A FARM-LEVEL ECONOMIC ANALYSIS OF AGRICULTURAL POLLUTION CONTROL

By

SUHK-HYUN KIM

Bachelor of Science
Seoul National University
Seoul, Korea
1984

Master of Science
Seoul National University
Seoul, Korea
1986

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Thesis Approved:

Harry P. Mapp

Thesis Adviser

Francis M. Epplin

D. Sanders

Keith Olson

Thomas C. Collins

Dean of the Graduate College

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TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Statement of the Problem

Pollution is defined as introduction of materials into the environment that are potentially harmful or interfere with man's use of the environment. The contamination of soil, water, and the atmosphere by various substances are three types of special concern (Tver, 1981, pp. 252-3). The economic meaning of pollution is determined by physical and biological effects of pollutant discharges on scarce resources and by the loss of human welfare (Pearce and Turner, 1990, pp. 61-2).

The large increase in the use of agricultural chemicals in modern agricultural practices has contributed to increased food and fiber production. However, intensive use of agricultural chemicals generates pesticide and nutrient residuals. These residuals can adversely affect water quality when they reach surface or ground water in excessive amounts (Duttweiler and Nicholson, 1983). In recent years, public concern over adverse effects of water pollution on both human health and environmental quality has been growing. This growing concern partly stems from widespread reports of agricultural pollutants in both surface and ground water.

Agricultural contaminants of major concern in surface water quality problems are soil particles, nutrients, and toxic chemicals including herbicides, insecticides, and fungicides. These materials reach nearby surface water carried by runoff water during rainfall, and contribute to three general forms of surface water pollution: (1) sedimentation; (2) nutrient enrichment by nitrogen and phosphorus; and, (3) contamination from toxic chemicals. Adverse impacts of sedimentation include damages to aquatic organisms, water-based recreation, and navigation, increased flood damages, and raised water treatment cost. Nutrient enrichment adversely affects aquatic habitats, damages water-based recreation, and hampers water purification by stimulating algal growth. Increased algal growth increases the cost of treating water for municipal and industrial uses. Furthermore, the combined effects of nutrient enrichment (eutrophication) in the stream can cause massive fish kills. The potential damage associated with a particular toxic pesticide depends upon its toxicity, solubility and persistence. Toxic chemicals in drinking water supplied by surface water may cause chronic effects such as cancer, miscarriage, and mutations (Libby and Boggess, 1990).

Agricultural contaminants most likely to adversely affect ground water quality are pesticides and nitrates. Pesticides and nitrates, along with the percolating water after rainfall or irrigation, pass through the soil profile and below the crop root zone and may reach ground water. The potential for agrichemical leaching is largely determined by three categories of factors including (1) natural characteristics of the site of agrichemical use that affect leaching of water and thus transport of agrichemicals; (2) nature and extent of human modification to those natural characteristics that may affect leaching patterns; and, (3) characteristics of the agrichemicals (Office of Technology Assessment, 1990). Factors included in the first category are local topography and landforms, vegetation, climatic parameters, the depth to the water table, and soil characteristics. The second category includes tillage practices, the amount and the timing of agrichemical applications, and irrigation. Chemical characteristics include solubility, mobility, degradation, and adsorption. (Office of Technology, 1990).

Since the mid-1970s, there have been increasing numbers of reports on pesticides and nitrates in ground water. In various regions in the United States, at least 5,500 contaminated wells with pesticide concentrations exceeding certain health advisory levels and at least 8,200 wells with nitrate concentrations exceeding the Maximum Contaminant Level established by the U.S. EPA to protect public health have been found (Cohen, 1989). Ground water has provided drinking water for approximately 50 percent of the total population and 90 percent of the rural population in the United States, and also is essential to agriculture in many regions of the country (Office of Technology, 1990). Ingestion of certain pesticide residues through drinking water can cause health problems such as cancer, nervous system disorders, birth defects, and male sterility. High concentration of nitrate in drinking water can cause methemoglobinemia (blue-baby disease) in infants and gastric cancer (Bouwer, 1990).

Contributions by agriculture to water pollution have led to agricultural water quality legislation at both federal and state levels. The Clean Water Act of 1972 was a significant action taken to protect the quality of water from point source pollution. The Clean Water Act was designed primarily to protect surface water from point source pollution. In the 1980s, public attention began to shift to nonpoint source pollution, including erosion and runoff from farmland, and ground water contamination. The soil conservation compliance provisions of the 1985 Farm Bill have contributed to improved water quality by reducing soil erosion. In the 1990s, the major concerns are pollutants in the water supply, where agricultural chemicals are one of the major sources of contamination (Knutson et al., 1990).

The Food Security Act of 1985 has been amended by adding a new chapter, 'Agricultural Water Quality Incentives', in the 1990 Farm Bill. This new chapter specifies that:

> The policy of Congress is that water quality protection, including source reduction of agricultural pollutants, henceforth shall be an important goal of the programs and policies of the Department of Agriculture. Furthermore, agricultural producers in environmentally sensitive areas should request assistance to develop and implement on-farm water quality protection plans in order to assist in compliance with State and Federal environmental laws and to enhance the environment.

The new chapter also defines that:

> The term 'agricultural water quality protection practice' means a farm-level practice or a system of practices designed to protect water quality by mitigating or reducing the release of agricultural pollutants, including nutrients, pesticides, animal waste, sediment, salts, biological contaminants, and other materials, into the environment.

Agricultural water quality provisions in the 1990 Farm Bill establish a voluntary incentive program "providing an annual incentive payment for developing and implementing agricultural production practices in accordance with an approved water quality protection plan submitted by the owner or operator of a farm" and a cost sharing program "providing cost share assistance for implementing the wetland preservation or wildlife habitat options." In order to receive annual incentive payments, a farm operator should (1) accurately report nutrient, pesticide and animal waste material usage rates on the management area for the past three years; (2) implement a water quality protection plan approved by USDA; and, (3) not conduct any practices on the farm that would tend to defeat the purpose of the agricultural water quality protection program. If the farm operator violates a term or condition of the agreement, any incentive or cost share payment received must be refunded with interest. In return for a voluntary incentive agreement, USDA will provide an eligibility assessment and technical assistance for developing and implementing water quality protection plans. A voluntary incentive program participant can receive up to $3,500 per year in the form of incentive payments, and receive yield and base protection on the farm during the agreement period.

Policies for controlling pollution can be classified into two groups: (1) incentive policies which intend to improve water quality indirectly by providing economic incentives, including taxes or subsidies for polluters to reduce pollution, and (2) regulatory policies which force the farmer to comply with certain restrictions on the magnitude of pollutant emissions (emission standards) or polluting activities. In the case of point source pollution, the use of incentive policies is more efficient than regulatory policies since the unit-tax approach can automatically produce the least-cost assignment of emission standards without the need for any complicated calculations by the regulatory agency (Baumol and Oates, 1975).

Pollution caused by agricultural chemicals poses special problems because (1) agricultural pollution is typically a result of generally accepted farm management practices, such as spreading fertilizers or applying pesticides according to label instructions; (2) most agricultural pollution sources are nonpoint-sources making monitoring and testing procedures and their management difficult and expensive; (3) the pollution potential of agricultural chemicals and the effectiveness of control methods are site-specific; (4) there is strong resistance from agriculturalists to traditional approaches that force the polluter to bear the full cost of the polluting action; and, (5) the health and safety implications of ground water contamination are uncertain (Batie et al., 1989). Because of the diffuse nature of discharges and the time lag between discharges and actual contamination of the water body, however, monitoring agricultural discharges is quite difficult and costly. Thus, policy makers tend to rely on regulatory policies, such as agricultural input use restrictions or permits, to abate agricultural pollution. Particularly, regulatory policies are known to be more effective in protecting local environmental conditions than incentive policies (Anderson et al., 1990).

The most probable regulatory options are policy measures requiring reductions in the use of agricultural inputs, such as nitrogen fertilizer and pesticides. Nitrogen fertilizer use restrictions might limit use to a certain percentage of historic applications for the farm as a whole, or limit use to a certain percentage of historic applications for each acre of crop cultivated on the farm (Mapp et al., 1991). Pesticide use restrictions might be a form of prohibition on using pesticides likely to leach through the soil profile, a percentage reduction in total pesticide application, or a restriction on the frequency of treatments. Other possible restrictions include limiting the amount of irrigation water pumped from ground water sources on a total farm or per crop-acre basis.

The magnitude of water pollution generated by agricultural production processes can be reduced by chemical input use reductions, input substitutions, crop rotations, and/or new technology adoption. Both incentive policies and regulatory policies would affect farm management practices, including tillage, chemical input usage, crop mix, and irrigation method which, in turn, would affect crop production and farm income.

Study Area

Caddo County, located in the west-central part of Oklahoma (Figure 1), is the area of concern in this study. Its land area is approximately 808,320 acres. The elevation of Caddo County ranges from 1,130 feet in the southeast to 1,718

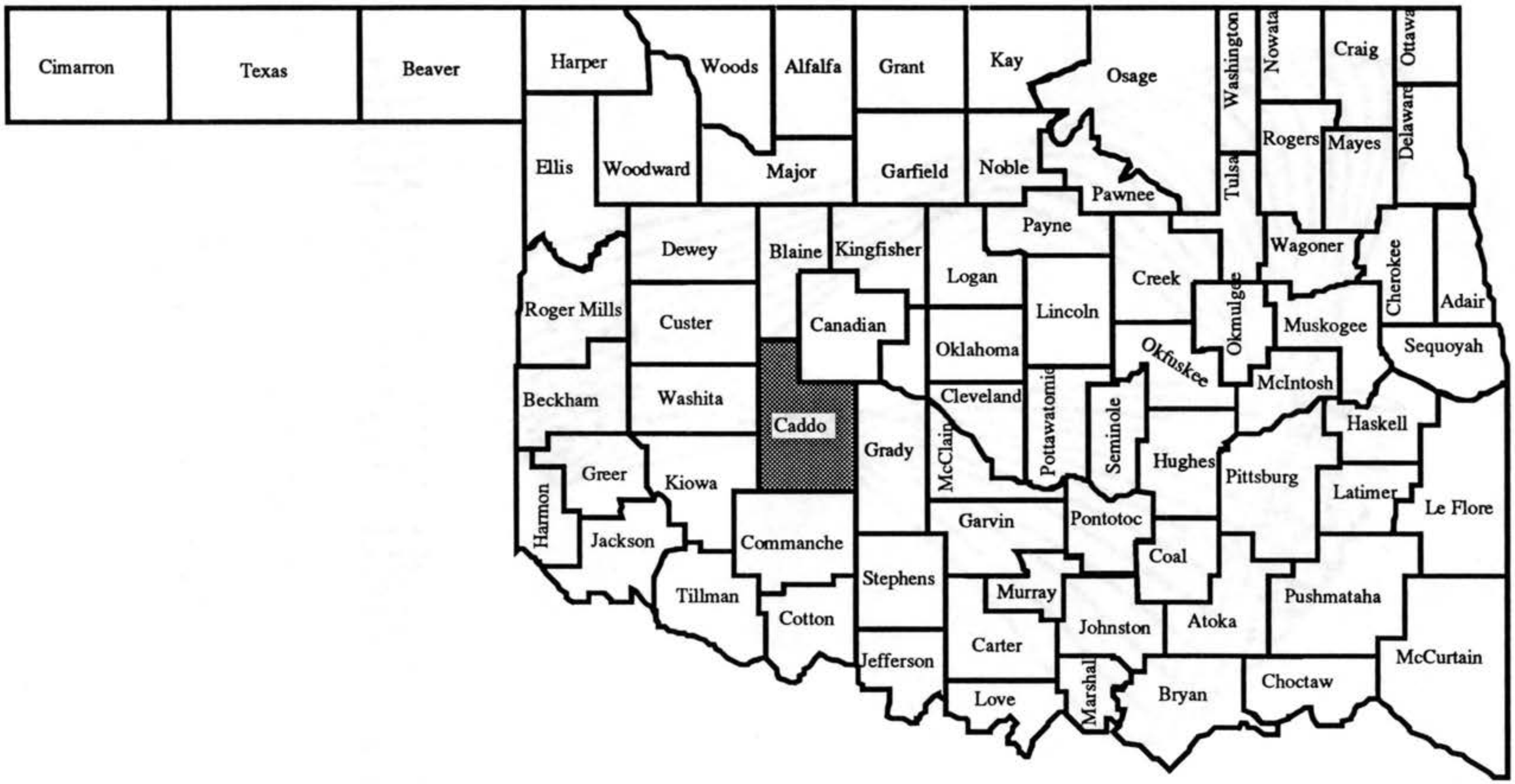

Figure 1. Map of Oklahoma Showing the Study Area

feet in the northwest. Mean annual precipitation in the county ranges from about 27 inches in the northwest to about 33 inches in the southeast. About 34 percent of the annual precipitation is in spring; 27 percent in summer; 24 percent in fall; and 15 percent in winter. The average daily minimum air temperature ranges from 28.0°F in January to 69.7°F in July. The average daily maximum air temperature ranges from 51.8°F in January to 97.2°F in August. Wind velocity in Caddo County averages about 12.5 miles per hour and ranges from 11 miles per hour in August to 15 miles per hour in March and April (USDA Soil Conservation Service).

