COST OF WATER POLLUTION ABATEMENT FOR POULTRY FARMS IN BEATY CREEK WATERSHED, OKLAHOMA

By

TAM THI GIAC PHAN

Bachelor of Science
University of Agriculture and Forestry
Ho Chi Minh City, Vietnam
1982

Master of Science
University of the Philippines
at Los Banos
Laguna, Philippines
1992

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2001

COST OF WATER POLLUTION ABATEMENT FOR POULTRY FARMS IN BEATY CREEK WATERSHED, OKLAHOMA

Thesis Approved:

Arthur Stoecker
Thesis Adviser

Dean F. Schreiner

J D Sanders

Jeanne S Hill

Francis Epplin

Don Fox

Alfred Carlozzi
Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my advisor, Dr. Arthur L. Stoecker, for his guidance, encouragement, and support throughout my graduate program at Oklahoma State University. Appreciation is also extended to Dr. Francis Epplin for his valuable guidance and encouragement during the difficult times. Special thanks to Dr. Daniel E. Storm for providing technical support and guidance in Hydrologic Water Quality Modeling. I also would like to thank the other members of my committee: Dr. Jeanne S. Hill, Dr. Larry D. Sanders and Dr. Dean F. Schreiner for their advice and help in the completion of this dissertation. Thanks also to Dr. Hailin Zhang and Mr. Michael White for their provision of inputs and assistance in the fields of Soil Sciences and Model Calibration, respectively. Mrs. Gracie Teague is appreciated for her support in formatting this thesis.

I would like to thank the Fulbright Scholarship Program and the Department of Agricultural Economics for providing me a scholarship and an assistantship, respectively, to complete the Ph.D. degree. Special thanks to the Economy and Environment Program for Southeast Asia, IDRC, for the long-term and all-round support in directing my interests toward Environmental Economics and Natural Resources, throughout the preparation and completion of my Ph.D. program. Many thanks to all of the faculty and staff members of the Department of Agricultural Economics for teaching and supporting during the time I studied at Oklahoma State University.

I would like to express my appreciation to Mr. Robert G. Glenn, Mrs. Bettie J. Glenn, Dr. Eddie Basler, Mrs. Ruby N. Basler, and Ms. Jonnie Hill for their love and warm care of my family and me during the time we lived in Stillwater, Oklahoma.

My Ph. D. program was not possible without the encouragement and support of the Rectors of the University of Agriculture and Forestry in Ho Chi Minh city: Dr. Duong Thanh Liem and Dr. Bui Cach Tuyen as well as Mr. Nguyen Anh Ngoc; the Dean of Agricultural Economics Department.

The deepest appreciation is to my mother, Phan Thi Giau, who had devoted all her life to our family and passed away while I was abroad for this program; and to my father who is always looking forward to my intellectual and academic achievement. Finally, I would like to share the happiness of my graduation with my husband, Nguyen Tran Nam, and my daughter, Nguyen Thi Hai Chau.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

1.1. Background of the Problem

Poultry production has become more industrialized during the last thirty years with a trend toward larger confinement systems that are more concentrated in certain geographic locations. While the total value of poultry and poultry products sold in U.S. has increased by 15% from 1987 to 1997, the number of farms with poultry sales declined by 42% (1997 Census of Agriculture, USDA). Christensen (1998) noted the number of birds per farm in broiler production increased from about 71,000 in 1969 to 238,000 in 1992. Most of the broiler production remains in the five leading states, Georgia, Arkansas, North Carolina, Alabama and Mississippi. However, recent increases in broiler production have been observed in Missouri, Kentucky, Oklahoma and West Virginia. This expansion of confinement operations in a few geographic locations is a result of the industry's effort to reap the economies of size. These economies have been enabled by technical changes in feed production, large-scale animal production facilities and modern processing plants.

The large amount of manure accompanied with the concentration of poultry production in small areas has caused environmental hazards. This is particularly true with the traditional method of spreading poultry litter on the fields adjacent to the poultry production units. As the production units have increased in size, land application of manure is more for disposal than for fertilization. Manure stockpiled on the land surface can release nitrogen into the air, and nitrogen and phosphorous into the water supply.

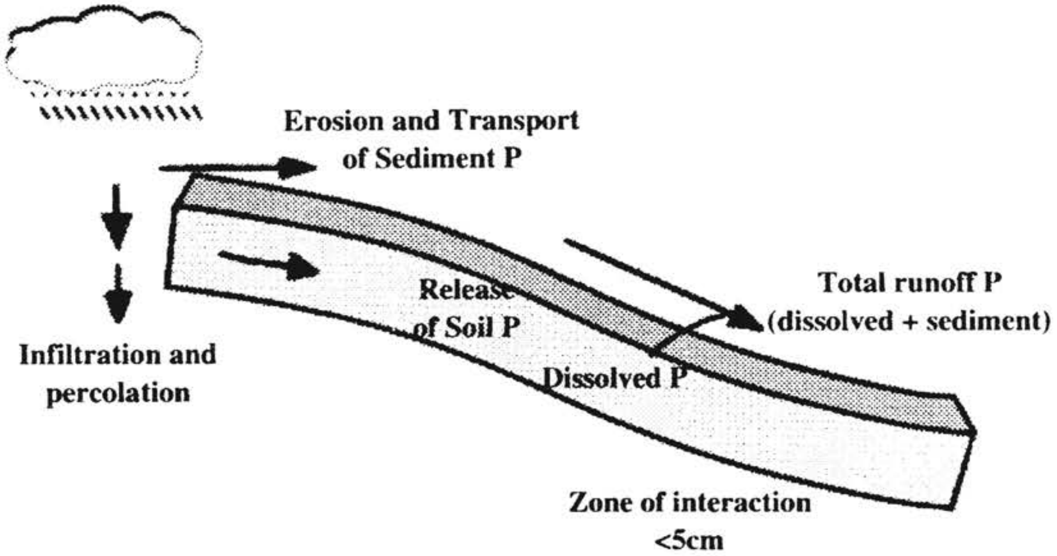
Poultry litter is a high value fertilizer due to its richness in nitrogen and phosphorus nutrients, but excess nutrients may have negative impacts on air, soil, surface water and ground water. Both organic and inorganic nitrogen are involved in the process of waste decomposition (Hatzell, 1995). Organic nitrogen includes amines, urea and uric acid. Inorganic forms of nitrogen include ammonia (NH_3), ammonium ($NH4^+$), nitrite (NO_2^-), nitrate ($N0_3^-$), molecular nitrogen (N_2) and nitrous oxide (N_20). Ammonia (NH_3) and nitrate ($N0_3^-$) are the most common pollutants to air and water respectively.

Air pollution resulting from poultry consists of two major components: dust and odor. The major portion of the dust in poultry operations is composed of skin debris, feather barbules and feces particles (Stroh et al., 1977). Odor is caused by the emission of such gaseous substances as hydrogen sulfide (H_2S), ammonia (NH_3), and other odorous gases. (Hasimoglu, 1998).

The most common water pollution resulting from poultry manure is nitrate leaching/runoff and phosphorus runoff. Ammonia (NH_3) is the most important end product of the biological process that takes place after excretion. Ammonia then volatilizes into the atmosphere if there is insufficient water. Ammonium ($NH4^+$) is formed from ammonia (NH_3) under conditions of sufficient water. Ammonium can either be stored in soils for plant uptake or be converted into nitrite (NO_2^-) and then into nitrate ($N0_3^-$) by oxidizing microorganisms under the nitrification process (Hatzell, 1995). Nitrate ($N0_3^-$) in soils may follow different pathways. It can be stored in the soils for plant uptake. Nitrate can be denitrified by the oxygen removing activities of certain microorganisms under anaerobic conditions and converted into gases such as molecular nitrogen (N_2) or nitrous oxide (N_20). Nitrate can be leached from the soil by the percolation of water. This occurs under the conditions of high concentration of nitrate (such as when manure is stockpiled on the land surface) and large volume of percolating water. Nitrate, once passing through soil profile, is not converted to other nitrogen forms through plant uptake. And denitrification by microorganisms is less likely to occur. As water containing nitrate percolates through the geologic formations and recharges an aquifer, the concentrations of nitrate in the aquifer water are increased, affecting water quality (Hatzell, 1995). High nitrate concentration in drinking water causes a blood disorder in humans and in some animals called "blue baby disease". These diseases occur when nitrates and nitrites reduce the oxygen carrying capacity of the blood hemoglobin (Watson, 1971). Nitrate contamination of water is one of the most prevalent problems of water quality in the world. In the U.S., nitrate contamination of ground water is greatest in the Great Plains. Nitrate leaching from inorganic nitrogen and from excessive manure application (Ahnstedt et al., 1998) along with insufficient denitrification activity near the surface (Hunter, 1998) were identified as the causes of ground water contamination in Colorado. Elevated nitrate levels associated with heavy application of poultry manure were also found in water in Delaware (Ritter et al., 1982) and in Florida (Hatzell, 1995).

Poultry litter is relatively high in phosphorous and excessive applications of poultry litter may cause surface water contamination if the fields amended with poultry litter are prone to runoff and erosion, or are near a water body. Phosphorous exists in either dissolved (soluble) or solid form. Dissolved phosphorous consists of ortho-phosphates, inorganic polyphosphates and organic phosphorous in the soil. The solid form is referred to as particulate phosphorous and consists of soil-adsorbed P, mineral-combined phosphorous (or precipitates) and organic matter. Forty five to seventy percent of manure phosphorous is in the inorganic form, essentially as an ortho-phosphate that is soluble and available for plant uptake. However, when manure comes in contact with the soil, most phosphorous is retained in the soil and becomes less soluble by adsorbing onto soil particles and combining with iron (Fe), aluminum (AL) in acid soils or with Calcium (Ca) in alkaline soils. Although phosphorous is immobile in soil, soluble phosphorous is moved off-site by runoff that is caused by the interaction between rainfall and the thin layer (<5 cm) of surface soil. Particulate forms of phosphorus can be carried to a stream or lake when soil erosion occurs. The two mechanisms of phosphorous transport are depicted in Figure1.

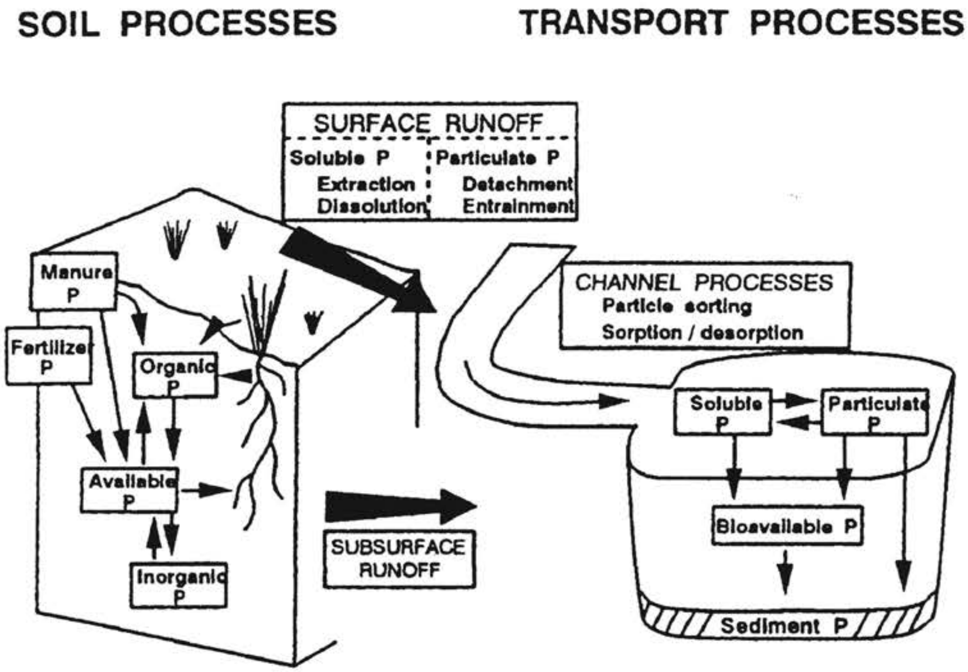
Figure 1: Mechanisms of Phosphorous Transport over a Landscape.



Source: Hailin Zhang, Gordon Johnson and Mitch Fram, OSU Extension Fact Sheet F-2249.

The transport of phosphorous (P) in water is a complicated process. It involves the transformation between soluble phosphorous and particulate phosphorous during the transport. In addition, particulate phosphorous may be deposited or eroded from the streambed with a change in stream flow (Sharpley and Halvorson, 1994) (Figure 2). As a result, the content of phosphorous in a stream is quite different from that of its field source. The amount of phosphorous transported is site-specific and stochastic due to spatial and temporal variations in climatic and agronomic conditions. Because of the complexity of nutrient transport in streams, the environmental impact assessment of agricultural practices to water quality has been possible only with the advanced information technologies such as geographic information system (GIS) and with the development of geographic data modeling.

Figure 2: Factors Influencing Phosphorous Availability in Soil and Water.



Source: Sharpley A.N. and A.D. Halvorson, 1994

Eutrophication, a surface water contamination, involves algae blooms in water due to excessive nutrients such as nitrogen and phosphorous. Eutrophication is a natural geological process, which gradually turns a large body of water into a marsh, bog, or swamp and eventually to dry land. This is a natural aging process of a water body. An excessive supply of nutrients in water bodies accelerates eutrophication. Although both nitrogen and phosphorous stimulate eutrophication, phosphorous is the most common factor which limits algae growth (Schindler, 1997). Phosphorous that is potentially available for algal uptake is referred to as bioavailable phosphorous. These forms are comprised of soluble phosphorous and bioavailable particulate phosphorous. When the algae decompose, the decomposing bacteria use up oxygen in the water, die and release taste and odor causing chemicals. As a result, massive algae blooms or eutrophication adversely affect water quality and may cause fish kills. According to Edwards and Daniel (1992 and 1993), phosphorus runoff from surface-applied poultry litter was one of the primary factors affecting water quality in northwest Arkansas. An extremely high phosphorous concentration in the runoff water was found in pastures receiving even low to moderate levels of poultry litter. Soluble phosphorous is the major component in the phosphorous runoff from grass and forest (Lal and Steward, 1994).

The dynamics of phosphorous levels in soil deserve environmental and economic consideration. It has been verified that long-term land application of large quantities of broiler litter caused accumulation of phosphorous as well as NO_3-, Cu, Zn, K, Ca and Mg in deep soils in Alabama (Kingery et al., 1994). Robinson D.L. et al (1994) studied relation between the length of time that manure had been applied and soil test values in Louisiana pastures. The study revealed that application of broiler litter increased soil fertility from phosphorous deficient to sufficient in 4 years. Levels of phosphorus and copper became excessively high after 10 years of land application. However, soil phosphorous levels were not higher where broiler litter had been applied for 40 to 45 years than they were after 10-14 years of application. One-time phosphorous applications even increased the soil test phosphorous above the initial level for more than 16 years on a Williams loam in Montana (Sharpley and Halvorson, 1994, p.24). A high level of soil test phosphorous is neither detrimental nor beneficial to crop growth, and it has no direct negative impact on land to which it is applied (Shreve et al., 1995). However high application levels do increase the risk of phosphorous loss by run-off or erosion, which in turn may have adverse impact on surface waters

An increasing concentration of manure on the land surface and the environmental implications has drawn public awareness and has led to stricter regulations on poultry producers. The unfavorable public attitude toward animal operations is derived from their potential to cause aesthetic problems, such as odor and dust, flies, mosquitoes and water pollution (EL-Ahraf and Willis, 1996). Among these problems, water pollution has been of the most concern to the public. The national concern for water quality was first reflected in the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), the Safe Drinking Water Act (PL 93-523) and the Coastal Zone Act Reauthorization Amendments, 1990. Despite the tremendous progress in the last 25 years, 40 percent of the national waterways still do not meet the goals. In February of 1998, president Clinton released the Clean Water Action Plan (CWAP) that provides a blueprint for restoring and protecting water quality across the nation. The U.S Environmental Protection Agency (EPA) has pointed out that future water quality improvement depends on the pollution reduction from urban run-off, agricultural activities, including animal feeding operations, and other sources. In agriculture, land application of animal manure was identified as a major non-point source of phosphorous pollution in water.

Pollutant sources are classified as either point sources (or direct source) or non-point sources (or diffuse source) for the purpose of pollution control. In agriculture, point sources are those which discharge pollutants via a discrete man-made conveyance such as pipe, lagoon, storage tank or ditches at identifiable locations. Non- point sources of pollution are dispersed and harder to pinpoint. Non-point source pollution results from land-based activities such as land application of fertilizer. Non-point discharges are intermittent and occur due to meteorological events (Loehr, 1984) while point-source discharges are more constant and related to the production activities. Poultry growers may be subject to both non-point source and point-source regulations. For example, an operation with 100,000 broilers is defined by the Clean Water Act (1972) as a confined animal feeding operation (CAFO) and is subject to point source regulations. CAFOs, like other point sources, must obtain an operating permit that prohibits discharge except from lagoons during storm events greater than 24-hours, 25-year frequency storm. While the CAFO's activities of waste collecting, storage are managed as a point source, activity of land application is managed as a non-point source. In general, the regulatory approach to pollution control is through the issuance of discharge permits for point sources. Education and site demonstration of Best Management Practices are often recommended to combat non-point source pollution. Best Management Practices (BMPs) are routine activities that can be incorporated into animal and crop farming to conserve natural resources and protect the environment. For example, BMPs to reduce non-point source phosphorous pollution include structures (poultry lagoons, poultry composters, poultry stack houses, filter strips), riparian areas (areas consisting of trees, or combination of trees and shrubs/vegetation) and nutrient management plans.

The Nutrient Management Plan (NMP) may be required in the future for all Animal Feeding Operations (AFOs). A Unified National Strategy for Animal Feeding Operations was proposed in September 1998. This would require all AFOs to develop and implement a comprehensive nutrient management plan (of which the NMP is a component) by 2008. It would also require Concentrated Animal Feeding Operations (CAFOs), operations with 1,000 or more animal units, to develop plans before getting permits under the Clean Water Act. The nutrient management plan must state the planned application rate, timing and method of manure application based on current soil test values for N, P, K, the expected crop yield and the crop nutrient requirements. For example, the nitrogen fertilizer rate is calculated by subtracting the soil test nitrogen value from the nitrogen requirement for a selected crop at an expected yield. In the case that only poultry manure or litter (i.e. manure mixed with bedding materials) is to be applied, an application that supplies the nitrogen requirement, will supply more phosphorous than is required by plants. There is currently a movement to phosphorous-based strategies, which limit manure application to phosphorous, rather than nitrogen needs.

In P-based manure management, the method of determining phosphorous application rates has great economic implications. There are three proposals of how phosphorous application rates should be calculated: Soil Test Phosphorous (STP), Phosphorous Index (PI) and Phosphorous Threshold. If the STP method were used, a producer with a field of corn with soil test phosphorous value of 40 would be able to apply 20 lbs of P2O5 per acre if the target yield required 60 lbs of P2O5 per acre (OSU Soil Test Interpretations, F-2225, Extension Facts). If STP reaches 65, it is assumed there is adequate phosphorous to meet the crop requirements so manure should not be applied. In brief, the STP method establishes a critical STP level that limits manure applications to the phosphorous needs of the crop. It does not assess how STP is related to water quality. The STP method is suggested because as STP increases, soluble phosphorous increases proportionally. Soluble phosphorous is a component of bioavailable phosphorous for algal uptake. Therefore, it is expected that applying more phosphorous than the crop require increases environmental risk. In fact, phosphorous transport in water is a complicated process that involves several factors such as soil type, phosphorous source, agricultural practices, distance from original fields to water bodies and hydrologic factors that are watershed dependent. Thus, manure application on a field that has high STP but not subjected to high runoff/erosion and far from a water body may not cause as much damages as manure application on a field that has low STP but flows directly to a neighboring water body. To correct the shortcoming of the STP method, the Phosphorous Index (PI) method is proposed. PI integrates phosphorous source factors (STP level, rate and method of phosphorous application) and transport characteristics (Soil erosion, irrigation erosion, runoff class, distance to water) of a field to assess the risk of phosphorous movement from soil to water (Zhang,, 2000). For example, a PI that is less than 8 means a low potential for phosphorous loss and a PI that is greater than 32 means a very high potential and adverse impact on waters. Manure application may be limited if the PI is high. More studies are underway to validate the PI method.

Furthermore, the issue of phosphorous build-up and its long-term effect on water quality is not clearly addressed by the PI method. The common method adapted by several states, including Oklahoma, is the phosphorous threshold. Like the STP method, the phosphorous threshold establishes a critical STP level to limit manure application, but this STP level would allow the phosphorous requirement to be exceeded if there is a low probability of phosphorous runoff impairing the watershed.

All proposed manure management strategies so far have not taken economic costs into account. As concerns about phosphorous pollution have increased, at least seven states have established phosphorous cutoff on phosphorous thresholds. P-based manure management with the STP method and phosphorous limit cutoff "... may resolve potential environmental issues, but at the same time may be placing unacceptable economic burdens on farmers" (Moore, 1996, Page 156). It is reasonable that a manure regulation based on a phosphorous limit should assess both short-run and long-run environmental impacts (i.e. phosphorous transport in water bodies), and economic losses for farmers in compliance with the new limit.

1.2. Statement of the Problem

Lake Eucha located in Delaware County, Oklahoma, provides drinking water for the cities of Tulsa and Jay, and is in need of immediate restoration (INCOG, 1999). The water quality problem in lake Eucha is eutrophication caused by excessive phosphorous (Kevin Wagner and Scott Wooddruff, 1997). The lake was invaded by blue-green algae, which released geosmin, which is one of seven taste and odor chemicals released by blue-green algae. Geosmin can be detected by humans at a level of 3-10 parts per trillion. As a result, the cost of water treatment has increased. Recreation benefits such as aesthetic and fishing are also impacted by the lake degradation.

Phosphorous pollution may come from point sources such as industry and waste treatment plants, as well as nonpoint sources such as private septic systems, urban runoff and agricultural runoff. In the case of Lake Eucha, the poor water quality has been linked by the Oklahoma Conservation Commission (1996) with the agricultural practices such as the increased poultry production in the watershed.

The Eucha watershed covers a large area of 1,335,376 Km^2, of which 60 percent is in Arkansas, and the rest is in Delaware County, Oklahoma. Delaware County is one of four Oklahoma counties receiving more than 100 million dollars in annual cash receipts from animal production (Oklahoma Agricultural Statistics, 1999). Poultry production in Delaware County has increased significantly since 1982. There were 946 poultry houses in the watershed and about 17,000 birds per house by 1998 and 1999 (TMUA)(Table 1). For decades, poultry farmers have applied poultry litter to pasture as fertilizer. As a result, soil test phosphorous (STP) in the watershed is high relative to crop needs. The average STP for soil samples from Delaware County in 1999 was 246 lbs per acre (OSU lab.) with a mode of 320. The high phosphorous content of the soil is one among other factors affecting the phosphorous loading in the water body.

In 1998 Oklahoma became the first state in the U. S. to regulate the disposal of poultry wastes (Lassek, 1999). The current regulation requires poultry growers to register with the Department of Agriculture, to conduct water monitoring and soil testing, and to participate in training courses offered by Oklahoma Extension Service. It prohibits the application of waste when the ground is frozen, phosphorus saturated, during rain or in areas subject to severe erosion. A fine of $200-per-day is charged for non-compliance (Lassek, 1998). The manure management strategy is based on phosphorous. As a result, a STP limit of 400 has been applied in Oklahoma. In April 1998 a STP limit of 300 was developed for Eucha/ Spavinaw watershed (NRCS-Conservation Practice Standard: Waste Utilization).

