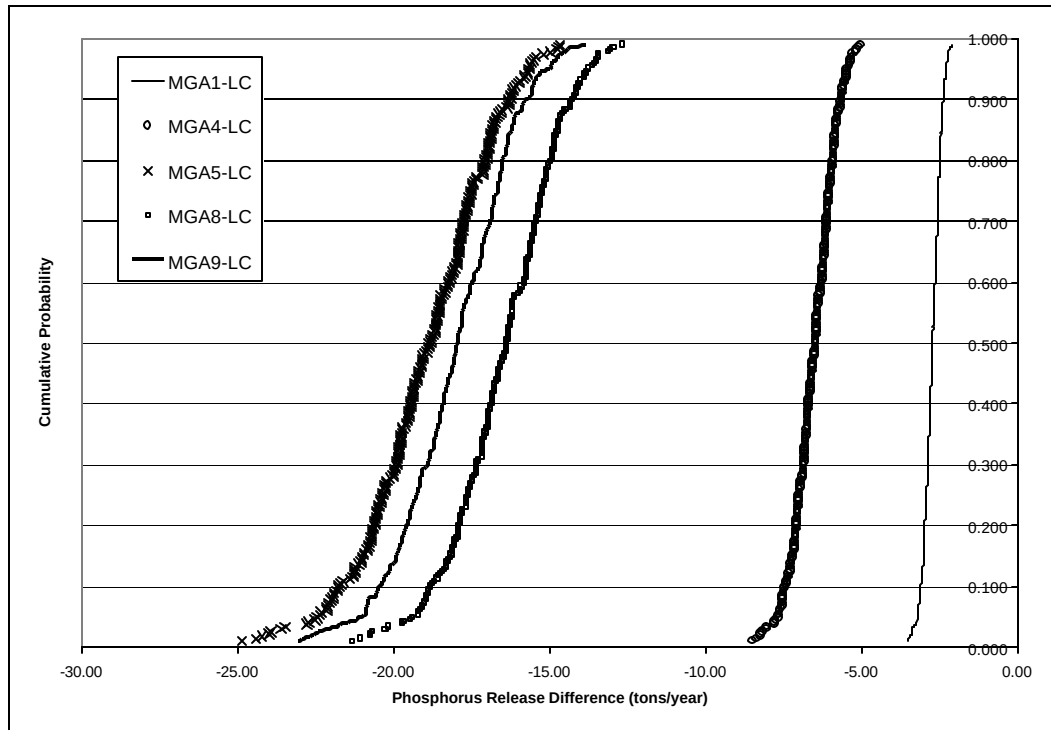


Figure 5.13 CDF curves of the differences in phosphorus release in alternatives 1, 4, 5, 8, and 9 and in the Least-Cost strategy.

5.4 Summary and Conclusions

A Latin Hypercube Sampling-based uncertainty analysis procedure was implemented on models used for regional animal waste management. The goal of the uncertainty analysis is to provide a tool that will assist in better decision-making. The procedure was demonstrated for a case study of swine waste management in the Lower Neuse River watershed in North Carolina. The management scenarios that were considered allocate the appropriate treatment technologies to swine farms of different sizes and operational characteristics. The environmental objective was defined as a 30% reduction, from current levels, of the nitrogen released in the watershed, for the least possible cost. The Least Cost Strategy and alternative management solutions were examined. The uncertainties in cost and environmental emissions of each management strategy were obtained by considering the uncertainty in the input parameters of the previously developed decision support models.

The difference in performance between pairs of management alternatives was estimated and superior alternatives were identified. The best alternatives allocate technologies to farms to achieve lower nitrogen loading for no increase in cost while having low variability in output estimates.

The results of the uncertainty importance (correlation) analysis identified the input parameters that contribute the most to the uncertainty of the outputs that may affect decisions and should thus be refined in the future.

Decision-making based on deterministic evaluations or based on uncertainty analysis may not always reach the same conclusions. An environmental manager would most probably adopt management alternative A, if he bases his decision on a deterministic evaluation, whereas management alternative B may be more attractive when uncertainty is considered. Many parameters of animal waste treatment technologies are uncertain. This paper demonstrated, through an illustrative example, that consideration of uncertainty in the models helps improve decision-making.

CHAPTER 6: Summary and Conclusions

In this dissertation, a methodology to assist decision-making in regional animal waste management has been presented through a series of four papers. Mathematical descriptions of waste treatment technologies have been developed. These were coupled with optimization techniques to generate low cost management strategies that meet regional environmental goals. Alternative scenarios were explored for various environmental and social objectives and their performance was evaluated under conditions of uncertainty. The overall framework was demonstrated through a case study of the swine farms in the Lower Neuse River watershed in North Carolina.

6.1 Summary of Findings

The design, the development, and the utility of a computer assisted waste system selection tool (CAWSST) were presented in Chapter 2. CAWSST consolidates and presents data on animal waste treatment technologies in a consistent and easy-to-read manner. The tool can be invaluable in comparing alternative swine waste treatment technologies and in helping farmers decide the best implementation for their farms. CAWSST indicates that no single technology is consistently superior in treatment efficiency, cost, or design-requirements for all farms. In addition to decision-making at the farm, CAWSST results can be coupled with additional data and with other computer applications and programs to assist regional environmental management.

In Chapter 3, an integrated modeling approach to identify collective animal waste treatment technology allocation strategies was presented. A systematic search procedure (specifically, mixed-integer programming) was used to solve this management model. Cost-effective strategies that meet specified environmental goals were identified. The methodology was tested through a case study of swine farms in a North Carolina watershed. A significant finding for this case study is that there is a lot of flexibility in meeting cost and environmental goals in a region. There are many strategies that are more cost effective than forcing all farms in a region to treat their waste to the same level. Another finding of this study was that phasing-out anaerobic lagoons altogether is likely not the most cost-efficient way to achieve the currently stated environmental and social goals. The presented model can assist managers in identifying and evaluating such strategies according to environmental, social, and economic criteria that are important to them for any region or farm.

In Chapter 4, different ways of allocating treatment technologies to specific farms to meet a collective environmental target in a region were explored. The generation of alternatives was important in this problem due to the many unmodeled factors that need to be considered by environmental managers in finding “good” solutions to the problem. Quantitative measures for equity in the treatment burdens and risk due to flooding were developed. Many cost efficient alternatives that were similar with respect to equity and risk were generated. These alternatives were quite different from each other in the decision space (i.e., which farm uses which technology in a region). The study made clear that swine waste in North Carolina could be managed in many ways without necessarily sacrificing any of the modeled objectives - cost and nutrient reduction - in the watershed.

In Chapter 5, alternative management strategies were examined under conditions of uncertainty. Results show that consideration of uncertainty may influence the selection of a management strategy for a region, due to the possibility that strategies may exceed a budget or not meet environmental criteria. Treatment technologies need to be characterized better. Uncertainty importance analysis indicated that uncertainty in the performance of regional management strategies can be reduced most by reducing the uncertainty in nitrogen and phosphorus removal efficiencies of the treatment technology unit processes. Until technologies are characterized with better data, uncertainty analysis can be invaluable to decision-making at the farm and at a regional level.

The developed framework was designed to be general enough so that it can be applied to any region or group of farms. Similar results, to the ones presented for the case study, can be obtained and thereby assist decision-making.

6.2 Contributions

Recent research in animal waste management has focused on identifying the one "magic" technology that would have a high treatment efficiency, would emit no odor, would allow no ammonia volatilization, and that would cost virtually nothing. Farmers, the public, and environmental groups have become increasingly polarized since scientists suggested that swine waste has lead to environmental problems, such as fish kills, in eastern North Carolina. Farmers want little or no regulation in the environmental protection programs that they adopt. They instead want to make decisions that affect their individual farms with minimal outside intervention. Environmental groups, on the other hand, demand that the

"evil" anaerobic lagoons, which have traditionally been used to treat swine-waste in North Carolina, be phased-out. Every stakeholder in the issue of animal waste management appears to be focusing on "one size fits all" or uniform treatment strategies for all farms.

In the meanwhile, both sides have ignored the real issues regarding waste management. The real focus should have been on achieving low cost treatment that meets regional goals of environmental and public health protection. Techniques that have traditionally been used in other areas of environmental management have not been considered for use in the field of animal waste. Mathematical optimization techniques have been used, for more than two decades now, in watershed management. The generation of alternatives has been explored in water resource management or in land uses problems for almost as long. Uncertainty analysis tools have also been extensively used in the fields of solid waste management and air pollution in the past. A number of quantitative analysis techniques are available and have gone unutilized in the regional management of animal waste. Their use can help stakeholders focus on the real issues, as opposed to focusing on positions.

It was shown in this dissertation that the use of a variety of quantitative techniques can help set and achieve clear targets for regions. The goal of the dissertation was not to trivialize the complicated issue of animal waste. Instead, this dissertation has detailed a procedure that uses *existing* data and *proven* techniques to identify "good" strategies for regional animal waste management.

6.3 Future Work

Alternative management approaches that are currently used in other environmental fields may also be useful to include in the presented framework. For example, the use of transferable (tradable) permits could be explored. Transferable permits are an economic policy instrument under which rights to discharge pollutants or exploit resources can be exchanged through either a free or a controlled permit-market. Transferable permits could be excellent instruments to meet regional environmental goals while allowing more freedom to farmers in implementing waste treatment options at their farms, thus addressing equity concerns. The framework presented in this dissertation can help analyze the efficiency in a trading program, as it can be used to anticipate the distribution of permits after trading.