About 90 percent of the county is made up of soils on uplands. On the prairie uplands, soils are level to gently sloping, deep, and loamy. These soils are the best soils in Caddo County for crop production. Over 50 percent of these soils consist of fine sandy loam soils and loamy fine sand soils (USDA Soil Conservation Service).

In Caddo County, the major part of income comes from the sale of crops, livestock, and livestock products. Acres and production of major crops in recent two years (1990-91) are shown in Table 1. The major crops in the county are wheat, peanuts, cotton, grain sorghum, and hay crops. Among them, peanuts receive the major part of irrigation water. Peanut and cotton production generally requires an intensive use of pesticides.

The intensive use of pesticides in peanut and cotton production poses a potential threat to water quality of the study area. The potential for environmental degradation is increased by intensive irrigation in most peanut acres. In addition, as stated above, sandy soils prevail in croplands of the study area. Sandy soils have large pores that allow water to drain rapidly, and they have few small pores to retain water for crop growth. Consequently, sandy soils increase the need for irrigation. Furthermore, sandy soils contain less clays

TABLE 1

ACRES AND PRODUCTION OF MAJOR CROPS IN CADDO COUNTY (1990-91)

Crops	Acres(Harvested)	Production	Yield
Wheat	2,600	119,000 bu	45.8 bu
(Irrigated)	1,200	47,000	39.2
Wheat	217,400	7,381,000 bu	34.0 bu
(Dryland)	168,800	5,763,000	34.1
Peanuts	33,000	106,210,000 lb	3,218 lb
(Irrigated)	33,300	99,575,000	2,990
Peanuts	2,300	5,200,000 lb	2,261 lb
(Dryland)	1,700	4,340,000	2,553
Cotton	4,150	2,652,000 lb	639 lb
(Irrigated)	2,600	1,200,000	462
Cotton	12,350	4,656,000 lb	377 lb
(Dryland)	16,400	5,040,000	307
Grain Sorghum	3,300	225,000 bu	68.2 bu
(Irrigated)	2,400	135,000	56.3
Grain Sorghum	11,700	475,000 bu	40.6 bu
(Dryland)	7,100	235,000	33.1
All Hay	62,000	147,000 ton	2.37 ton
	73,000	166,000	2.27

Source: Oklahoma Department of Agriculture. Oklahoma Agricultural Statistics 1990, 1991.

which can increase a soil's ability to hold organic and inorganic compounds, including most pollutants (Jackson et al., 1987). This may result in relatively rapid leaching of some potential ground water pollutants in the study area. In this context, it is important to conduct economic studies which address the policy question of what is the most efficient way to achieve certain water quality standards or to reduce the potential for environmental degradation in the study area. Nevertheless, few economic studies of production alternatives to achieve water quality objectives have been conducted.

Objectives of the Study

This study intends to enhance the understanding of the relationships between farm management practices, soil characteristics, the magnitude of major pollutants generated from the agricultural production process, types of pollution control policy measures and their effectiveness, and possible changes in net returns to the farm caused by alternative pollution control policy measures. The overall objective of this study is to develop an analytical framework and determine optimal farm-level responses to alternative agricultural water pollution control policies. The analytical framework is used to evaluate the effectiveness and distributional effects of alternative policy measures. More specific objectives are:

1. To identify a representative farm reflecting the general crop production environment in the study area;
2. To identify alternative crop management practices involving alternative crop rotation systems, input use levels, and irrigation technologies for crop production available to farm operators in the study area;

3. To simulate crop yields, and the magnitude of pollutants generated from alternative farm management practices;

4. To develop a modeling framework that will determine sets of production activities which maximize net returns, subject to the resource endowment, environmental constraints, and policy parameters;

5. To determine both economic and water quality consequences of alternative agricultural pollution control policy measures.

Procedures for Analysis

In this study, a farm-level linear programming model is used to analyze economic and water quality consequences of alternative agricultural pollution control policy measures. Formulation of the linear programming model begins with a review of the literature and a generalization of nonpoint externality theory which is delineated using a classical optimization framework (Griffin and Bromley, 1982). Nonlinear programming theory is widely used for the generalization of the theoretical basis, the derivation of economically efficient incentive and regulatory pollution control policies, and for the mathematical specification of optimal parameters.

Modeling of the real world problem requires accurate representation of the production environment, crop yield responses to alternative crop management practices, estimates of costs and returns, and the magnitude of pollutants generated by the agricultural production process. Using data from the 1987 Census of Agriculture-County Data and the Soil Survey of Caddo County, a hypothetical farm is developed for Caddo County, Oklahoma. For the representation of farm management practices, combinations of published data available from various sources and interviews with the County Extension Agent (Beerwinkle, 1991, 1992) are used. Management practices-crop growth-chemical movement relationships are developed using results from a bio-physical simulation model, EPIC-PST (Sabbagh et al., 1991). To estimate operating costs associated with each farm management practice, the Expanded Budget Generator (Norris, 1990) is utilized.

By linking data obtained from these preceding procedures, 36 linear programs, representing the combinations of nine agricultural pollution control policy scenarios and four alternative irrigation methods, are developed. The solution of each linear program provides (1) optimal production decisions for complying with the corresponding policy scenario; (2) the magnitude of various contaminants generated from the farm; (3) estimates of other policy parameters which would engender the same water quality consequences; and, (4) net returns to the farm. The investigation of effectiveness and influences of probable agricultural pollution control measures is conducted based on the solutions of these linear programs.

Organization of the Dissertation

This dissertation consists of six chapters. Chapter II presents a review of the literature addressing the issue of agricultural pollution control, and develops the theoretical basis for a conceptual analysis of the problem at issue. The subject of Chapter III is the representation of the bio-physical simulation model and the description of crop production activities. Chapter III also presents the procedure of the empirical model formulation for conducting the economic analysis of agricultural pollution control. Chapter IV discusses data requirements for this study and the process of data acquisition. Chapter V uses the empirical model to analyze the effectiveness and influences of probable agricultural pollution control measures, and reports results of the analyses.

Chapter VI presents the summary and conclusions, draws policy implications, and discusses the limitations of the study and future study needs.

CHAPTER II

ECONOMICS OF AGRICULTURAL POLLUTION CONTROL

This chapter discusses the theoretical and methodological foundation of the mathematical programming model developed in Chapter III and the investigation of the empirical pollution control problem conducted in Chapter V. The first part of this chapter reviews the theory and literature on economics of pollution control. In the second part of this chapter, the main elements of nonlinear programming theory are introduced for a rigorous delineation of the economics of the agricultural pollution control problem. For a practical treatment of the agricultural pollution control problem, the linear programming approach is derived as a special case of nonlinear programming theory.

Review of the Theory and Literature

Simplistic Illustrations of the Problem

The model in this section describes the nature of the economics of pollution control problem in a simplistic way. Consider a firm which produces a primary product (y) using a single type of input (x) in a competitive market. The firm is assumed to attempt to maximize profit. Consider also that the production process generates a single type of effluent (z) as a joint product. The production functions for these joint products are represented by:

$$y = f(x) \tag{2.01}$$

$$z = g(x) \tag{2.02}$$

where f is assumed to be a twice continuously differentiable strictly concave function, while g is assumed to be a twice continuously differentiable strictly convex function. Assume that these production functions are known with certainty by the firm as well as the regulatory agency. For the sake of simplicity, assume also that the damage cost per unit of effluent (c) is a constant and is known by the regulatory agency. If there are neither incentives nor regulations for reducing effluent discharges, the objective of the profit maximizing firm is:

$$\text{maximize}(x):\ \pi(x) = pf(x) - rx \tag{2.03}$$

where p denotes the price of the primary product, and r represent the price of the input. Then the optimality condition for the profit maximizing firm is:

$$pf_x(x) = r \tag{2.04}$$

Equation (2.04) indicates that the firm needs to set the value of marginal product equal to the price of input.

Meanwhile, the objective of society can be described by:

$$\text{maximize}(x):\ s(x) = pf(x) - rx - cg(x) \tag{2.05}$$

The optimality condition for society is:

$$pf_x(x) = r + cg_x(x) \tag{2.06}$$

Equation (2.06) indicates that the social optimum requires the value of marginal product be equal to the sum of the price of input and the marginal damage cost of the input at a certain input use level.

In this example, the price of input represents the firm's (private) marginal cost, while the marginal damage cost represents the social marginal cost. Let us assume that x^* denotes the input use level at which the social optimum condition (2.06) is satisfied. Because the production function (2.01) is assumed to be strictly concave, the input level satisfying the optimality condition for the firm (2.04) would be greater than x^*. In other words, if there are no incentives or regulations for reducing discharges, the firm would increase input use beyond the socially optimal level. This level of input use occurs because the social costs of the input use do not enter the firm's objective function. Therefore, it is necessary for society to formulate appropriate pollution control measures in order to attain the socially optimal level of input use. Four possible means of pollution control that can motivate the producer's optimal behavior, or that enforce optimal input use, are (1) an effluent tax; (2) an effluent standard; (3) an input tax; and, (4) an input use standard.

The first policy tool imposes a tax (t_z) per unit of effluent generated from the production process. The firm's new objective function under this tax policy is represented by:

$$\text{maximize}(x): \ \pi(x) = pf(x) - rx - t_z g(x) \qquad (2.07)$$

The optimality condition for problem (2.07) is:

$$pf_x(x) = r + t_z g_x(x) \qquad (2.08)$$

Equations (2.06) and (2.08) reveal that the effluent tax rate (t_z^*) needed to attain the social optimum equals to the damage cost per unit of the effluent (c). In this context, the optimal effluent tax is equivalent to a Pigouvian tax (Pearce and Turner, 1990, pp. 85-7).

The second policy tool sets an upper limit (z^o) on the magnitude of the effluent the firm may generate without penalty. Under this effluent standard, the objective function of the firm is:

$$\text{maximize}(x): \ \pi(x) = pf(x) - rx$$

$$\text{subject to: } \ z^o = g(x) \qquad (2.09)$$

The Lagrangian to problem (2.09) is:

$$L(x; p,r,z) = pf(x) - rx + \mu(z^o - g(x)) \qquad (2.10)$$

Optimality conditions for the problem are:

$$pf_x(x) = r + \mu g_x(x) \qquad (2.11)$$

$$z^{o} = g(x) \tag{2.12}$$

Comparison of equations (2.06), (2.08), and (2.11) reveal the following relationships between choice variables and parameters:

$$z^{*} = g(x^{*}) \tag{2.13}$$

$$c = t_{z}^{*} = \mu(p,r,z^{*}) \tag{2.14}$$

Equation (2.13) indicates that the optimum effluent standard needs to be set at the same level as the magnitude of effluent generated by the socially optimal input use level x^{*}. Equation (2.14) indicates that the optimal effluent tax t_{z}^{*} and the optimal standard z^{*} are the dual of each other.