The regulation on the land application of manure becomes stricter in Oklahoma with the policy to require farmers to develop nutrient management plans by May 2001. The three options being considered by NRCS to determine phosphorous application rate are phosphorous Index (PI), phosphorous threshold and STP limit. In addition, a lower soil test phosphorous (STP) limit was proposed. By STP standard method, a STP of 65 is adequate for production of most crops. However, due to soil variability, a field–average STP value of 120 is acceptable to ensure most areas of a field have phosphorous sufficiency (Johnson et al., 1998). Thus, OSU proposed a phosphorous threshold of 120.

If a lower STP limit is to be implemented the application of manure to crop and pasture would have to be reduced. Some land users may need to eliminate all use of manure as fertilizer for a period of a year or more. This reduction in the use of manure will increase costs to poultry farmers and to hay and pasture producers in the watershed. These costs are referred to as abatement costs. Abatement costs include any costs undertaken to reduce pollution either by installing pollution control devices or loss of income due to the reduction of manure application. These costs do not include the damage cost to society. As the success of a non-point source pollution control program very much depends on the co-operation of the farmers, the more costly the abatement cost is, the less likely it will voluntarily be adopted by farmers.

The theory of environmental economics has pointed out that setting a uniform standard such as STP limit is an inefficient way to attain the environmental goal. This was confirmed by a study on agricultural phosphorous pollution in the Minnessota River (Westra, 1999) and a study on phosphorous loading policies for pastureland applications of poultry litter in Arkansas (Govindasamy et al., 1994). The least–cost way is to allow a soil which has high yield response to manure application and/ or low phosphorous loss to receive more manure than a soil having low yield response and/or high phosphorous loss. The case is more complicated as the volume of manure affects both crop yield and abatement costs in a dynamic way. Crop yield responds not only to the amount of manure applied this year but also to the residual nutrients from manure applied in previous years. Elimination of manure on P- saturated soil may result in the deficiency of phosphorous in soil after some years. In contrast, applying more phosphorous through manure than plants will use even on a P- deficient soil may ultimately result in excessive soil phosphorous levels in the future. However it is not clear that all forms of phosphorous residuals in a soil necessarily have a negative impact on water quality. In other words, the abatement cost of a soil does not depend on how much effluent it emits at the source, critical issues are the amount of phosphorous loss and the proportion of the loss that reaches a water body. Consequently, a sound strategy to manage manure should take into account differences in land characteristics along with the spatial and temporal aspects of transport on nutrients such as phosphorous.

The phosphorous index method is a risk-based approach to guide manure application and was advocated by a group of scientists, educators, and government personnel. From the economic point of view, PI could be a more cost-effective way than a uniform STP limit because it allows a field having less negative impacts on water quality to apply more manure than fields having more impacts. However, the PI method does not directly address the dynamic aspect of phosphorous levels nor does it assess how much of the phosphorous transported to the stream might be reduced if manure application were limited by the PI method.

In brief, none of the existing P- management methods assess directly the volume of phosphorous reduction in the water and the corresponding cost to obtain that level of phosphorous abatement. Thus, the economic costs for farmers to comply with the poultry manure management plans are not fully considered when the policy variables are determined.

1.3. Objectives of the Study

The overall objective of this study is to develop a model that can be used to determine the minimum marginal abatement costs of reducing the ambient concentration of phosphorous leaving a watershed. Specific objectives are as follows:

1/ Delineate a study area and classify it into sub-basins by using SWAT (Soil and Water Assessment Tool) model with GIS (Geographical Information System) data. Identify the main soil types, land uses, and topographical characteristics in each of the sub-basins.

2/ For each soil type, estimate the response of Bermuda grass hay to the application of poultry manure and commercial nitrogen.

3/ Estimate the phosphorous and nitrogen carryover in each soil type.

4/ Estimate the amount of phosphorous that is lost from each soil as the level of poultry manure and soil phosphorous levels change.

5/ Determine the loss in maximum profit as the level of poultry manure applications for each land use soil type unit is reduced to meet alternative ambient concentrations of phosphorous in the surface water. The loss of profit due to a change in the ambient phosphorous limit measures the marginal abatement cost. The marginal abatement cost curve will provide valuable information that can be used when setting a standard for phosphorous.

CHAPTER II

LITERATURE REVIEW

2.1. Theory of Optimal Pollution and Marginal Abatement Cost

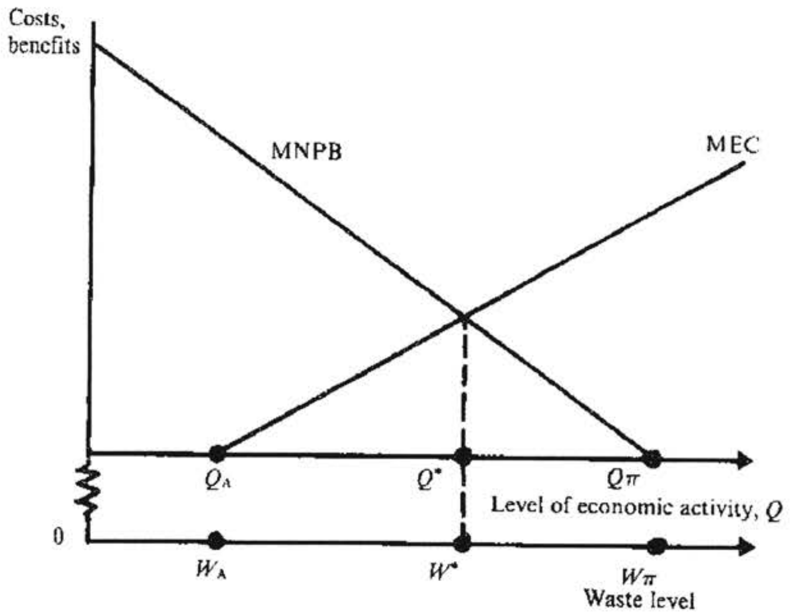
Pearce and Turner (1990) distinguished between physical pollution and economic pollution. Physical pollution is a state in which the wastes from production and consumption discharged/emitted into the air, or water or onto the land cause changes in the environment. If these changes cause welfare loss (i.e. harmful effects, unpleasantness, distastes) to some party in the society and compensation is not made for the effected party, then economic pollution exists. Since these environmental damage costs are not reflected in the cost of production, they are usually referred to as external costs. The private net benefits of the producer who causes the pollution reflect only the difference between the benefit received and the cost incurred.

In the economic point of view, the optimal level of pollution is generally not zero but is at the point where the marginal net private benefit (MNPB) equals the marginal externality cost (MEC). In other words, welfare is maximized at the point where net benefit obtained by producing one more unit of pollution is equal to the marginal externality cost incurred by others affected by this unit of pollution. This principle of optimal pollution is depicted in Figure 3. If there exists some abatement technology, it always involves a cost to reduce pollution either by installation of pollution control devices or by the reduction of the pollutant causing inputs. This cost is referred to as an abatement cost. The per unit abatement cost is assumed to increase with the level of abatement. Marginal abatement cost is the cost to obtain one more unit of abatement or to emit one less unit of pollution. The optimum level of pollution is where the marginal abatement cost (MAC) equals the marginal external cost (MEC) as depicted in Figure 4.

In practice there is not sufficient information about abatement costs and damage costs for policy makers to determine the optimal level of pollution. Environmental standards are set by other means such as the precautionary principle or a safe minimum standard. Environmental standards may range from strictly zero-emission to critical loads (i.e. thresholds of damage below which pollution levels are to be maintained) or to an acceptable level that can be obtained by using the best available technology (BAT). The BAT is a technology commercially available at a reasonable cost and technically reliable in controlling pollution. Once an environmental standard is established, then the question is how to achieve that standard at minimum cost.

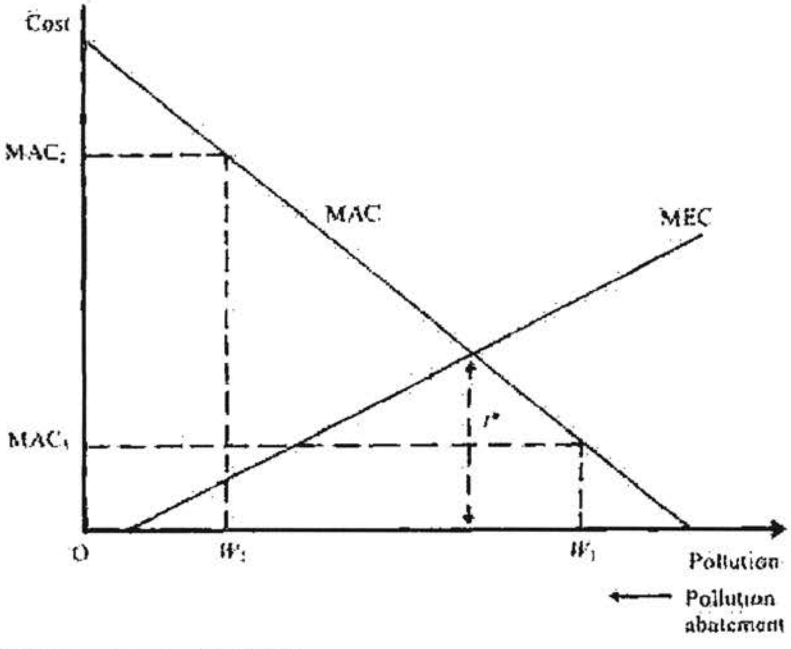
The least-cost criterion requires that the marginal abatement costs of all polluting agents are equal when the environmental target is met. Suppose there are three different polluting agents with different marginal abatement cost curves as depicted in Figure 5. Suppose that the environmental goal could be achieved either by setting a uniform standard at where each firm removes S2 units or by setting an effluent charge at t. A uniform standard enforced via legislation is a typical command-and-control (CAC) approach. In contrast with the CAC approach is the market-based incentives approach in which economic instruments such as effluent charges, product charges, deposit-refund

Figure 3: Economic Definition of Optimal Pollution.



Source: Pearce and Turner, 1990.

Figure 4: Optimal Pollution: The Abatement Cost-External Cost Approach

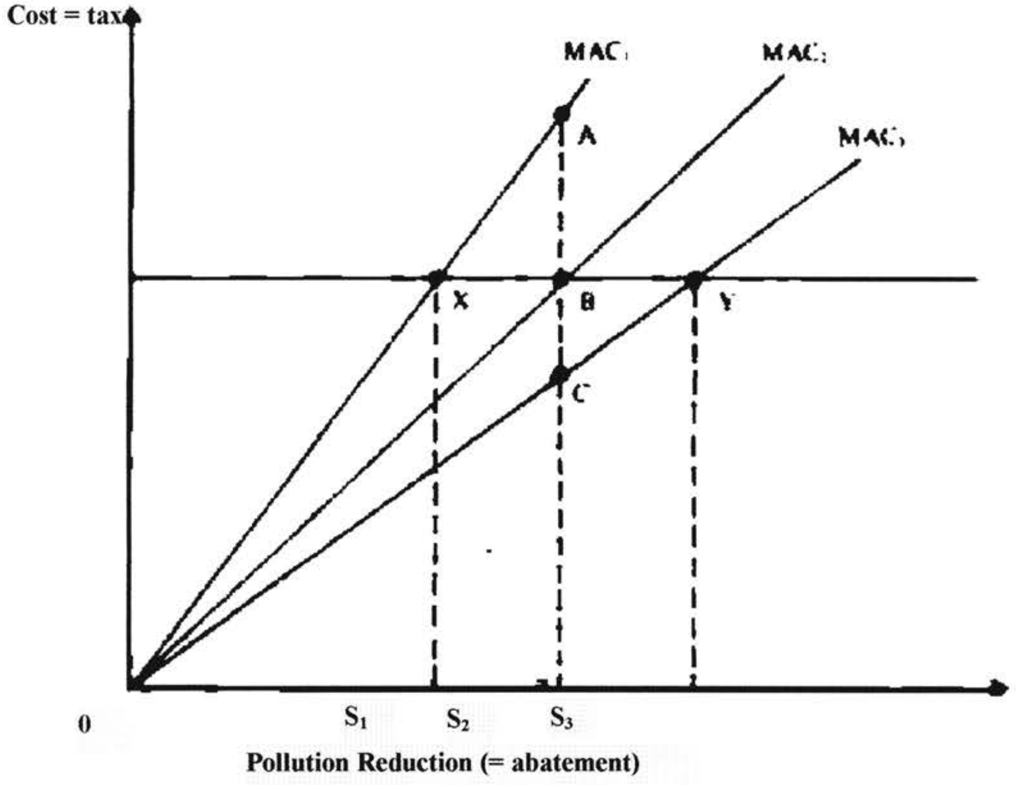


Source: Pearce and Turner, 1990.

system, subsidies, non-compliance fees, or emission-trading are used to influence the behavior of the polluters in a way that is favorable to the environment. Economic instruments are preferable to uniform standards in terms of cost efficiency. As depicted in Figure 5, when a uniform standard is used, all polluters will end up at the same environmental standard but at different marginal costs that are represented at points A, B and C in Figure 5. The respective total abatement costs for agents 1, 2 and 3 are OAS_2, OBS_2, and OCS_2. In contrast, if an effluent charge is used, it allows a polluter the flexibility to adjust to the environmental standard. A polluter with high abatement cost will prefer to pay the charge. A polluter with low abatement cost will prefer to install abatement equipment. All polluters will equate their marginal abatement costs with the charge and end up at different levels of abatement. The one with lower abatement cost will produce higher abatement level (point S_3), the one with higher abatement cost will produce lower abatement level (point S_1). The total cost under the method of environmental charge is the lowest cost. Total abatement costs for agents 1, 2, and 3 are now areas OXS_1, OBS_2, and OYS_3 respectively. Since $S_1+S_2+S_3= 3S_2$ the same amount of pollution is removed. However, the total abatement cost with the tax or effluent charge is less than with the uniform standard. The least cost approach implies that different polluters would be responsible for different amounts of abatement. Equal marginal abatement costs, therefore, are the indicator of policy efficiency.

It should be noticed that the command and control approach, although less efficient, is usually favored by the regulatory agency because it requires less information to introduce regulations, and because each source is responsible for equal or proportional amounts of abatement. The market–based incentives approach is advocated by many

Figure 5: Tax As a Low-cost Method of Achieving a Standard.



Source: Pearce and Turner, 1990

economists because of its cost-saving potential, however this approach requires information may or may not be revealed by the market mechanism. In practice, only in few instances, are economic instruments operated in isolation. Deposit-refund systems and user charges for household waste collection are examples of this system (OECD, 1991). In most cases, a mixed approach where economic instruments are used in conjunction with CAC approach is employed either to reinforce the regulation or to raise revenues. An example is non-compliance fees in combination with direct regulation. Tradable emissions permits for sulfur and nitrogenous gasses are being used under the 1990 Clean Air Act (Tietenberg, 2000).

2.2. Empirical Studies on Marginal Abatement Cost

Studies on abatement costs have been done for air pollution control and for point-source pollution where emissions are observable and measurable. The purposes of estimating abatement costs were to examine the efficiency of the existing pollution control policy based upon the equi-marginal (abatement costs) principle, to select the most cost-efficient abatement technology and to estimate the trading price of emission permits.

Abatement costs based on engineering models of a few technologies were often overestimated because they did not reflect adjustment possibilities available to specific firms. When firms were required to adopt mandated technologies they were precluded from adopting more efficient methods. A few econometric models that used observed data have been developed to estimate marginal abatement cost. Hartman et al. (1997) estimated abatement cost functions for seven major air pollutants by industry sector, using data on 100,000 US factories. The abatement cost C (k) was assumed separable from the firm's production function and thus was a function solely of the air pollutant. Marginal abatement cost was derived from the total cost as the first derivative of the total cost function with respect to k. Gollop and Roberts (1983) estimated the marginal abatement costs of sulfur dioxide for a sample of electric utilities in the 1973-79 period. The marginal abatement cost was derived from a cost function that was defined as a function of input prices, output, technology index and level of regulatory intensity. The translog functional form was specified. The translog cost function was then estimated jointly with cost share forms of the input demand equations using an iterative-Zellner algorithm. Pittman (1981) estimated marginal abatement cost for a cross section of 30 integrated paper mills in Wisconsin and Michigan in 1976. He specified a translog production function based on inputs and the pollutant output. Two first-order equations were drawn from a profit-maximizing problem with the constraints on output and on the pollution level. One of the two equations contained a parameter to be estimated as the shadow price of the pollution constraint, or the marginal cost of pollution control or, marginal abatement cost. The translog production function and the two first-order equations were estimated simultaneously. The same data used in Pittman's study was used by F̈are et al., (1993) to re-estimate the marginal abatement costs for the undesirable pollution outputs. Fare employed a linear programming technique to estimate the parameters of a deterministic translog output distance function that had been introduced by Shephard in 1970. The output distance function can be used to estimate the price of both good outputs and "bad" or undesirable pollution outputs. Hadley (1998) employed this method to estimate the "price" of nitrogen residuals in UK dairy farms. Nitrogen residuals are represented in the model as an index – The Groundwater Vulnerability Index (GWVIN) consists of two components: nitrogen leaching index and an estimate of excess nitrogen. This index must be constructed for each farm in each year.

None of the above methods to estimate marginal abatement costs, with the exception of the output distance function method, can be used in the case of non-point source (NPS) pollution. The main reason is that neither production data nor emission discharge data from the individual sources are directly observable or measurable. Fortunately, several biophysical models of NPS pollution have been developed to estimate emissions at their sources and their depositions at receptor points. The results from these models were used to estimate the erosion function, pollutant loading functions for an optimal spatial management model. Braden et al., (1989) employed the SEDEC (Sediment Economic) model to determine a full abatement cost frontier. SEDEC consists of three components: farm profit functions, erosion function based on the universal soil loss equation (USLE), and spatial sediment movement functions. SEDEC optimizes farm profit subject to constraints on sediment.

2.3. Hydrologic Water Quality (HWQ) Model

As pollution from numerous nonpoint sources cannot be easily estimated directly, watershed models are often employed to estimate them. This type of modeling is commonly denoted as hydrologic and water quality modeling. These models incorporate hydrology and water quality parameters, and describe the occurrence and movement of water, nutrients, pesticides and other materials through a hydrologic system. (Haan and Storm, 1996). A large-scale watershed has a great variability in soil characteristics, topography and climate across the area. Thus large-scale hydrologic modeling requires a large amount of geographic information and should be capable of partitioning a watershed into smaller, homogenous units. These requirements have been made easier with the advance of geographical information systems.

2.3.1. Geographic Information System (GIS) and Nonpoint Source Pollution Modeling

GIS is a computer-based technology for handling geographical data in digital form (Singh and Fiorentino, 1996). Geographic data includes both spatial and non-spatial data. Spatial data refers to the shape, size and location of geographic features. Non-spatial data describe attributes associated with the same features such as name, area, population etc. GIS accepts data from multiple sources with multiple types such as maps, pictures and digital data. Digital data may be input from computer disks, CD-ROM disks, tapes, telecommunication networks, and global positioning systems (GPS). Data may also be in graphic and text as well as in tabular formats. These types of data are combined and integrated into GIS in the form of databases from which maps and reports can be made. (Davis, 1996)

Most spatial data are built as theme or data layers. Each layer contains mapped objects of a single category such as a drainage network, soil association, land use, topography, etc. These layers are superimposed to describe the real world (Fig. 4). The GIS format is useful for a nonpoint source pollution model for it allows for the inclusion of land uses, soil types, geology, topography, precipitation, and surface drainage patterns (Gade, 1998). Furthermore GIS can be used to display modeling results in a way that is understandable by the layperson (Haan, and Storm, 1996)

ArcView is the one of the world's most popular desktop GIS packages. ArcView first appeared in the early 1990's and has evolved to its third version. It allows users to quickly learn and use basic GIS tools for creating map displays and analyzing data in a visual way. SWAT (Soil and Water Assessment Tool), as well as other models, have been formulated as ArcView extensions.

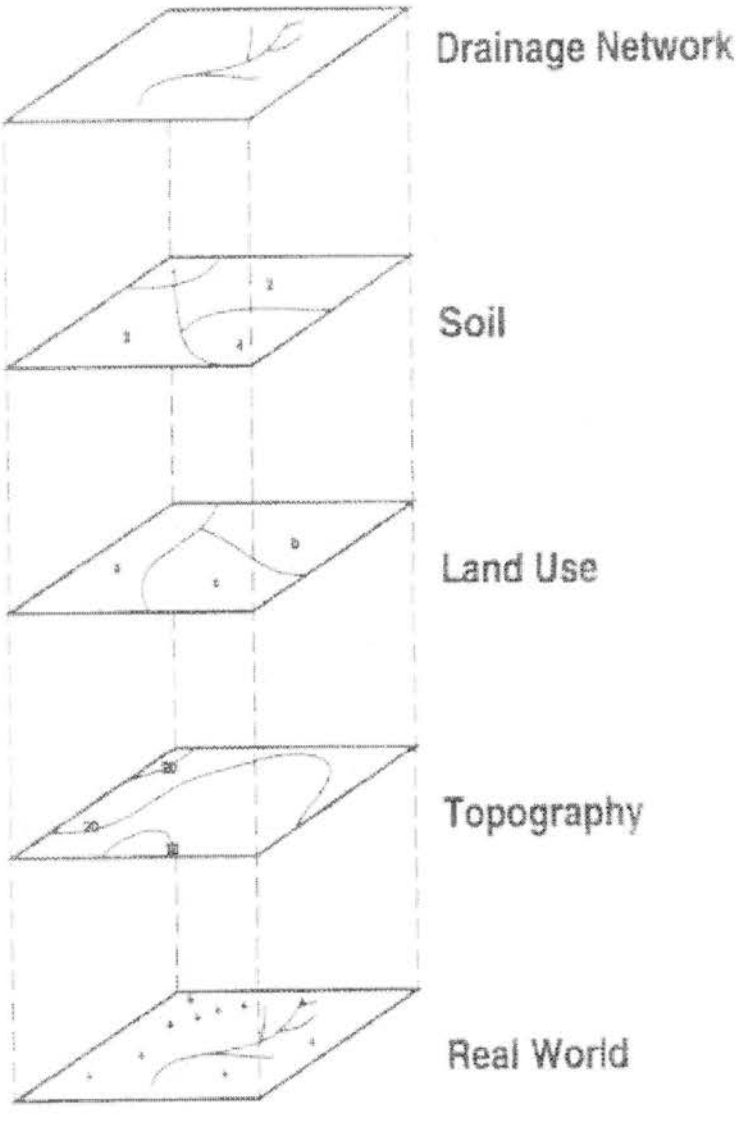
2.3.2. Nonpoint Source Model: SWAT (Soil and Water Assessment Tool) :

Several hydrologic water quality models have integrated GIS for parameter estimation and/or graphical displays. These include the Spatially Integrated Model for

Phosphorous Loading and Erosion (SIMPLE) (Chen et al., 1994); Agricultural Nonpoint Source (AGNPS) (He et al., 1994; Kang et al., 1992; Srinivasan and Engle, 1991a, 1991b; Vieux and Kang, 1990; Hession et al., 1989); Soil and Watershed Assessment Tool (SWAT) (Srinivasan and Arnold, 1994), Area Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) (Rewerts and Engle, 1991), a field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems-Water Table (CREAMS-WT) and CREAMS (Kiker et al., 1992; Bekdash et al., 1991) and Finite Element Storm Hydrograph Model (FESHM) (Wolfe and Neale, 1988; Hession et al., 1987).

SWAT is a large area hydrologic model. It was developed to assess the impact of management on water supplies and non-point source pollution in watersheds and large river basins. SWAT is the continuation of a long-term effort to model non-point source pollution in response to the Clean Water Act. The CREAMS model developed by Knisel in 1980 was the first non-point source pollution model that was designed for field scale level studies (Srinivasan R. et al, 1998). Several models such as GLEAMS (1987) and EPIC (1984) have evolved from CREAMS. Recent advances in computer hardware and software for GIS (Geographic Information System)/ spatial analysis enables the simulation on a basin level such as SWAT. SWAT is also a continuous time model that is capable of simulating long periods for computing the effects of changes in agricultural practices. In Oklahoma, SWAT was used to estimate nonpoint source phosphorous and sediment loading in the Upper little Deep Fork watershed (Storm et al, 1999),and to estimate watershed nonpoint source loading for the whole state (Storm et al, 2000).