Computing power continues to improve and high performance computing options become increasingly available. Problems that were unsolvable twenty years ago are now possible. The development of a

computer-based decision support tool (DST) will make the methodologies described in this dissertation more accessible to farmers, environmental managers, policy-makers, and the public. Such a DST would allow easier examination of various important issues in a systematic manner. Development of this tool should consider inputs from the industry and the public, thereby incorporating more criteria in the analysis than the ones mentioned in this research. A decision support tool that is based on the proposed methodology will undoubtedly lead to better decision-making in animal waste management.

Finally, it is my belief that more interdisciplinary research is necessary to bring techniques that have evolved separately within application areas into the field of animal waste management. True progress requires that scientists look beyond the narrow bounds of their fields and research areas. The tools necessary to solve many of the problems we are facing abound. While innovation and development of new tools is important, the wealth of existing ones awaits implementation in new areas of study.

Bibliography

- Anastasiou C., S. Liehr, and S. Ranjithan. (2002). Chapter 2 - Computer Assisted Waste System Selection Tool.
- Anastasiou C., S. Liehr, and S. Ranjithan. (2002). Chapter 3 - Design of Animal Waste Management Strategies to Achieve Regional Environmental Objectives.
- Anastasiou C., S. Liehr, and S. Ranjithan. (2002). Chapter 4 - Managing Swine Waste in North Carolina: Examination of Alternatives.
- Barker, J.C., Zublena, J.P., Campbell, C.R. (1994). Livestock manure production and characterization in North Carolina. North Carolina Cooperative Extension Service. Raleigh, N.C.
- Bicudo, J., Classen, J., Goldsmith, D. Jr., Smith, T. (1999). Effects of Aeration Cycles and Hydraulic Retention Time on the Sequencing Batch Treatment of Flushed Swine Manure. *Advances in Environmental Research*, 3 (1): 58-73.
- Brill, E.D., J.C. Liebman, and C.S. Revelle. (1976). Equity Measures for Exploring Water-Quality Management Alternatives. *Water Resources Research* 12(5): 845-851.
- Brill, E. D. (1979). The Use of Optimization Models in Public-Sector Planning. *Management Science*, 25(5): 413-422.
- Brill, E. D., Jr., Chang, S. Y., Hopkins, L. D. (1982). Modeling to generate alternatives: The HSJ approach. *Management Science*, 28(3): 221-225.
- Brill, E.D. Jr., J.M. Flach, L.D. Hopkins, and S. Ranjithan. (1990). MGA: A Decision Support System for Complex, Incompletely Defined Problems. *IEEE Transactions on Systems, Man, and Cybernetics*, 20(4): 745-757.

- Burkholder, JM; MA Mallin; HB Glasgow Jr.; LM Larsen; MR McIver; GC Shank; N Deamer Melia; DS Briley; J Springer; BW Touchette; and EK Hannon. (1997). Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. *Journal of Environmental Quality*, 26(6): 1451-1466.
- Chang, Shouu-Yuh. (1981). Methods for Generating Alternative Solutions to Environmental Planning Problems. Ph.D. Dissertation, University of Illinois at Urbana-Champaign, May 1981.
- Chang, S., E. D. Brill, and L. D. Hopkins. (1982). Efficient Random Generation of Feasible Alternatives: A Land Use Example. *Journal of Regional Science*, 22(3): 303-313.
- Cheng, J., K. F. Roos, and L. M. Saele. (1999). Evaluation of Covered Anaerobic Lagoon System for Swine Waste Treatment and Energy Recovery. In: *Proceedings 1999 Animal Waste Management Symposium*, 261-264. January 1999, Cary, NC.
- Cheng, J. and B. Liu. (2002). Swine wastewater treatment in anaerobic digesters with floating medium. *Transactions of the ASAE*, 45(3): 799-805.
- Church, Richard L. and Dennis D. Huber. (1979). On Finding Close to Optimal Solutions As Well As Determining a Noninferior Set Tradeoff Envelope for Multi-Objective Location Models. Research Series No. 34, Department of Civil Engineering, University of Tennessee, July 1979.
- Classen J. J. and J. R. Bicudo. 1999. Two Alternative Treatments for Flushed Swine Waste. In: *Proceedings 1999 Animal Waste Management Symposium*, 14-21. January 1999, Cary, NC.
- Cox, D. C. and Baybutt, P. (1981). Methods for Uncertainty Analysis: A Comparative Survey. *Risk Analysis*, 1: 251-258.
- Crites, R. and G. Tchobanoglous. (1998). Small and decentralized wastewater management systems. WCB / McGraw Hill, Boston, MA.
- USEPA, Office of Water. (2000). "Proposed Regulations to Address Water Pollution from Concentrated Animal Feeding Operations." EPA 833-F-00-016. Washington, D.C.

- Fenz, R., M. Zessner, N. Kreuzinger and H. Kroiss. (1998). "Integrated waste water management for a small river basin - a case study". *Water Science and Technology*, Volume 38(11): 87-95
- Gillon, D.L. (1999). Alternative Management Strategies for Air Quality Control. MS Thesis, North Carolina State University, May, 1999.
- Harrison, K.W., R.D. Dumas, E. Solano, M.A. Barlaz, E. D. Brill Jr., and S. Ranjithan. (2001). "Decision Support Tool for Life-Cycle-Based Solid Waste Management." *Journal of Computing in Civil Engineering*, 15(1): 44-58.
- Harrell, L. J. and S. Ranjithan. (1997). Generating Efficient Watershed Management Strategies Using a Genetic Algorithms-Based Method. Ed: D. H. Merritt *Proceedings of the 24th Annual Water Resources Planning and Management Conference (ASCE)*, 272-277, Houston, TX, April 6-9, 1997
- Harrell, L. J. (1998). Methods for Generating Alternatives to Manage Water Quality in Watersheds. Ph.D. Dissertation, North Carolina State University, December 1998.
- Harrell, L. J. and S. Ranjithan. (1999). "Evaluation of Alternative Penalty Function Implementations in a Watershed Management Design Problem," In *GECCO-99: Proceedings of the Genetic and Evolutionary Computation Conference*, 1551-1558, Orlando, Florida USA, July 13-17, 1999.
- Henze, M., C.P.L. Grady, Jr., W. Gujer, G. v.R. Marais, and T. Matsuo. (1987). A general model for single-sludge wastewater treatment systems. *Water Research* 21: 505-515.
- Henze, M., W. Gujer, T. Mino, T. Matsue, M.C. Wentzel, and G. V.R. Marais. (1995). Wastewater and biomass characterization for the activated sludge model No. 2: Biological phosphorus removal. *Water Science and Technology* 31(2): 13-23.
- Hopkins, L.D., E.D. Brill, and B. Wong. (1982). Generating Alternative Solutions for Dynamic Programming Models of Water Resources Problems. *Water Resources Research*, 18(4): 782-790.
- Humenik, F.J., M.R. Overcash, J.C. Barker, and P.W. Westerman. (1981). Lagoons: State-of-the-Art. In: *Livestock Waste: A Renewable Resource*, In *Proceedings of the Fourth International Symposium on Livestock Waste*, ASAE, St. Joseph, MI 49085-9659 USA.

- Hunt, P.G.; Thom, W.O.; Szogi, A.A.; Humenik, F.J. (1995). State of the art for animal wastewater treatment in constructed wetlands. *In Proceedings. ASAE 7th Int. Symposium on Agricultural and Food Processing Wastes (ISAFPW95)*, held Chicago, IL, USA, 18-20 Jun. 1995. Ross, C.C. (ed). American Society of Agricultural Engineers (ASAE), ASAE Publication 7-95: 53-65.
- Johnson, E.L. (1967). A study in the economics of water quality management. *Water Resources Research*, 3: 291-305.
- Liebman, J.C. (1976). Some Simple-Minded Observations on the Role of Optimization in Public Systems Decisionmaking. *Interfaces*, 6(4): 102-108.
- Liehr, S., N. Khare, J. J. Classen, F. Humenick, K. Zering, and S. Cavanaugh. (1999). The Computer Assisted Animal Waste Selection Tool (CAAWST). Abstract *In*: 1999 Animal Waste Management Symposium, January 1999, Cary, NC, Proceedings. North Carolina State University, Raleigh, NC, 328.
- Loughlin, D.H. and S. Ranjithan. (1997). The Neighborhood Constraint Method: A Genetic Algorithm-Based Multiobjective Optimization Technique. *Proceedings of the 7th International Conference on Genetic Algorithms*, ed. Thomas Back, 666-673, East Lansing, Michigan, July 19-23, 1997.
- Loughlin, D.H., Ranjithan, S., Brill, E.D. Jr. (1999). Genetic Algorithm Approach for Addressing Unmodeled Objectives in Optimization Problems. *Engineering Optimization*, 33: 549-569.
- Loughlin, D. H., S. Ranjithan, J. W. Baugh, and E. D. Brill. (2000). Application of Genetic Algorithms for the Design of Ozone Control Strategies. *Journal of the Air and Waste Management Association*, 50: 1050-1063.
- Metcalf & Eddy Inc. (1991). Wastewater engineering: treatment, disposal, and reuse, 3rd Edition. Revised by George Tchobanoglous, Franklin L. Burton. McGraw Hill, New York, NY.
- Morgan, M.G., and Max Henrion. (1990). *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, New York.