The third policy tool imposes a tax (t_x) on the level of input use. The objective function of the firm under the input tax scheme is:

$$\text{maximize}(x)\text{:} \;\; \pi(x) = pf(x) - (r + t_x)x \tag{2.15}$$

The optimality condition for problem (2.15) is:

$$pf_x(x) = r + t_x \tag{2.16}$$

Equations (2.06) and (2.16) identify the optimal input tax rate (t_x^{*}) as:

$$t_x^{*} = cg_x(x^{*}) \tag{2.17}$$

Equation (2.17) indicates that the optimal input tax rate (t_x^{*}) needs to be set at a level which equals the marginal damage cost of the input used at the optimal level x^{*}.

The fourth policy tool sets an upper limit (x^{o}) on input use. The objective function of the firm under the input use standard is:

$$\text{maximize}(x)\text{:} \;\; \pi(x) = pf(x) - rx$$

$$\text{subject to:} \;\; x = x^{o} \tag{2.18}$$

The Lagrangian to problem (2.18) is:

$$L(x; p,r,x^{o}) = pf(x) - rx + \lambda(x^{o} - x) \tag{2.19}$$

Optimality conditions for the problem are:

$$pf_x(x) = r + \lambda \tag{2.20}$$

$$x = x^o \quad (2.21)$$

Comparison of equations (2.06), (2.16), and (2.20) reveals the following relationships between the Lagrangian multiplier λ and parameters:

$$cg_x(x^*) = t_x^* = \lambda(p,r,x^*) \quad (2.22)$$

Equation (2.22) indicates that the optimal input standard should be set at x^*, and that the optimal input tax and the optimal input use standard are the dual of each other. Optimality conditions for the firm and the society, and optimal policy options are summarized in Table 2.

Taxes, Standards, and Their Distributional Implications

Economic analysis of policy options for controlling pollution must address the efficiency and distributional implications of the policy options. Economists have argued that economic incentives, such as taxes on effluent discharges or a subsidy for abatement of discharges, would lead to the least-cost achievement of certain environmental quality targets since these incentives do not deprive private decision makers of flexibility of choice (Kneese and Bouwer, 1968; Baumol and Oates, 1975; Braden, 1988). Meanwhile, Anderson et al. (1990) argue that the superiority of the price mechanism is less apparent with limited information or considerable transaction cost. Furthermore, Miltz et al. (1988) demonstrate that the uniform standard outperforms the uniform tax in controlling ambient pollution levels over a potentially wide range of parameter values. Subsidies are not a viable policy option for controlling nonpoint pollution since they are too costly and subject to perversion (Braden, 1988). This section compares taxes and standards as alternative pollution control policy options.

TABLE 2

OPTIMALITY CONDITIONS AND OPTIMAL POLICY OPTIONS TO CORRECT THE EXTERNALITY PROBLEM

Optimality Conditions

Problem of the Society

$pf_x(x) = r + cg_x(x)$

Problem of the Firm

(1) Without Regulation: $pf_x(x) = r$

(2) With Effluent Tax: $pf_x(x) = r + t_z g_x(x)$

(3) With Effluent Standard: $g(x) = z^o$

(4) With Input Tax: $pf_x(x) = r + t_x g_x(x)$

(5) With Input Use Standard: $x = x^o$

Optimal Policy Options

(1) Optimal Effluent Tax: $t_z^* = c$

(2) Optimal Effluent Standard: $z^* = g(x^*)$

(3) Optimal Input Tax: $t_x^* = cg_x(x)$

(4) Optimal Input Use Standard: $x^o = x^*$

In the theoretical discussions of pollution control, it is often assumed that evaluation of environmental damages caused by pollution is possible. Freeman et al. (1973, p.83) interpret damages of pollution as society's maximum willingness to pay to restore the environment to a unpolluted state. However, it is difficult to determine the monetary value of damages caused by pollution. On the other hand, a regulatory agency can set minimum standards or acceptable standards of environmental quality that must be met in order to achieve a reasonable quality of life. No data on costs or damages of certain pollution levels are required to set these standards. An example of these standards is an upper limit on concentration of a certain pollutant in a waterway. To attain these standards through the price mechanism, the tax rates should be selected so as to achieve specific acceptable standards rather than attempting to base them on the unknown value of marginal damages (Baumol and Oates, 1971).

Consider a single firm that generates an effluent in the production process. The marginal abatement cost of effluent discharge for the firm is represented by MAC curve in Figure 2. Assume that the regulatory agency has determined z^* as an acceptable standard. Then the tax rate for achieving this acceptable standard is t^*: the optimal tax rate t^* is the dual of the acceptable standard z^*. Hence, both the tax policy and the standard policy are efficient. But these two policy options have quite different equity implications. Under the standard policy, total cost to the firm to comply with the standard is AZz^*, and the cost of damages resulting from effluent discharges z^* is internalized by the affected group in society. On the other hand, if the regulatory agency adopts the tax policy, then the firm should additionally pay Ot^*Az^* as an effluent tax. This tax is interpreted as the firm's compensation for the damages caused by effluent discharges z^* (Anderson et al., 1990).

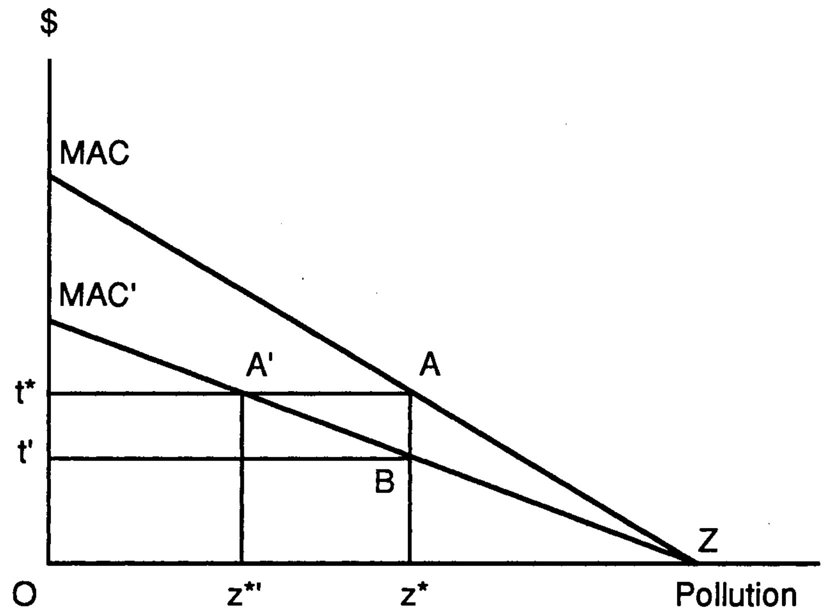

Figure 2. Taxes versus Standards

Both the tax policy and the standard policy provide an incentive to shift the marginal abatement cost curve from MAC down to MAC'. After the shift of the marginal abatement cost curve, the firm would reduce the level of discharges to z^{*}' to save an amount of tax equal to the area ABZ under the tax policy. Under the standard policy, the firm would maintain the level of discharges at z^{*} since there is no additional incentive to reduce effluent discharges. If there is no need of further improvement in environmental quality, then the tax rate needs to be lowered from t^{*} to t'.

Now consider two firms that have different marginal abatement costs: the marginal abatement cost curve of the first firm is represented by MAC_1, and that of the second firm is represented by MAC_2 in Figure 3. Assume that the regulatory agency has determined $2z_m$ ($Oz_m + Oz_m$) to be the acceptable standard. In this case, the optimal tax rate t^* for achieving the standard needs to be set at the level rendering $z_m z_1$ equal to $z_2 z_m$. Under the tax policy, the firm with MAC_1 bears abatement cost equal to the area A_1Zz_1 and pays an amount equivalent to the area $Ot^*A_1z_1$ as an effluent tax. On the other hand, the firm with MAC_2 bears abatement cost equal to the area A_2Zz_2 and pays an amount equivalent to the area $Ot^*A_2z_2$ as an effluent tax. Notice that a firm with lower marginal abatement cost pays less tax than a firm with higher marginal abatement cost. Under the standard policy, two differential standards are required for minimization of the total abatement cost: z_1 for the first firm and z_2 for the second firm. Notice that a firm with lower marginal abatement cost bears a relatively heavier burden than a firm with higher marginal abatement cost under the differential standard policy.

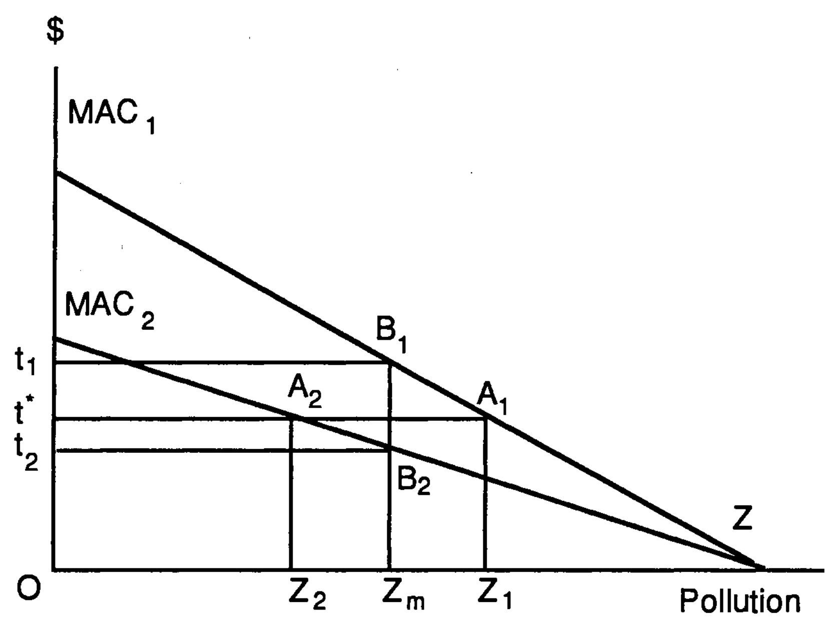

Figure 3. Differential Standards versus Uniform Standards

Previously discussed pollution control policy options do not consider either who is going to pay the costs for improving environmental quality or how much a group should pay. Under the tax policy, firms bear the burden of the effluent tax as well as the abatement cost. It may be questionable whether such an additional burden (tax) beyond abatement costs should be imposed on polluters. The tax revenue could be used to further improve environmental quality or to compensate the affected group for loss of welfare. However, the main objective of imposing the effluent tax is to achieve the acceptable standard. In this context, the tax policy is considerably more disadvantageous to the affected firms than the standard policy. Furthermore, the economically efficient standard policy, which imposes a differential standard to each firm, emphasizes reducing discharges by firms with low marginal abatement cost. Consequently, the differential standard policy heavily penalizes firms with lower marginal abatement costs while allowing other firms with higher marginal abatement costs to continue their polluting activities.

To rectify this inequity, one may propose a uniform standard policy whereby all polluting firms are forced to reduce discharges by certain percentages of their original discharge levels. In case no regulations are imposed, both firms in Figure 3 would discharge an amount of effluent equal to Z and bear neither the tax nor the abatement cost. Now, consider that the regulatory agency imposes the uniform standard z_m on both firms. Notice that this uniform standard policy results in the same environmental quality with both the differential standards and the tax policy discussed above. The total amount of discharges from both firms is $2z_m$. Under the uniform standard policy, the first firm bears abatement cost equivalent to the area B_1Zz_m while the second firm bears abatement cost equivalent to the area B_2Zz_m. Compared with results under the differential standard policy, the firm with higher marginal abatement cost bears greater abatement cost by an amount equivalent to the area $A_1B_1z_mz_1$. The firm with lower marginal abatement cost bears less abatement cost by an amount equivalent to the area $A_2B_2z_mz_2$. Consequently, the uniform standard policy involves a deadweight efficiency loss equivalent to the area $A_1B_1B_2$, although it contributes to the rectification of inequity problems.