Figure 6: Categorical Approach for Handling Spatial Data



Source: Singh and Fiorentino, 1996.

Input data for SWAT include data layers as following:

a/ Digital Elevation Model (DEM) data: DEM is a digital representation of the variation of relief over space. It describes the topography of a region, and helps determine the structure of a distributed rainfall-runoff model by detecting ridges, streamlines and the boundary of catchments. (Muzik, 1996).

b/ Soil data layer.

c/ Land cover data layer.

d/ Climate files contain climate and precipitation files.

e/ Streamflow data.

Based on this information and a specification of thresholds for area, land use and soil type, SWAT partitions the area into sub-basins, and creates one or more unique land use/soil combinations (or hydrologic response units or HRU) for each sub-basin. Each HRU is assumed to have homogenous land use and soil type. SWAT also calculates the parameters for the catchments and simulates the hydrologic cycle that is the driving force of nutrient movement in surface and ground water. The hydrologic cycle concerns the circulation of water at the earth's surface. Hydrologic cycle has three fundamental components: precipitation, the movement of water over the land surface and the return of water to the atmosphere. The simulation of the hydrologic cycle includes the land phase and the water or routing phase. The land phase controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The routing phase controls the movement of water, sediment, nutrient and pesticide loadings through the channel network of the watershed to the outlet.

The parameters estimated by SWAT need to be modified to make the simulated results close to the actual observation. This process is called calibration. Calibration is based on the observed data of the total flows measured at the nearest gage station and on the water chemistry data. Calibration is based upon a period of time. Calibrated parameters are then used for model validation.

Model validation is concerned with whether a model behaves sufficiently close to the real system that is being modeled. The expectation is that the model would give the same output as the real system, over the same range of variables. Validation is made by comparing the simulated results with observed data in a time domain that is beyond the time frame from which the model is calibrated.

2.4. Biophysical Model: Epic (Erosion Productivity - Impact Calculator):

The EPIC model (Williams et al., 1984) which is a daily time step, field level simulation model was originally developed to determine the relationship between soil erosion and crop productivity. EPIC included a comprehensive phosphorous mineralization model developed by Jones et al., (1984). The phosphorous part of the model simulates plant uptake and transformations between several inorganic and organic phosphorous pools in up to 10 soil layers. EPIC has been shown to simulate reliably soil phosphorous availability for several soils in Great Plains (Sharpley and Halvorson, 1994). EPIC was used successfully to simulate growth and yield of several crops by Cabelguenne et al., (1990,1991). Segarra (1989) used EPIC to evaluate optimum nitrogen fertilizer rates for cotton in the Southern High Plains of Texas.

Recent development of EPIC (Sharpley and Williams, 1990) has focused on water quality and global climate change. EPIC has been also used to estimate nutrient runoff, and soil and fertilizer dynamics.

A simplified version of the EPIC crop model is used as the crop model in SWAT. In addition, the formulas for calculation of phosphorous loss in surface runoff in the EPIC model are the same as those of the SWAT model in the land phase of hydrologic cycle. The difference between EPIC and SWAT is that EPIC simulates nutrient transport on a field level scale for a homogenous area; SWAT allows simultaneous simulation on different areas in a large-scale basin. In addition, SWAT includes a simplistic simulation of nutrient transport in the water phase of the hydrologic cycle. SWAT assumes that all soluble phosphorous runoff exits the watershed. Part of the sediment adsorbed phosphorous is deposited along the channel beds and part remains in suspension and leaves the watershed. However, the transport mechanism is much more complex.

CHAPTER III

METHODS AND PROCEDURES

3.1. Empirical Model

3.1.1. Simplistic Illustration of the Problem

Consider a farm that uses a single type of input (X) to produce a primary product (Y) and a by-product as an effluent (Z) in a competitive market. The production function of these joint products are assumed to be strictly concave and represented by

$$Y= f(x) \tag{1}$$

$$Z=g\ (x) \tag{2}$$

If the production of Z is assumed to have no cost to the firm, then the profit maximization problem is as follows:

$$\text{Maximize(x): } \pi(x) = pf(x) - rx \tag{3}$$

Where p and r are the prices for the output and input respectively. The optimality condition for profit maximization is:

$$\frac{\partial(\pi)}{\partial(x)} = p\frac{\partial f(x)}{\partial(x)} - r = 0 \tag{4}$$

$$\text{or: } pf_x(x) = r \tag{5}$$

Equation (5) indicates that the farm should increase production until the value of the product generated by the last unit of input x equals to the price of this input.

However, if the regulatory agency wants to set an effluent standard (Z), then the objective function of the farm in compliance with the regulation is as follows:

Maximize(x): $\pi(x) = pf(x) - rx$

Subject to: $z \leq g(x)$. (6)

The above model can be solved by Lagrange method:

$$L(x; p, r, z) = pf(x) - rx + \lambda(z - g(x)) \tag{7}$$

The optimality condition becomes:

$$pf_x(x) = r + \lambda g_x(x) \tag{8}$$

and $z = g(x)$. (9)

Alternatively, the regulatory agency may want to impose a tax (t_z) per unit of effluent. The farm's objective under this tax policy is presented by:

Maximize(x): $\pi(x) = pf(x) - rx - t_z g(x)$ (10)

The optimality condition to the problem (10) is:

$$pf_x(x) = r + t_z g_x(x). \tag{11}$$

Comparison of equations (8), (9) and (11) shows the relationships between choice variables and parameters:

$$z = g(x^*) \tag{12}$$

$$\lambda(r, y, z^*) = t_z^* \tag{13}$$

The Lagrange multiplier (λ) represents the marginal abatement cost or the shadow price of pollution control, i.e. the reduction in profit when one unit of pollution is removed.

Equations (12) and (13) indicate that (a) the effluent standard is a dual of the effluent tax in the sense that the two policies will lead to the same desired amount of effluent and (b) at the optimum level of input (x^*), if the effluent tax (t_z^*) is equal to the marginal abatement cost ($\lambda(r, y, z^*)$). Based on this, the marginal abatement cost can be derived either from a constrained optimization model in which profit is maximized subject to a specific limit of pollution (e.g. phosphorous in the surface water) or a non-constrained profit maximization model in which a tax is placed on the output of pollution.

Thus, there are two ways to derive the points along a marginal abatement cost curve: The first is to specify an amount of pollution in the constraint of the profit-maximizing model. Then this amount is varied the problem is resolved. The decline in profits from a reduction in inputs to reduce pollution by one unit is the marginal abatement cost. An alternative way to find the marginal abatement cost is to place a charge on the pollution and maximize profits subject to this charge. The pollution charge is then changed and profits are re-maximized.

3.1.2. Empirical Model

The empirical model at the basin-level consists of S sub-basins and a 20-year planning period. Assume that each sub-basin contains one or more hydraulic response units (HRU). Each HRU represents a unique soil type-land use combination in a sub-basin (b). The major types of land use in the study area are pasture and forest. Thus, the

HRUs were classified into two sub-groups according to land use, and only the sub-group of HRUs with hay was used in the optimization model.

The assumptions of the model are: (a) Each soil type and land use (HRU) has a unique crop yield response to fertilizer and uniquely contributes phosphorous loading to the watershed, (b) Soluble phosphorous is the source of water contamination since soluble phosphorous is the major form of phosphorous loss in surface runoff from pastures. Nitrate is not problematic in the study area. (c) All soluble phosphorous when entering the stream will remain unchanged (i.e. No transformation between soluble and particulate forms of phosphorous occurs during transport process in the channel network). (d) The amount of phosphorous loss from forests and other lands exogenous to the economic model remains fixed, and (d) The environmental cost can be monetized as a tax per unit of soluble phosphorous that each HRU contributes to the water.

The overall objective is to maximize the net present value of profits subject to a limit on the quantity of phosphorous that emits into the stream each year for a 20-year period. The overall model to be solved can be expressed as:

$$Max\,PV(M,N)=\sum_{t}^{T-1}\left[\frac{\sum_{b}^{B}\sum_{s}^{S}\{PY_{bst}(M_{bst},N_{bst},NR_{bst},PR_{bst})-WM_{bst}-CN_{bst}\}A_{bst}{}_{t}}{(1+r)^{t}}\right]$$

Subject to:

$$(1)\sum_{b}^{B}\sum_{s}^{S}PLOS_{bst}A_{bst}\leq TPW_{t}^{*} \qquad \text{For all t}$$

Equation (1) expresses that the total amount of soluble phosphorous loading from pastures must not exceed a certain level (TPW*).

$$(2)\ PLOS_{bst}=h(PR_{bst},M_{bst})$$

h( ) is a function giving the amount of soluble phosphorous in runoff from soil s of sub-basin b in year t as affected by past and current applications of manure.

(3) $NR_{bst} = f\left(M_{bst}, N_{bst}, NR_{bs,t-1}\right)$

f ( )is a function giving the amount of nitrogen buildup in soil s of sub-basin b in year t, which is affected by the current application of manure (M), commercial nitrogen fertilizer (N), and the amount of nitrogen residuals in the soil (NR).

(4) $PR_{bst} = k\left(M_{bst,} PR_{bs,t-1}\right)$

k( ) is a function giving the amount of phosphorous buildup in soil s of sub-basin b in year t, which is affected by the current application of manure (M) and the amount of phosphorous residuals in the soil (PR).

(5) $NR_{bs0} = \overline{NR}_{bs0}$

$N\overline{R}_{bso}$ is the nitrogen soil test value at the beginning of the simulation period for soil s in basin b.

(6) $PR_{bs0} = \overline{PR}_{bs0}$

$P\overline{R}_{bso}$ is the phosphorous soil test value at the beginning of the simulation period for soil s in basin b.

(7) $M, N \geq 0$

Where:

$b \in B$: Sub-basin

$s \in S$: Soil type

$t \in T$: Year

P: Price of hay ($/ton)

Y: Yield (ton/ha)

M_{bst}: Poultry litter (metric ton/ha) applied to soil s of sub-basin b in year t.

N_{bst}: Commercial nitrogen (kg/ha) applied to soil s of sub-basin b in year t.

NR_{bst}: Total NO3_nitrogen present in the s soil profile (kg/ha) of sub-basin b in year t.

PR_{bst}: Labile (plant-available) phosphorous (kg/ha) in the soil s profile of sub-basin b in year t

A_{bst}: areas (ha) of soil s in sub-basin b in year t

$PLOS_{bst}$: Soluble phosphorous in runoff that derives from soil s of sub-basin b in year t.

TPW: Total phosphorous (kg/P) transported with water into the watershed outlet.

TPW* is the phosphorous limit.

W: Price of hauling poultry litter ($/ton)

C: Price of nitrogen fertilizer ($/ton)

The outputs from the model are: optimal manure and nitrogen fertilizer application rates for each year and each soil type (M_{bst}*, N_{bst}*); estimated annual total phosphorous in the soil and in the runoff for each HRU, and the associated marginal abatement costs for each HRU for the 20-year period.

3.2. Optimization Process

The process of solving the above model is through decomposition. Decomposition is the process of solving a larger overall model by the repeated solution of a series of smaller sub-problems. The reasoning for the decomposition approach is as follows. Assume the watershed contains two land areas and there is only 1 time period. The simple watershed model is:

$$Max\ \Pi(M_1,M_2) = A_1(PY_1(M_1)-WM_1)+A_2(PY_2(M_2)-WM_2)$$

$$ST: \qquad PLOS(M_1)A_1 + PLOS(M_2)A_2 \leq TPW^{\bullet}$$

$$M_i \geq 0$$

The equivalent Lagrange formulation of the above problem is:

$$\begin{aligned} L(M_1,M_2,\lambda) = A_1(PY_1(M_1)-WM_1)+A_2(PY_2(M_2)-WM_2)+ \\ \lambda[TP - Plos(M_1)A_1 - Plos(M_2)A_2] \end{aligned}$$

The terms A$_1$, A$_2$, M_1, and M_2, represent the hectares of land and the quantity of manure applied to each hectare in each of the respective areas. The functions $Y_1(\ )$ and $Y_2(\ )$ represent the per hectare yield from manure application in areas 1 and 2 respectively. The functions $Plos_1(M_1)$ and $Plos_2(M_2)$ represent the phosphorus runoff due to manure applications in each area that actually reaches the base of watershed.

This is a typical inequality-constrained nonlinear optimization problem. Kuhn and Tucker, in 1951, developed the necessary conditions for optimality as follows:

1) $$\frac{\partial L}{\partial M_i} = A_i\left[P\frac{\partial Y_i}{\partial M_i} - W - \lambda\frac{\partial Plos(M_i)}{\partial M_i}\right] \leq 0 \quad \text{i=1,2}$$

2) $$M_i\frac{\partial L}{\partial M_i} = 0$$

3) $$M_i \geq 0$$

4) $$\frac{\partial L}{\partial \lambda} = TP - Plos(M_1)A_1 - Plos(M_2)A_2 \geq 0$$

5) $$\lambda\frac{\partial L}{\partial \lambda} = 0$$

6) $\lambda \geq 0$

The above problem has an optimal solution if there exist $M^{*}, \lambda^{\bullet}$ that satisfy all six above equations. The sufficient condition for optimality requires concavity of the profit function (π) and convexity of the constraint function PLOS(M_i).

The necessary conditions from the above model involve variables that can uniquely determined separately for each land use-soil combination with the exception of the Lagrange multiplier (λ) associated with condition (4), which involves the total phosphorus leaving the watershed. The Lagrange multiplier acts as a charge or additional cost in the condition (1) that will cause the quantity of applied manure to decline as λ is increased.

The proposed decomposition approach is to parameterize the Lagrange multiplier. This is the same as replacing the Lagrange multiplier with a hypothetical tax or charge on phosphorus runoff and solve for the quantity of manure to be applied for each crop-soil-sub-basin combination. For each value of λ, the total quantity of phosphorus reaching the base of the watershed is summed. If the amount exceeds (falls below) the target quantity, the tax rate is increased (decreased) and the problem is resolved until convergence is obtained. This approach also moves the nonlinearity from the constraint to the objective function which eases problem solving.

The empirical model for the sub-problem of optimization profit for a soil type s in sub-basin b is:

$$Max\,PV_{bs}(M_{bst}, N_{bst}) = \sum_{t=1}^{T} \left[\frac{\begin{array}{c} P * Y(M_{bst}, N_{bst}, NR_{bst}, PR_{bst}) - W * M_{bst} - C * N_{bst} \\ - \lambda_t * PLOS(M_{bst}, PR_{rst}) \end{array}}{(1+r)^t} \right] * A_{bst}$$

Subject to:

$$M_{bst}, N_{bst} \geq 0$$

The equivalent Lagrange version of the above problem is:

$$L_{bs}(M_{bst}, N_{bst}, \alpha_{bst}, \beta_{bst}) = \sum_{t}^{T} \left[\frac{\begin{array}{c} PY_{bst}(M_{bst}, N_{bst}, NR_{bst}, PR_{bst}) - WM_{bst} \\ -CN_{bst} - \lambda_t PLOS(M_{bst}, PR_{bst}) \end{array}}{(1+r)^t} \right] A_{bst}$$

The total phosphorous loss (TPW_t) from the basin each year was summed over all of the bs units each year and is compared to the phosphorous limit. An iterative procedure was used to increase (decrease) each λ_t as the phosphorous output exceeded (fell below) the phosphorous limit.

The necessary conditions for the reduced model with respect to manure application and nitrogen application are:

$$1) \quad \frac{\partial L}{\partial M_{bst}} = \left[\frac{P\dfrac{\partial Y_{bst}}{\partial M_{bst}} - W - \lambda_t \dfrac{\partial PLOS_{bst}}{\partial M_{bst}}}{(1+r)^t} \right] A_{bst} = 0$$

$$\text{or} \quad P\frac{\partial Y_{bst}}{\partial M_{bst}} = W + \lambda_t \frac{\partial PLOS_{bst}}{\partial M_{bst}}$$

Condition (1) states that manure input should be used in production until the present value of marginal value product of using an additional manure unit on the soil s equals to the present value of the marginal cost of using that manure unit. The marginal cost consists of cost of applying manure and the cost of phosphorous emission.

$$2) \quad \frac{\partial L}{\partial N_{bst}} = \left[\frac{P\dfrac{\partial Y_{bst}}{\partial N_{bst}} - C}{(1+r)^t} \right] A_{bst} = 0$$

$$\text{or} \quad P\frac{\partial Y_{bst}}{\partial N_{bst}} = C$$

Condition (2) states that nitrogen should be used in production until the present value of marginal value product equals the present value of purchasing commercial nitrogen fertilizer.

$$3)\ M_{bst}, N_{bst} \geq 0$$

3.3. Study Area:

The study area is the Beaty creek watershed in Delaware County, Oklahoma. Beaty creak watershed is one of eight sub-basins of the Eucha/Spavinaw watershed. The total area of Beaty creek watershed is 153,556 Km^2, which is mainly located in Delaware County and partly in Benton County of Arkansas (Figure 7).

The Beaty Creek watershed has the second largest number of poultry in the Eucha watershed (Table 1). Beaty Creek contributes 39 percent of the total phosphorous load to Eucha lake, just after Spavinaw creek (Wagner and Woodruff, 1997). About 60 percent of the land is in pasture with Bermudagrass as the main variety. The rest of the land is in forest or woodland.

Figure 7: Eucha Watershed with Eight Sub-basins. (Number 1 is Beaty Creek).

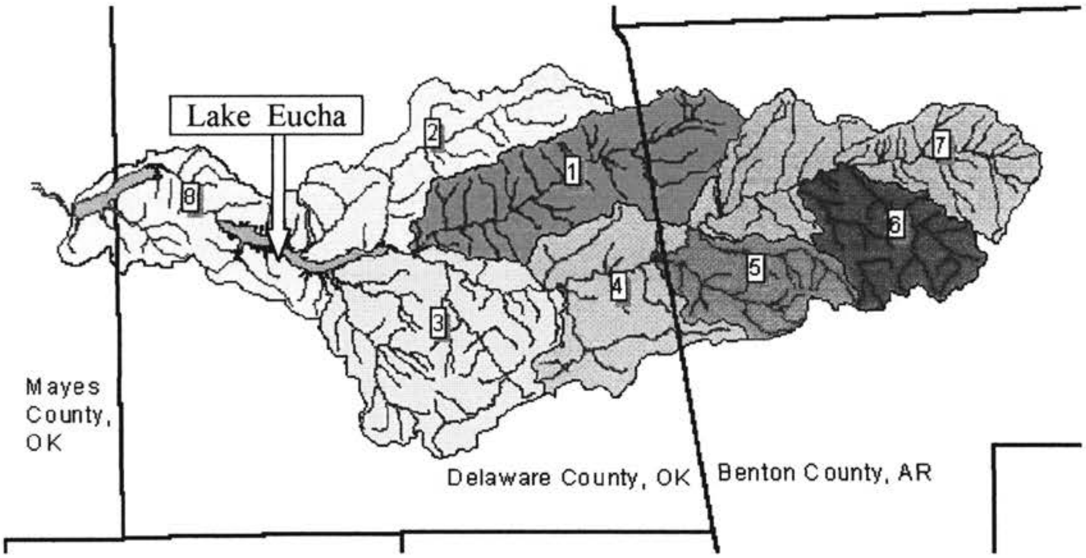


Table 1: Poultry Farms, Poultry Litter and Phosphorous Excretion in the Eucha/Spavinaw Watershed

SUB-GROUP	NAME	Farms	Poultry Houses	Animals (Head)	Litter (Tons)	P (lbs)
1	Beaty Creek	47	159	2,881,600 (18%)	14,653	516,655.39
2	Brush Creek & Rattlesnake Creek	18	59	980,100 (6%)	5,461	198,502.71
3	Dry Creek & Cloud Creek	17	42	738,900 (5%)	3,732	131,263.90
4	Cherokee Creek	52	141	2,469,300 (15%)	12,815	455,053.61
5	Decatur Branch & Coon Creek	53	149	2,665,100 (17%)	13,287	470,590.10
6	Wolf Creek	39	160	2,460,200 (15%)	13,311	494,679.46
7	Spring Branch	73	230	3,855,650 (24%)	21,201	792,072.36
8	West Lake Eucha & Spavinaw Lake	3	6	85,000 (0%)	553.45	21,027.30

Source: Tulsa Metropolitan Utility Authority, 1998-1999

3.4. Data Requirements

3.4.1 Input Data for the SWAT Model

The economic model uses biophysical data generated from the ArcView-SWAT and EPIC models

Data layers for the SWAT include:

a/ Digital Elevation Model (DEM) data: DEM data files are produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program.

b/ Soil data layer: constructed with MIADS data and a Benton county soil layer. Source of soil data is State Soil Geographic (STATSGO) database that is developed by the National Cooperative Soil Survey.

c/ Land cover data layer is constructed using Oklahoma and Akansas GAP data.

d/ Climate files contain climate and precipitation files based on NOAA COOP observations. NOAA (the National Oceanic and Atmospheric Administration) is responsible for all U.S. weather and climate forecasting. A COOP (Cooperation) weather station is a station at which observations are taken or other services are rendered by volunteers. NOAA has a database of 19,000 stations across the U.S.

e/ Stream flow data are based on USGS stream gage observations.

The primary results from SWAT are the number of sub-basins and the number of hydrologic response units or HRUs from which all geographic information can be drawn. The number of sub-basins and the HRUs were determined from a specification of threshold values on the stream as well as thresholds on land use and soil type. The value in the stream threshold cell dictates the detail of the stream network. The lower the value, the greater the resulting number of sub-basins is. However, as the number of sub-basins reaches a maximum, further changes in the threshold have no effect. The threshold for land use over a sub-basin allows SWAT to include or exclude minor land uses in each sub-basin. Land uses that cover a percentage of the sub-basin area less than the threshold level are eliminated. In the same way, the threshold on soil type is used to eliminate minor soils within a land use area.

In this study, the threshold value for a stream was specified at 1,000 hectares or 6/1,000,000 of the total area. This value allowed the maximum number of sub-basins for the entire Beaty creek. The chosen threshold values for land use and soil type were 5 percent and 15 percent respectively. The number of HRU's in the watershed was more sensitive to the threshold value of soil type than that of land use. This fact indicated that soil type in the watershed is more diversified than land use. As a result, the number of

HRUs for the entire watershed at the selected thresholds (5 percent for land use and 15 percent for soil type) was 16 while the maximum attainable number was 35 HRUs and the minimum was 3 HRUs.

3.4.2. Input Data for EPIC Model

Results drawn from SWAT that were selected as inputs for EPIC were the HRU's, soil type, slope steepness and slope length. Fertilizer application rates were also designed as essential management inputs for SWAT. Fertilizer response, nitrogen / phosphorous carryover, and phosphorous loss were determined from EPIC simulations. Sixteen different combinations of poultry manure and commercial nitrogen fertilizer shown in Table 2 were used to estimate the above equations. Each combination was simulated for a period of 48 years.

Table 2: Fertilizer Treatments as Inputs for EPIC Model

Treatment	Manure (kg/ha)	33.5-0-0 (kg/ha)
1	10	10
2	10	75
3	10	150
4	1124	10
5	1124	75
6	1124	150
7	2247	10
8	2247	75
9	2247	150
10	3371	10
11	3371	75
12	3371	150
13	4494	10
14	8989	10
15	13483	10
16	17976	10

3.4.3. Observed Data

Observed data consists of economic data and observed data on the flows and water chemistry that were available on the web site of TMUA (Tulsa Metropolitan Utility Authority)

Economic data includes

Average prices of Bermuda hay were: \$ 71.20 / metric ton (Oklahoma Agricultural Statistics 1999).