- Nakamura, M. and E.D. Brill, Jr. (1997). Mathematical Methods for Use in Planning Regional Wastewater treatment System. *Research Report No. 130 University of Illinois at Urbana-Champaign, Water Resources Center.*
- Payne Engineering and CH2M Hill. (1997). Constructed Wetlands for Animal Waste Treatment. (V. Payne and R.L. Knight, Eds.) *Report prepared for the Gulf of Mexico Program, Nutrient Enrichment Committee*, June 1997.
- ReVelle, C. and A. E. McGarity. (1997). Design and Operation of Civil and Environmental Engineering Systems, Wiley-Interscience, John Wiley, New York.
- Eric Solano, S. Ranji Ranjithan, Morton A. Barlaz, and E. Downey Brill. (2002a). Life-Cycle-based Solid Waste Management. I: Model Development. *ASCE Journal of Environmental Engineering* 128: 981-992.
- Eric Solano, Robert D. Dumas, Kenneth W. Harrison, S. Ranji Ranjithan, Morton A. Barlaz, and E. Downey Brill. (2002b). "Life Cycle -Based Solid Waste Management – 2. Illustrative Applications," *ASCE Journal of Environmental Engineering* 128: 993-1005.
- Szogi, A.A. and P.G. Hunt. (2001). Distribution of ammonium-N in the water-soil interface of a surface-flow constructed wetland for swine wastewater treatment. *Water Science and Technology*, 44 (11/12): 157-162.
- Tabachow, Ross M., Chase Stock, and J. Jeffrey Peirce. (2002). Options for Centralized Management of Swine Waste. *ASCE Journal of Environmental Engineering*. 128(5): 476-478.
- Westerman, PW, and JR Bicudo. (1998). Tangential flow separation and chemical enhancement to recover swine manure solids and phosphorus. In. *Proceedings 1998 ASAE Annual International Meeting*. Disney's Coronado Springs Resort Orlando, Florida July 12-16, 1998.
- Westerman, P. W., J. R. Bicudo, and A. Kantardjieff. (1999). Aeration and Mixing Pond for Nitrification of Flushed Swine Manure. In: *1999 Animal Waste Management Symposium*. 31-38. January 1999, Cary, N.C.

Westerman, PW, JR Bicudo; and A. Kantardjieff. (2000). Upflow biological aerated filters for the treatment of flushed swine manure. *Bioresource Technology* 74 (3): 181-190.

Williams, Mike. (2002). Development Of Environmentally Superior Technologies: Two-Year Progress Report for Technology Determination per Agreements Between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms, and Frontline Farmers. Waste Management Programs of the College of Agriculture and Life Sciences at North Carolina State University. July 25, 2002. (http://www.cals.ncsu.edu/waste_mgt/2yrreport.pdf).

APPENDIX A:

List of constants used in the CAWSST models

1. Volume of manure produced per hog = $2.55 \text{ gallons} / \text{day} / 150 \text{ lb pig}$
(manvol_per_hog)
 This is calculated from Dr. Barker's database (based on data for 150 lb. finishing hogs). This is the mean manure-mass produced per day per hog divided by the mean density of manure. i.e. $[(11.1/61.5)*\text{conversion factor of cubic feet to gallons}]$.
2. % Removal of TN in Anaerobic Lagoon = **80.0%**
(AL_TN_removal)
 This removal rate is obtained from the mass balance on the net input to the system. The boundary of the mass balance system is defined so as not to take recycle in to account. That is, 80% of the mass of Nitrogen that enters the system (from the total swine manure) gets removed in the system. According to the assumptions used, the flushing schedule of the swine houses does not affect the percent mass removal. The 80% removal rate by mass is used in the design of Anaerobic Lagoons (2001). This removal efficiency comes from the Karl Schaefer (NCSU) database.
3. TP concentration in effluent of anaerobic lagoon = **65.0%**
(AL_TP_removal)
 This removal rate is obtained from the mass balance on the net input to the system. The boundary of the mass balance system is defined so as not to take recycle in to account. That is, 65% of the mass of Phosphorus that enters the system (from the total swine manure) gets removed in the system. According to the assumptions used, the flushing schedule of the swine houses does not affect the percent mass removal. The 65% removal rate by mass is used in the design of Anaerobic Lagoons (2001). This removal efficiency comes from the Karl Schaffer (NCSU) database.
4. Nitrogen mass in manure = $0.164 \text{ lb N} / \text{lb swine} / \text{year}$
(Nmanure_mass)
 This number comes from Karl Shaffer's data. He reports $0.15 \text{ lb N} / \text{lb animal} / \text{year}$.
5. Phosphorus mass in manure = $0.0511 \text{ lb P} / \text{lb swine} / \text{year}$
(Pmanure_mass)
 This number comes from Karl Shaffer's data. He reports $0.13 \text{ lb P} / \text{lb animal} / \text{year}$.
6. TKN concentration in raw manure of animals = $3175 \text{ g} / \text{m}^3$
(TKNconc_manure)
 This number comes from Karl Shaffer's data. He reports $0.15 \text{ lb N} / \text{lb animal} / \text{year}$. If we use this number in combination to the $2.55 \text{ gallons} / \text{day}$ of manure production for every 150-lb pig (reported in Jim Barker's most recent database, as of 2002), and we back-calculate the concentration, we get $2900 \text{ g} / \text{m}^3$, the number reported here.
7. TP concentration in raw manure of animals = $990 \text{ g} / \text{m}^3$
(Pconc_manure)
 This number comes from Karl Shaffer's data. He reports $0.13 \text{ lb P} / \text{lb animal} / \text{year}$. If we use this number in combination to the $2.55 \text{ gallons} / \text{day}$ of manure production for every 150-lb pig (reported in Jim Barker's most recent database, as of 2002), and we back-calculate the concentration, we get $1100 \text{ g} / \text{m}^3$, the number reported here.
8. Annual excess rainfall accumulating in lagoon = $0.18 \text{ m} / \text{year}$
(annualexcessrainfall)
 This is the 7 inches of average rain accumulation.

9. Nitrogen Loading Rate of Constructed Wetland = $25 \text{ Kg} / \text{hectare} / \text{day}$
(Nuprate)
 This is the design constant used for constructed wetlands. This number is obtained from the Duplin County Wetland project. **Ask Sarah for the proper reference.**
10. Retention Time of water in a Constructed Wetland = **12 days**
(retentiontime)
 This number is obtained from the Duplin County Wetland project. .
11. Water Depth in Constructed Wetlands = **0.15 m**
(waterdepth)
 This is assumed to be the average depth in wetlands. The number is also obtained from the Duplin county study.
12. Vegetation area adjustment factor = **0.75**
(veg_area_adjustment)
 This factor adjusts for the volume available for water in a constructed wetland. We assume that plants occupy the rest 25% of the wetland's volume. Duplin county study as well as common Constructed Wetland design practice.
13. Lagoon volume design factor = $2 \text{ ft}^3 / \text{lb of hog weight}$
(lag_vol_des_factor)
 This is the required volume of an anaerobic lagoon based on a per pound hog weight for a farm. The "break-down" of this design factor follows:
 Specific treatment volume = $1 \text{ ft}^3 / \text{lb of hog weight}$
 SpecificManure wastewater volume = $0.5 \text{ ft}^3 / \text{lb of hog weight}$
 Specific sludge volume = $0.5 \text{ ft}^3 / \text{lb of hog weight}$
14. Average hog weight of a finishing hog = **150 lbs**
(hog_weight)
 This is the average weight of a finishing hog. Obtained from Jim Barker's database (as of 4 / 2202)
15. Excavation Cost for a Constructed Wetland storage pond = $1.99 \$ / \text{m}^3$
(excavcost)
 This is the cost per cubic meter for excavating the area for the constructed wetland. Source is the Duplin county study (number obtained from Nidhi's code).
16. Labor, wiring and pumping costs for Constructed Wetlands = **1050 \$**
(labor_wiring_pump_cost)
 This is the average cost for all the electrical installation work, including labor, for a 3000 sow farm. Source is the Duplin county study (number obtained from Nidhi's code).
17. Vegetation cost for a constructed wetland = **533.76 \$ / hectare**
(vegcost)
 This is the average one-time cost per hectare for planting the treatment area of the constructed wetland. This number was obtained from the Duplin County farm study (Nidhi's code was the source)