Review of the Literature on Economics of Pollution Control

Baumol and Oates (1975, p. 18) define that "An externality is present whenever the decision maker, whose activity affects others' utility levels or enters their production functions, does not receive (pay) in compensation for this activity an amount equal in value to the resulting (marginal) benefits or costs to others." Pollution is a good example of an externality for which polluters do not pay. In the absence of economic incentives to internalize the externality, firms release pollutants at a level higher than is socially optimal. For this reason, it has been conceived that taxes on the emission of pollutants, pollution generating inputs, or polluting activities, are necessary to motivate firms to economize on pollutant emissions. Plott (1966) shows that the tax to correct externalities should be placed on pollution generating inputs, and that it is impossible to attain optimality by placing a tax on the primary product.

Baumol and Oates (1975) provide an extensive conceptual discussion of externalities and the complexities of environmental policies. They assert that the quality of the environment depends on private, individual decisions and on collective action undertaken through the public sector because environmental quality is a public good consumed by all members of society. Therefore, they express doubts about the reliability of partial analysis and provide a theoretical discussion of point source pollution problems utilizing general equilibrium models. Their analysis implies the standard Pigouvian result which requires a tax per unit of pollution generating activity equal to its marginal external damage.

Holterman (1976) discusses the use of taxes to correct externalities, and identifies three alternative methods of taxing externalities: (1) a tax placed on every unit of the externality produced; (2) a tax imposed only on the externality above a specified level; and, (3) a subsidy paid for every unit of the externality abatement below a specified level. Holterman (1976) concludes that Pareto optimality can be attained by imposing a set of taxes or subsidies on all inputs and outputs which contribute to the externality creation, even though it is not possible to impose taxes on externalities directly.

In a practical sense, it would be either impossible or too costly to determine consumers' valuations of marginal benefits of pollution abatement. For this reason, Griffin and Bromley (1982) develop a nonpoint externality theory by reformulating Baumol and Oates' general equilibrium models into a classical programming (optimization with equality constraints) framework. Assuming that a regional limit on pollutant emission discharges has been determined, and the objective is to achieve this goal at least cost to the region, they identify and model four types of policies regulating nonpoint-source pollution: (1) nonpoint incentives; (2) nonpoint standards; (3) management practice incentives; and, (4) management practice standards. Nonpoint incentives can be either a net charge or subsidy to each firm and depend on the incentive base level of pollutant emission. Management practice incentives also can be either a net charge or subsidy to each firm, and depend on the incentive base level of management practices. Nonpoint standards are the dual of nonpoint incentives, and management practice standards are the dual of management practice incentives in Griffin and Bromley's framework. Therefore, once the optimal levels of incentives are determined, the optimal standards can be obtained by applying Hotelling's lemma (Varian, 1984).

Griffin and Bromley (1982) consider just a single index of pollution since they implicitly assume that only a single pollutant is problematic in the region or that each pollutant is a perfect substitute for other pollutants. This assumption has been adopted in many conceptual studies. Shortle (1984) explicitly assumes that there is only one agricultural pollutant. He concludes that uncertainty regarding the magnitude of an agricultural pollutant would affect expected net benefits of alternative policy approaches and, therefore, should be considered when selecting appropriate pollution control policies. Shortle and Dunn (1986) incorporate the stochastic nature of runoff in their analysis and examine the relative expected efficiency of four general strategies proposed by Griffin and Bromley (1982). Assuming that farmers have better information about the effects of changes in farm management practices on profits, Shortle and Dunn (1986) suggest that appropriately specified management practice incentives would generally outperform the other three nonpoint-source pollution control policy options.

Many empirical studies have dealt with a single type of agricultural pollutant. Among others, Abrams and Barr (1974) consider surface water nitrate pollution in the State of Illinois. Taylor (1975) considers nitrate concentrations in drinking water supplies in the State of Illinois. Horner (1975) considers nitrate-nitrogen irrigation return flows in the western San Joaquin Valley. Jacobs and Casler (1979) consider phosphorus pollution of the Fall Creek watershed in central New York. Miller and Gill (1976) consider equity problems in controlling cropland sediment in Indiana. Wade and Heady (1977) examine effects of alternative policies to control sediment in the rivers and streams of the

United States. Boggess et al. (1980) consider the agricultural cropland sediment problem of a subbasin of the Iowa River in east central Iowa. Walker and Timmons (1980) consider agricultural cropland sediment problems in the Nishnabotna River Basin in southwestern Iowa. Segarra et al. (1985) conduct an analysis of soil erosion control on a representative farm in the Piedmont area of South-Central Virginia using a stochastic programming model. Gardener and Young (1988) consider salt discharges from irrigated cropland of the Grand Valley in western Colorado. Wu et al. (1989), and Braden et al. (1989) consider cropland sediment control problems in Illinois watersheds. Dinar et al. (1989), Knapp et al. (1990), and Caswell et al. (1990) consider quantity of drainage water for cotton production in the San Joaquin Valley of California. Bouzaher et al. (1990) discuss various mathematical models for efficient control of agricultural sediment and apply the models to examine effects of sediment control in Illinois. Johnson et al. (1991) consider nitrate ground water pollution problems caused by irrigated farms in the Columbia Basin of Oregon. Oh (1991) considers nitrate ground water pollution in western Franklin County and eastern Benton County in the State of Washington. Cole (1991) considers nitrate ground water pollution in Northwest Tennessee. Weinberg (1991) considers quantity of the agricultural drainage water for multiple crop production in California's San Joaquin Valley.

Only a few agricultural pollution control studies consider more than one kind of pollution load even though all types of agricultural pollutants deteriorate environmental quality or interfere with the use of natural resources. Taylor and Frohberg (1977) examine welfare effects of alternative erosion control methods, banning pesticides, and limiting nitrogen fertilizer for reducing agricultural pollution in the Corn Belt. Pfeiffer and Whittlesey (1978) consider river nitrogen concentration, water temperature, and cropland soil losses in Washington

State's Yakima River Basin. Braden et al. (1991) investigate the expected changes in farming practices and consequent losses in farming profit caused by control of soil erosion, sediment load, and pesticide losses in Lake Michigan tributaries. Richardson et al. (1991) attempt to quantify the impacts of pesticide and inorganic nitrogen fertilizer bans on farming profits for representative farms in several southern States. Hoag et al. (1991) consider soil erosion, pesticide leaching, pesticide runoff, and excess nitrogen simultaneously, and assess the effects of alternative abatement targets on net returns to various cropping systems typical of the North Carolina Piedmont region. Taylor (1991) considers nitrate loss with percolation, nitrate and organic nitrogen loss with runoff, and assesses the required cost of complying with alternative control policy options to representative farms in the Willamette Valley of Oregon. He emphasizes that if only one type of pollutant is targeted for control, the other pollutants may be exacerbated.

The equity of pollution control policies should also be addressed. As discussed in the previous section, an efficient pollution control policy from society's point of view does not consider who is going to pay the costs of improving environmental quality. An efficient policy only emphasizes pollution abatement by polluters with low marginal costs of the abatement. Thus, it could heavily penalize those with low costs of abatement, while letting the polluters with higher costs of abatement continue their effluent discharges unmodified (Kneese and Bower, 1968, pp. 139-41). Political acceptability of such efficient policy options is highly questionable because of the expected strong resistance of affected groups, and the perceived inequity of the redistribution of factor income. Sharp and Bromley (1979), and Park and Shabman (1982) provide additional discussions of these distributional issues.

Jacobs and Casler (1979) propose an alternative effluent tax policy which would preserve the benefits of the tax policy, yet not be excessively burdensome to farmer as polluters. Their approach is to identify the maximum allowable level of discharge and impose no tax up to this amount. This approach has exactly the same effects as the differential standard policy since no tax is actually collected. Thus, every firm would comply with the differential standard. Consequently, this approach also imposes a heavier burden on firms with lower marginal abatement cost, as does the differential standard approach. Freeman et al. (1973, pp. 143-8) suggest the need to redistribute pollution control costs through direct subsidies or indirect cost subsidies, such as favorable tax treatment for certain kinds of pollution control activities.

Theoretical and Methodological Foundation

As mentioned previously, few agricultural pollution control studies consider more than one pollutant. If different pollutants can be assumed to be perfect substitutes, or if only one pollutant is problematic in the study area, then dealing with a single index of pollution can be justified. However, the assumption of perfect substitution between different pollutants may not be reasonable because there are broad types of pollutants, such as nitrate loss with surface runoff, nitrogen loss with percolation, pesticide loss with surface runoff, pesticide loss with percolation, and soil loss from water erosion that have quite different physical, chemical, and/or biological effects on natural resources. Furthermore, a policy mechanism restricting a particular pollutant may induce an increase in another pollutant currently not problematic up to a level exceeding the maximum allowable level. For this reason, the analytical model needs to incorporate as many pollutants as possible without introducing nonessential detail or complexity. In this section, a mathematical model that satisfies this need is developed utilizing nonlinear and linear programming theory[1].

Nonlinear Programming

Nonlinear programming extends the simplistic model in the previous section by accommodating the situation where a farm produces multiple outputs using multiple inputs and generates several types of effluents as byproducts.

Let $\mathbf{x} = (x_1, \ldots, x_n)'$, $\mathbf{x} \in \Omega \subset R^n$, be a vector of inputs to the farm production process, $\mathbf{F}[(f_1(\mathbf{x}), \ldots, f_m(\mathbf{x}))']$ be a vector of produced crops, $\mathbf{G}[(g_1(\mathbf{x}), \ldots, g_h(\mathbf{x}))']$ be a vector of effluent discharges as a set of functions of inputs, and $\mathbf{z} = (z_1, \ldots, z_h)$ be a vector of limits on effluent discharges imposed on the farm by the regulatory agency. Suppose that all functions above are deterministic and known by the farmer as well as the regulatory agency. Assume further that the objective of the farm is maximization of net returns over fixed costs subject to the resource endowments and discharge limits imposed on the farm. Mathematical representation of the farm problem is

$$\begin{aligned} &\text{maximize}(\mathbf{x}): && \pi(\mathbf{x}) = \mathbf{p}'\mathbf{F}(\mathbf{x}) - \mathbf{w}'\mathbf{x} \\ &\text{subject to:} && \mathbf{G}(\mathbf{x}) \leq \mathbf{z} \\ &&& \mathbf{x} \in \Omega \end{aligned} \tag{2.23}$$

where $\mathbf{F}: R^n \rightarrow R^m$, $\mathbf{G}: R^n \rightarrow R^h$, Ω is a set constraint on input availability and is a convex set, $\mathbf{p}$ is an m-dimensional vector of crop prices, and $\mathbf{w}$ is an n-dimensional vector of input prices. The Lagrangian to the problem (2.23) is defined as

[1] A large portion of material in this section regarding nonlinear and linear programming theory was adapted from Pyles (1986) and Pyles (1990).

$$L(\mathbf{x},\boldsymbol{\mu}) = \mathbf{p}'\mathbf{F}(\mathbf{x}) - \mathbf{w}'\mathbf{x} + \boldsymbol{\mu}'[\mathbf{G}(\mathbf{x}) - \mathbf{z}] \quad (2.24)$$

where $\boldsymbol{\mu} \in R^h$. Suppose that $\mathbf{x}^o$ is a local maximum solution to the nonlinear programming problem (2.23) and let both **G** and **z** be partitioned into two conformable sets of component functions as:

$$\mathbf{G}(\mathbf{x}) = [(\mathbf{G}_1(\mathbf{x}))', (\mathbf{G}_2(\mathbf{x}))']'$$

$$\mathbf{z} = [\mathbf{z}_1', \mathbf{z}_2']'$$

where $\mathbf{G}_1(\mathbf{x}^o) < \mathbf{z}_1$ and $\mathbf{G}_2(\mathbf{x}^o) = \mathbf{z}_2$.

In the classical programming problem, which has neither explicit restrictions on the domain of the choice variables nor inequality constraints, the necessary condition for a local extremum is that the first-order partial derivative of the Lagrangian to the problem with respect to each choice variable and Lagrangian multiplier be zero. Similar types of necessary conditions in the nonlinear programming problem are known as the Kuhn-Tucker conditions. Kuhn-Tucker conditions are first-order necessary conditions only if certain restrictions on the constraint functions, called constraint qualifications (Chiang, 1984, pp. 731-38), are satisfied. While the movement of the choice variable in the classical programming problem is confined to the level set defined by equality constraints, the possibilities of movements into the interiors of the upper set or lower set is allowed in the nonlinear programming problem. Such a less restrictive set of constraints leads to the more restrictive set of necessary conditions for local optimality.