Average price of ammonium nitrate (33.5-0-0): \$ 247 / metric ton in 1999 (NASS Home Page: http:www.usda.gov/nass/). The equivalent cost per kg nitrogen is \$ 0.74 / kg N.

Price of transporting poultry litter: \$0.05 / ton / mile for a trailer that can carry a load of 20 tons (Donald and Blake, 1990).

The economic results may be sensitive to changes in output / input price ratio. The actual price of Bermuda hay was lower than the average price quoted above. The hauling cost of poultry litter may be higher than the quoted price that was estimated in 1990. In order to take into account of these price changes. A sensitivity analysis was made with the price of Bermuda hay at \$60.0/ metric ton and with an increased hauling cost of poultry litter of \$0.08 / ton / mile. Sensitivity analysis was also made to compare the economic results that derived from the discount rates of 7% and 10%.

Selected observed data from TMUA are:

Average total flow from Aug. 1998 to April 2000: 1.78 m^3/s.

Average soluble phosphorous / year: 0.0497 mg / l.

From these data the calculated data are

$$\text{Runoff (Q)} = \frac{Flow(m^3)}{Area(m^2)} = \frac{1.78 * 60s * 60\min utes * 24hours * 365days}{153.556km^2 * 10^6}$$

$$= 0.3655m/yr \approx 365.5mm/yr$$

Annual average phosphorous loading (kg / ha):

$$P(kg/ha) = \frac{0.0497mg/l * 1.78m^3/s * 60 * 60 * 24 * 365 * 1000l}{9175Ha(pasture)}$$

$$P(kg/ha) = 304072mg/ha \approx 0.3kg/ha$$

Average annual poultry litter application in Beaty creek:

$$Application = \frac{14653.65kg}{9175.15ha} = 1597kg/ha \approx 1.6ton/ha.$$

3.5. General Procedure

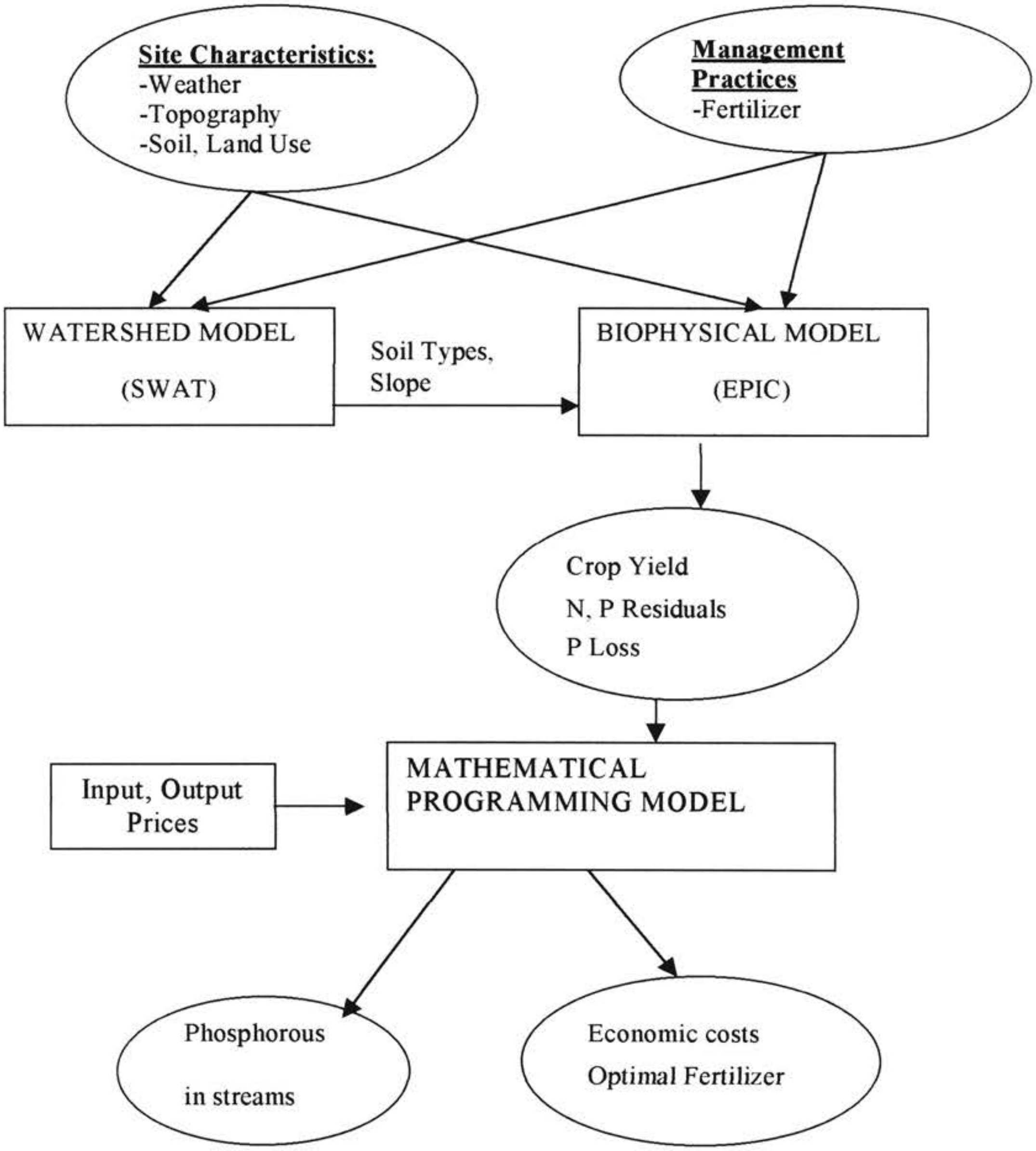
To assess the environmental and economic consequences of reduced poultry litter applications, the empirical analysis requires hydrologic, agronomic, biochemical and economic information. The modeling framework is based on the integration of EPIC, SWAT and a dynamic economic optimization model. The analysis proceeded in four stages:

1/ Use the ArcView-SWAT watershed model to delineate the study area, to identify sub-basins and the number of HRUs within a sub-basin. Information of one HRUs that are soil type, slop steepness and slope length were drawn and used as inputs for EPIC model.

2/ Use the EPIC model to generate crop yields for Bermudagrass, nitrogen and phosphorous content in the soil profile as well as soluble phosphorous loss in water runoff for each soil type. In this stage, EPIC simulations were modeled with poultry manure and commercial nitrogen application. Each simulation run was made for a 48 year period. The crop is Bermudagrass hay.

3/ Use regression techniques to estimate the dynamic response functions based on soil nitrogen and phosphorous levels from EPIC output data. The equations to be estimated in stage 3 for each soil-crop combination were yield responses, soil nitrate levels, labile soil phosphorous levels, and soluble phosphorous loss in runoff.

Figure 8: Modeling Framework.



4/ Use the equations developed in stage 3 to develop an economic model that can be optimized to analyze the abatement costs of reducing poultry litter applications subject to restriction on phosphorous runoff (Fig. 8).

3.6. Estimation Method

The data in this study were generated from the EPIC model. Production, soil nutrient levels and phosphorous ruoff were recorded from sixteen treatments or simulation runs. Each simulation run was for a period of 48 years. The selected outcomes were Bermudagrass response yield, labile phosphorous, nitrate in soil and soluble phosphorous runoff. These data are typical ones of repeated measurements. Repeated measurements involve several response observations for each unit or individual or object. In this study, an object or unit is an HRU where several observations on its crop yield; soil nutrients (N, P) and phosphorous loss are made. A similar example of repeated measurements in economic studies is *panel* data in which time-series and cross-section data are pooled or *longitudinal* data of which observations are made on individuals or households over time.

In fitting the model, the most important assumption is the independence of the response observations. For repeated measurements, measurements that are taken over a period of time on a given unit may be serially correlated. Thus the assumption of independence is violated. In biological data such as crop yield response, variance of the response changes systematically with the ferlilizer level (X), therefore, problem of heteroscedasticity (i.e. different variances) also exists.

3.6.1. Estimation of Yield Response Function

A general regression model for repeated measurement in this study can be as follow:

$$y_{it} = \alpha + \beta' x_{it} + e_{it} \tag{1}$$

where e_{it} is the error term to capture uncertainty

i denotes the treatment, i=1,...16, t denotes the number of observations over time t=1,...48.

The assumptions of the classical regression framework are as follows:

1. The error terms have mean zero:

$E(e_{it}) = 0$.

This assumption ensures that the model for mean response is correctly specified.

2. The error terms have a constant variance:

$E(e_{it}^2) = \sigma^2$.

3. The error terms corresponding to different points in time are not correlated:

$E(e_{it}e_{is}) = 0$ if $t \neq s$.

4. The error terms are normally distributed.

The assumption of normality forms the basis for the standard approach to inference. If assumption 3 and 4 both hold, they ensure the independence in the error terms, and in turn, the independence of the response y_{it}.

To correct for the problem of heterocesdaticity and serial correlation in repeated measurements, the model (1) can be reformulated as follows:

$$y_{it} = \alpha + \beta' x_{it} + u_i + e_{it} \tag{2}$$

The term u_i is the random error and is assumed to be constant through time. The variance structure of u_i needs to be specified in such a way to depict the correlation between all observations of Yit within a treatment i. The error term e_{it} needs to reflect the fact that responses between treatments change according to the level of treatments (i.e. the level of fertilizer). The assumptions for the model (2) are:

1. $E(e_{it}) = E(u_i) = 0$
2. $E(e_{it}) = \sigma_e^2$
3. $E(u_i^2) = \sigma_u^2$
4. $E(e_{it}u_j) = 0$ for all i, t and j,
5. $E(e_{it}e_{js}) = 0$ if $t \neq s$ or $i \neq j$,

$E(u_i u) = 0$ if $i \neq j$.

Crop yield responds to fertilizer according to Mitscherlitch law of diminishing returns. Mitscherlitch (Johnson, 2000) expressed the mathematical relationship between crop yield and a growing-limiting factor as $\frac{dy}{dx} = (A - y) * c$

Where:

dy/dx is the change in yield from an increment addition of a single limiting growth factor (x), or nutrient.

A is the maximum yield when all growth factors are at their optimum.

Y is the initial yield or from the last addition of the limiting nutrient.

C is a proportional constant or efficiency factor.

The curve of yield response to fertilizer approaches an asymptote with increase in fertilizer x without an inflection point. The general regression form adopted from Mitserlitch's law is as follows:

$$y = \alpha - \beta\gamma^{x}$$

Where α,β and γ are parameters to be estimated.

Several specific functional forms have been used to estimate a Mischerlitch type crop yield response. They are as follows: (Ratkowsky, 1983, p. 95)

1. $Y = \alpha - \beta \exp(-\gamma X)$
2. $Y = \alpha\{1 - \exp[-(X + \beta)\gamma]\}$
3. $Y = \alpha - \exp[-(\beta + \gamma X)]$
4. $Y = \alpha - \exp(-\beta)\gamma^{X}$
5. $Y = \frac{1}{\alpha} - \beta\gamma^{X}$
6. $Y = \exp(\alpha) - \beta\gamma^{X}$

The functional form number 1 is most popular of this group in estimating yield in response to fertilizer and was chosen in this study. The specific form was:

$$y_{it} = \beta_0 - \beta_1 \exp(\beta_2 TN_{it} + \beta_3 TNO3L_{it} * PLABL_{it}) + u_i + \varepsilon_{it} \qquad (3)$$

Where y_{it} is the yield response of treatment i and year t (kg/ha).

TN_{it} is total Nitrogen applied in year t (kg/ha).

$TNO3L_{it}$ is nitrate in the soil in the previous year (kg/ha).

$PLABL_{it}$ is labile phosphorous in the soil in the previous year (kg/ha).

$\beta_2, \beta_3 \prec 0$

This functional form is nonlinear and was estimated with the NLMIXED procedure in SAS. The within-treatment variance and the between-treatment variance were specified respectively as follows:

$E(u_i^2) = \frac{\rho^2}{1-\rho^2}$ and $E(e_{it}^2) = \exp(\alpha_0 + \alpha_1 * TN_{it})$

Where ρ is the coefficient in an autoregressive process:

$e_t = \rho e_{t-1} + v_t$

Where $E(v_t) = 0, E(v_t^2) = \sigma_v^2, E(v_t v_s) = 0$ for $t \neq s$

3.6.2. Estimation of the Carryover Functions and Phosphorous Loss Function:

The general regression form for these time series data has the following form:

$y_{it} = \beta' x_{it} + \varepsilon_{it}$ for i=1,…16 t=2,…48. (4)

The assumptions of (4) are:

1. $E(\varepsilon_{it}^2) = \sigma_i^2$ heterokesdasticity.

2. $E(\varepsilon_{it}\varepsilon_{jt}) = \sigma_{ij}$ for $i \neq j$, Cross-section correlation because all the responses resulted from the same formulations established in EPIC regardless whatever treatment is.

3. $\varepsilon_{it} = \rho_i \varepsilon_{i,t-1} + v_{it}$

Where $E(v_{it}) = 0, E(v_{it}^2) = \phi_{ii}, E(v_{it}v_{jt}) = \phi_{ij}$ for $i \neq j$ and $E(v_{it}v_{js}) = 0$ for $t \neq s$.

a/ The carryover function of nitrogen is specified as follows:

$Y_{it} = \beta_0 + \beta_1 NTOT_{it} + \beta_2 TN_{it} * YIELD_{it} + \varepsilon_{it}$

Where y_{it} is the amount of nitrate in the soil at treatment i and year t (kg/ha).

$NTOT_{it}$ is the sum of residual nitrate nitrogen and total nitrogen applied at treatment i year t (kg/ha).

$TN_{it}*YIELD_{it}$ is an interactive term between total nitrogen applied and the response yield (kg/ha).

b/. The carryover function of phosphorous:

$$y_{it} = \beta_0 + \beta_1 PTOT_{it} + \beta_3 YIELD_{it} * PAP_{it} + \varepsilon_{it}$$

Where y_{it} is the labile phosphorous in the soil at treatment i year t (kg/ha).

$PTOT_{it}$ is the sum of labile phosphorous in previous year and labile phosphorous of year t with treatment i (kg/ha).

PAP_{it} is the phosphorous applied at treatment i year t (kg/ha).

c/. Phosphorous loss function:

$$y_{it} = \beta_0 + \beta_1 PTOT_{it} + \beta_2 Q_t + \varepsilon_{it}$$

Where:

Y_{it} is the amount of soluble phosphorous lost in runoff (kg/ha).

$PTOT_{it}$ is the sum of labile phosphorous of the previous year and phosphorous applied at treatment i of year t (kg/ha).

Q_t is the amount of runoff that came from soil in year t (mm).

All the above functions were estimated with the procedure of Pooled Cross-section Time-Series in SHAZAM.

CHAPTER IV

RESULTS

4.1. Simulation Results

4.1.1. Results from SWAT Model.

SWAT divided the watershed into five sub-basins (Figure 9a) based upon the elevation and stream network. The levels of elevation were indicated by the color in DEM (Digital Elevation Model). Sub-basin 1 and 2 located in Arkansas State are high land. The remaining sub-basins that are located in Oklahoma are low land. Pasture and forest are the two main land uses in the area (Figure 9b). About 60 percent of the land is in pasture.

There are 16 HRUs identified by SWAT (Table 3). The total pasture area is subdivided into nine HRUs with five main soil types: Jay, Newtonia, Macedonia, Clarksvilles and Nixa. The distribution of soils over the watershed is shown in Figure 9c. Newtonia is the most common soil type and is distributed throughout four of five sub-basins (Sub-basins number 1,2, 3 and 4). Macedonia is the second most common soil type and located in sub-basins 4 and 5.

Sub-basins differ from one another mainly by topography. Slope steepness and slope length of each HRU provided by SWAT were used as inputs along with soil type in

Figure 9a: SWAT Delineation of Sub-basins for Beaty Watershed.

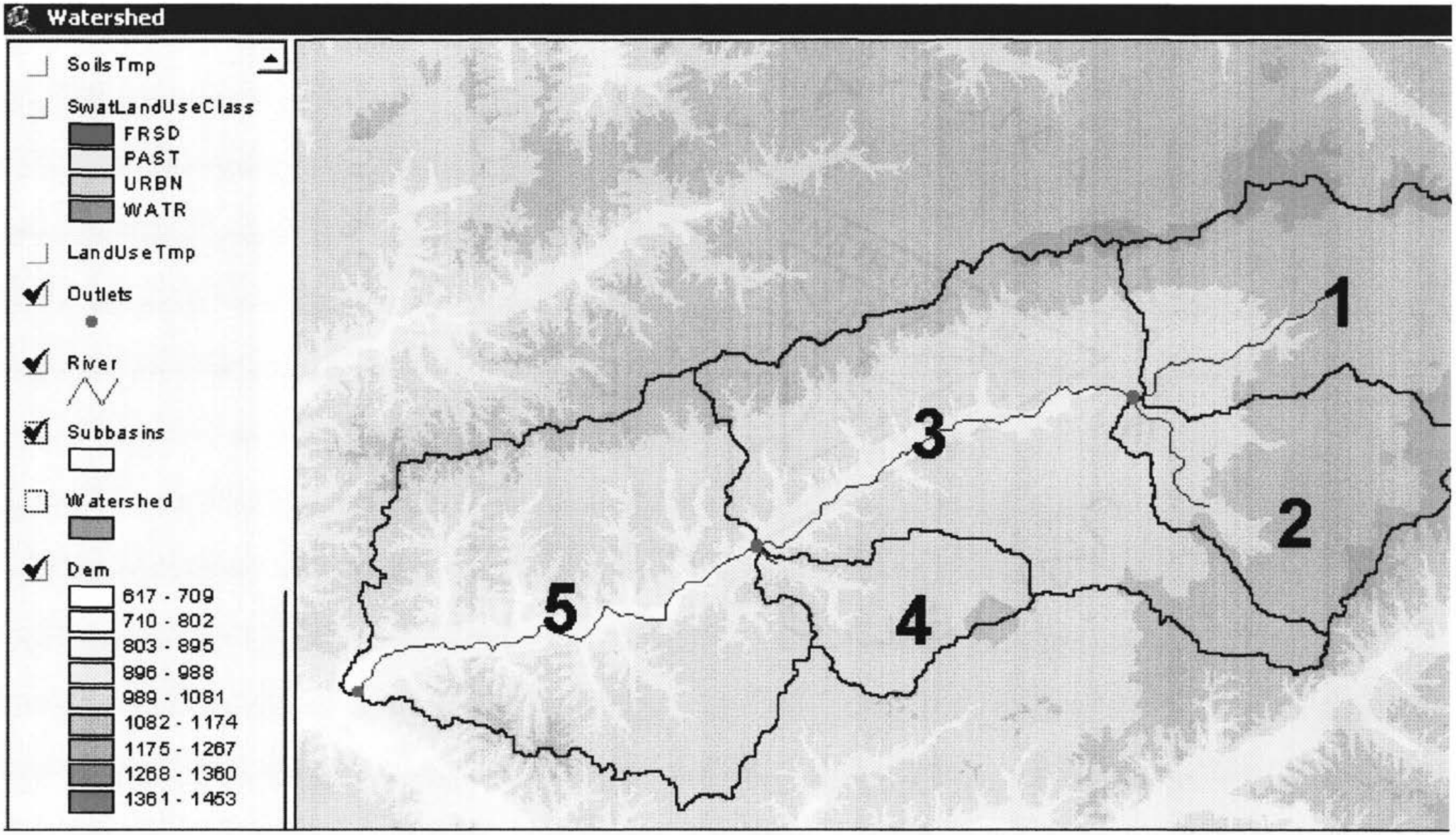


Figure 9b: SWAT Identification of Land Use in Beaty Creek Watershed.

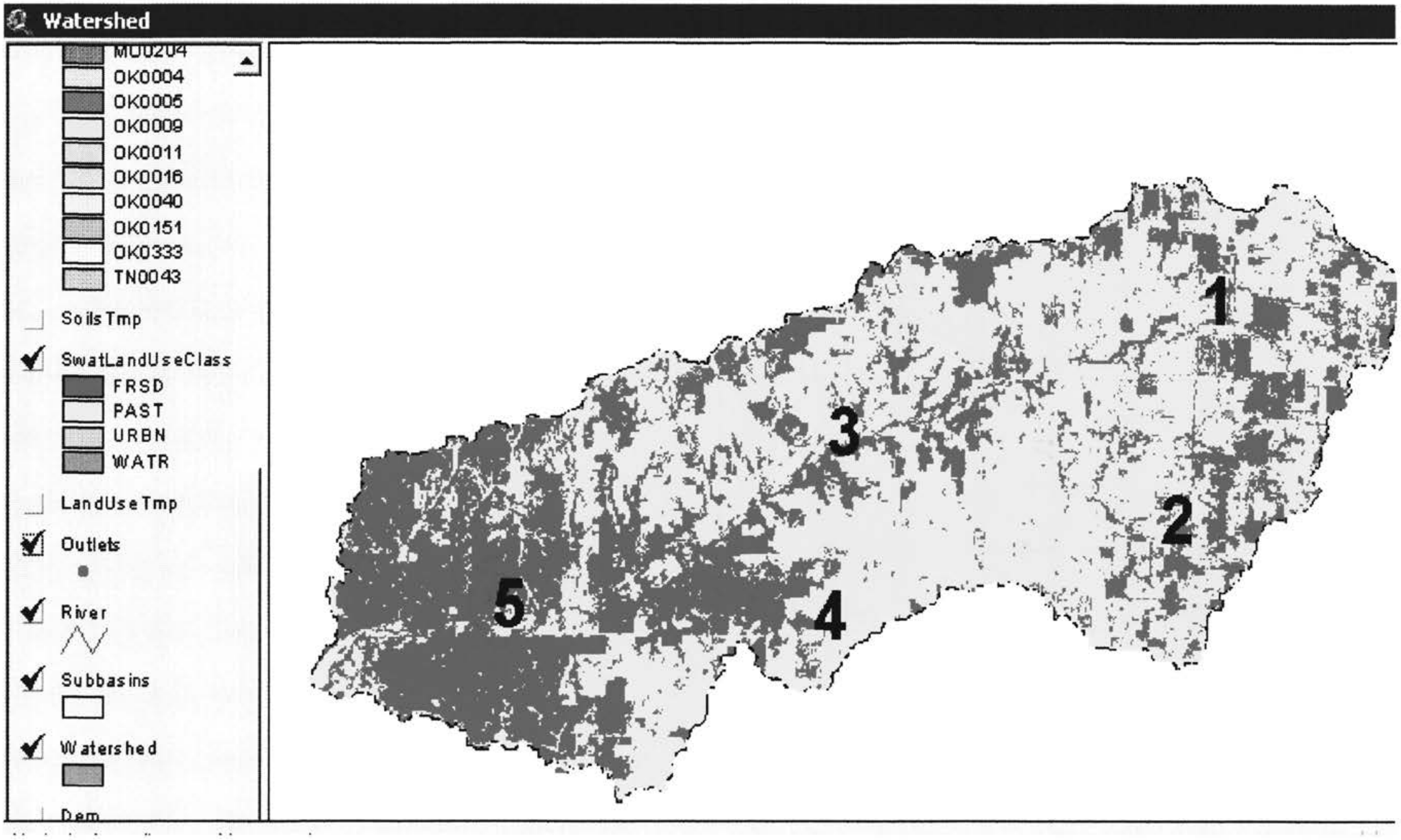
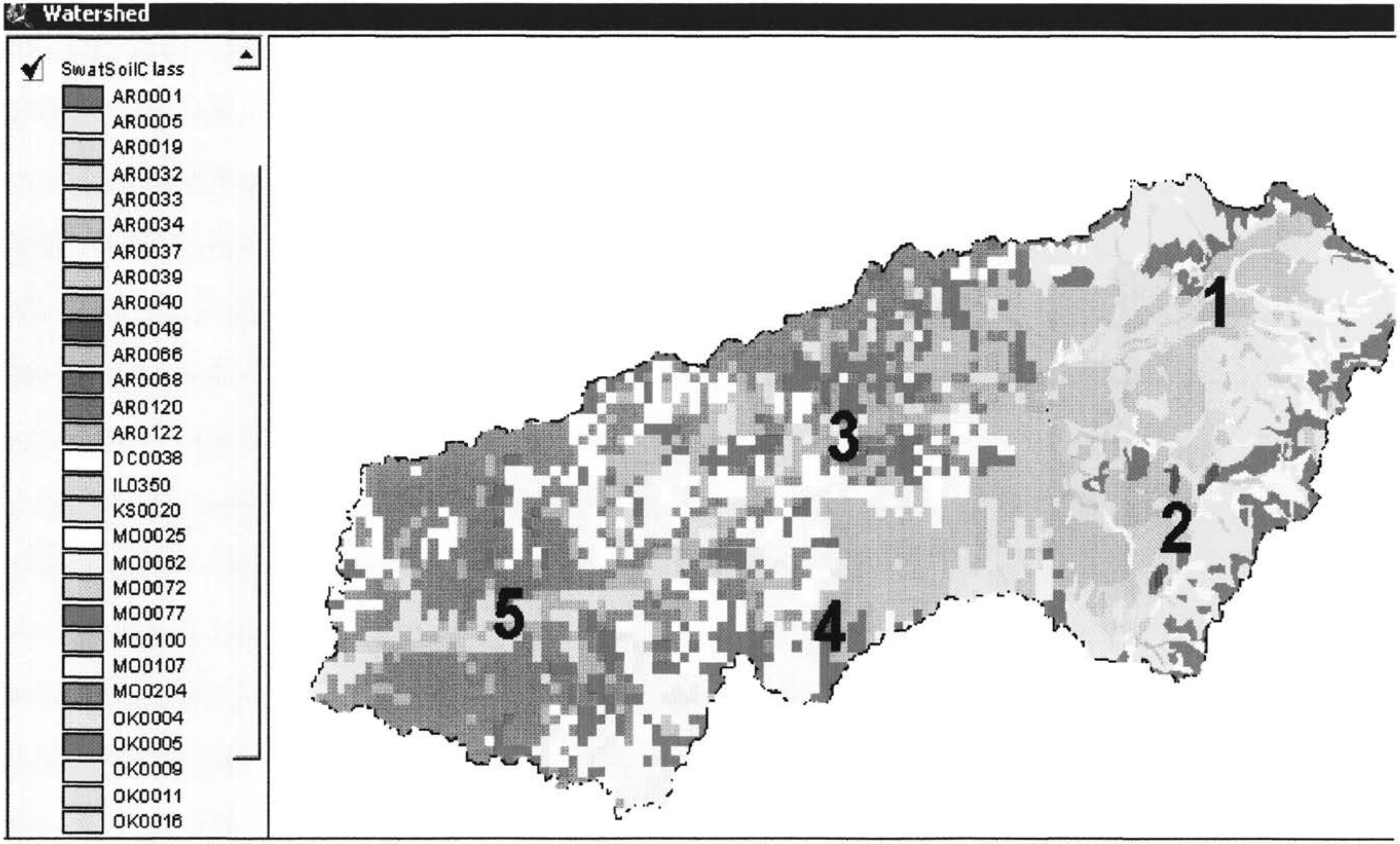