- 18 Cost of land rental for constructed wetland = **123.55 \$ / hectare**
(landrentalcost)
 The average yearly cost of renting a hectare of land that will be occupied by the constructed wetland system. This value was obtained from the Duplin county project.
- 19 Excavation cost for an anaerobic lagoon = **1.1 \$ / yard³**
(excavcost_lagoon)
 This is the price quoted for the anaerobic lagoon excavation cost. This was obtained from Nidhi's code. Values of \$1.8/yard³ is reported in Kadlec & Knight (1995) for excavation of a constructed wetland. The EPA Manual for Constructed Wetlands for the Treatment of Municipal Waste report a value of \$2.3/m³ (i.e. also \$1.8/yard³).
- 20 Flush water TKN concentration for SBR = **40 g / m³**
(TKNconc_FlushWater1)
(TKNconc_FlushWater1_g_per_cum)
 This is the concentration of TKN in the flush water for the Sequencing Batch Reactor treatment system. Table 3 of the Bicudo et al. paper (1999). Similar numbers are reported in Nidhi's code.
- 21 Flush water TKN concentration for Digester and Biofilter = **30 g / m³**
(TKNconc_FlushWater)
(TKNconc_FlushWater_g_per_cum)
 This is the concentration of TKN in the flush water for the Ambient Anaerobic Digester and the Upflow Aerated Biofilter treatment systems. This number is derived from a series of mass balances for the system, taking percent removal rates from the Westerman et al (2000) paper.
- 22 TP concentration in the flush water into SBR = **50 g / m³**
(TPconc_FlushWater1)
 This is the concentration of TP in the flush water for the Sequencing Batch Reactor treatment system. Table 3 of the Bicudo et al. paper (1999).
- 23 Flush water TP concentration for Digester and Biofilter = **30 g / m³**
(TPconc_FlushWater)
 This is the concentration of TP in the flush water for the Ambient Anaerobic Digester and the Upflow Aerated Biofilter treatment systems. This number is derived from a series of mass balances for the system, taking percent removal rates from the Westerman et al (2000) paper.
- 24 Methane production from waste = **24 ft³ / 1000 hogs day**
(methane_production)
 This value was obtained from a paper (Italian author, **Find reference**). The number is not used in CAWSST, since value-added by-products are not currently activated.
- 25 % Reduction of TP by the solids separation screen = **20.00%**
(separator_P_removal)
 The percent of Phosphorus that is removed by the solids separator is the phosphorus that is present in the separated solids. Westerman and Bicudo (1998)
- 26 % Reduction of TKN by the solids separation screen = **15.00%**
(separator_TKN_removal)
 The percent of Nitrogen that is removed by the solids separator is the nitrogen that is present in the separated solids. Westerman and Bicudo (1998)

- 27 Depth to be excavated for the constructed wetland = **1.22 m**
(excav_depth_cw)
 The depth of a constructed wetland is calculated by using as basis the required 0.6 meters for water depth. Liner clay (liner thickness is 1.5 feet, the same as in an anaerobic lagoon) and gravel (0.5 feet) also needs to be accommodated in the excavated depth, therefore, the total excavation depth is approximately 1.22 meters. Total media thickness (clay liner and gravel) is reported to be 0.5-0.6 meters in the USEPA manual for CW for Municipal Wastewater Treatment.
- 28 Wetland Efficiency in removing TKN from waste = **87.00%**
(wetland_efficiency_TKN)
 This is the percent removal of Nitrogen in Constructed Wetlands. This percentage does not include the percent removal of nitrogen in either an anaerobic lagoon or a solids separator that precedes the wetland. (Payne Engineering and CH2M Hill, 1997)
- 29 Density of Manure = **61 lb / ft³**
(manure_density)
 The wet based density of fresh swine manure. Number obtained from Barker's database.
- 30 Mass removal efficiency of inclined screen separator = **50.00%**
(screen_separator_efficiency)
 The percent of solids that is removed by the inclined screen solids separator. Westerman and Bicudo (1998)
- 31 **Cost of Construction of Tanks for SBR System**
 No constant is associated with these parameters. Instead, a series of equations describes the cost of the reactor tank for the SBR system. Each equation describes the cost of tanks of different size categories. This cost depends on the size (volume and depth) of the concrete tank that we need for the specific operation in the system. Reference: "Cost Estimating Guide for Animal Management Systems", USDA, Natural Resources Conservation Service (IA210_VI-AWMFH, Amend. IA3, May 1995) IA17-(0_1).
- 32 Electricity used for the SBR system = **0.012262 Kwh / gal of flushed effluent volume**
(electricity_pergallon_SBR)
 This is the electricity used per gallon of treated effluent in the SBR system. Reference: "Economic analysis of RemTec SBR System" by Kelly Zering, Ag. Economics, NCSU
 This constant is provided by the REmTech technologies and it is only 3-4% of the electricity observed for the pilot scale system. This seems highly unlikely; therefore, this value will be kept as the value to operate the pumps and the mixer alone. The cost of operation for the air blower is calculated separately.
- 33 Cost of Electricity = **0.09 \$ / Kwh**
(electricity_cost)
 The cost of electricity per kilowatt-hour is an average for the eastern part of North Carolina (where the greatest concentration of swine farms occurs). Prices typically range from \$0.06 to \$0.13 / Kwh
- 34 Maintenance and Improvement for SBR = **3.00%**
(maintain_cost_ratio)
 This is a percent of the initial cost for an SBR system. It is standard engineering practice to allocate a percent of the capital cost for maintenance of a system. The 3% value came from personal judgment and from discussions with Dr Classen.

- 35 Labor rate for SBR system = **10 \$ / hour**
(salary_perhour_SBR)
 This is the average hourly salary for a skilled worker that can operate the SBR system. This value is higher than the salary allocated to personnel that operate anaerobic lagoons or other more basic treatment systems.
- 36 Cycles per day for the SBR system (e.g 12 & 24 hr cycles) = **1 hrs / hrs**
(cycles_per_day)
 These are the cycles allowed in the SBR system in one day. For example, if the cycle duration is 12 hours, then we are dealing with 2 cycles per day. In our case, we are describing the SBR system under Condition I of the Bicudo et al. (1999) paper, detailed in Table 1.
- 37 % removal rate of TKN in the SBR system = **96.40%**
(SBR_TKN_removal_rate)
 A mass balance was performed to determine the nitrogen removal rate of the SBR system (i.e. its removal efficiency in terms of nitrogen by mass). The nitrogen concentration values for the wastewater and the operating conditions for the SBR used were obtained from the Bicudo et al. (1999) paper. The boundaries of the mass balance system were drawn so that it includes the recycle (flush) water.
- 38 % removal rate of TP in the SBR system = **70.00%**
(SBR_TP_removal_rate)
 A mass balance was performed to determine the phosphorus removal rate of the SBR system (i.e. its removal efficiency in terms of phosphorus by mass). The phosphorus concentration values for the wastewater and the operating conditions for the SBR used were obtained from the Bicudo et al. (1999) paper. The boundaries of the mass balance system were drawn so that it includes the recycle (flush) water.
- 39 Hydraulic Retention Time for the SBR system = **10 days**
(SBR_HRT)
 Depending on the hydraulic residence time, the SBR has different nitrogen, phosphorus and solids removal efficiencies. In our case, we are describing the SBR system under Condition I of the Bicudo et al. (1999) paper, detailed in Table 1.
- 40 Effluent retention time in holding tank for SBR system = **135 days**
(SBR_eff_ret_time)
 This is the residence time of treated water in the effluent holding tank for the SBR system. This number ranges from 3-6 months. A higher nutrient content of the water will dictate a longer retention time. Let me also note here that the detention time of swine waste in an anaerobic lagoon is approximately 180 days Barker (1994).
- 41 Solids Retention time for SBR system = **35 days**
(sludge_holding_time_SBR)
 Reported in Table 1 of the Bicudo et al. (1999) paper, under operating Condition I.
- 42 Belt Filter Press Width = **2 m**
(belt_width)
 The width of the belt filter press was obtained from Metcalf & Eddy book (page 866). The most common size used for municipal sludge applications is reported to be the 2 meters width. Lacking any further information, I am using this. Belt width *ranges* from 0.5-3.5m.

- 43 Belt Filter Press Loading Rate = **600 lbs / m hour**
(filterpress_loading_rate)
 This is an average value, again obtained from Metcalf & Eddy's "Waste Engineering" Text. The loading rates *range* from 200 – 1500 lb/m/h.
- 44 Belt Filter Press operation time per day = **8 hours / day**
(press_operation_time)
 This assumes that the belt is operated 8 hours a day (full operation mode). This is an assumption made from experience with certain municipal wastewater treatment systems. The value is quite *uncertain* as to the animal waste operation mode.
- 45 Cost for Pumps and Blowers for SBR system = 84,000 \$
(base_cost_pumpblowerSBR)
 This value is obtained from Kelly Zering (the RemTec economic evaluation of the SBR system). The cost corresponds to a 3400-sow farm.
- 46 Cost for Pumps and Blowers for SBR system = 1.05 \$ / gallon of reactor capacity
(cost_pergallon_pumpblowerSBR)
 This is the per-gallon (of the daily volume of wastewater – the flush water is included in this volume - going through the system) cost for Pumps and Blowers used in the SBR system. This number was derived from the following relation: \$84,000 for an 80,000 / day SBR system, taken from Kelly Zering (the RemTec economic evaluation of the SBR system). The cost corresponds to a 3400-sow farm.
- 47 Cost for Process Controls for SBR system = **21000 \$**
(cost_operationcontrolSBR)
 Reference: This value is obtained from Kelly Zering (the RemTec economic evaluation of the SBR system). The cost is a "standard value" and it corresponds to a 3400-sow farm.
- 48 Cost for Labor, materials, subcontractors for SBR system = 1.0625 \$
(cost_pergallon_constructionSBR)
 This is a base cost for Process Control, estimated from a proposed RemTec SBR system for a 3400 sow Farrow-to-Wean Farm (economic analysis of SBR by Kelly Zering)
 \$85,000 for an 80,000 gallon / day SBR system
- 49 % removal rate of TKN in an Ambient Digester = **38.00%**
(percent_removal_TKN_CAL)
 Reference: From Jay Cheng's data from his Barham Farm study (for a 4000 sow farm) (Cheng et al., 1999). This percent removal corresponds to only the digester itself, NOT the whole system. Therefore, the nitrogen removed by the storage pond that follows the digester is not included in this percentage.
- 50 % removal rate of TKN in a storage lagoon of CAL = **80.00 %**
(rem_effic_TKN_storLag_CAL)
 From Jay Cheng's data from his Barham Farm study (for a 4000 sow farm) (Cheng et al., 1999). This is the same percent removal of nitrogen as in any anaerobic lagoon. The 80% removal rate by mass is used in the design of Anaerobic Lagoons (2001). This removal efficiency comes from the Karl Schaefer (NCSU) database.