<u>Theorem 1 Kuhn-Tucker (First-Order Necessary) Conditions</u>: Assume that $\mathbf{x}^o$ is a local maximum solution to the nonlinear programming problem (2.23); each component function of **F** is differentiable at $\mathbf{x}^o$, and **G** is continuously differentiable at $\mathbf{x}^o$. Assume further that $\mathbf{x}^o$ is a regular point of the

binding constraints (i.e., $\mathbf{G}_2$ is continuously differentiable at $\mathbf{x}^o$ and $[\nabla \mathbf{G}_2(\mathbf{x}^o)]'$ is of full column rank), then there exists $\boldsymbol{\mu}^o \in R^h$ such that:

$$\mathbf{p}'\mathbf{F}_x(\mathbf{x}^o) - \mathbf{w}' - \boldsymbol{\mu}^{o\prime}\nabla\mathbf{G}(\mathbf{x}^o) = \mathbf{0}$$

$$\boldsymbol{\mu}^{o\prime}[\mathbf{z} - \mathbf{G}(\mathbf{x}^o)] = 0$$

$$\boldsymbol{\mu}^o \geq \mathbf{0}$$

for the Lagrangian (2.24).

Theorem 2 Second-Order Necessary Conditions for Local Maxima: Assume that $\mathbf{x}^o$ is a local maximum solution to the nonlinear programming problem (2.23); each component function of $\mathbf{F}$ is twice differentiable at $\mathbf{x}^o$, and that $\mathbf{G}$ is twice continuously differentiable at $\mathbf{x}^o$. Assume further that $\mathbf{x}^o$ is a regular point of the binding constraints. Then there exists $\boldsymbol{\mu}^o \in R^h$ such that

$$\mathbf{p}'\mathbf{F}_x(\mathbf{x}^o) - \mathbf{w}' - \boldsymbol{\mu}^{o\prime}\nabla\mathbf{G}(\mathbf{x}^o) = \mathbf{0}$$

$$\boldsymbol{\mu}^{o\prime}[\mathbf{z} - \mathbf{G}(\mathbf{x}^o)] = 0$$

$$\boldsymbol{\mu}^o \geq \mathbf{0}$$

for the Lagrangian (2.24). Suppose that $\boldsymbol{\mu}^o$ and $[\mathbf{z} - \mathbf{G}]$ are conformably partitioned as:

$$\boldsymbol{\mu}^o = [\boldsymbol{\mu}_1^{o\prime}, \boldsymbol{\mu}_2^{o\prime}]'$$

$$[\mathbf{z} - \mathbf{G}(\mathbf{x}^o)] = [(\mathbf{z}_1 - \mathbf{G}_1^*(\mathbf{x}^o)), (\mathbf{z}_2 - \mathbf{G}_2^*(\mathbf{x}^o))']'$$

where $\boldsymbol{\mu}_1^o = \mathbf{0}$ and $\boldsymbol{\mu}_2^o > \mathbf{0}$, then $L_{xx}(\mathbf{x}^o, \boldsymbol{\mu}^o)$ is negative semidefinite on the kernel of $\nabla \mathbf{G}_2^*(\mathbf{x}^o)$.

Theorem 3 Second-Order Sufficient Conditions for Local Maxima: Assume that $\mathbf{x}^o$ satisfies all constraints to the nonlinear programming problem (2.23). Assume also that there exists $\boldsymbol{\mu}^o \in R^h$ such that:

$$\mathbf{p}'\mathbf{F}_x(\mathbf{x}^o) - \mathbf{w}' - \boldsymbol{\mu}^{o\prime}\nabla\mathbf{G}(\mathbf{x}^o) = \mathbf{0}$$

$$\boldsymbol{\mu}^{o\prime}[\mathbf{z} - \mathbf{G}(\mathbf{x}^o)] = 0$$

$$\boldsymbol{\mu}^o \geq \mathbf{0}$$

for the Lagrangian (2.24). Suppose that $\boldsymbol{\mu}^o$ and $[\mathbf{z}^* - \mathbf{G}]$ are conformably partitioned as:

$$\boldsymbol{\mu}^o = [\boldsymbol{\mu}_1^{o\prime}, \boldsymbol{\mu}_2^{o\prime}]'$$

$$[\mathbf{z} - \mathbf{G}(\mathbf{x}^o)] = [(\mathbf{z}_1 - \mathbf{G}_1^*(\mathbf{x}^o))', (\mathbf{z}_2 - \mathbf{G}_2^*(\mathbf{x}^o))']'$$

where $\boldsymbol{\mu}_1^o = \mathbf{0}$ and $\boldsymbol{\mu}_2^o > \mathbf{0}$. Suppose further that $L_{xx}(\mathbf{x}^o,\boldsymbol{\mu}^o)$ is negative definite on the kernel of $\nabla\mathbf{G}_2^*(\mathbf{x}^o)$, then $\mathbf{x}^o$ is a strict local maximum solution.

To apply the local maximization theory to the determination of global maxima, the objective function needs to satisfy certain concavity properties and the feasible region to the maximization problem needs to be a convex set satisfying certain concavity properties. The following section reviews mathematical concepts and theorems related to the concavity properties.

Definition 1 Upper Set, Lower Set, Level Set: Suppose that X is a nonempty set in R^n and that $g:X \rightarrow R^1$, then

1) The set $\{\mathbf{x} \in X: g(\mathbf{x}) \leq z\}$ is a lower set.

2) The set $\{\mathbf{x} \in X: g(\mathbf{x}) < z\}$ is a strict lower set.

3) The set $\{\mathbf{x} \in X: g(\mathbf{x}) \geq z\}$ is an upper set.

4) The set $\{\mathbf{x} \in X: g(\mathbf{x}) > z\}$ is a strict upper set.

5) The set $\{\mathbf{x} \in X: g(\mathbf{x}) = z\}$ is a level set.

Definition 2 Concavity, Quasiconcavity: Suppose that X is a nonempty convex set in R^n and that $f:X \rightarrow R^1$.

1) f is concave over X if:

$f[\alpha\mathbf{x}_1 + (1 - \alpha)\mathbf{x}_2] \geq \alpha f(\mathbf{x}_1) + (1 - \alpha)f(\mathbf{x}_2)\ \forall\ \alpha \in (0,1)$ and $\forall\ \mathbf{x}_1, \mathbf{x}_2 \in X$

f is strictly concave over X if the strict inequality holds.

2) f is convex over X if:

$f[\alpha\mathbf{x}_1 + (1 - \alpha)\mathbf{x}_2] \leq \alpha f(\mathbf{x}_1) + (1 - \alpha)f(\mathbf{x}_2)\ \forall\ \alpha \in (0,1)$ and $\forall\ \mathbf{x}_1, \mathbf{x}_2 \in X$

f is strictly convex over X if the strict inequality holds.

3) f is quasiconcave if:

$f[\alpha\mathbf{x}_1 + (1 - \alpha)\mathbf{x}_2] \geq \min[f(\mathbf{x}_1),f(\mathbf{x}_2)]\ \forall\ \alpha \in (0,1)$ and $\forall\ \mathbf{x}_1, \mathbf{x}_2 \in X$

f is strictly quasiconcave over X if the strict inequality holds.
f is explicitly quasiconcave if the strict quasiconcavity holds for distinct $f(\mathbf{x}_1)$ and $f(\mathbf{x}_2)$.

Corollary 1: Every concave function is both quasiconcave and explicitly quasiconcave.

Corollary 2: Every strictly concave function is strictly quasiconcave.

Corollary 3: Every strictly quasiconcave function is both quasiconcave and explicitly quasiconcave.

Definition 3 Convex Set: Suppose that $X \subset R^n$. X is a convex set if:
$\alpha\mathbf{x}_1 + (1 - \alpha)\mathbf{x}_2 \in X\ \forall\ \alpha \in (0,1)$ and $\forall\ \mathbf{x}_1, \mathbf{x}_2 \in X$.

Theorem 4: Suppose that X is a nonempty convex set in R^n. If $g:X \to R^1$ is convex on X, then the (strict) lower set is a convex set. Conversely, if $g:X \to R^1$ is concave on X, then the (strict) upper set is a convex set.

Definition 4: A vector valued function is convex (concave) if each of its component function is convex (concave).

<u>Theorem 5</u>: Suppose that X is a convex set in R_n; $\mathbf{z} \in R^h$; $\mathbf{G}$:X $\rightarrow R^h$ is convex on X; and that $\mathbf{K}$:X $\rightarrow R^h$ is concave on X. Then, by Theorem 4 and Definition 2,

1) The lower set $\{\mathbf{x} \in X: \mathbf{G}(\mathbf{x}) \leq \mathbf{z}\}$ is a convex set.

2) The strict lower set $\{\mathbf{x} \in X: \mathbf{G}(\mathbf{x}) < \mathbf{z}\}$ is a convex set.

3) The upper set $\{\mathbf{x} \in X: \mathbf{K}(\mathbf{x}) \geq \mathbf{z}\}$ is a convex set.

4) The strict upper set $\{\mathbf{x} \in X: \mathbf{K}(\mathbf{x}) > \mathbf{z}\}$ is a convex set.

<u>Theorem 6 Kuhn-Tucker Sufficiency Theorem (Equivalence Theorem)</u>: Suppose $\mathbf{x}^o$ is a local maximum solution to a nonlinear programming problem. If the feasible region is a convex set, and if the objective function is differentiable and concave over the feasible region, then $\mathbf{x}^o$ is a global maximum solution (Kuhn and Tucker, 1951).

The concavity and convexity requirements in the Kuhn-Tucker theorem are relaxed to the quasiconcavity and quasiconvexity requirements in the Arrow-Enthoven sufficiency theorem. These relaxed requirements have widened the scope of applicability of nonlinear programming (Chiang, 1984, p. 744).

<u>Theorem 7 Arrow-Enthoven Sufficiency Theorem</u>: Assume that the objective function of a nonlinear programming problem, $\pi(\mathbf{x})$, is differentiable and quasiconcave over the feasible region, and that every constraint function $(z_. - g_.(\mathbf{x}))$ is differentiable and quasiconcave over the feasible region. Let $\mathbf{x}^o$ satisfy the Kuhn-Tucker conditions, and let one of the following conditions be satisfied:

1) $\partial\pi(\mathbf{x}^o)/\partial x_i < 0$ for at least one variable x_i

2) $\partial\pi(\mathbf{x}^o)/\partial x_i > 0$ for some variable x_i which is in the feasible region

3) $\partial\pi(\mathbf{x}^o)/\partial x_i \neq 0$ for at least one variable x_i and $\pi(\mathbf{x})$ is twice differentiable in the neighborhood of $\mathbf{x}^o$

4) $\pi(\mathbf{x})$ is concave.

Then $\mathbf{x}^o$ maximizes $\pi(\mathbf{x})$ subject to the constraints $\mathbf{z} - \mathbf{G}(\mathbf{x}) \geq \mathbf{0}$, $\mathbf{x} \in \Omega$ (Arrow and Enthoven, 1961).

Unfortunately, there is a possibility that some component functions of the vector function **G** which represents effluent production functions may be neither quasiconcave nor quasiconvex over Ω. For example, a lack of synchronization between soil nitrogen availability and crop nitrogen requirement caused by disproportionate use of irrigation water and nitrogen fertilizer leads to more nitrogen losses even with less use of both inputs. In this case, there is no guarantee that a local maximum solution provided by a nonlinear programming software is a true global optimum solution for the problem. However, linear programming (LP) provides an acceptable framework for solving the problem involving multiple crops, multiple soil types, and multiple types of effluent discharges.