Figure 9c: SWAT Identification of Soil Types in Beaty Creek Watershed.



EPIC (Table 4). These inputs physically distinguish one HRU from another HRU even though they have the same land use and soil type. For example, HRU number 2 in sub-basin 1 had Newtonia soil and was denoted as 1-2 Newtonia. The HRU 1-2 Newtonia was not identical with the HRU of 2-1 Newtonia because of spatial location and different average slope and slope length shown in Table 3 and 4. Slope length and slope steepness partly influence the amount of water runoff, therefore affect the amount of phosphorous loss in runoff.

4.1.2. EPIC Simulated Yield Responses and Soluble Phosphorous Loss.

The differences in soil fertility and topographical characteristics were reflected in yield reponses among HRUs . The average yield response to various treatments are presented in Figure 10 and presented in more detail in Table 4. Different HRUs in the same sub-basin may have different yield responses due to the differences in soil type. For example, sub-basin 1 has three HRUs, 1-1 Jay, 1-2 Newtonia and 1-3 Nixa. These HRUs have different yield responses. The HRU 1-1 Jay has the highest yield followed by 1-2 Newtonia and 1-3 Nixa. The differences in yield responses also reflect the differences in topographical properties. HRUs may have the same soil type though they are located in different sub-basins. Examples are 1-2 Newtonia, 2-1 Newtonia, 3-1 Newtonia and 4-2 Newtonia that have slightly different yield responses because of differences in slope and slope length.

With irrigation, Bermuda grass consistently yields 10-15 tons per acre. For dryland production in Delaware County, the suggested yield target is 7 short tons per acre, or 15.7 metric tons per ha (Johnson and Woods). The average yield simulated by

EPIC for nine soils in the Beaty watershed was 5.7 metric tons. This was higher than the actual average yield reported in Delaware County (3,000kgs/ha) but less than the average yields observed in the Bermuda grass fertilizer and variety trials in Haskel, Oklahoma. Haskel and Delaware Counties have the same expected target yields (Taliaferro et al., 1995).

The height and the shape of yield curves as depicted in Figure 10 has important implications for the response of farmers facing environmental regulations that might reduce poultry manure or nitrogen application. In general, 1-1 Jay has the highest yield when nitrogen application is 300 kg per hectare or less. The remaining soils in order of declining responses to applied nitrogen are the group of Newtonia soils, the Macedonia group, Nixa and Clarksville. Assume that the two HRUs generate the same amount of phosphorous loss, the production function implies that if an environmental restriction were imposed, farmers with Newtonia soils would be more willing to give up using poultry manure than producers with Jay soils, because its profit of using one unit of manure is less than that of Jay.

The loss of soluble phosphorous is another factor influencing the economic behavior of farmers in facing an environmental regulation. And it is the major focus of the environmental protection effort. Figure 11 and Table 5 summarize the EPIC estimated average soluble phosphorous loss by all pasture HRUs. In general, the amount of soluble phosphorous loss in runoff had a tendency to increase as the amount of phosphorous application increased. However, just like with yield response, there was a great variation among HRUs within and between treatments. For example, 5-1 Clarksville and 5-2 Macedonia were located in the same sub-basin 5. At the medium level of phosphorous application (from 74 to 99kg/ ha), the 5-1 Clarksville generated the most phosphorous loss. However, at the higher phosphorous application rates (from 198 to 399kg/ha), 5-1 Clarksville had a smaller phosphorous loss than the other HRUs. The 5-2 Macedonia was among the HRUs generating the most phosphorous loss. The 4-1 Macedonia with the second greatest slope generated the most phosphorous loss. Of course, phosphorous loss from soil is not readily observable and more information is needed to validate the result. However, the model results indicate that the abatement efforts should not focus only on soil slope but also on soil type and application rates. Soil types that generate a high soluble phosphorous loss per unit of applied manure may have potential low abatement cost because giving up of using one unit of manure on this soil will reduce more phosphorous loss than on other soils. This is especially true for the soil that has high phosphorous loss and low crop yield.

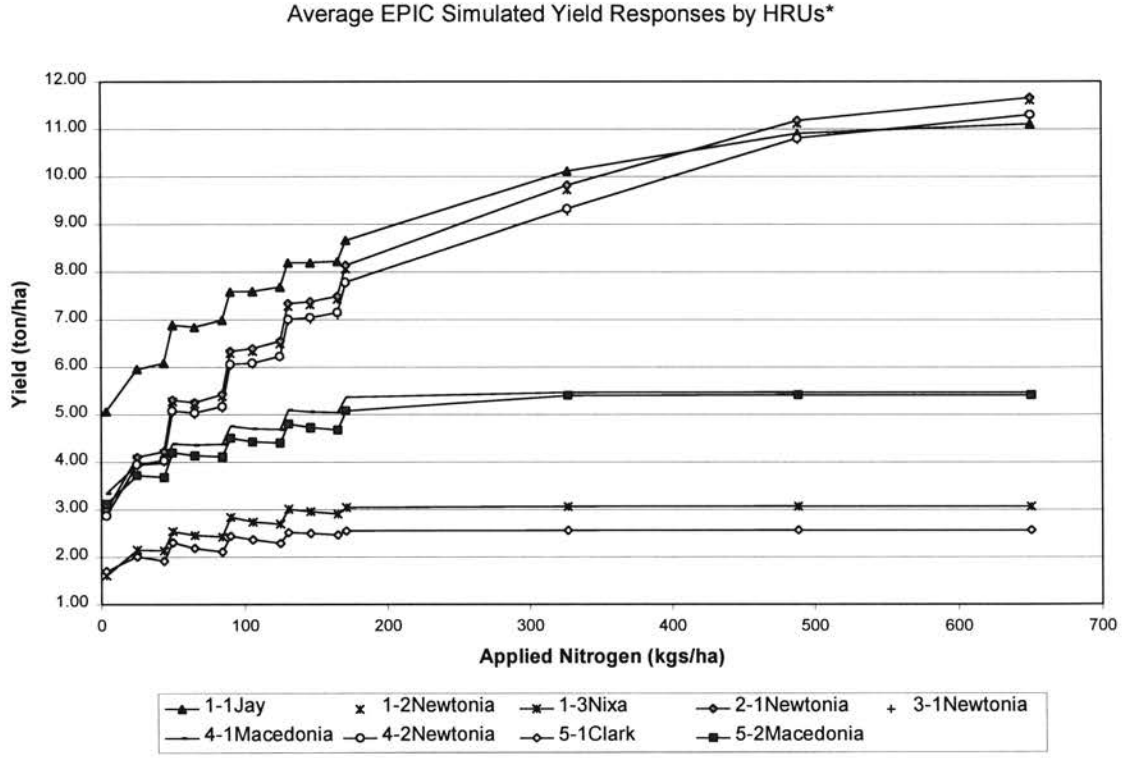
Table 3: Sub-basins and Hydrologic Response Units Determined by SWAT Model.

LANDUSE	SUBBASIN	HRU	SOIL	SOIL NAME	AREA (ha)
Forest	1	4	AR0005	NIXA	832.96
	2	2	AR0001	CAPTINA	228.16
	2	3	AR0005	NIXA	372.42
	3	2	MO0204	CLARKSVILLE	1234.56
	4	3	MO0204	CLARKSVILLE	157.57
	4	4	MO0107	MACEDONIA	182.31
	5	3	MO0204	CLARKSVILLE	3171.94
Total Forest					6179.92
Pasture	1	1	AR0066	JAY	660.48
	1	2	OK0151	NEWTONIA	558.37
	1	3	AR0005	NIXA	726.02
	2	1	OK0151	NEWTONIA	1385.45
	3	1	OK0151	NEWTONIA	3450.66
	4	1	MO0107	MACEDONIA	286.35
	4	2	OK0151	NEWTONIA	393.82
	5	1	MO0204	CLARKSVILLE	987.08
	5	2	MO0107	MACEDONIA	726.90
Total Pasture					9175.15
Total Watershed					15355.06

Table 4: Topographical Characteristics of Different Pasture Hydrologic Response Units.

SUB-BASIN	HRU	Soil name	Slope (m/m)	Slope length (m)
1	1	JAY	0.071	60.976
1	2	NEWTONIA	0.071	60.976
1	3	NIXA	0.071	60.976
2	1	NEWTONIA	0.062	60.976
3	1	NEWTONIA	0.151	24.390
4	1	MACEDONIA	0.148	24.390
4	2	NEWTONIA	0.148	24.390
5	1	CLARKSVILE	0.386	9.146
5	2	MACEDONIA	0.386	9.146

Figure 10: EPIC Simulated Yield Responses of Bermuda Grass by HRUs.



* An average yield when nitrogen is applied as poultry manure or inorganic nitrogen at the levels indicated for 48 years. The level of nitrates and labile phosphorous vary with the level of applied nitrogen.

Table 5: EPIC Simulated Average Yield Responses by HRUs and by Treatments.

Treatment	N equivalent (kg/ha)	1-1 Jay Avg Yield (Ton/ha)	1-2 Newton Avg Yield (Ton/ha)	1-3 Nixa Avg Yield (Ton/ha)	2-1 Newton Avg Yield (Ton/ha)	3-1 Newton Avg Yield (Ton/ha)	4-1 Macedo Avg Yield (Ton/ha)	4-2Newton Avg Yield (Ton/ha)	5-1Clark Avg Yield (Ton/ha)	5-2Macedo Avg Yld (Ton/ha)
1	3.66	5.07	2.98	1.61	3.00	2.87	3.34	2.88	1.70	3.12
2	25.11	5.96	4.07	2.15	4.10	3.92	3.94	3.95	2.01	3.71
4	43.76	6.08	4.18	2.14	4.22	4.01	3.98	4.04	1.91	3.68
3	49.86	6.89	5.27	2.54	5.30	5.05	4.38	5.07	2.30	4.19
5	65.21	6.84	5.21	2.45	5.25	5.00	4.35	5.03	2.19	4.13
7	84.19	6.99	5.38	2.43	5.42	5.14	4.37	5.17	2.11	4.11
6	89.96	7.59	6.29	2.84	6.33	6.03	4.75	6.06	2.44	4.50
8	105.64	7.60	6.34	2.74	6.39	6.06	4.70	6.09	2.36	4.42
10	124.66	7.69	6.50	2.70	6.55	6.21	4.69	6.23	2.29	4.40
9	130.39	8.20	7.28	3.01	7.34	6.97	5.09	7.01	2.51	4.80
11	146.11	8.20	7.31	2.96	7.38	7.00	5.05	7.04	2.50	4.73
13	165.04	8.23	7.43	2.91	7.49	7.10	5.04	7.15	2.46	4.68
12	170.86	8.67	8.07	3.05	8.14	7.77	5.36	7.79	2.55	5.08
14	326.9	10.12	9.73	3.07	9.82	9.27	5.46	9.32	2.56	5.40
15	488.63	10.91	11.13	3.07	11.18	10.77	5.47	10.81	2.56	5.42
16	650.48	11.11	11.61	3.07	11.66	11.27	5.47	11.30	2.56	5.42
Average	166.90	7.88	6.80	2.67	6.85	6.53	4.72	6.56	2.31	4.49

Figure 11: EPIC Simulated Phosphorous Loss by Hydrologic Response Units and by Treatment Levels.

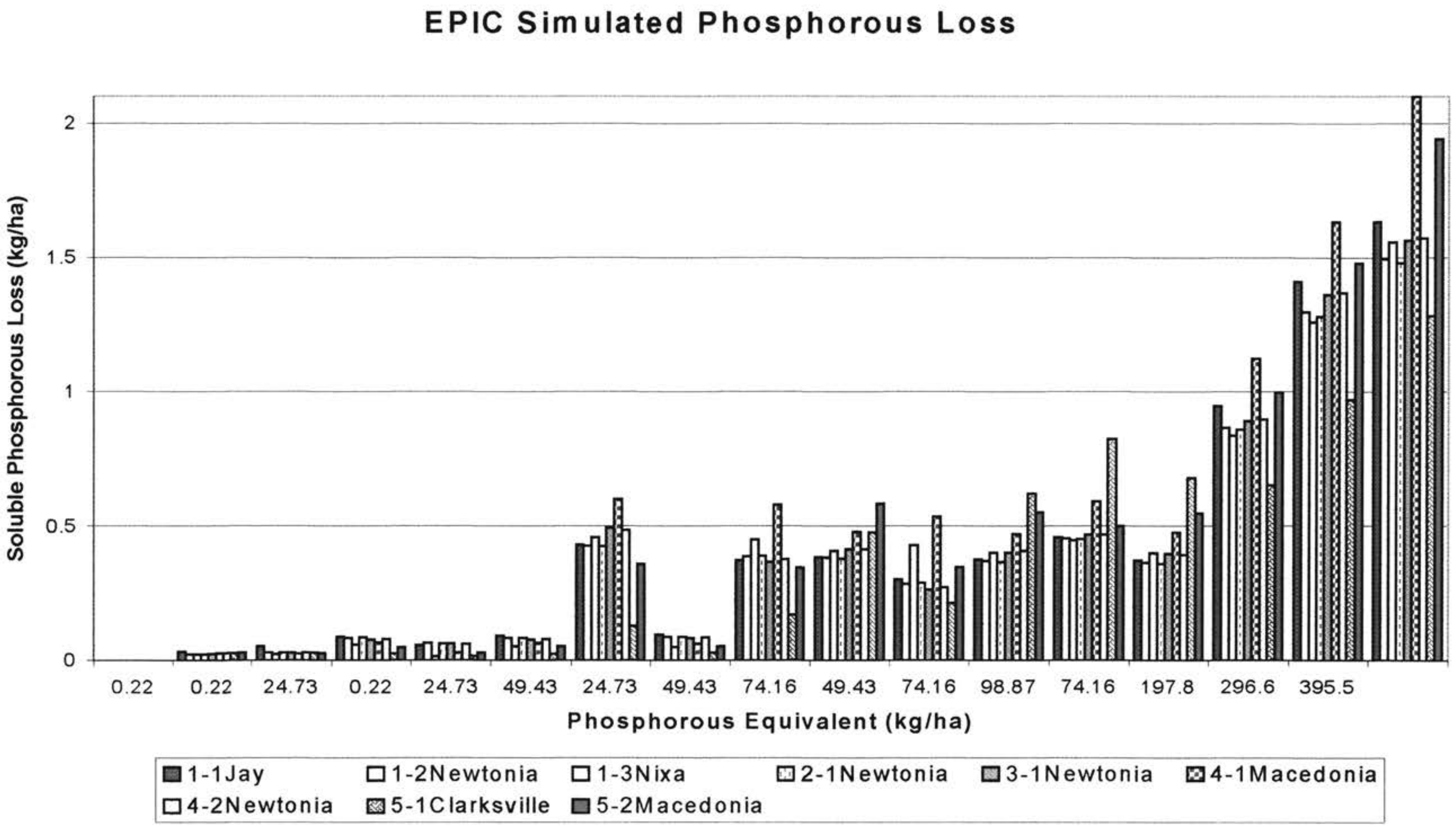


Table 6: EPIC Simulated Average Phosphorous Loss by Hydrologic Response Units and by Treatments*.

Treatment	P equivalent	1-1Jay	1-2Newto	1-3Nixa	2-1Newto	3-1Newto	4-1Macedon	4-2Newto	5-1Clark	5-2Macedo
	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
1	0.22	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03
2	0.22	0.05	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03
4	24.73	0.09	0.08	0.06	0.09	0.08	0.07	0.08	0.02	0.05
3	0.22	0.06	0.06	0.01	0.06	0.06	0.03	0.06	0.02	0.03
5	24.73	0.09	0.08	0.05	0.08	0.08	0.06	0.08	0.03	0.05
7	49.43	0.43	0.43	0.46	0.43	0.50	0.60	0.49	0.13	0.36
6	24.73	0.10	0.09	0.05	0.09	0.08	0.06	0.09	0.03	0.05
8	49.43	0.37	0.39	0.45	0.39	0.37	0.58	0.38	0.17	0.35
10	74.16	0.39	0.38	0.41	0.38	0.41	0.48	0.41	0.48	0.59
9	49.43	0.30	0.28	0.43	0.29	0.26	0.54	0.27	0.21	0.35
11	74.16	0.38	0.37	0.40	0.37	0.40	0.47	0.41	0.62	0.55
13	98.87	0.46	0.45	0.45	0.45	0.47	0.59	0.47	0.82	0.50
12	74.16	0.37	0.37	0.40	0.36	0.40	0.48	0.39	0.68	0.55
14	197.8	0.95	0.87	0.84	0.86	0.89	1.12	0.90	0.65	1.00
15	296.6	1.41	1.30	1.26	1.28	1.36	1.63	1.37	0.97	1.48
16	395.5	1.64	1.50	1.56	1.48	1.57	2.10	1.57	1.28	1.94
Average	89.65	0.44	0.42	0.43	0.42	0.44	0.55	0.44	0.39	0.49

*Average over 48 years.

4.2. Statistical Estimation

4.2.1. Yield Response Functions:

Non-linear regression estimation requires the provision of starting values. Starting values are important in obtaining the solutions and in increasing the speed of convergence. Without prior knowledge of these starting values, the estimation can be done by a trial and error method that consumes a lot of effort and time. A few methods have been developed to obtain good starting values. Even when solutions are obtained, one needs to try many other sets of starting values to make sure that the same solutions are found. In this study, the estimation procedure started with the nonlinear program in SHAZAM because this computer package is easy to use. The residuals from each model were plotted against the estimated values and against each of the predictor variables. It was found that yield variations tend to change with the level of total nitrogen. Testing for autoregressive errors was done and strong evidence of autocorrelation was found. This analysis led to the specification of the variance-covariance structure as reported in chapter III. Formal estimation was then made with the SAS computer package with PROC NLMIXED. Starting values were also obtained from the trial models obtained from SHAZAM.

The estimated yield response functions for all pasture HRUs are presented in Table 7. All coefficients are highly statistically significant. The fit of a nonlinear regression model cannot be measured by the coefficient of determination (R^2). The diagnosis was done by plotting residuals versus the fitted values and the predictor value.

Table 7: Yield Response Functions.

Subbasin	HRU	Soil Name	A	TN	TNO3L*PLABL	Intercept
1	1	JAY	8.0198 (7.77)[a]	-0.01402 (-4.89)	-0.00020 (-3.74)	9.6689 (26.54)
1	2	NEWTONIA	8.9640 (26.38)	-0.00405 (-9.61)	-0.00001 (-2.18)	11.8497 (43.27)
1	3	NIXA	1.8443 (8.24)	-0.01829 (-4.47)	-0.00033 (-2.64)	2.9647 (45.98)
2	1	NEWTONIA	9.0176 (24.93)	-0.00396 (-9.01)	-0.00002 (-2.39)	11.9398 (42.77)
3	1	NEWTONIA	8.5800 (27.56)	-0.00416 (-10.25)	-0.00001 (-1.92)	11.3412 (42.42)
4	1	MACEDONIA	3.0491 (10.87)	-0.00739 (-4.51)	-0.00017 (-5.55)	5.3781 (56.38)
4	2	NEWTONIA	8.5838 (28.16)	-0.00414 (-10.25)	-0.00001 (-2.00)	11.3699 (42.97)
5	1	CLARKSVILLE	1.4830 (10.89)	-0.00709 (-3.87)	-0.00053 (-5.88)	2.5414 (65.00)
5	2	MACEDONIA	3.1965 (11.66)	-0.00483 (-3.75)	-0.00019 (-6.13)	5.4268 (45.70)

[a] t-value in parenthesis.

TN: Total nitrogen applied from both poutry manure and commercial nitrogen.

TNO3L: Nitrate-N in the soil in previous year.

PLABL: Labile phosphorous in the soil in previous year.