- 51 % removal rate of TP in an Ambient Digester = **72.00 %**
(percent_removal_TP_CAL)
 Reference: From Jay Cheng's data from his Barham county farm study (for a 4000 sow farm) (Cheng et al., 1999). This percent removal corresponds to only the digester itself, NOT the whole system. Therefore, the phosphorus removed by the storage pond that follows the digester is not included in this percentage.
- 52 % removal rate of TP in a storage lagoon of CAL = **65.00 %**
(rem_effic_TP_storLag_CAL)
 From Jay Cheng's data from his Barham Farm study (for a 4000 sow farm) (Cheng et al., 1999). This is the same percent removal of phosphorus as in any anaerobic lagoon. The 80% removal rate by mass is used in the design of Anaerobic Lagoons (2001). This removal efficiency comes from the Karl Schaefer (NCSU) database.
- 53 Hydraulic Retention Time for an Anaerobic Digester (for CAL) = **65 days**
(CAL_HRT)
 This is the number used to size the anaerobic digester. Reference: Cheng et al., 1999.
- 54 Storage capacity of storage lagoon for CAL system = **180 days**
(storage_time_SL)
 This is the storage time of water that leaves the digester and enters the storage pond. The retention time is the same as for the anaerobic lagoon. This is standard practice in the design and operation of anaerobic lagoons.
- 55 Height (depth) of Storage Lagoon for the CAL system = **8 feet**
(SL_depth)
 Reference: Cheng et al., 1999. The 8 feet is referring to the storage lagoon depth. The digester depth is about *20 feet* deep rather than 10 feet.
- 56 Slope of the Storage Lagoon sides for the CAL system = 1/3
(SL_slope)
 Standard design value for lagoons. The slope is usually no steeper than 1 unit run to 3 units rise. It can be as low as 1:2 but normally no higher than 1:3
- 57 Cost of liner material for Lagoons (for CAL) = 1.64 \$ / cubic yard
(liner_cost)
 This is the cost of the lining material in per volume units.
 Mark Rice of NCSU provided the following information on 5/11/02:
 For an 8 acre constructed wetland, the cost of Bentonite was \$61,000 and the installation & compaction cost was an additional \$2,500 (thus bringing the total cost for lining the 8 acre lagoon to \$63,500). Calculating from this information, and assuming a clay liner thickness of 1.5 feet, we obtain a cost of \$1.64 / yd³.
 The cost of *clay liner ranges \$1.25 - \$6.25 / yd³* depending on hauling distance, etc.
 The cost of *synthetic liner ranges \$0.50 - \$4.00 / yd²*.
- 58 Thickness of the liner used in a lagoon in CW, AL or CAL systems = **1.5 feet**
(liner_thickness)
 Standard practice for anaerobic lagoons. I assumed that the liner of any similar lagoon-based structure will have a similar thickness of it is going to be effective. Humenick et al. 1981, as well as a number of other design manuals for Als.

- 59 Slope of the CAL (z) **3**
(CAL_slope)
Standard design value for lagoons. The slope is usually no steeper than 1 unit run to 3 units rise. It can be as low as 1:2 but normally no higher than 1:3
- 60 Cost of the cover for the Covered Anaerobic Lagoon = 4.3 \$ / meter²
(CAL_cover_cost)
This is the cost of the cover needed for the Covered Anaerobic Lagoon. It is given in units of dollars per area. Kelly Zering (4/26/02) quoted \$0.40/ft² (that is \$4.3/m²). Verify with Jay Cheng
- 61 Basic Inground Digester Height (h) = **20 feet**
(CAL_basic_height)
Reference: Cheng et al., 1999. This number is highly uncertain. The 8 feet is referring to the storage lagoon depth. The digester depth is about *20 feet* deep rather than 10 feet.
- 62 Freeboard height = **2 feet**
(freeboard_height)
It is standard engineering practice to choose a safety factor of 2 feet for any lagoon structure.
- 63 Basic Storage Lagoon Height (h) = **8 feet**
(SL_basic_height)
Reference: Cheng et al., 1999. This number is used for all storage lagoons. It was used in designing the storage lagoon for the Ambient anaerobic digester system as well.
- 64 Rainfall and Runoff height = **2 feet**
(rainfall_runoff_height)
We allow this height in all of our open lagoons for rainfall and for any runoff water (for design safety purposes). This value comes from standard engineering practice.
- 65 Depth of the equalization tank for the SBR system = **11 feet**
(SBR_equal_tank_depth)
- 66 % removal rate of TKN in the UAB System = **72.00 %**
(EK_TKN_removal_rate)
This is the removal rate assumed for TKN in the Upflow Aerated Biofilter system. This number is taken from the Westerman, Zering, Bicudo, Classen, technology evaluation available through the APWMC. According to the report (page 7 of 12) this is the overall reduction in TKN in both biofilters. This percentage involves reduction occurring due to backwash.
- 67 % removal rate of TP in the UAB system = **26.00%**
(EK_TP_removal_rate)
This is the removal rate assumed for TP in the Ekokan system. This number is taken from the Westerman, Zering, Bicudo, Classen, technology evaluation available through the APWMC. According to the report (page 7 of 12) this is the overall reduction in TP in both biofilters. This percentage involves reduction occurring due to backwash.

- 68 Specific Surface Area of Plastic Media for Biofilters = **$140 \text{ m}^2 / \text{m}^3$ of filter volume**
(EK_specific_SA_plastic_media)
This is the average of the specific surface area of the plastic media used in the pilot scale plant described in the Westerman, Zering, Classen, and Bicudo analysis for the Ekokan System. (i.e. $140 \text{ m}^2 / \text{m}^3$ is the average of the 115-165 range in the specific surface area).
- 69 Surface area of Plastic media needed / wastewater volume = **$31 \text{ m}^2 / \text{m}^3 \text{ wastewater} / \text{day}$**
(EK_SA_plastic_media_per_waste_vol)
This is the average of the specific surface area of the plastic media used in the pilot scale plant described in the Westerman, Zering, Classen, and Bicudo analysis for the Ekokan System. (i.e. the value of 31 is calculated from the following: $(140 \text{ m}^2 / \text{m}^3 \text{ of biofilter volume} * 1.76 \text{ m}^3 \text{ of biofilter volume used}) / (8 \text{ m}^3 \text{ of wastewater treated per day})$).
- 70 Height of UAB Towers = **13 feet**
(EK_biofilter_height)
This is the assumed height of the biofilters used in the Ekokan system. Reference: the design of the pilot scale plant (Westerman, Zering, Classen, Bicudo Analysis)
- 71 Polishing tank "specific" volume for UAB = **0.25 m^3 of tank volume / m^3 of wastewater**
(EK_polishing_tank_specific_volume)
This number was deduced from the analysis of the pilot scale system at hand (Westerman, Zering, Classen, Bicudo).
Since $2 * 1 \text{ m}^3$ polishing tanks were used for 8 m^3 of waste, then 0.25 m^3 of tank volume is needed for 1 m^3 of waste.
- 72 Height of Polishing Tanks for the Ekokan System = **7 feet**
(EK_polishing_tank_height)
Personal Assumption. I used 5 feet of basic height plus 2 feet of freeboard. *Highly Uncertain.*
- 73 Equalization Tank "specific" volume for UAB system = **3.32 m^3 of tank volume / m^3 of wastewater**
(EK_equal_settle_tank_specific_volume)
This is an assumption that stems from the Ekokan system analysis paper (Westerman, Zering, Bicudo, and Classen). The design of the pilot scale system included a settling tank of 26.5 m^3 for a water flow of $8 \text{ m}^3 / \text{day}$. I assumed that an HRT of 4 days (plus safety factors) was used in sizing this tank. However, a "specific volume" was assigned as a constant for easier (more straightforward calculation of the tank volume. Thus, for every 1 m^3 of wastewater flow, we assign 3.32 m^3 of equalization tank volume.
- 74 Height of Equalization / Settling Tank for the UAB System = **12 feet**
(EK_equal_settle_tank_height)
Personal Assumption. I used 10 feet of basic height plus 2 feet of freeboard
- 75 Feed Tank "specific" volume for UAB system = **0.6 m^3 of tank volume / m^3 of wastewater**
(EK_feed_tank_specific_volume)
This is an assumption that stems from the Ekokan system analysis paper (Westerman, Zering, Bicudo, and Classen). The design of the pilot scale system included a feed tank of 4.2 m^3 for a water flow of $8 \text{ m}^3 / \text{day}$. From this, a "specific volume" was assigned as a constant for calculation of the feed tank volume. Thus, for every 1 m^3 of wastewater flow, we assign 0.6 m^3 of feed tank volume.