Linear Programming

A linear programming model can be represented by following general form:

$$\begin{aligned} &\text{maximize}(\mathbf{x}): && \mathbf{c}'\mathbf{x} \\ &\text{subject to:} && \mathbf{A}\mathbf{x} \leq \mathbf{b} \\ & && \mathbf{x} \geq \mathbf{0} \end{aligned} \tag{2.25}$$

where **A** is a matrix of constants, **c** and **b** are constant vectors, and **x** is an activity vector. Since a linear programming problem is a special case of nonlinear programming problems, the nonlinear programming theory pertaining to necessary conditions and sufficient conditions strictly applies also to the linear programming problem. In the linear programming model, however, both the objective function and constraint functions are linear functions, which are concave as well as convex. Hence, a local optimum solution to a linear programming problem is always a global optimum solution to the problem.

A reformulation of the problem (2.23) in a more explicit linear programming framework is:

$$\begin{aligned} \text{maximize}(\mathbf{x}): \quad & \pi(\mathbf{x}) = \mathbf{p}'\mathbf{F}\mathbf{x} - \mathbf{w}'\mathbf{x} \\ \text{subject to:} \quad & \mathbf{A}\mathbf{x} \le \mathbf{b} \\ & \mathbf{G}\mathbf{x} \le \mathbf{z} \\ & \mathbf{x} \ge \mathbf{0} \end{aligned} \tag{2.26}$$

where **x** is an nx1 vector of farm production activity levels; **F** is an mxn coefficient matrix representing technological relationships between activities and output; **A** is an kxn technical coefficient matrix; **b** is an kx1 vector of RHS values; **G** is an hxn coefficient matrix representing relationships between activities and the magnitude of effluent discharges; **z** is an hx1 vector of emission limits imposed on the farm; **p** is an mx1 vector of product prices; and **w** is an nx1 vector of unit costs for activities.

Suppose that $\mathbf{x}^*$ is a global maximum solution to the linear programming problem (2.26) and assume that $\boldsymbol{\lambda}$ and $[\mathbf{b} - \mathbf{A}\mathbf{x}]$ are conformably partitioned as:

$$\boldsymbol{\lambda}^* = [\boldsymbol{\lambda}_1^{*\prime}, \boldsymbol{\lambda}_2^{*\prime}]'$$

$$[\mathbf{b} - \mathbf{A}\mathbf{x}^*] = [(\mathbf{b}_1 - \mathbf{A}_1\mathbf{x}^*)', (\mathbf{b}_2 - \mathbf{A}_2\mathbf{x}^*)']'$$

where $\boldsymbol{\lambda}_1^* = \mathbf{0}$ and $\boldsymbol{\lambda}_2^* > \mathbf{0}$. Assume further that $\boldsymbol{\mu}$ and $[\mathbf{z} - \mathbf{G}]$ are conformably partitioned as:

$$\mu^* = [\mu_1^{*\prime}, \mu_2^{*\prime}]'$$

$$[z - Gx^*] = [(z_1 - G_1x^*)', (z_2 - G_2x^*)']'$$

where $\mu_1^* = 0$ and $\mu_2^* > 0$. Then x^* is the global maximum solution to the following problem:

$$\text{maximize}(x): \quad \pi(x) = p'Fx - w'x$$

$$\text{subject to:} \quad A_2x = b_2$$

$$G_2x = z_2 \tag{2.27}$$

The Lagrangian to the problem is

$$L(x,\lambda_2,\mu_2;\ p,w,b_2,z_2) = p'Fx - w'x + \lambda_2'(b_2 - A_2x) + \mu_2'[z_2 - G_2x] \tag{2.28}$$

Since the problem (2.28) is simply a classical programming problem, the theory pertaining to the classical programming problem can be readily applied. Suppose the parameters to the problem are fixed at (p^o,w^o,b_2^o,z_2^o). Necessary conditions for a solution to occur at x^o are that there exist λ_2^o and μ_2^o such that

$$L_x(x^o,\lambda_2^o,\mu_2^o;\ p^o,w^o,b_2^o,z_2^o) = p^{o\prime}F - w^{o\prime} - \lambda_2^{o\prime}A_2 - \mu_2^{o\prime}G_2 = 0$$

$$L\lambda_2(x^o,\lambda_2^o,\mu_2^o;\ p^o,w^o,b_2^o,z_2^o) = b_2^o - A_2x^o = 0$$

$$L_{\mu 2}(x^o,\lambda_2^o,\mu_2^o;\ p^o,w^o,b_2^o,z_2^o) = z^o{}_2 - G_2x^o = 0 \tag{2.29}$$

To justify writing the endogenous variables as functions of the exogenous variables, the utilization of the implicit function theorem is essential.

<u>Theorem 8 Implicit Function Theorem</u>: Suppose a vector function $\mathbf{E}(\mathbf{x},\boldsymbol{\alpha})$ where $\mathbf{E}:R^{n+m} \rightarrow R^n$, $\mathbf{x} \in R^n$ is a vector of endogenous variables, and $\boldsymbol{\alpha} \in R^m$ is a vector of exogenous variables. Consider the system of equations $\mathbf{E}(\mathbf{x},\boldsymbol{\alpha}) = \mathbf{0}$. If there exist $\mathbf{x}^o \in R^n$ and $\boldsymbol{\alpha}^o \in R^m$ such that all of the following conditions hold:

1) $\mathbf{E}(\mathbf{x}^o,\boldsymbol{\alpha}^o) = \mathbf{0}$

2) $\mathbf{E}$ is continuously differentiable to degree $c \geq 1$ at $(\mathbf{x}^o,\boldsymbol{\alpha}^o)$

3) $\partial\mathbf{E}(\mathbf{x}^o,\boldsymbol{\alpha}^o)/\partial\mathbf{x}$ is nonsingular

then there exists an implicit vector function $\mathbf{X}:R_m \rightarrow R^n$ and an open neighborhood N of $\boldsymbol{\alpha}^o$ such that all of the following conditions hold:

1) $\mathbf{E}[\mathbf{X}(\boldsymbol{\alpha}),\boldsymbol{\alpha}] = \mathbf{0} \quad \forall\, \boldsymbol{\alpha} \in N$

2) $\mathbf{X}(\boldsymbol{\alpha}^o) = \mathbf{x}^o$

3) $\mathbf{X}$ is continuously differentiable to degree c on N.

If the system of equations (2.29) is continuously differentiable over some open neighborhood of $(\mathbf{p}^o,\mathbf{w}^o,\mathbf{b}_2^o,\mathbf{z}_2^o)$, and if the endogenous-variable Jacobian matrix to the system of equations (2.29) is nonsingular, then, by the implicit function theorem, there exist choice functions $\mathbf{X}^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$, $\boldsymbol{\lambda}_2^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$, and $\boldsymbol{\mu}_2^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$ such that $\mathbf{x} = \mathbf{X}^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$, $\boldsymbol{\lambda}_2 = \boldsymbol{\lambda}_2^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$, and $\boldsymbol{\mu}_2 = \boldsymbol{\mu}_2^o(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$ solve the first-order conditions for all $(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$ in some open neighborhood of $(\mathbf{p}^o,\mathbf{w}^o,\mathbf{b}_2^o,\mathbf{z}_2^o)$.

Clearly, the linear system (2.29) is continuously differentiable at every $(\mathbf{x},\boldsymbol{\lambda}_2,\boldsymbol{\mu}_2,\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2)$, and the endogenous-variable Jacobian matrix to the linear system is always nonsingular since $[\mathbf{A}_2',\mathbf{G}_2']'$ is of full column rank by the Kuhn-Tucker conditions. Hence the economic meaning pertaining to each variable of the linear programming problem is at one's disposal. Now, consider the farm problem (2.26) again. The original emission limits imposed on the farm by the regulatory agency were assumed to be $\mathbf{z}$. If the farmer is rational, however, there is no need to impose restrictions on all kinds of emissions. The agency needs to impose restrictions only on the kinds of emissions that fall under the category of $\mathbf{z}_2$, which is a reduced set of the original restrictions. This vector of binding emission limits ($\mathbf{z}_2^*$) conforming to the optimum solution represents nonpoint standards.

The second pollution control policy parameter is a set of economic incentives the farm operator would be confronted with for reducing pollutant emissions to the levels that are equal or below the limit prescribed by the regulatory agency. This set of economic incentives represents nonpoint incentives. In terms of mathematical economics theory, nonpoint incentives can be obtained from equation (2.28) using the envelope theorem:

$$\boldsymbol{\mu}_2^* = \partial\pi^*(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2^*)/\partial\mathbf{z}_2 = \partial L(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2^*)/\partial\mathbf{z}_2 \qquad (2.30)$$

The existence of $\boldsymbol{\mu}_2^*$, which is interpreted as a vector of shadow prices of binding emission limits, is guaranteed by the implicit function theorem. The original limits on emissions, which is $\mathbf{z}$, would be achieved by imposing $\boldsymbol{\mu}_2^*$ as effluent taxes on effluents associated with the binding limits. There are some alternative ways to charge these effluent taxes. Each alternative is equally efficient in the economic sense, but has quite different equity implications. Effluent taxes charged to every unit of effluent ($\boldsymbol{\mu}_2^{*\prime}\mathbf{G}_2\mathbf{x}$) would significantly decrease net returns to the farm relative to effluent taxes charged to the excess effluents over the emission limits [($\boldsymbol{\mu}_2^{*\prime}(\mathbf{G}_2\mathbf{x} - \mathbf{z}_2^*)$)], even though the resultant effluent discharge levels for both cases would be exactly the same if the farmer is rational. In the empirical analysis chapter (Chapter V), the equity implications of the alternative ways of charging the effluent taxes will be discussed. Also the changes in both composition and values of $\boldsymbol{\mu}_2^*$ with respect to changes in the vector of emission limits $\mathbf{z}$ will be discussed in the empirical analysis chapter.

The third pollution control policy tool, which enforces certain crop mixes and input use levels, represents management practice standards. The management practice standards are defined by a vector of choice functions $\mathbf{x}^* = \mathbf{X}^*(\mathbf{p},\mathbf{w},\mathbf{b}_2,\mathbf{z}_2^*)$. The last pollution control policy tool, management practice incentives, uses $\boldsymbol{\mu}_2^{*\prime}\mathbf{G}_2$ as a vector of charges on corresponding activity levels undertaken by the farmer. The total amount of management practice incentives paid by the farmer would be $\boldsymbol{\mu}_2^{*\prime}\mathbf{G}_2\mathbf{x}^*$ since the rational farmer would adopt the optimal production activities $\mathbf{x}^*$. Consequently, all four policy options induce the least-cost rearrangement of production activities to comply with the given policy goal. In this sense, the four policies are equally efficient, even though administration costs may be different. The decrease in net returns to the farmer can be compensated through lump-sum payments without losing economic efficiency.

Monitoring effluent discharges from agriculture is extremely difficult since most cases of water pollution from agriculture appertain to nonpoint source pollution that cannot be traced to a specific spot. However, monitoring effluent discharges is not necessary to implement the four policy tools in the above framework. If the linkage between production activities and effluent generation is explicitly included in the analysis, the levels of effluent discharges can be estimated whenever production activities are known. The use of a crop growth/chemical movement simulation model like EPIC-PST (Sabbagh et al.) provides technical data showing the linkages for the analysis.

In Chapter 5, alternative policy scenarios of changing certain elements of vectors **w** and/or **b** (e.g., total nitrogen use limits, taxes on nitrogen and pesticide use, limits on the total quantity of groundwater use, taxes on groundwater use, etc.) will also be tested to determine whether the policy goal can be attained through policy options incurring less policy transaction costs than the above four efficient policy options.

CHAPTER III

THE EMPIRICAL MODELS

As stated in the first chapter, the primary objective of this study is assessing both economic and environmental consequences of alternative water quality policies on a typical farm in the study area. Thus, the empirical analysis requires agronomic, biochemical, hydrologic, and economic information. To meet these requirements, the analysis proceeds in a two-stage simulation involving crop growth/chemical movements and economic optimization. This chapter outlines the empirical framework used for the farm-level economic analysis of agricultural pollution control.