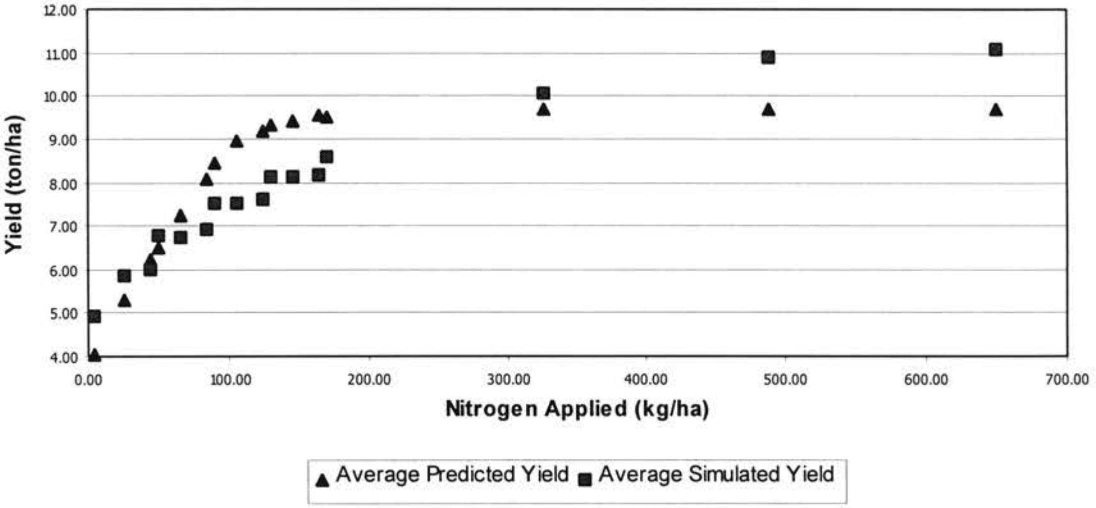
The choice among alternative models was based upon the Akaike Information Criterion (AIC) values reported in the output. The model having the smaller AIC was used. Figure 12 shows the plots of predicted yields versus the average EPIC simulated yields. The graphs show that the models fit the data well. The model for 1-1 Jay yields fit less well than the models for other soils because the data were quite variable at high fertilizer levels. Figure 13 is included so that the estimated yield responses curves can be compared.

The yield responses not only fit the data well but also allow an interpretation consistent with agronomic studies. Consider the simple model of $Y = \alpha - \beta \exp(-\gamma X)$ where α is the maximum yield. An increase in the input X will cause an increase in Y by the amount $dy/dx = \gamma\beta \exp(-\gamma X)$. However the response of Y to additional inputs X becomes zero after a certain level of X is reached. Beyond that level of X, Y becomes constant at α. Without input X, the minimum yield is (α-β) if β is less than α. If β is greater than α then some minimum level of input X is required before any yield is possible.

There are three variables in the yield response function. They are total nitrogen applied in the current year (TN), residual nitrate-N (TNO3L) and residual labile phosphorous (PLABL) from previous year. The negative sign of the coefficients associated with these variables indicated that yield responds positively with an increase in the above inputs. The interaction term between nitrate-N and labile phosphorous indicates that nitrogen is the main limiting factor. Without nitrogen, yield is at the minimum level (α-β). In the presence of nitrogen, an increase of phosphorous enhances the yield of Bermudagrass. Since a forage crop like Bermudagrass requires a lower amount of P than it does of nitrogen, the corresponding coefficient has a small value and it varies from soil to soil.

Figure 12: Graphs of Predicted Yield and Simulated Yield for Different HRUs

Simulated versus Predicted Yields for 1-1 Jay



Simulated versus Predicted Yields for 1-3 Nixa

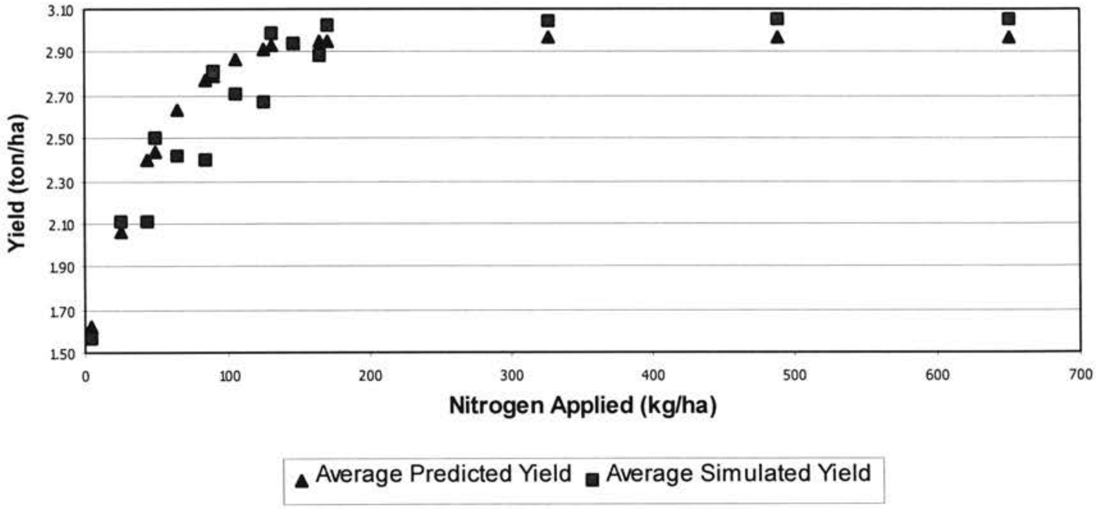
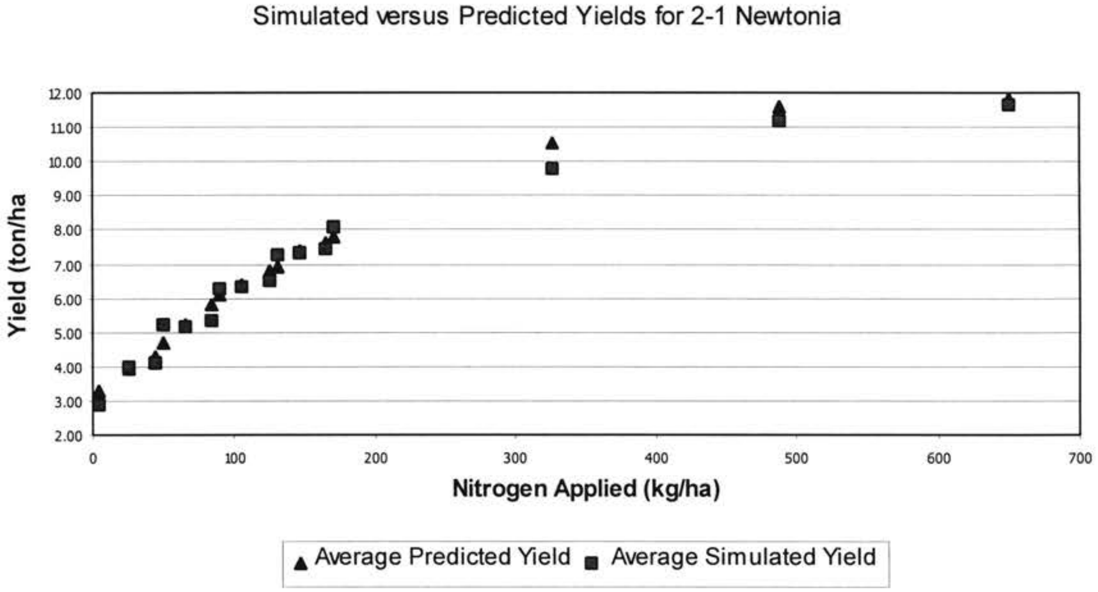


Figure 12: Continued



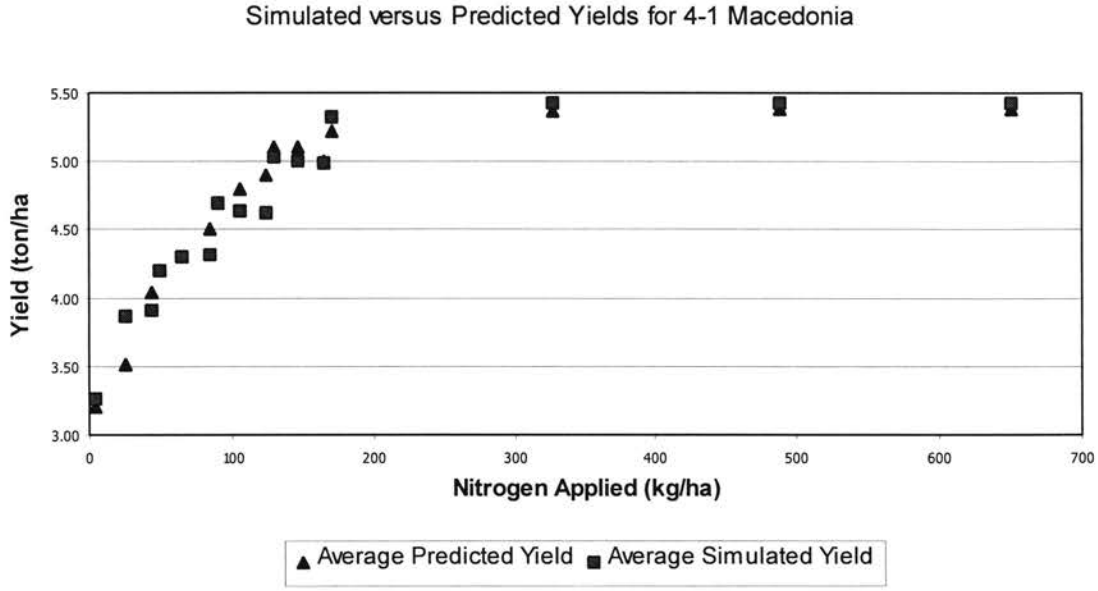
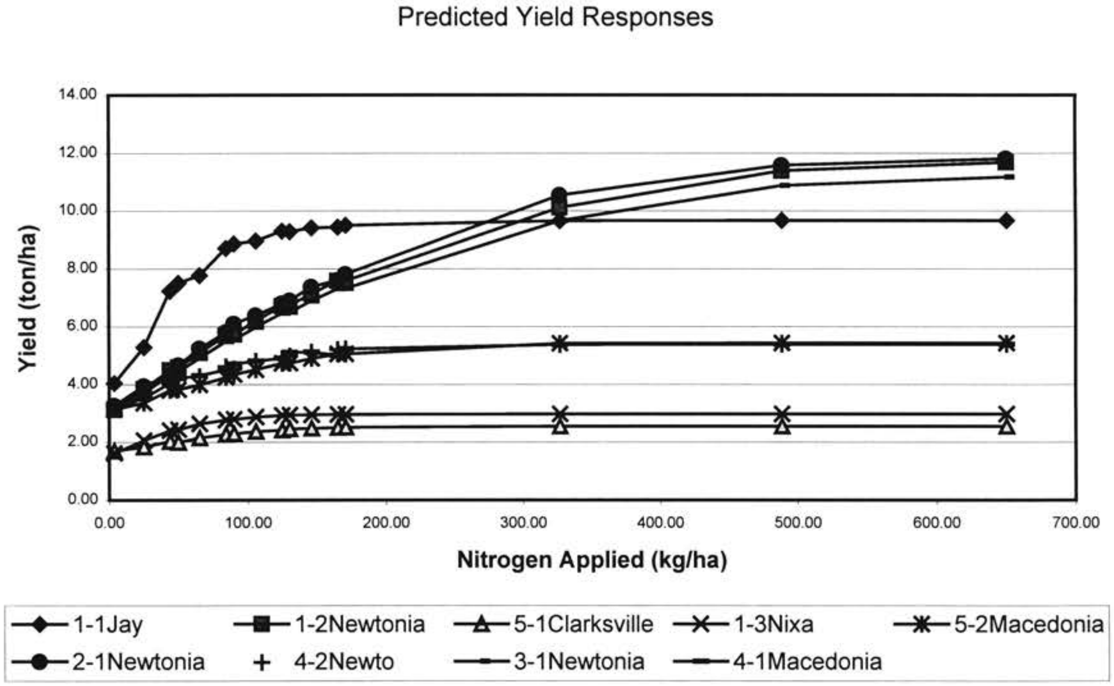


Figure 13: Estimated Yield Responses by HRUs



4.2.2. Carryover Functions

Carryover functions describe the relationship of a specific soil nutrient between one period and the next. The amount of soil residual nitrogen or phosphorous at the end of current year is affected by the amount of nitrogen or phosphorous at the end of previous year and by the amount of nitrogen or phosphorous applied in the current year. Nitrogen or phosphorous that exceeds the plant intake will become residual and will be partially transferred to the following year. The residual nutrients of interest in this study are soil nitrate-nitrogen and labile phosphorous.

The nitrate-N and labile phosphorous appear in the economic model as transform or state variables that link nutrient applications from one year to another. The decision variables in each year for the profit-maximizing problem are poultry manure and commercial nitrogen application rates. The model specification for the carryover effect, therefore, is subject to the requirement that the carryover functions not only statistically fit the data but also enable the economic model to operate appropriately. The first consideration for model specification is that the model should include at least one decision variable; otherwise an optimal solution could not be obtained. For example, a univariate autoregressive model of nitrogen (i.e. nitrogen in year t is only regressed with nitrogen in year t-1) may provide a good statistical fit for the nitrogen carry-over effect. It, however, does not contain any control or decision variables such as manure or commercial nitrogen application and therefore, it is not appropriate for the economic model. The second consideration is that the objective function be a concave and the constraints must be convex or be linear so that the problem can be maximized.

The linear form was selected for all the carryover functions of nitrogen and phosphorous. The nitrogen carryover function included three variables: NTOT as the sum of residual nitrate-nitrogen (transform variable) denoted as TNO3L and the current applied nitrogen (decision variable) that is denoted as TN, and crop yield (YLD). All coefficients in the model were statistically significant, the overall goodness-of–fit of the carryover models was moderately high (R^2 varied from 0.69 to 0.88). The positive sign of NTOT and the negative sign of the interactive term TN*YIELD confirmed the demand and supply approach for crop growth used in EPIC. The amount of nitrate-N in the soil this year increases with nitrogen applied as manure or as commercial fertilizer and with previous nitrate N in soil. The demand for nitrogen by the plant reduces the future availability of nitrate-N. The maximum crop growth can be attained if there are sufficient amounts of nitrogen, water, and phosphorous. The negative sign on the interaction term, TN*YIELD implies that future soil nitrate levels are reduced as applied nitrogen and yield increase. The negative intercept indicates that soil nitrate level will decline because of denitrification or leaching.

The phosphorous carryover function is also a non-linear function with three variables: PTOT is the sum of residual labile phosphorous (PLABL, a transform variable) and the current applied manure (PAP, decision variable). The last variable is an interaction term between PAP and crop yield. All coefficients were statistically significant except the intercepts for the Macedonia soils. The adjusted coefficients of determination were above 0.90 for all equations. Notice that the coefficient of PTOT is very high (i.e. close to 1), indicating that most applied phosphorous remained in the soil over time. This is consistent with the fact that phosphorous is highly immobile in the soil. The negative sign of the intercept indicated that labile phosphorous levels would decline if manure application ceased.

4.2.3. Soluble Phosphorous Loss Functions

The regression coefficients are shown in Table 10. The linear form was selected for this type of function. The model included two variables, PTOT that was defined above and the amount of water runoff that is denoted as Qrunoff. The fit of the models was good with R squares ranging from 0.74 to 0.87. All variables are highly significant. The positive sign of PTOT and Qrunoff stated that the amount of phosphorous loss in runoff increased with the amount of phosphorous in the soil and the amount of storm water runoff. The negative sign of the intercept means that some minimum level of phosphorous must be present in the soil before any phosphorous loss in runoff occurs. The coefficients of phosphorous loss for the 5-1 Clarksville soil were the lowest, and those of Macedonia soils were the highest. This is consistent with the data presented in Figure 11.

Table 8: Nitrogen Carryover Function.

Subbasin	HRU	Soil Name	NTOT	TN*YIELD	Intercept	R^2
1	1	JAY	0.72511 (42.16)[a]	-0.04458 (-21.03)	-29.147 (-15.10)	77.1
1	2	NEWTONIA	0.67257 (35.86)	-0.03992 (-25.05)	-34.921 (-19.92)	76.3
1	3	NIXA	0.22509 (16.58)	-0.01685 (-3.673)	-2.0483 (-2.917)	76.7
2	1	NEWTONIA	0.65642 (34.56)	-0.03871 (-24.44)	-32.981 (-18.71)	76.1
3	1	NEWTONIA	0.66053 (33.46)	-0.03999 (-23.97)	-35.557 (-18.92)	74.6
4	1	MACEDONIA	0.65023 (37.44)	-0.06488 (-14.00)	-21.142 (-15.15)	78.6
4	2	NEWTONIA	0.65131 (32.67)	-0.03923 (-23.27)	-34.802 (-18.14)	74.2
5	1	CLARKSVILLE	0.23434 (17.96)	-0.00550 (-1.94)	-3.911 (-1.94)	69.3
5	2	MACEDONIA	0.59929 (42.64)	-0.03576 (-8.88)	-33.595 (-24.36)	88.6

[a] t-value in parenthesis.

NTOT: Sum of nitrate-N in previous year and applied total nitrogenin current year.

TN: Total nitrogenfrom poultry manure and commercial nitrogenapplication in current year.

Table 9: Phosphorous Carryover Functions.

Subbasin	HRU	Soil Name	PTOT	YIELD*PAP	Intercept	R^2
1	1	JAY	0.94731 (293.20)a	-0.059361 (-51.59)	-14.486 (-20.81)	99.6
1	2	NEWTONIA	0.97901 (286.00)	-0.06222 (-57.23)	-25.239 (-28.41)	99.7
1	3	NIXA	0.93030 (172.3)	-0.21636 (-46.54)	-1.0632 (-1.96)	99.9
2	1	NEWTONIA	0.98108 (309.7)	-0.06259 (-54.98)	-25.178 (-29.88)	99.7
3	1	NEWTONIA	0.96464 (299.3)	-0.05892 (-49.87)	-25.012 (-30.25)	99.7
4	1	MACEDONIA	0.90548 (171.6)	-0.11010 (-45.79)	-0.209 (-0.20)	99.8
4	2	NEWTONIA	0.96627 (287.70)	-0.05920 (-49.98)	-25.300 (-29.31)	99.7
5	1	CLARKSVILLE	0.78997 (128.2)	-0.15798 (-29.78)	-9.7160 (-6.74)	99.6
5	2	MACEDONIA	0.86367 (163.6)	-0.09146 (-42.74)	-1.2711 (-1.02)	99.6

[a] t-value in parenthesis.

PTOT: Sum of labile phosphorous in previous year and phosphorous applied in current year.

PAP: phosphorous applied in current year.

Table 10: Soluble Phosphorous Loss Functions.

Subbasin	HRU	Soil Name	PTOT	Qrunoff	Intercept	R^2
1	1	JAY	0.014927 (31.33)[a]	0.01285 (17.21)	-3.9383 (-17.17)	78.1
1	2	NEWTONIA	0.015323 (35.66)	0.011939 (20.26)	-4.1753 (-19.91)	86.4
1	3	NIXA	0.014773 (31.04)	0.010546 (21.63)	-4.4279 (-24.46)	82.3
2	1	NEWTONIA	0.01500 (39.44)	0.012271 (24.81)	-4.1651 (-22.93)	86.4
3	1	NEWTONIA	0.01688 (35.89)	0.01199 (28.83)	-4.6853 (-28.75)	87.3
4	1	MACEDONIA	0.01925 (25.96)	0.01219 (26.58)	-6.0675 (-23.58)	86.7
4	2	NEWTONIA	0.01684 (34.44)	0.01210 (30.70)	-4.6792 (-27.58)	87.4
5	1	CLARKSVILLE	0.01360 (24.08)	0.00500 (15.76)	-2.8434 (-18.08)	74.2
5	2	MACEDONIA	0.01883 (21.45)	0.01047 (19.38)	-5.5154 (-19.16)	86.6

[a] t-value in parenthesis.

PTOT: Sum of labile phosphorous in previous year and phosphorous applied in current year .

Qrunoff: The amount of runoff in current year.

4.3. Economic Results

The approach used for the economic model is a dynamic approach. Dynamic approach solves a complex problem by dividing it into several small, simpler sub-problems. There are no standard techniques for dynamic programming; rather a specific structure is created for each situation. In this study decomposition and non-linear programming are used.

The model used in this study involves both temporal and spatial dimensions. In the temporal dimension, there is a 20-year planning horizon. The net present value (NPV) - maximizing problem involves determining poultry manure and nitrogen application on each HRU subject to phosphorous changes for each year. In the spatial aspect, the model involved allocating manure and phosphorous runoff while maximizing the net present value for nine HRUs. The problem was solved separately for each individual HRU. The linkage between these HRU sub-problems was the common hypothetical tax on soluble phosphorous loss. This tax is the Lagrange multiplier of the pollution constraint and is often referred to as the shadow price of the pollution control, or, the marginal abatement cost. (i.e. incremental cost of phosphorous reduction).

The problem was solved with the Microsoft EXCEL SOLVER. Each 20- year profit maximizing HRU sub-problem was solved separately in its own worksheet. There were nine worksheets, one for each of the HRU, and one worksheet as the main page. A macro program written with VBA (Visual Basic Application for EXCEL) was used to control the inputting of economic variables such as input, output prices and phosphorous loss tax in the main page and to operate the optimization process across the nine worksheets. The main page then summarized all important results such as decisions on manure application, phosphorous loss, and net present value for each HRU (Table 11).

Table 11: Baseline Results of the Economic Model.

Prices Used Throughout							
	Unit	Amount					
Poultry Manure	$/Metric ton	0.05					
Commerical Nitrogen	$/kg	0.75					
Bermuda Grass Hay	$/Metric ton	71.2					
Charge for Phos. Loss	$/kg	0					
Discount Rate	percent	7%					
				|------Years 1-10--------|		|------Years 11-20------|	
				Ave. Poul. Man.Appl.	Ave P loss	Ave. Poul. Man.Appl.	Ave P loss
Watershed Results	Area (Ha)	Npv/ha	Tot NPV	mt/ha	kg/ha	mt/ha	kg/ha
1-1 Jay	660.48	6876.02141	4541474.62	1.6	0.49	1.6	0.44
1-2 Newtonia	558.37	5974.88292	3336195.37	1.6	0.37	1.6	0.60
1-3 Nixa	726.02	2147.27466	1558964.35	1.6	0.35	1.6	0.26
2-1 Newtonia	1385.45	6400.52638	8867609.27	1.6	0.53	1.6	0.59
3-1 Newtonia	3450.66	5517.86484	19040275.5	1.6	0.37	1.6	0.45
4-1 Macedonia	286.35	3459.70963	990687.854	1.6	0.28	1.6	0.21
4-2 Newtonia	393.82	5522.42934	2174843.12	1.6	0.37	1.6	0.46
5-1 Clark	987.08	1633.35784	1612254.86	1.6	0.13	1.6	0.07
5-2 Macedonia	726.9	3312.50487	2407859.79	1.6	0.22	1.6	0.14
Forest	6179.92						
Total for Watershed	15355.05		44530164.7	14680.208	3319.22	14680.208	3605.52
Area Weighted Avg.	9175.13	4853.35518	9641634.3	1.6	0.36	1.6	0.39
Overall P Loss per ha					0.38		

The values for the two state variables (i.e. nitrate-nitrogen and labile P) in the beginning period need to be specified prior to optimization. The values for soil test phosphorous that were obtained from the survey of the watershed in the year 2000 were used as estimates for the starting values of labile phosphorous. Each sub-basin had different starting values of labile phosphorous (Table 12). Due to limited data, all HRUs were assumed to have the same starting value of nitrate-nitrogen of 12 lbs/a or 13.44 kgs/ha. This was the median nitrate-nitrogen value of all agricultural soil samples in Oklahoma from 1994-1999 (Zhang).

Table 12: Estimates of the Labile Phosphorous and Nitrate-Nitrogen for Each Sub-basin

Sub-basin	Soil Test Phosphorous (kg/ha)	Estimated Nitrate-N (kg/ha)
1	347.2	13.4
2	352.8	13.4
3	229.6	13.4
4	226.24	13.4
5	226.24	13.4

The net present value represents the total present values of all discounted net benefits in a 20-year period. The selected discount rate was 7%. For private profit maximization, a high discount rate was recommended because people naturally put more weight on values in the near future.