- 76 Height of Feed Tank for the UAB System = **7 feet**
(EK_feed_tank_height)
 Personal Assumption. I used 5 feet of basic height plus 2 feet of freeboard. *Highly Uncertain.*
- 77 % of Biofilter Volume Water used in Backwashing (UAB system) = **20.00 %**
(EK_backwash_percent_water)
 Percent of the water contained in the Ekokan biofilters that is used in the backwash procedure and thus needs to be stored in the backwash water storage tanks. Reference: Westerman, Zering, Bicudo, and Classen; evaluation of Ekokan technology
- 78 Frequency of biofilter backwashing (UAB system) = **2 /day**
(EK_backwash_frequency)
 The analysis of the pilot plant indicates a backwashing frequency of 4 times / day for the first biofilter, and a frequency of 1 time / 2 days for the second biofilter. Since in this description I did not separate the system in more than one biofilter, I am using an average backwash rate.
- 79 Hydraulic Residence time of water in backwash storage tank (UAB system) = **3 days**
(EK_backwash_tank_HRT)
 This is a personal choice for the HRT. I allowed the normal time for adequate settling to take place as it is used in municipal wastewater treatment systems (Metcalf & Eddy)
- 80 Height of Backwash Storage Tank for the UAB System = **7 feet**
(EK_backwash_tank_height)
 Personal Assumption. I used 5 feet of basic height plus 2 feet of freeboard. *Highly Uncertain.*
- 81 Interest Rate for Amortization of a Treatment System = **8.00 %**
(interest_rate)
 This is the percent interest rate. It is added to the initial (capital) investment when building a new treatment system. The number is standard practice in the industry. Kelly Zering is the source of this.
- 82 Life period of a treatment system = **20 years**
(system_lifetime)
 A treatment system will be designed to last for this number of years. After this amount of time it is assumed that the treatment system has a zero value. This is a standard engineering practice value. 15 years system life is also used. The 25-year life is more rare in its use.
- 83 Depth of the reactor tank for the SBR system = **12 feet**
(SBR_reactor_tank_depth)
 Personal Assumption. I used 10 feet of basic height plus 2 feet of freeboard. *Reconfirmed with Dr Classen as a logical assumption.*
- 84 Depth of the Sludge thickening holding tank for the SBR system = **10 feet**
(SBR_sludge_tank_depth)
 Personal Assumption. I used 10 feet of basic height plus 2 feet of freeboard. *Highly Uncertain.*

- 85 Life period of the Inclined Screen Solid Separator system = **15 years**
(SolidSeparator_lifetime)
 A treatment system will be designed to last for this number of years. After this amount of time it is assumed that the treatment system has a zero value. This is a standard engineering practice value. 20 years system life is most commonly used. The 25-year life is more rare in its use.
- 86 Excavation depth to accommodate SBR concrete tanks = **2 feet**
(SBR_excavation_depth)
 Assumption based on engineering experience. *Uncertain*
- 87 Slope of the Storage Lagoon sides for the CAL system = **1/3**
(AL_slope)
 Standard design value for lagoons. The slope is usually no steeper than 1 unit run to 3 units rise. It can be as low as 1:2 but normally no higher than 1:3
- 88 Basic Storage Lagoon Height (h) = **8 feet**
(AL_basic_height)
 This is the basic depth of an anaerobic lagoon. This does NOT take into account other height considerations such as freeboard and allowance for excess rainfall. Reference: Cheng et al., 1999. This number is used for all storage lagoons. It was used in designing the storage lagoon for the Ambient anaerobic digester system as well.
- 89 % of Total-N in separated biosolids in SBR = **7.00 %**
(SBR_TN_in_TS)
 This number (7%) is found in section titled "Biosolids Characteristics" of Bicudo and Classen paper.
- 90 % of TP in separated biosolids in SBR = **4.00 %**
(SBR_TP_in_TS)
 This number (4%) is found in section titled "Biosolids Characteristics" of Bicudo and Classen paper.
- 91 Equalization Tank Cost for UAB (per hog capacity) = **3 \$ / hog capacity**
(equal_tank_unit_cost_EK)
 This value was obtained from cost data sheet for the Ekokan System Economics for the Southern Region (see notes file on CAWSST).
- 92 Biofilter Cost for UAB (per hog capacity) = **24.65 \$ / hog capacity**
(biofilter_unit_cost)
 This value was obtained from cost data sheet for Ekokan System Economics for the Southern Region (see notes file on CAWSST)
- 93 Design Life of the UAB Biofilters = **12 years**
(Ekokan_life)
 This value was obtained from cost data sheet for Ekokan System Economics for the Southern Region (see notes file on CAWSST)
- 94 Electricity Cost per unit hog capacity per year for Ekokan = **5.18 \$ / hog capacity / year**
(EK_electricity_cost_per_hog)
 This value was obtained from cost data sheet for Ekokan System Economics for the Southern Region (see notes file on CAWSST)

- 95 Labor Cost per unit hog capacity per year for Ekokan = **0.832 \$ / hog capacity / year**
(EK_labor_cost_per_hog)
This value was obtained from cost data sheet for Ekokan System Economics for the Southern Region (see notes file on CAWSST)
- 96 % Phosphorus removal in a Constructed Wetland = 15%
(wetland_efficiency_TP)
This number was reported by Humenick et al. for the Duplin County wetland. (personal communication).

APPENDIX B:

Uncertainty Importance Analysis Results for the CAWSST Models

Anaerobic Lagoon

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
hog_weight	0.731306595	system_lifetime	-0.246638887
excavcost_lagoon	0.528434091	AL_basic_height	-0.213829765
liner_thickness	0.167267329	landrentalcost	-0.038012047
liner_cost	0.145403755	maintain_cost_ratio	-0.037376301
interest_rate	0.097691524	annualexcessrainfall	-0.00912617
AL_slope	0.079257889	Pconc_manure	-0.001721743

Capital Investment		Capital Investment	
hog_weight	0.764672517	AL_basic_height	-0.209891947
excavcost_lagoon	0.567714348	interest_rate	-0.089938199
liner_thickness	0.186616469	landrentalcost	-0.051939774
liner_cost	0.172944391	maintain_cost_ratio	-0.037566977

O&M Cost		O&M Cost	
hog_weight	0.783616749	AL_basic_height	-0.378981031
excavcost_lagoon	0.43163125	interest_rate	-0.096706756
liner_thickness	0.147385709	maintain_cost_ratio	-0.041948038
landrentalcost	0.146953997		
liner_cost	0.131698014		

AL Area		AL Area	
hog_weight	0.669407047	AL_basic_height	-0.752207063
CAL_basic_height	0.205299462	Pconc_manure	-0.010837779
AL_slope	0.142211391	AL_TN_removal	-0.000587813

AL TKN Remaining		AL TKN Remaining	
Nmanure_mass	0.273034604	AL_TN_removal	-0.935329995
hog_weight	0.224014388	manure_density	-0.099176026
AL_slope	0.040155629	AL_basic_height	-0.03193522
Pmanure_mass	0.037417379	AL_TP_removal	-0.022006772

AL TP Remaining		AL TP Remaining	
Pmanure_mass	0.437574091	AL_TP_removal	-0.787626887
hog_weight	0.407985641	AL_slope	-0.057594846
Nmanure_mass	0.053412042	AL_basic_height	-0.040281041

Anaerobic Digester (with Anaerobic Lagoon structure present)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
CAL_slope	0.542688904	system_lifetime	-0.236725682
CAL_cover_cost	0.540762914	annualexcessrainfall	-0.081556368
CAL_HRT	0.420372771	AL_TP_removal	-0.075558009
excavcost_lagoon	0.202350021	Pconc_manure	-0.060130108
interest_rate	0.183524893	percent_removal_TP_CAL	-0.06012259
liner_thickness	0.165522773	TKNconc_FlushWater	-0.049874609
freeboard_height	0.123287382	labor_wiring_pump_cost	-0.034158213

Capital Investment		Capital Investment	
CAL_cover_cost	0.581965274	annualexcessrainfall	-0.074540706
CAL_slope	0.570542986	AL_TP_removal	-0.059428608
CAL_HRT	0.461968429	percent_removal_TP_CAL	-0.052599681
excavcost_lagoon	0.194459623	TKNconc_FlushWater	-0.05127084
liner_thickness	0.17457735	Pconc_manure	-0.050225514
freeboard_height	0.115892123	rem_effic_TKN_storLag_CAL	-0.048898191

O&M Cost		O&M Cost	
CAL_cover_cost	0.450083127	AL_basic_height	-0.20462245
hog_weight	0.448757483	interest_rate	-0.060588683
CAL_slope	0.444170027	percent_removal_TP_CAL	-0.056933043
excavcost_lagoon	0.388247775	annualexcessrainfall	-0.049412482
CAL_HRT	0.338246336	TKNconc_FlushWater	-0.044294731
liner_thickness	0.216072111	maintain_cost_ratio	-0.04299862
Landrentalcost	0.10999054	TKNconc_FlushWater1	-0.0388685