The entire modelling framework is presented in Figure 4. The modeling procedure centers around the biophysical simulator and the mathematical programming model. Input sets for the biophysical simulator are site characteristics and crop management practices. The former input set includes weather, topography of the land, and chemical/physical properties of major soils in the study area. The latter input set includes crop management practices, such as tillage, fertilizer and pesticide applications, and irrigation. The biophysical simulator provides crop yield and the magnitude of effluents from alternative crop management practices. The mathematical programming model links operating costs, prices, outputs of EPIC-PST simulation, and pollution control policy alternatives. An intermediate step involves calculating operating costs using the Expanded Budget Generator (Norris, 1990). The outputs of the

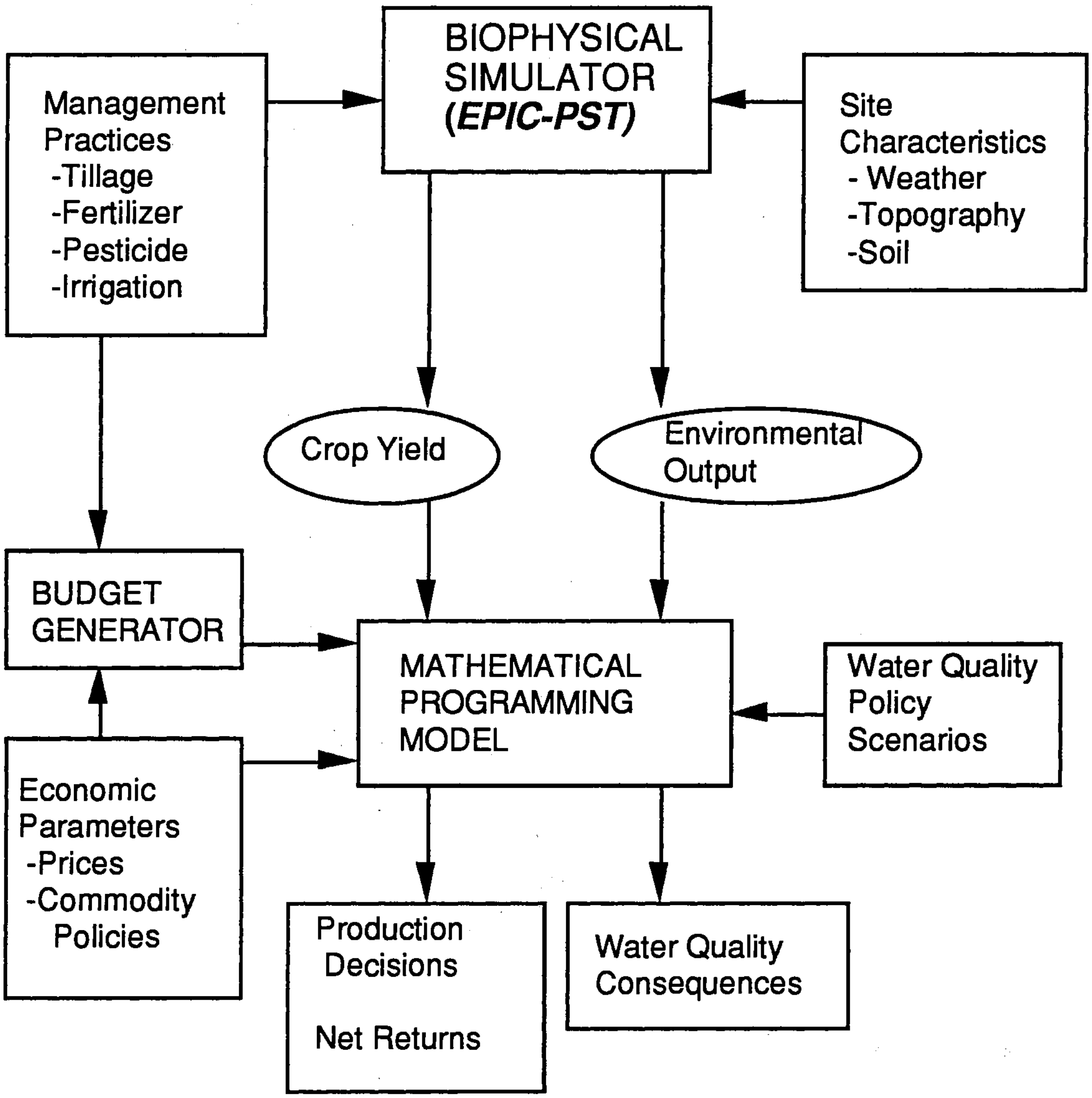

Figure 4. Overall Modeling Framework

mathematical programming model include optimal production decisions, net returns, and water quality consequences. Based on these results, the evaluation of the effectiveness and impact of alternative policies is conducted.

EPIC-PST: A Biophysical Simulation Model

In most cases, agricultural pollution is nonpoint source pollution that cannot be traced to a specific spot with reasonable accuracy and at reasonable cost. Bailey and Swank (1983, p. 29) characterize agricultural nonpoint source pollution as:

1. Nonpoint source discharges are diffuse in nature and primarily occur during rainfall events when storm runoff from the land surface carries sediment, sediment-adsorbed chemicals, and dissolved chemicals (nutrients, pesticides, heavy metals, easily oxidizable organics) into receiving water systems. Dissolved chemicals may also percolate through soil to interflow regions and groundwater which may eventually reappear in surface waters as baseflow.

2. Nonpoint source pollution is stochastic and dynamic and has multimedia dimensions. It is dynamic in the sense that land uses and configurations change over time making the pollutant mix vary both spatially and temporally.

3. Nonpoint source discharge of some chemicals may have no apparent direct adverse impacts in the receiving medium. However, intermedia transfer, together with the formation of degradation products, may be cause for concern in other media.

The potential for discharge of dissolved or adsorbed chemicals is related to chemical, topographical, and chemical/physical characteristics of the soil, and crop production management practices, such as tillage, crop rotations, irrigation, fertilizer use, and pesticide applications. Furthermore, as stated above, the magnitude of agricultural effluent discharges is stochastic in nature due, in part, to the stochastic weather process. Thus, policy analysts must rely on a biophysical simulation model that can represent both the complex characteristics of the agricultural nonpoint source pollution problem and the relationships between farm management practices, crop production, and environmental outputs.

Several crop growth or environmental flow simulation models such as CREAMS (Knisel, 1980), EPIC (Williams et al., 1984), DRASTIC (Kerr, 1985), CERES-MAIZE (Jones and Kiniry, 1986), GLEAMS (Leonard et al., 1987), PNUTGRO (Boote et al, 1988), SOYGRO (Jones et al., 1989), and EPIC-PST (Sabbagh et al., 1991) are available in the literature. Among them, CREAMS, DRASTIC, and GLEAMS do not provide information on crop growth because they are developed to simulate mainly pesticide and/or nutrient activities. On the other hand, CERES-MAIZE, PNUTGRO, and SOYGRO are not able to provide information on chemical related activities since they are crop growth-oriented models.

The EPIC (Erosion Productivity Impact Calculator) model (Williams et al., 1983, 1984, 1989) was developed to determine the relationship between soil erosion and soil productivity . It is a mathematical model consisting of subroutines for simulating soil erosion, crop growth, and related processes. Major components of EPIC consist of weather, hydrology, erosion-sedimentation, nutrient cycling, crop growth, tillage, soil temperature, economics, and crop environment control (Williams et al., 1984). EPIC is efficiently and conveniently applicable to a wide range of soils, climates, and crops in the United States because major input data, such as weather, soils, crop parameters, and tillage/operation parameters, are readily available from EPIC data files. Daily precipitation, air temperature, and solar radiation can be either read from the user-supplied data file or simulated by the weather subprogram itself. If daily maximum and minimum air temperature and solar radiation are simulated by the weather subprogram, they are generated from a multivariate normal distribution. Snowfall is determined by precipitation and air temperature.

The hydrology subprogram simulates runoff, lateral subsurface flow, drainage, and percolation as functions of daily rainfall and irrigation. The runoff model uses the SCS curve number equation (USDA Soil Conservation Service, 1972) to predict surface runoff volume. The percolation model of EPIC uses a storage routing technique to predict water flow through soil layers. If soil water content exceeds field capacity, then water flow from a layer occurs. Water drainage stops when the water content returns to field capacity. Lateral subsurface flow is estimated simultaneously with percolation.

Nitrogen and phosphorus are two plant nutrients EPIC considers. EPIC predicts nitrate loss with surface runoff, organic nitrogen loss with sediment loss, nitrate loss with percolation, upward nitrate movement by evaporation, and crop uptake, given fertilizer application, precipitation, and irrigation. Also it simulates soluble phosphorus with runoff, and mineral and organic phosphorus loss with sediment.

A general plant growth model is used in EPIC for simulating above-ground biomass, yield, and roots of all considered crops (corn, grain sorghum, wheat, barley, oats, sunflower, soybean, alfalfa, cotton, peanuts, potatoes, Durham wheat, winter peas, faba beans, rapeseed, sugarcane, sorghum hay, range grass, rice, cassava, lentils, and pine trees). Each crop has its own crop parameters for the plant growth simulation. EPIC is capable of accommodating multiple crops during a year and any crop rotation. The plant growth subroutine simulates energy interception, energy conversion, and plant uptake of water and nutrition. Water, nutrient, and air temperature stresses constrain crop growth.

The EPIC tillage subprogram simulates the change in soil bulk density, the transition from standing crop residue to flat residue, and mixing of soil layers, nutrients, and crop residues within the plow depth. The EPIC farm machinery data file lists about 50 types of farm equipment and related data. The data can be modified or equipment can be added to the data file to better suit the user's local conditions.

Management practice information for EPIC simulation runs is supplied by the user based on various operation codes (Sharpley and Williams, 1990b). The irrigation code specifies the irrigation technology (sprinkler, furrow, dryland). Two modes of irrigation, manual and automatic, are available. With manual irrigation, the user specifies the irrigation dates and volumes of water to be irrigated. With automatic irrigation, the user specifies the minimum application interval in days and the water stress factor between 0 and 1. If the plant water stress factor reaches the specified level after the specified minimum application interval, EPIC triggers automatic irrigation. The user can regulate individual irrigation volume by specifying the minimum and maximum volumes allowed for single irrigation. Total irrigation volume allowed for a year can be limited by the user. Operation codes for two nitrogen fertilizer application modes function much like irrigation codes.

In EPIC, the user can provide the tillage operations listed by date and operation identification number. For planting and harvesting operations, the crop identification number, date of operation, and the operating equipment can be specified. If the manual fertilizer application mode is selected, the user can specify the date, rate, and depth of individual application. Likewise, if the manual irrigation mode is selected, the user can specify the date and volume of individual irrigations.

The EPIC model has been extensively evaluated and validated at various locations in the continental United States and in Hawaii (Sharpley and Williams, 1990a). Evaluation results indicate that the EPIC model simulates weather, soil erosion, nutrient loss, and crop yield with reasonable accuracy.

Even though EPIC is capable of simulating soil erosion, nutrient losses, and crop growth reasonably well, it is not capable of simulating pesticide activities. The need for a more comprehensive mathematical model that can simultaneously simulate the effects of different agricultural practices on crop yield and nutrient/pesticide losses by surface runoff, sediment movement, and leaching below the crop root zone has prompted the development of EPIC-PST (Sabbagh et al., 1991). EPIC-PST is developed by incorporating pesticide subroutines of the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model into EPIC. GLEAMS is a mathematical model that simulates the impacts of agricultural management practices on the movement of pesticides into, within, and through the crop root zone, as well as the runoff and sediment transport of pesticides (Leonard et al., 1987). EPIC-PST uses the same parameter editor developed for the pesticide component of GLEAMS. The user can provide the date and rate of individual pesticide application, depth of incorporation when a pesticide is incorporated into the soil, and pesticide characteristics such as water solubility, foliar residue half-life, partitioning coefficient (ratio of the concentration of pesticide in organic carbon to concentration of pesticide in water), and soil half-life.