4.3.1. Baseline Solution.

The baseline result was obtained, given a zero charge on phosphorous loss and a constraint that no more than 1.6 tons of poultry manure could be applied to each hectare of pastureland. The average quantity of manure produced per hectare of pasture land in the Beaty Creek basin was 1.6 metric tons. At the solution, all HRUs used manure at the maximum level of 1.6 tons/ha and generated an average overall phosphorous loss of 380g/ha for the whole watershed. The overall phosphorous loss obtained from this model was higher than that of observed values of about 304g/ha (see Chapter III, page 44). The NPV for the average hectare over a period of 20 years was $4853. Fixed and variable harvesting expenses were not deducted.

The problem solving procedure was repeated with an incremental increase of $0.10/ g in the value of phosphorous loss charge. A constant interval of $0.10/ g phosphorous loss was made unless the result of phosphorous loss showed a large increase, in which case the interval was made smaller to trace out the change in phosphorous loss. The procedure stopped at the value of $1.00 / g phosphorous loss because the amount of phosphorous loss reduction no longer increased beyond this point (Table 13).

In general, as the charge for phosphorous loss increased, the annual phosphorous loss per hectare for the whole watershed decreased because less manure was applied. However, the phosphorous reduction was not proportional with the charge. The summary of selected solutions is presented in Table 13 and Figure 14. As the costs increased from zero to $0.3/g, there was only a slight reduction in manure. And the average phosphorous loss per hectare for the whole watershed dropped only 2.3 percent (Table 13). From $0.3 to $0.6/ g, the reduction of phosphorous loss for all HRUs was much greater. The average phosphorous loss per hectare for the whole watershed dropped 47 percent as the charge

Figure 14: Overall Marginal Abatement Cost Curve for Beaty Watershed.

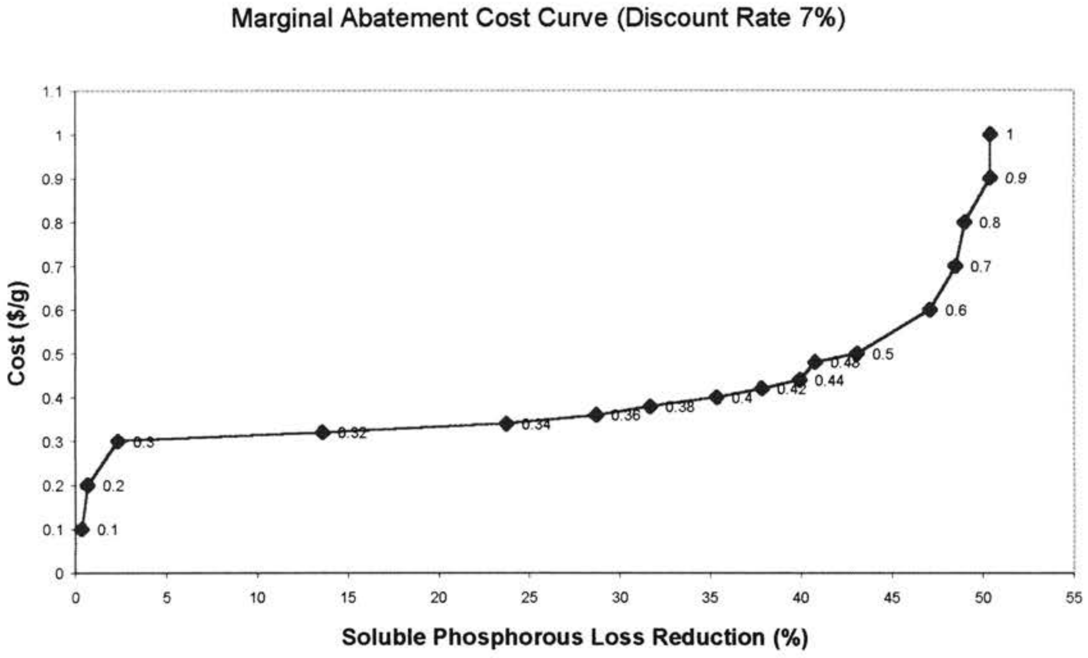


Table 13: Overall Marginal Costs for Beaty Watershed.

P Charge ($/g)	Avg. P Loss (g/ha/yr)	P Loss Reduction (%)	Abatement Cost ($/ha/year)	Avr. Manure (ton/ha/yr)	Soil Test P (lb/a)
0.00	377.36			1.60	
0.10	376.13	0.33	0.12	1.60	297.01
0.20	374.90	0.65	0.37	1.60	295.30
0.30	368.59	2.33	2.26	1.56	294.52
0.40	243.97	35.35	52.11	0.72	245.33
0.50	214.82	43.07	66.68	0.60	243.08
0.60	199.77	47.06	75.71	0.51	243.08
0.70	194.39	48.49	79.49	0.44	243.08
0.80	192.50	48.99	80.99	0.39	243.08
0.90	187.25	50.38	85.72	0.36	243.08
1.00	187.25	50.38	85.72	0.31	243.08

increased from zero to \$0.6/ g (or \$ 600/kg). After this point, an increase in the charge for phosphorous runoff resulted in only a small additional reduction in phosphorous runoff.

The change in the slope of the marginal abatement cost curve as depicted in Figure 14 is determined by the relative changes in the slopes of the production function and the phosphorous loss function as the amount of applied manure declined due to the charge.

Let Y=f (x) represent the production function of applied manure (x). Let G=g (x) denote the phosphorous loss function. Let P, r, and t represent the price of hay, hauling cost of manure and phosphorous loss charge respectively.

Assume $x_0 > x_1$.

Let Π(x; p,r,t) be the profit function, so

$$\Pi(x_0) = Pf(x_0) - rx_0 - tg(x_0) \tag{1}$$

$$\Pi(x_1) = Pf(x_1) - rx_1 - tg(x_1) \tag{2}$$

As x declines from x_0 to x_1 due to the charge, the loss in profit is:

$$\Pi(x_0) - \Pi(x_1) = P[f(x_0) - f(x_1)] - r[x_0 - x_1] - t[g(x_0) - g(x_1)] \tag{3}$$

or $\Delta\Pi = P\Delta f(x) - r\Delta x - t\Delta g(x)$ (4)

as Δx becomes small, the marginal change in profit due to a marginal reduction in applied manure is the marginal abatement cost λ, where λ can be stated:

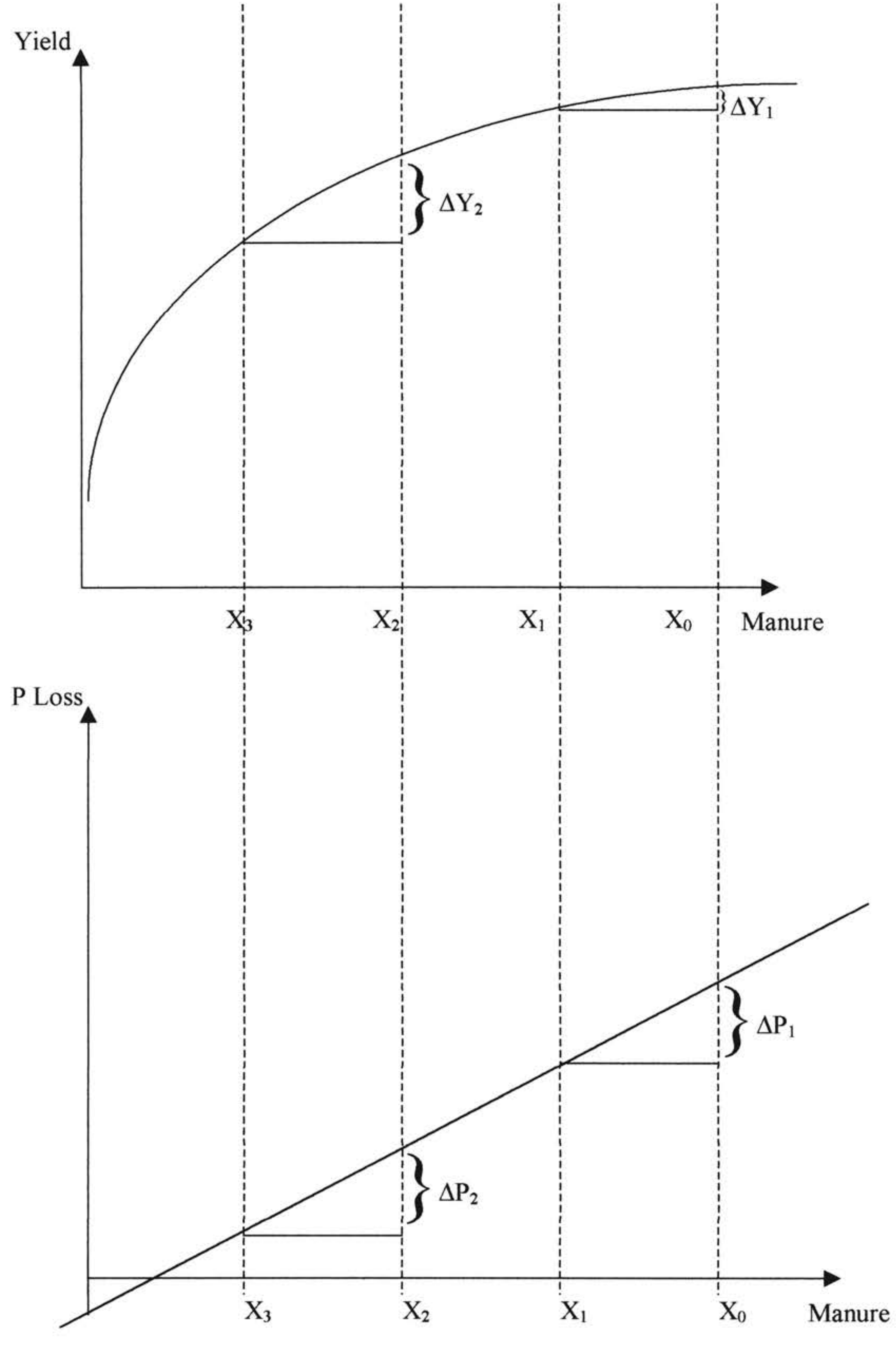
$$\lambda = \frac{d\Pi}{dx} = P\frac{df(x)}{d(x)} - r - t\frac{dg(x)}{d(x)} \tag{5}$$

Equation (5) indicates that the magnitude of marginal abatement cost depends upon the slopes of the production function f (x) and the phosphorous loss function g (x), given constant prices. The larger the slope of the production function and the smaller the slope of the phosphorous loss function, the higher is the marginal abatement cost.

Suppose that as the charge on phosphorus runoff increases, farmers respond by reducing manure use to maximize profit. This causes a reduction in output. At the low charge, the input level is at X_0 (Figure 15). The flat slope in the production function at the level of X_0 indicates a small reduction in production ΔY_1. Therefore the change in profit $\Delta\Pi_1$ or the marginal abatement cost is small. As a result, the slope of the MAC curve is relatively flat at the low level of phosphorous charge. However, at the higher charge, the input level is at X_2. A further reduction in input from x_2 to x_3 causes the marginal reduction in production ΔY_2 that is larger than ΔY_1. Therefore the marginal reduction in profit or MAC becomes larger at this level of X. The slope of the MAC curve becomes steeper at a higher level of phosphorous charge.

The amount of reduction in phosphorous runoff to a given charge varied from HRU to HRU indicated the existence of different marginal abatement costs. Figure 16 showed that HRUs had different amounts of phosphorous loss at the baseline scenario. Generally, HRUs in the sub-basin that already had high labile phosphorous in soil also generated a high annual phosphorous loss when there was no environmental charge imposed. For example, in Figure 16, the 2-1 Newtonia had the highest initial phosphorous loss per hectare because the sub-basin 2 had the highest initial soil labile phosphorous. The next highest HRUs were Newtonia and Jay soils. This can be predicted by examining the coefficients in the phosphorous loss function in Table 10: 1-2 Newtonia has larger coefficients than 1-1 Jay. At the other end of the horizontal axis was 5-1 Clarksville. This HRU generated the least phosphorous loss in the watershed when no charge was imposed. It was understandable because this HRU was located in one of the lowest soil test phosphorous sub-basins. Furthermore, its phosphorous loss function had the lowest coefficients in comparison with all other HRUs. In the same manner, the relative positions of other HRUs on the axis were determined by the beginning value of labile

Figure 15: The Changes in The Slopes of Production Function and Phosphorous Loss Function at Different Levels of Applied Manure.



phosphorous in the soil, the phosphorous loss function, the phosphorous carryover function and water runoff from each basin.

The fact that the individual HRUs have different MAC curves implied the potential of reducing phosphorous loss for the watershed at a lower cost than could be obtained by uniform reductions in manure applications. Several of the curves in Figure 16 exhibit a range where they are fairly flat. Within this range it is possible to secure considerable reduction in phosphorous runoff at a cost between \$.30-\$.40 per gram per hectare (\$300-\$400 per kg / ha. The 1-1 Jay and 5-1 Clark, the highest and the lowest polluting soils in the baseline scenario, showed to poses the steepest slope, or alternately, high abatement cost (Figure 16). The reason is the 1-1Jay had the highest yield; and its value marginal product (i.e. increment value of product produced from using an additional unit of manure) is high enough to offset the phosphorous loss charge. The 5-1 Clark had the lowest yield yet produced the least phosphorous loss.

An HRU with a low marginal abatement cost (MAC) for an agricultural area implies that this area is in need of more supervision or incentives to reduce pollution. The HRU with low MAC means a potential of reducing pollution at a lesser cost than other HRU's. The problem is how to encourage more pollution abatement in HRUs with low MACs in the absence of pollution charges or taxes. This could be accomplished with a system of tradable permits or targeted abatement subsidies.

Regulating land application of manure is expensive. If the cost is too high farmers may be unable to comply with the regulation, use of the land may change. The results presented in Figure 14 show the general marginal abatement cost curve for the whole Beaty creek basin. The MAC increases sharply beyond the price of 0.6 \$/ g phosphorous

Figure 16: Marginal Abatement Cost Curves of Different Hydrologic Response Units (Discount Rate of 7%).

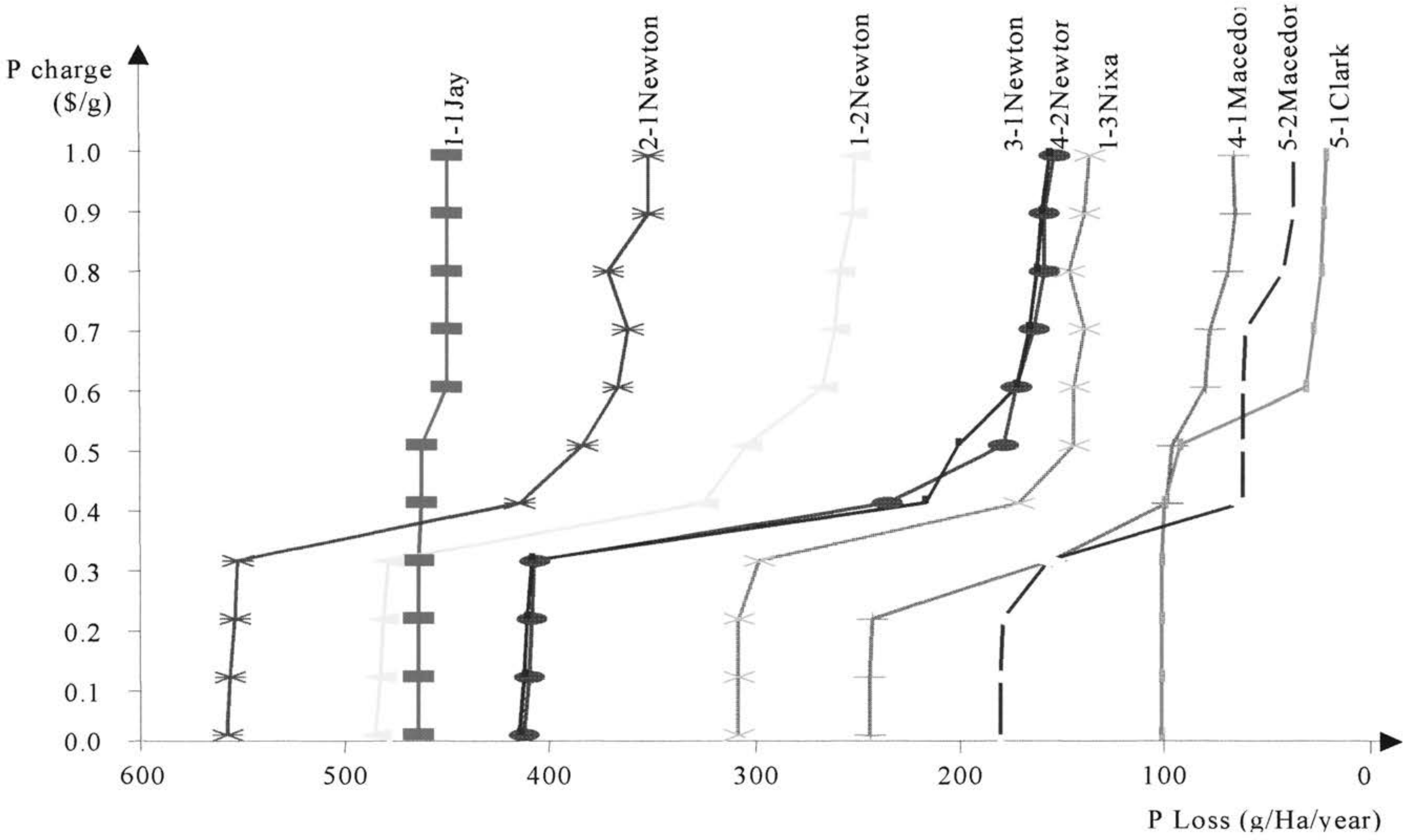


Table 14: The Marginal Abatement Costs and Phosphorous Discharges for Different Hydrologic Response Units.

P Loss Charge ($/g)	1-1Jay (g/ha/yr)	1-2Newton (g/ha/yr)	1-3Nixa (g/ha/yr)	2-1Newton (g/ha/yr)	3-1Newton (g/ha/yr)	4-1Macedon (g/ha/yr)	4-2Newton (g/ha/yr)	5-1Clark (g/ha/yr)	5-2Macedon (g/ha/yr)
0.0	464	485	308	558	413	244	415	102	180
0.1	464	483	308	556	411	243	413	101	180
0.2	464	481	308	555	409	243	411	101	179
0.3	464	479	298	553	407	156	410	101	156
0.4	464	325	171	415	236	98	217	100	62
0.5	464	305	144	385	178	96	201	92	62
0.6	451	267	144	368	173	80	173	31	61
0.7	451	261	140	362	164	78	166	28	61
0.8	451	259	146	372	159	69	163	23	42
0.9	451	252	140	352	159	66	161	22	37
1.0	450	251	137	352	154	66	156	21	36

loss. The results show that a charge of $ 0.6 / g / hectare would reduce phosphorous runoff by 47 percent. A further reduction in phosphorous runoff would become more costly for farmers.

4.3.2. Sensitivity Analysis.

Two additional scenarios are compared to the base solution to test the sensitivity of the results. In scenario (a), the discount rate is changed from 7 percent to 10 percent, while other prices are unchanged. In scenario (b), the price of Bermuda hay was reduced from $71.2/ metric ton to $60.0 / metric ton while the hauling cost of manure increased from $0.05/ metric ton/ mile to $0.08/ metric ton /mile. The discount rate was unchanged at 7 percent.

In general, a high discount rate favors investments that have high returns in the near future. A low discount rate favors investments that have high returns in more distant future. Therefore, in scenario (a), at a higher discount rate, farmers tend to use more manure in first few years, generating more phosphorous runoff than the baseline scenario. As a result, there is less phosphorous reduction at each level of phosphorous charge (Figure 16 and Table 15) for the scenario (a) than the baseline.

In contrast with scenario (a), farmers in scenario (b) are more willing to give up using manure because their profits shrink as the price of hay decreased and the hauling cost of manure increased. The aggregate phosphorous reduction in scenario (b) is more than that of the baseline scenario and of scenario (a) at each cost level.

Figure 17 includes the MAC curves of the three scenarios. The MAC's increase rapidly after the phosphorous reduction reaches 50 percent. This implies that setting a goal of phosphorous reduction that is higher than 50 percent would be very costly.

Figure 17: Comparision of Maginal Abatement Costs of Different Scenarios

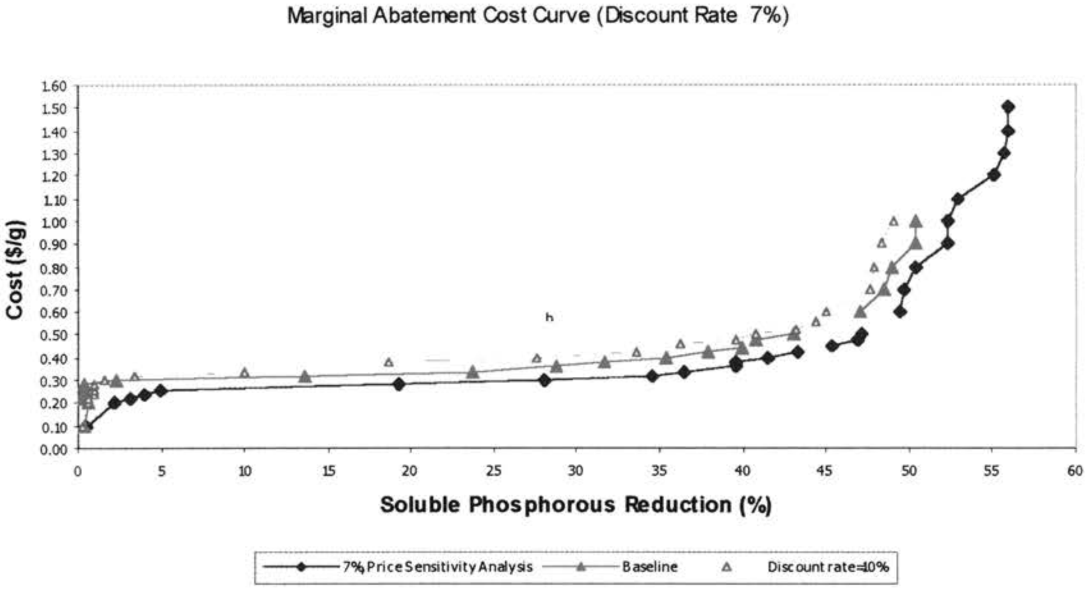


Table 15 : Comparision of Maginal Abatement Costs of Different Scenarios.