Area		Area	
hog_weight	0.638916142	AL_basic_height	-0.725620387
CAL_basic_height	0.210230917	TPconc_FlushWater1	-0.054175247
CAL_slope	0.200477439	percent_removal_TKN_CAL	-0.034422368
AL_slope	0.129607948	TKNconc_FlushWater1	-0.033685683
CAL_HRT	0.097035332	press_operation_time	-0.033214732

TKN Remaining		TKN Remaining	
Manvol_per_hog	0.470188334	rem_effic_TKN_storLag_CAL	-0.79626075
TKNconc_manure	0.279209453	percent_removal_TKN_CAL	-0.191351095
Annualexcessrainfall	0.097463387	AL_basic_height	-0.099945597
CAL_slope	0.0493675	rainfall_runoff_height	-0.045709884

TP Remaining		TP Remaining	
manvol_per_hog	0.460102558	percent_removal_TP_CAL	-0.781045293
Pconc_manure	0.281676212	rem_effic_TP_storLag_CAL	-0.36582138
annualexcessrainfall	0.057440623	manure_density	-0.064018545
hog_weight	0.050078594	SL_slope	-0.059769923

Anaerobic Digester (no Anaerobic Lagoon structure present)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
CAL_cover_cost	0.442069011	system_lifetime	-0.306314666
CAL_slope	0.428392024	annualexcessrainfall	-0.069304552
excavcost_lagoon	0.392357628	percent_removal_TP_CAL	-0.06658792
hog_weight	0.345576019	Pconc_manure	-0.049232538
CAL_HRT	0.314724568	maintain_cost_ratio	-0.03784316
liner_thickness	0.203625507	landrentalcost	-0.036063397
interest_rate	0.196898448	SL_slope	-0.026054367
freeboard_height	0.11862916	storage_time_SL	-0.010955405
manvol_per_hog	0.079977521	rainfall_runoff_height	-0.001207679

Capital Investment		Capital Investment	
CAL_cover_cost	0.490500837	AL_basic_height	-0.090644057
CAL_slope	0.456954803	percent_removal_TP_CAL	-0.060405978
excavcost_lagoon	0.436832035	annualexcessrainfall	-0.05891962
hog_weight	0.382673609	interest_rate	-0.050117079
CAL_HRT	0.359178866	landrentalcost	-0.041388925
liner_thickness	0.232322122	SL_slope	-0.040998077
freeboard_height	0.112551846	maintain_cost_ratio	-0.038510818

(The rest of the results are the same as for the Anaerobic Digester WITH the anaerobic lagoon structure)

Constructed Wetland (preceded by an Anaerobic Lagoon as pre-treatment)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
excavcost_lagoon	0.263099187	AL_TN_removal	-0.744115527
manvol_per_hog	0.254570931	system_lifetime	-0.204616653
hog_weight	0.245133503	SL_basic_height	-0.115740352
Nmanure_mass	0.237359628	manure_density	-0.085257417
storage_time_SL	0.217313469	AL_TP_removal	-0.05075293
excav_depth_cw	0.200200024	AL_basic_height	-0.039564445
Capital Investment		Capital Investment	
manvol_per_hog	0.244033099	AL_TN_removal	-0.801796749
Nmanure_mass	0.243897629	SL_basic_height	-0.103174635
excavcost_lagoon	0.231804792	manure_density	-0.091827725
storage_time_SL	0.222057795	AL_TP_removal	-0.048130018
excav_depth_cw	0.20560629	system_lifetime	-0.041788847
excavcost	0.19849385	SL_slope	-0.026752409
O&M Cost		O&M Cost	
hog_weight	0.666104686	AL_basic_height	-0.380397307
excavcost_lagoon	0.38784659	AL_TN_removal	-0.215613351
landrentalcost	0.334381388	interest_rate	-0.088102448
manvol_per_hog	0.182952319	SL_basic_height	-0.079060238
storage_time_SL	0.160427738	electricity_cost	-0.043095387
liner_thickness	0.125117331	veg_area_adjustment	-0.030986519
AL_slope	0.108112051	maintain_cost_ratio	-0.021187993
Nmanure_mass	0.092844672	TKNconc_FlushWater1	-0.020435946
Area		Area	
hog_weight	0.528752043	AL_TN_removal	-0.692156528
Nmanure_mass	0.221748551	AL_basic_height	-0.431407477
CAL_basic_height	0.130716236	manure_density	-0.086753042
AL_slope	0.110282345	interest_rate	-0.055558839
manvol_per_hog	0.093048319	electricity_cost	-0.050568265
storage_time_SL	0.054336448	SL_basic_height	-0.031921484
Pmanure_mass	0.047326452	TPconc_FlushWater1	-0.021208777
TKN Remaining		TKN Remaining	
Nmanure_mass	0.091884455	wetland_efficiency_TKN	-0.850911279
TKNconc_FlushWater1	0.067035874	AL_TN_removal	-0.497849597
hog_weight	0.056954497	veg_area_adjustment	-0.094791831
waterdepth	0.043169632	manure_density	-0.055164132
TPconc_FlushWater1	0.035177185	TKNconc_manure	-0.044881688
TP Remaining		TP Remaining	
Pmanure_mass	0.43544506	AL_TP_removal	-0.797158617
hog_weight	0.349002691	AL_TN_removal	-0.137284364
Nmanure_mass	0.084772882	wetland_efficiency_TP	-0.081366359
manvol_per_hog	0.061655394	AL_slope	-0.071147905
TPconc_FlushWater	0.056963498	SL_slope	-0.045585223

Constructed Wetland (with solids separator used for pre-treatment)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
manvol_per_hog	0.531727811	system_lifetime	-0.254943395
TKNconc_manure	0.472922552	SolidSeparator_lifetime	-0.125024608
Excavcost	0.463163559	Pmanure_mass	-0.078953902
excav_depth_cw	0.455127601	SL_basic_height	-0.078400235
interest_rate	0.228933587	separator_TKN_removal	-0.067156148
excavcost_lagoon	0.15603183	waterdepth	-0.063789018
storage_time_SL	0.117675877	TPconc_FlushWater1	-0.05929442
TKNconc_FlushWater	0.086804776	manure_density	-0.05689708
Capital investment		Capital investment	
manvol_per_hog	0.539848946	separator_TKN_removal	-0.080753896
TKNconc_manure	0.502819307	Pmanure_mass	-0.079795168
Excavcost	0.5007003	manure_density	-0.063525999
excav_depth_cw	0.485583531	SL_basic_height	-0.058771162
excavcost_lagoon	0.167812319	waterdepth	-0.054400494
storage_time_SL	0.122509584	TPconc_FlushWater1	-0.052628399
TKNconc_FlushWater	0.083423334	system_lifetime	-0.05230158
O&M Cost		O&M Cost	
manvol_per_hog	0.635702597	SL_basic_height	-0.173794755
Landrentalcost	0.536752973	separator_TKN_removal	-0.06208834
TKNconc_manure	0.46205118	manure_density	-0.035520507
storage_time_SL	0.265039237	veg_area_adjustment	-0.030330291
excavcost_lagoon	0.194967112	waterdepth	-0.0293389
Area		Area	
TKNconc_manure	0.710934963	separator_TKN_removal	-0.106599216
manvol_per_hog	0.69366284	Pmanure_mass	-0.065215519
storage_time_SL	0.061324111	manure_density	-0.057081446
separator_P_removal	0.060533803	SL_basic_height	-0.051207776
TKN Remaining		TKN Remaining	
manvol_per_hog	0.199416559	wetland_efficiency_TKN	-0.950251154
TKNconc_manure	0.137421608	veg_area_adjustment	-0.100305216
TKNconc_FlushWater1	0.069732398	CAL_basic_height	-0.079909673
Annualexcessrainfall	0.063629617	belt_width	-0.076591931
TPconc_FlushWater1	0.044875687	separator_TKN_removal	-0.074738575
TP Remaining		TP Remaining	
manvol_per_hog	0.812061137	separator_P_removal	-0.094300878
Pconc_manure	0.507735603	wetland_efficiency_TP	-0.081450477
TKNconc_manure	0.18478261	veg_area_adjustment	-0.04852825
Annualexcessrainfall	0.154266818	rainfall_runoff_height	-0.041639713
excav_depth_cw	0.038487166	manure_density	-0.039776474

Sequencing Batch Reactor (with Anaerobic Lagoon structure present)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
base_cost_pumpblowerSBR	0.705886979	system_lifetime	-0.380669671
maintain_cost_ratio	0.265130275	SBR_TKN_removal_rate	-0.082653418
interest_rate	0.261442292	liner_cost	-0.068671132
cost_pergallon_constructionSBR	0.236597077	manure_density	-0.053606113
salary_perhour_SBR	0.217261665	SBR_sludge_tank_depth	-0.047241419
manvol_per_hog	0.203466643	landrentalcost	-0.045960091
cost_operationcontrolSBR	0.200505431	AL_TP_removal	-0.042877242
electricity_pergallon_SBR	0.143906078	liner_thickness	-0.039166842
electricity_cost	0.122848809	TKNconc_FlushWater	-0.032765026