Scenario	**Scenario B** (Price Changes, Discount Rate 7%)	**Baseline** (Discount Rate 7%)	**Scenario A** (Discount Rate 10%)
P Charge ($/g)	P Loss Reduction (%)	P Loss Reduction (%)	P Loss Reduction (%)
0.00			
0.10	0.43	0.33	0.28
0.20	2.20	0.65	0.55
0.30	27.97	2.33	1.58
0.40	41.46	35.35	27.52
0.50	47.13	43.07	40.73
0.60	49.47	47.06	42.32
0.70	49.69	48.49	48.27
0.80	50.35	48.99	48.39
0.90	52.26	50.38	48.86
1.00	52.60	50.38	49.00

Table 16: Marginal Abatement Costs for Beaty Creek Watershed in Scenario (a) (Discounted Rate of 10%, Hay Price of $ 71.20 / ton, Poultry lLitter Hauling Cost of $0.05 / ton / Mile)

P Charge ($/g)	Avg P Loss (g/ha/year)	P Reduction (%)	Abatement Cost ($/ha/year)	Avr. Manure (ton/ha/yr)	Soil Test P (kg/ha)
0.00	377.78			1.60	333.08
0.10	376.72	0.28	0.11	1.60	332.22
0.20	375.71	0.55	0.31	1.60	331.40
0.30	371.80	1.58	1.48	1.58	330.62
0.40	273.80	27.52	40.68	1.09	294.25
0.50	223.92	40.73	65.62	0.60	272.34
0.60	217.91	42.32	69.22	0.51	272.25
0.70	195.41	48.27	84.97	0.45	272.25
0.80	194.98	48.39	85.32	0.41	272.25
0.90	193.20	48.86	86.92	0.35	272.25
1.00	192.66	49.00	87.46	0.32	272.25

Table 17: Marginal Abatement Costs for Beaty Creek Watershed in Scenario (b) (Discounted Rate of 7%, Hay Price of $60 / ton, Poultry Litter Hauling Cost of $0.08 / ton / Mile)

P Charge ($/g)	Avg. P Loss (g/ha/yr)	P Loss Reduction (%)	Abatement Cost ($/ha/yr)	Avr. Manure (ton/ha/yr)	Soil Test P (kg/ha)
0.00	384			1.60	339.46
0.10	382	0.43	0.17	1.60	338.14
0.20	375	2.20	1.53	1.59	336.90
0.30	277	27.97	31.21	1.59	294.75
0.40	225	41.46	51.92	0.59	272.25
0.50	203	47.13	62.80	0.51	272.25
0.60	194	49.47	68.21	0.42	272.25
0.70	193	49.69	68.80	0.35	272.25
0.80	191	50.35	70.82	0.34	272.25
0.90	183	52.26	77.42	0.30	272.25
1.00	182	52.60	78.70	0.24	272.25
1.10	181	52.93	80.12	0.24	272.25
1.20	173	55.07	89.97	0.19	272.25
1.30	170	55.72	93.23	0.19	272.25
1.40	169	55.89	94.11	0.17	272.25
1.50	169	55.89	94.11	0.17	272.25

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1. Summary of Results

The study has successfully achieved the five objectives stated in chapter I:

1. The pastureland in the Beaty creek watershed was divided by SWAT model into five sub-basins with nine hydrologic response units (HRU). Pasture HRUs differed with each other by soil types and by topographical characteristics. HRUs in the same sub-basin have the same topographical properties. Sub-basins 1 and 2 that are located in Arkansas are flat highland areas. Sub-basins 2, 3 and 4 that are located in Oklahoma have lower elevation and steeper gradients.
2. Five main soil types were identified: Newtonia, Macedonia, Jay, Nixa and Clarksville. EPIC simulated yield response data showed that the HRUs of Jay and Newtonia soil types had the highest Bermudagrass yields. These were followed by the HRUs with Macedonia soils. The HRUs with the Nixa and Clarksville soils had the lowest yields. A Mitscherlitch production function was used to quantify the yield response to nitrogen and phosphorous.
3. The linear models that followed the supply and demand approach of nutrients for crop growth fitted well the EPIC simulated data on soil nitrogen and phosphorous.

4. The estimated phosphorous loss functions were linear. The independent variables used to explain phosphorous were soil phosphorous residuals, applied manure and water runoff. These models predicted well the simulated data on phosphorous runoff.
5. Marginal abatement costs were successfully derived from solutions of the mathematical programming model. The delineation from the SWAT model showed a great variation in soil types, and slopes in the Beaty creek watershed. This in turn resulted in a remarkable variation in marginal abatement costs (MAC) of HRUs within one sub-basin and among sub-basins.

In brief, the model helps identify the areas where non-point source pollution can be reduced at least cost. These areas are not easily identified by visual examination of the data. These areas may or may not correspond to areas designated as "hot spots" or major source of pollution. This result allows the regulatory agency to focus its effort to these areas and thus, be able to reduce its administrative and enforcement costs.

The total MAC for the entire watershed, as the result of the study, shows the relationship between the level of phosphorous loading and the cost to obtain that abatement level. A desirable reduction of phosphorous loading cannot be read from this curve without knowing the value of marginal damages caused by a specific level of phosphorous runoff. However examination of the marginal abatement cost curve indicates that costs will rise very rapidly if phosphorous runoff is reduced by more than 50 percent.

5.2. CONCLUSIONS

The feasibility of developing a model to determine least -cost phosphorous abatement as an alternative to uniform restrictions in a watershed has been shown. The state-of- the- art in hydrology and water quality modeling gives the promise to provide adequate information on these emission rates for an improved method of managing manure.

Information about emission rate from specific fields is necessary but not sufficient for policy makers. Two fields having identical emission rates may differ greatly in their abatement costs, depending upon how sensitive the crop yield in each field responses to manure. The information on the abatement cost can assist policy makers in meeting emission targets at least cost.

The integration of SWAT with EPIC allows a better estimation on the impacts of manure on crop growth and phosphorous runoff by incorporation the topographical characteristics identified by SWAT into EPIC model. This resulting information when combined with economic model will result in the estimates for the marginal abatement cost of reducing phosphorous loss from agricultural land. In addition, the advantage of EPIC as a crop growth, small-scale oriented model allows the workability of providing a tool for manure managing on individual field.

5.3. Limitations and Further Study

This study is a first attempt to address the abatement cost of non- point source phosphorous pollution from agriculture. Previous studies have focused on either nitrate loss or sediment in soil erosion. Unlike SEDEC model that integrated three components of soil erosion, sediment transport and economic analysis in one model, this method is an attempt to use outputs from SWAT as inputs for EPIC, and outputs from EPIC are in turn used as inputs to economic model by means of regression functions. The success of this study enables a further effort in integration of the three models into one for the ease of predicting impacts of alternative polices.

In the absence of information about actual field management practices, the result of the economic model in this study is based on a uniform constraint of maximum manure application of 1.6 ton per hectare so as to make the baseline result close to the observed data. The reliability of the results may be greatly improved with two conditions. The inclusion of information on farm yield, and agricultural management practices in the study areas as inputs for EPIC model will enhance the accuracy of the prediction from the model. Second, by increasing the maximum number of HRUs analyzed by SWAT, which are to be used in the economic analysis. All the above conditions are possible as more time is allowed to collect necessary data and to validate the models. The fate of phosphorous during the routing phase was not considered in this study.

It should be noted that both EPIC and SWAT assume that all manure applied to the soil surface becomes incorporated into the top 0.01m of the soil profile rather than initially residing on the soil surface. The amount of manure lost in storm runoff following manure spreading is therefore underestimated. However this discrepancy is reduced where runoff is recorded on an annual basis. The results from these two models therefore can only be used for a comparison of relative changes.

References

Ahnstedt, B.D. G.L Butters, J.G. Davis and K.V. Iverson. "Nitrate Leaching under Variable Rates of Manure Application." Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Iowa State University, Des Moines, Iowa.1998.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. "Large Area Hydrologic Modeling and Assessment. Part 1: Model Development." *Journal of the American Water Resources Association 34 (Feb. 1997): 73-89.*

Bates, D. M., and D. G. Watts. Nonlinear Regression Analysis and Its Applications. John Wiley & Sons Inc. United States of America. 1988.

Braden B.J., G.V. Johnson, A. Bouzaher, and D. Miltz. "Optimal Spatial Management of Agricultural Pollution." *American Journal of Agricultural Economics. (May 1989): 405-413.*

Cabelguenne M., C.A. Jones, A.Chalamet, J.L. Charpenteau, and J.R.Marty. "Simulation of Soybean Nitrogen for a Silty Clay Soil in Southern France." *Field Crops Res.26(1991):19-34.*

Cabelguenne M., C.A. Jones, J.R. Marty, P.T. Dyke, and J.R. Williams. "Calibration and Validation of EPIC for Crop Rotations in Southern France." *Agri. Systems 33(1990): 153-171.*

Christensen, Lee A. "How Economic and Environmental Forces are Changing Livestock and Poultry Production in the United States." Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Iowa State University, Des Moines, Iowa. 1998.

Davidian, M., and D. M. Giltinan. Nonlinear Models for Repeated Measurement Data. Chapman & Hall. Great Britain. 1995.

Davis B.E. GIS: A Visual Approach. OnWord Press. Santa Fe, USA. 1996

Edwards, D. R. and T. C. Daniel. "Effects of Poultry Litter Application Rate and Rainfall Intensity on Quality of Runoff from Fescuegrass Plots." *J. Environ. Qual.22 (1993)361-365.*

Edwards, D. R. and T. C. Daniel. "Environmental Impacts of On-farm Poultry Waste Disposal – A Review." *Bioresour. Technol. 41(1992): 9-33.*

El-Ahraf, A. and W.V. Willis. Management of Animal Waste: Environmental Health Problems and Technological Solutions. Praeger Publisher. 1996.

Fare, R., S. Grosskorpf, C.A. Knox Lovell and S. Yaisawarng. "Derivation Of Shadow Prices For Undesirable Outputs: A Distance Function Approach." *The Review of Economics and Statistics 75,374-380.1992.*

Gade, David R. An Investigation of The Sources and Transport of Nonpoint Source Nutrients in The Illinois River Basin in Oklahama and Arkansas. Unpublished Dissertation. Oklahoma State University. 1998.

Giddens, Joel, A.M. Rao and Herbert W. Fordham. Microbial Changes and Possible Ground Water Pollution from Poultry. Department of Agronomy, University of Georgia, Athens, Georgia. 1973.

Gollop F. M. and M. J. Roberts. "Cost-Minimizing Regulation of Sulfur Emissions: Regional Gains in Electric Power." *The Review of Economics and Statistics 67,81-90. 1985.*

Govindasamy R., M.J. Cochran, and E. Buchberger. "Economic Implications of Phosphorous Loading Policies for Pasture land Applications of Poultry Litter." *Water Resources Bullentin 30(Oct. 1994): 901-909.*

Govindasamy R., M.J. Cochran. "Implications of Alternative Environmental Policies on Phosphorous Loading From Poultry Litter." *Agricultural Economics 13(1995): 137-148.*

Govindasamy R., M.J. Cochran. "Implications of Policy Regulations on Land Applications of Poultry Litter." *Agricultural and Resource Economics Review (1998): 85-93.*

Haan C.T. and D.E. Storm. Nonpoint Source Pollution Modelling (with GIS*).* In*:* Vijay P. Singh and M. Fiorentino (Eds.), Geographical Information Systems in Hydrology. Kluwer Academic Publishers. Netherlands. 1996.

Hadley, D. Estimation of Shadow Prices for Undesirable Outputs: An application to UK Dairy Farms. Paper presented at the American Agricultural Economics Association Annual Meetings, Salt Lake City, Utah. August 1998.

Hartman, R.S., D. Wheeler, and M. Singh. "The Cost of Air Pollution Abatement." *Applied Economics 29(1997): 759-774.*

Hasimoglu, Sumer. "Environmental Impact of Livestock Production Systems on Air Quality, Odor Nuisance, Global Warming and Health Concerns." Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Iowa State University, Des Moines, Iowa. 1998

Hatzell, Hida H. Effects of Waste-Disposal Practices on Ground-Water Quality at Five Poultry (Broiler) Farms in North-Central Florida, 1992-1993. U.S. Dept. of the Interior, U.S. Geological Survey; Denver, Colorado. 1995.

Hunter, William J. "Nitrate Levels and Denitrification Activity Beneath a Cattle Holding Pen." Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Iowa State University, Des Moines, Iowa. 1998.

INCOG (Indian Nations Council of Government*)*. Watershed Restoration Action Strategy (WRAS) for the Eucha/Spavinaw Watershed. Draft. May 13, 1999.

Izaurralde R.C., P.W. Gassman, A. Bouzaher, J.Tajek, P.G. Laksminarayan, J.Dumanski and J.R. Kiniry. Application of EPIC Within an Integrated Modelling System to Evaluate Soil Erosion in The Canadian Prairies. In: Rosen et al. (Eds), Modern Agriculture and the Environment. Kluwer Academic Publishers. Great Britain. 1997.

Johnson G.V., N.T. Basta. H.A. Zhang, J.A. Hattey, W.R. Raun, and J.H. Stiegler. Sience-Based Animal Waste Phosphorous Management For Oklahoma. Oklahoma Cooperative Extension Service Vol.10, No.1.1998.

Johnson, G., and R. Woods. Available Nitrogen: Bermudagrass and Other Forages. OSU Extension Fact F-2235.

Kingery W. L., C.W. Wood, D. P. Delaney, J. C. Williams, and G. L. Mullins. "Impact of Long-Term Land Application of Broiler Litter on Environmentally Related Soil Properties*." J. Environ. Qual. 23(1994):139-147.*

Knapp, L. "Human Health , Hazards from Working in Confinement Livestock Facilities." Proceedings of Livestock Waste Management Conference. Cooperative Extension Service, University of Illinois, Urbana-Champaign. 1985.

Kwon, O. S., and W. Yun. "Estimation of the Marginal Abatement Cost of Airbone Pollutants in Korea's Power Generation Sector." *Energy Economics 21(1999): 547-560.*

Lal R., and B.A. Steward. Soil Processes and Water Quality. Lewis Publishers. Washington D.C. 1994.

Lassek, P. J. Oklahoma isn't chicken .5/18/98. World Staff Writer. 1998.

Lassek, P. J., Cost of Treating Drinking Water More Than Double This Year.4/25/99. World Staff Writer. 1999.

Letson D., and N. Gollehon. " Spatial Economicss of Targeting Manure Policy. " *Journal of the American Water Resources Association. 34(1998):185-193.*

Loehr, R.C. Pollution Control for Agriculture. 2nd edition. Academic Press, Inc. Orlando, Florida. 1984.

Mc Cann and K. William Easter. Estimating Transaction Costs of Alternative Policies to Reduce Phospgorous Pollution in the Minnesota River. Staff paper P98-7. Department of Applied Economics. University of Minnesota. 1998.

Moore, P.A.. State of the Art in Ammonia and Phosphorous Issues. Proceedings 1996 National Poultry Waste Management Symposium. Auburn University printing Service. 1996.

Norman E.M., and J.D. Keenan. "Market Incentives to Reduce Nonpoint Source Agricultural Nutrient Pollution: A Theoretical and Implementational Discussion." *Environmental Systems 24(2) 151-167.* 1995.

Oklahoma Agricultural Statistics. Oklahoma Department of Agriculture. Oklahoma. U.S.A. 1999.

Panayotou, T. Basic Concepts and Common Valuation Errors in Cost-Benefit Analysis. Paper presented at EEPSEA (Economy and Environment Program For Southeast Asia) Biannual Meeting in March 1997

Paudel P. K, and C.S. McIntosh. Economics of Poultry Liter Utilization and Optimal Environmental Policy for Phosphorus Disposal in Georgia. Selected paper at the annual meeting of Southern Agricultural Economics Association Meeting. Lexington, KY. 2000.

Pearce D.W., and R. K. Turner. Economics of Natural Resources Environment. 2rd Edition. The Johns Hopkins University Press. Baltimore, Maryland. 1991.

Pittman R. W. "Issue in Pollution Control: Interplant Cost Differences and Economies of Scale." *Land Economics 57(1981):1-13.*

Ratkowsky, D.A. Nonlinear Regression Modelling: A Unified Practical Approach. Marcel Dekker, Inc. Newyork. 1983.

Ritter, W. F. and A. E. M. Chirnside. Ground Water Quality in Selected Areas of Kent and Sussex Counties, Delaware. Delaware Agric. Exp. Station Project Completion Report. 1982.

Robinson, D. L., A. B. Curry, III, and H. D. Gryder. "Poultry Litter Influences on Fertility Levels in Pastures of North Louisiana." *Louisiana Agriculture37(1994):12-13.*

Robinson, J. S. and A. N. Sharpley. "Water Quality: Release of Nitrogen and Phosphorus from Poultry Litter." *J. Environ. Qual. 24(1995):62-67.*

Rolling, N. Extension Science: Information System In Agricultural Development. Cambridge University Press, Cambridge, UK. 1998.

Schindler, D. W. " Evolution of Phosphorus Limitation in Lakes*". Science (Washington DC) 195(1997):260-262. 1997.*

Segarra, E. Optimizing Nitrogen Use in Cotton production. In: 1989 Summer Computer Simulation Conference. Society For Computer Simulation. San Diego, California, U.S.A. 1989.

Sharpley A.N. and A.D. Halvorson. The Management of Soil Phosphorous Availability and Its Impact on Surface Water Quality. In R.Lal and B.A. Steward (Eds), Soil Processes and Water Quality. Lewis Publishers. Washington, D.C. USA. 1994.

Sharpley, Andrew N. "Rainfall Frequency and Nitrogen and Phosphorus Runoff from Soil Amended with Poultry Litter." *J. Environ. Qual. 26(1997):1127-1132.*

Shreve, B.R., P.A. Moore, Jr. T. C. Daniel, D. R. Edwards, and D.M. Miller. "Reduction of Phosphorus in Runoff from Field-Applied Poultry Litter Using Chemical Amendments." *J. Environ. Qual. 24(1995):106-111.*

Singh V.P., and M. Fiorentino. Geographical Information Systems in Hydrology. . Kluwer Academic Publishers. Netherlands.1996.

Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz. Large Area Hydrologic Modeling and Assessment. Part 2: Model Application. *Journal of the American Water Resources Association 34 (Feb. 1997): 91-101*

Storm D. E., David Gade, Hailin Zhang, Michael D. Smoden, Jason Hollenba, C. Tom Haan, and Mark S. Gregory. Modeling Phosphorus Loading for The Lake Eucha Basin. OSU. Stillwater, Oklahoma. U.S.A. 2000.

Storm E.D., D. Gade, W. R. Marshall, and M.S. Gregory. Estimating NPS Phosphorous and Sediment Loading to The Upper Little Deep Fork watershed. Final report. Oklahoma State University. 1999.

Storm, D.E., D. Gade, Ronald Tejral, M. D. Smolen, P. Kenkel, and M.S. Gregory. Estimating Watershed Level Nonpoint Source Loading For The State of Oklahoma. Final Report. Oklahoma State University. 2000.

Stroh, R.C., J.E. Dixon, C.F. Peterson, E.A.Sauter, J.F. Parkinson and E.E. Steele. Effect of Poultry House Environment on Airbone Particulates. Paper No.PNW-77 presented at the 32nd Annual Meeting, Pacific Northwest Region, American Society of Agricultural Engineers. Pendleton, OR. 1977.

Taghavi A. S. R. E. Howitt, and M.A. Marino. "Optimal Control of Ground-Water Quality Management: Nonlinear Programming Approach*." Journal of Water Resources Planning and Management. 120(*1994*): 962-981.*

Taliaferro C.M., G.L. Williams, J. Enis, S.W. Coleman, and F.T. McCollum. Performance of Forage Bermuda Grass Varieties in Oklahoma Tests, 1992-1994. Production Technology Crops. Department of Agronomy. Division of Agricultural Sciences and Natural Resources. Oklahoma State University. February 1995.

Tietenberg, T. Environmental and Natural Resource Economics. Fifth Edition. Addson-Wesley Longman, Inc. U.S.A. 2000.

TMUA (Tulsa Metropolitan Utility Authority). WWW.tulsawater.com/

Vonesh F.E., and V.M. Chinchilli. Linear and Nonlinear Models for The Analysis of Repeated Measurements. Marcel Dekker, Inc. Newyork. 1997.

Wagner K., S. Woodruff. Phase I Clean Lakes Project: Diagnostic and Feasibility Study of Lake Eucha. Final Report. WWW.tulsawater.com/.

Watson, J. R. "Reducing Feedlot Nitrates in Your Ground Water". *Crops and Soils Magazine (December 1971): 17-18.*

Welchert, W. T., F. Wiersma, O. G. Lough, and D. V. Armstrong. Dairy Design Practices for Semi-Arid Climates. ASAE Paper No. PR 81-011 for presentation at the A.S.A.E. Pacific Region Annual Meeting, American Society of Agricultural Engineers. 1981.

Westra, J.V., Agricultural Phosphorous Nonpoint Source Pollution in the Minnesota River. Selected paper. Annual Meeting of the American Agricultural Economics Association. August 8-11, 1999. Nasville TN. 1999

Zhang Hailin, B. Raun, J.Hattey, G. Johnson, and N. Basta. OSU Soil Test Interpretations. OSU Extension Fact F-2225

Zhang Hailin, G. Johnson, and M. Fram. Managing Phosphorous from Animal Manure. OSU Extension Fact F-2249.

Zhang Hailin. " P Loss Index As a Guide to Manure Application." BMP Symposium: BMPs For Chicken Litter to Protect Water Quality. OSU Oklahoma Cooperative Extension. 2000.

Zhang Hailin. Oklahoma Agricultural Soil Test Summary 1994-1999. OSU Extension Fact CR-2247. 1999. http:/agweb.okstate.edu/pearl/

APPENDIX

APPENDIX A

Beaty Creek Observed Water Flows

Month	Flow (m^3/ s)
Aug-98	0.07
Sep-98	0.32
Oct-98	4.00
Nov-98	0.64
Dec-98	0.68
Jan-99	0.99
Feb-99	3.92
Mar-99	4.13
Apr-99	3.08
May-99	4.10
Jun-99	5.43
Jul-99	3.36
Aug-99	0.26
Sep-99	0.38
Oct-99	0.16
Nov-99	0.13
Dec-99	2.45
Jan-00	0.45
Feb-00	0.94
Mar-00	1.41
Apr-00	0.49
AVE	1.78

APPENDIX B

A SAS Program for Nonlinear Regression.

```
filename sasdat "d:\48ct-trmnt\Yldclark3.dbf";

proc dbf db3=sasdat out=one;

proc NLMIXED COV data=one;
parms b0=2 b1=1 b2=-0.01 b3=-0.001 b4=-0.001
a0=0.5 a1=-0.01
rho=0.1;
nrho=rho**2;
drho=1-rho**2;
s2u=nrho/drho;
ex=exp(b2*tn+b3*tno3l*plabl);
mean=b0-b1*ex+u;
MODEL Yield ~ NORMAL(mean,s2e);
RANDOM u ~ NORMAL(0,s2u) Subject=tn;

run;
quit;
```

VITA

Tam Thi Giac Phan

Candidate for the Degree of

Doctor of Phylosophy

Thesis: COST OF WATER POLLUTION ABATEMENT FOR POULTRY FARMS IN BEATY CREEK WATERSHED, OKLAHOMA

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Saigon, Vietnam, December 17, 1957.

Education: Graduated from Le Van Duyet State High School, Saigon, Vietnam in 1976; received a Bachelor of Science degree in Agriculture Economics with distinction from University of Agriculture and Forestry, Ho Chi Minh City, Vietnam, in 1982. Attended 3-month training in Socio-economics in Farming System Research at the International Rice Research Institute, the Philippines in 1988. Received a Master of Science degree with major in Agricultural Economics and minor in Economics from University of the Philippines at Los Banos, the Philippines in 1992. Attended 2-month training in Environment and Policy Analysis at Harvard University, in June 1993. Attended biannual workshops on Environmental Economics held by the Economy and Environment Program For Southeast Asia (EEPSEA) in Singapore from 1994-1997. Attended Ecological Economics Teaching workshop held by the Beijer Institute in Malaysia in March 96. Attended courses in Ecological Economics, Rural Development and Women Studies in The University of British Columbia, Vancouver Canada in 1996-1997. Attended Advanced Course in Ecological Modeling held at the Santa Fe Institute, New Mexico in December 1998. Attended Workshop on Pollution Control for Economists held by EEPSEA in December 1999. Received Fulbright scholarship in August 1998 for the Doctor of Philosophy Degree in Agricultural Economics at Oklahoma State University and completed the requirements for this degree in May 2001.

Professional Experience: Lecturer, the Department of Agricultural Economics in the University of Agriculture and Forestry since 1983. Coordinator of training workshops on Environmental Economics in Vietnam. Project team leader and project evaluator.