Capital Cost		Capital Cost	
equal_tank_unit_cost_EK	0.938391854	storage_time_SL	-0.063200941
percent_removal_TP_CAL	0.314391355	cost_operationcontrolSBR	-0.056438133
SL_slope	0.25687619	TPconc_FlushWater	-0.056325952
manure_density	0.065070277	SBR_TKN_removal_rate	-0.052457124

O&M Cost		O&M Cost	
maintain_cost_ratio	0.560808084	labor_wiring_pump_cost	-0.076670445
salary_perhour_SBR	0.471301573	AL_basic_height	-0.075405474
base_cost_pumpblowerSBR	0.34504475	SBR_TKN_removal_rate	-0.061181352
manvol_per_hog	0.318223326	SBR_TP_in_TS	-0.058857232
electricity_pergallon_SBR	0.305923037	AL_TN_removal	-0.048815603
electricity_cost	0.303716069	manure_density	-0.046696613
Annualexcessrainfall	0.129177005	liner_cost	-0.044717725
cost_operationcontrolSBR	0.084245505	SBR_sludge_tank_depth	-0.03848436

Area		Area	
hog_weight	0.669364394	AL_basic_height	-0.75178837
CAL_basic_height	0.206256573	SBR_TKN_removal_rate	-0.076407662
AL_slope	0.141542185	SBR_HRT	-0.05736508
rainfall_runoff_height	0.062854443	SBR_eff_ret_time	-0.050354013
TKN Remaining		TKN Remaining	
TKNconc_manure	0.182577412	SBR_TKN_removal_rate	-0.965832011
manvol_per_hog	0.158629113	EK_backwash_percent_water	-0.101092133
Pconc_manure	0.100835263	AL_basic_height	-0.087517405
AL_slope	0.059758248	freeboard_height	-0.070547065
TP Remaining		TP Remaining	
Pconc_manure	0.369142228	SBR_TP_removal_rate	-0.871343599
manvol_per_hog	0.313999155	SBR_TKN_removal_rate	-0.068515155
SBR_TP_in_TS	0.047301879	Pmanure_mass	-0.065738303
SBR_reactor_tank_depth	0.042071459	AL_basic_height	-0.059126169

Sequencing Batch Reactor (no Anaerobic Lagoon structure present)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
base_cost_pumpblowerSBR	0.670784247	system_lifetime	-0.396552918
manvol_per_hog	0.280120689	SBR_TKN_removal_rate	-0.081371205
maintain_cost_ratio	0.280093041	liner_cost	-0.061425857
interest_rate	0.27417668	landrentalcost	-0.051636639
cost_pergallon_constructionSBR	0.228470084	SBR_sludge_tank_depth	-0.045715327
salary_perhour_SBR	0.208954699	SL_basic_height	-0.034237932
cost_operationcontrolSBR	0.188871444	TKNconc_FlushWater	-0.027694131
electricity_pergallon_SBR	0.10978511	labor_wiring_pump_cost	-0.026403714
electricity_cost	0.096567717	TPconc_FlushWater1	-0.024400241

	Capital Cost		Capital Cost
base_cost_pumpblowerSBR	0.914480573	TKNconc_FlushWater	-0.060473555
cost_pergallon_constructionSBR	0.309593988	SBR_TKN_removal_rate	-0.053778569
cost_operationcontrolSBR	0.248414847	landrentalcost	-0.046072251
manvol_per_hog	0.153223868	SL_basic_height	-0.040093008
excavcost_lagoon	0.082002698	manure_density	-0.035421909

	O&M Cost		O&M Cost
maintain_cost_ratio	0.604435724	labor_wiring_pump_cost	-0.077379123
salary_perhour_SBR	0.466161247	SBR_TP_in_TS	-0.059764421
manvol_per_hog	0.367250365	SBR_TKN_removal_rate	-0.053892845
base_cost_pumpblowerSBR	0.334825156	manure_density	-0.042365278
electricity_cost	0.260223699	liner_cost	-0.03817019
electricity_pergallon_SBR	0.249715548	SBR_sludge_tank_depth	-0.037447108

	Area		Area
storage_time_SL	0.597054412	SL_basic_height	-0.592588228
manvol_per_hog	0.532960164	SBR_equal_tank_depth	-0.066107036
SBR_HRT	0.103170363	SBR_reactor_tank_depth	-0.058817512

	TKN Remaining		TKN Remaining
TKNconc_manure	0.182577412	SBR_TKN_removal_rate	-0.965832011
manvol_per_hog	0.158629113	EK_backwash_percent_water	-0.101092133
Pconc_manure	0.100835263	AL_basic_height	-0.087517405

	TP Remaining		TP Remaining
Pconc_manure	0.369142228	SBR_TP_removal_rate	-0.871343599
manvol_per_hog	0.313999155	SBR_TKN_removal_rate	-0.068515155
SBR_TP_in_TS	0.047301879	Pmanure_mass	-0.065738303

Upflow Aerated Biofilter (preceded by an Anaerobic Lagoon as pre-treatment)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
EK_electricity_cost_per_hog	0.69038695	Ekokan_life	-0.300729806
biofilter_unit_cost	0.504841511	SL_basic_height	-0.078332233
maintain_cost_ratio	0.188115288	AL_TN_removal	-0.053636781
excavcost_lagoon	0.143126408	Excavcost	-0.05257916
EK_labor_cost_per_hog	0.131547102	EK_TKN_removal_rate	-0.044584718
interest_rate	0.117994353	Pconc_manure	-0.036181304
manvol_per_hog	0.111338738	TKNconc_manure	-0.032921133

	Capital Cost		Capital Cost
biofilter_unit_cost	0.930392297	SL_basic_height	-0.093296394
manvol_per_hog	0.193653144	EK_polishing_tank_height	-0.05860755
Storage_time_SL	0.172112264	EK_electricity_cost_per_hog	-0.056632702
excavcost_lagoon	0.15721462	EK_backwash_percent_water	-0.049336085
equal_tank_unit_cost_EK	0.130827223	EK_biofilter_height	-0.037499767

	O&M Cost		O&M Cost
EK_electricity_cost_per_hog	0.959174761	AL_TN_removal	-0.086150301
maintain_cost_ratio	0.204180623	TKNconc_manure	-0.061542554
EK_labor_cost_per_hog	0.172162091	Pconc_manure	-0.056862612

	Area		Area
hog_weight	0.652539707	AL_basic_height	-0.735120594
CAL_basic_height	0.209022229	SL_basic_height	-0.079431191
AL_slope	0.142728703	EK_backwash_tank_height	-0.04765425
Storage_time_SL	0.120530085	EK_electricity_cost_per_hog	-0.042532397
manvol_per_hog	0.11011872	EK_SA_plastic_media_per_waste_vol	-0.033551008

	TKN Remaining		TKN Remaining
Nmanure_mass	0.233909171	AL_TN_removal	-0.790648916
hog_weight	0.186882525	EK_TKN_removal_rate	-0.525118268

	TP Remaining		TP Remaining
Pmanure_mass	0.437643307	AL_TP_removal	-0.776497416
hog_weight	0.403771726	EK_TP_removal_rate	-0.141596257
EK_polishing_tank_specific_volume	0.072056717	EK_biofilter_height	-0.085331025

Upflow Aerated Biofilter (uses solids separator for pre-treatment)

Positive Correlation		Negative Correlation	
Inputs	Annualized Cost	Inputs	Annualized Cost
EK_electricity_cost_per_hog	0.650780243	Ekokan_life	-0.39137146
biofilter_unit_cost	0.479419322	SL_basic_height	-0.073797784
maintain_cost_ratio	0.221587685	excavcost	-0.05068644
interest_rate	0.145328681	EK_TKN_removal_rate	-0.044334644
excavcost_lagoon	0.137160134	EK_specific_SA_plastic_media	-0.036290185
EK_labor_cost_per_hog	0.117839688	Pmanure_mass	-0.035097897
manvol_per_hog	0.106587263	electricity_cost	-0.029919434

Capital Cost		Capital Cost	
biofilter_unit_cost	0.930278618	SL_basic_height	-0.093513544
manvol_per_hog	0.194030838	EK_polishing_tank_height	-0.058574789
storage_time_SL	0.172149839	EK_electricity_cost_per_hog	-0.056677153
excavcost_lagoon	0.157183873	EK_backwash_percent_water	-0.049365551
Equal_tank_unit_cost_EK	0.130951203	EK_biofilter_height	-0.037553362

O&M Cost		O&M Cost	
EK_electricity_cost_per_hog	0.948326616	TKNconc_manure	-0.061411139
maintain_cost_ratio	0.256800024	Pconc_manure	-0.05740229
EK_labor_cost_per_hog	0.169763125	excavcost	-0.049740533

Area		Area	
storage_time_SL	0.605282602	SL_basic_height	-0.602265763
manvol_per_hog	0.523465673	EK_equal_settle_tank_height	-0.052557

TKN Remaining		TKN Remaining	
TKNconc_manure	0.342957642	EK_TKN_removal_rate	-0.883829201
manvol_per_hog	0.262761439	SL_basic_height	-0.078625827

TP Remaining		TP Remaining	
Pconc_manure	0.695003372	EK_TP_removal_rate	-0.254292364
manvol_per_hog	0.643204345	separator_P_removal	-0.167266353