The resulting model can simulate nutrient and pesticide losses by surface runoff, sediment movement, and leaching below the soil profile as well as the effects of different agricultural management practices in a specific soil on crop yield. Ability of EPIC-PST to simulate chemical movements has been validated by comparing simulated results with observed data from Ben Hur

Research Farm, Baton Rouge, Louisiana, and a farm which is located near Tifton, Georgia (Sabbagh et al., 1991). Ability to simulate crop yields also has been validated by comparing simulated yields with yield data for four crops (wheat, grain sorghum, corn, and alfalfa) from the Panhandle Research Station, Goodwell, Oklahoma (Mapp et al., 1991). Simulated crop yields for the soils and production practices under both irrigated and dryland conditions in Caddo County are higher than county averages, but match the yields experienced by highly-managing farm operators in the area reasonably well (Beerwinkle, 1992). Field data on chemical movements do not exist for Caddo County, so field validation of that component of the model was not possible. Nevertheless, chemical movements were predicted using EPIC-PST, and the analysis was based on those predictions.

The Mathematical Programming Model

Basic Assumptions

The response of the farmer to alternative water quality policies can be simulated using a mathematical programming model. The primary role of the mathematical programming model is the efficient allocation of limited resources among various production enterprise alternatives. Furthermore, the farm level mathematical programming model in this study needs to be capable of evaluating both the economic and environmental impacts of alternative water quality policies. Nonlinear programming is not considered to be capable of providing an acceptable framework for solving the problem since EPIC-PST simulation results indicate that the functional form of the effluent production function is not quasiconcave. Instead, linear programming is chosen for the analysis of the economic and environmental consequences of alternative water quality policies.

A general form of the maximizing linear programming model may be described as:

$$\text{maximize}(\mathbf{x}): \quad \mathbf{c}'\mathbf{x}$$
$$\text{subject to:} \quad \mathbf{A}\mathbf{x} \geq \mathbf{b}$$
$$\mathbf{x} \geq \mathbf{0}$$

where **x** is a n x 1 vector of activities, **c** is a n x 1 vector of objective function coefficients, **A** is a m x n matrix of technical coefficients, and **b** is a m x 1 vector of resource endowments.

A number of assumptions are implicit in the generalized linear programming model. The assumptions are (Hazell and Norton, 1986, pp. 12-13):

1. Determinism: all coefficients in the model are assumed to be known with certainty.
2. Additivity: interaction effects between activities are not permitted.
3. Continuity: both activities and resources uses can be fractional units.
4. Homogeneity: all units of the same resources or activities are identical.
5. Proportionality: gross margin and resource requirements per unit of activity are assumed to be constant regardless of the level of the activity used.

In this study, it is assumed that the objective of the farmer is to maximize net returns (returns above total operating cost) from crop production subject to the resource endowments and water quality policy parameters. If a standard policy, such as the maximum level of effluents the farm may discharge, is imposed at the farm level, then the farm problem may be formulated in a more explicit linear programming model as follows:

$$\begin{aligned} \text{maximize}(\mathbf{x}): \quad & \pi(\mathbf{x}) = \mathbf{p}'\mathbf{F}\mathbf{x} - \mathbf{w}'\mathbf{x} \\ \text{subject to:} \quad & \mathbf{A}\mathbf{x} \leq \mathbf{b} \\ & \mathbf{G}\mathbf{x} \leq \mathbf{z} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned}$$

where **x** is a n x 1 vector of farm production activity levels, **F** is a m x n matrix of coefficients representing relationships between activities and output, **A** is a k x n matrix of technical coefficients, and **b** is a k x 1 vector of right hand side (RHS) values, **G** is a h x n matrix of coefficients representing relationships between farming activities and effluent generation, **z** is a h x 1 vector of effluent limits set by the regulatory agency, **p** is a m x 1 vector of output prices, and **w** is a n x 1 vector of unit costs for activities. The matrix of coefficients representing relationships between farming activities and effluent generation (**G**) is assumed to be known to both the farmer and the regulatory agency. If economic incentives such as effluent taxes are imposed, then the farm problem may be reformulated as:

$$\begin{aligned} \text{maximize}(\mathbf{x}): \quad & \pi(\mathbf{x}) = \mathbf{p}'\mathbf{F}\mathbf{x} - \mathbf{w}'\mathbf{x} - \boldsymbol{\mu}'\mathbf{G}\mathbf{x} \\ \text{subject to:} \quad & \mathbf{A}\mathbf{x} \leq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned}$$

where $\boldsymbol{\mu}$ denotes a vector of effluent taxes.

To reduce the mathematical programming model to a manageable size, certain simplifying assumptions are necessary. Although these assumptions may not be exact descriptions of the farm situation in the study area, they are necessary for developing a set of mathematical programming models sufficiently comprehensive and detailed to address the objectives of the analysis. The assumptions are as follows:

1. The hypothetical farm consists of four different soils that have different yield and hydrologic implications.
2. The farmer has the choice of producing four crops (wheat, peanuts, cotton, grain sorghum) which dominate crop production in the study area.
3. The farmer has the choice of producing each of the four crops under 9 different input levels - 3 irrigation levels (High, Medium, Dryland) and 3 different nitrogen application levels (High, Medium, Low) for each irrigation level.
4. Both the tillage system and the set of pesticides used for each crop are fixed, and represent the most common tillage practices and pesticides used by study area producers.
5. The regulatory agency has information for setting the acceptable standards of environmental quality that must be met in order to achieve a reasonable water quality.

The first assumption is necessary to keep the size of the mathematical programming model manageable, while representing most of soils of the study area without sacrificing accuracy. The fourth assumption also is required keep the number of EPIC-PST runs and activities in the mathematical programming model within a manageable size. The third assumption is necessary to provide the economic model more flexibility in choosing profitable cropping systems while easily complying with the given water quality policies.

Model Formulation

Benefits which accrue from peanut and cotton rotations are well documented in the literature. Peanuts are quite susceptible to attack by nematodes and soil-borne diseases, and should be rotated with other crops such as small grain or grain sorghum that are not susceptible to the same pathogens (Woodroof, 1983). Cotton rotations with grain sorghum, small grain, or legumes decrease the incidence and severity of diseases and weed problems (Bell, 1984; Chandler, 1984). Higgs et al. (1990) argue that crop rotations that include grain and forage crops are profitable and contribute to a sustainable agriculture.

The importance of peanut and cotton rotations requires adequate modeling of multi-year crop rotations. In addition, the model should allow flexibility in choosing input use levels associated with each rotation system and free adjustment in response to pollution control policy restrictions. Before presenting rotational combinations that are actually adopted by farmers in the study area, certain simplifying assumptions on agronomic matters that reflect the crop production environment of the study area need to be mentioned. The assumptions are:

1. The yields of peanuts and cotton depend on rotation crops grown during the previous two years because of rotational effects. The second year peanut production following the first year peanuts would require more pesticide application (e.g., full label dose and/or more frequent treatment) and result in certain percentage of yield reduction. Three-year continuous peanut production on the same soil is assumed not feasible due to adverse yield impacts. Three-year continuous cotton production is feasible, however, would result in increasing yield reduction year by year. Details on the yield effects are discussed in the following chapter.
2. Peanuts are extremely sensitive to the effects of other crops grown in the rotation. Furthermore, peanuts and cotton have common pests

such as nematodes, thrips, and mites. Thus, rotations composed of only peanuts and cotton are not economically viable and are, hence, not included in the analysis.

3. The quantity of nitrogen fertilizer or the volume of irrigation water applied in the previous two years does not affect yield in the third year because the soil loses residual nitrogen through runoff or percolation below the crop root zone and recovers the moisture level during the period following harvest. This assumption is realistic since even the highest nitrogen level specified for the crop growth/chemical movement simulation is below the level that causes accumulation of excess nitrogen in the soil. In addition, the mean annual precipitation in the study area is about 30 inches. However, this assumption is not applied to double cropping systems since preceding crop management practices have considerable impact on the soil moisture and nitrogen carryover for the following crop.
4. Peanuts or cotton may not be planted right after harvesting wheat. Only grain sorghum can be planted right after wheat harvest as a double crop activity. This wheat/grain sorghum double crop can be practiced at most in one of every three years.
5. Wheat may not be planted right after harvesting cotton, but may be planted right after harvesting grain sorghum or Spanish type peanuts that can be grown in short-season conditions. Either grain sorghum/wheat or peanuts/wheat double cropping can be practiced at most in one of every three years.
6. When wheat and grain sorghum are grown as a double crop activity, or when wheat is planted right after harvesting peanuts or grain sorghum, each crop has an effect on operating costs and yield for the

other crop since soil moisture, tillage practices, planting period, and harvesting period for each crop depend on that of the other crop placed in the double crop activity. If wheat or grain sorghum is grown after an ordinary fallow period, then there will be no yield reduction regardless of the preceding crop placed in the rotation.

Considering the above assumptions on agronomic matters, 23 cropping systems involving the four crops are identified: (1) Peanuts-Peanuts-Grain sorghum (P-P-G); (2) Peanuts-Grain sorghum-Grain Sorghum (P-G-G); (3) Peanuts-Cotton-Grain sorghum (P-C-G); (4) Grain sorghum-Grain sorghum-Cotton (G-G-C); (5) Grain sorghum-Cotton-Cotton (G-C-C); (6) Peanuts-Peanuts-Wheat/Grain sorghum (P-P-W/G); (7) Grain sorghum-Peanuts-Wheat/Grain sorghum (G-P-W/G); (8) Cotton-Peanuts-Wheat/Grain sorghum (C-P-W/G); (9) Peanuts-Grain sorghum-Wheat/Grain sorghum (P-G-W/G); (10) Grain sorghum-Grain sorghum-Wheat/Grain sorghum (G-G-W/G); (11) Cotton-Grain sorghum-Wheat/Grain sorghum (C-G-W/G); (12) Peanuts-Fallow-Wheat/Grain sorghum (P-F-W/G); (13) Grain sorghum-Fallow-Wheat/Grain sorghum (G-F-W/G); (14) Cotton-Fallow-Wheat/Grain sorghum (C-F-W/G); (15) Peanuts-Wheat-Wheat/Grain sorghum (P-W-W/G); (16) Grain sorghum-Wheat-Wheat/Grain sorghum (G-W-W/G); (17) Fallow-Wheat-Wheat/Grain sorghum (F-W-W/G); (18) Continuous Grain sorghum; (19) Continuous cotton; (20) Continuous wheat; (21) Peanuts-Wheat/Grain sorghum (P-W/G); (22) Grain sorghum-Wheat/Grain sorghum (G-W/G); and (23) Fallow-Wheat/Grain sorghum (F-W/G), where "-" separates crop years and "/" separates double crops within a year.

In the previous section, it was assumed that the farmer has the choice of producing each of the four crops under 9 different input levels - 3 irrigation levels (High, Medium, Dryland) and 3 different nitrogen application levels (High, Medium, Low) for each irrigation level. The purpose of this assumption is to provide the mathematical programming model more flexibility in choosing profitable production activities while complying with the given water quality policy options. No doubt, sometimes changing the cropping system is more profitable than changing the input level within the system. However, when a rotation system is much more profitable than the others, changing the input level within the more profitable cropping system would bring less profit loss than changing to another cropping system. With the choice of various input levels within a cropping system, the economic model may freely change the input levels within the profitable cropping system to comply with the given water quality constraints. Otherwise, the economic model has to choose among other cropping systems with greater profit losses. In that case, economic impacts of water quality policies may be exaggerated. In this context, providing the economic model with flexibility in choosing alternative input levels within a cropping system is necessary. One important problem associated with the provision of multiple input levels in a cropping system is the exponentially increasing number of activities. To keep the empirical model to a manageable size, a special modeling approach is needed.

Suppose that the yield of a crop depends on the crops grown on the same soil in the previous two years because of rotational effects. Suppose further that the nitrogen application and irrigation levels of the previous years do not affect yield the following year because the soil loses residual nitrogen through runoff or percolation below the crop root zone and recovers the moisture level during the period following harvest. Consider three-year crop rotation systems peanuts-cotton-grain sorghum (P-C-G), cotton-grain sorghum-grain sorghum (C-G-G), and cotton-cotton-grain sorghum (C-C-G) that have the choice of high (H), medium (M), and low (L) input levels for each crop within the rotation systems. This farm situation leads to a rotation model with activities and constraints as in Table 3.

To illustrate, suppose we wish the model to yield a three-year rotation system of peanuts with the high input level followed by cotton with the medium input level followed by grain sorghum with the low input level (PH-CM-GL). This rotation could be produced by a combination consists of CGPH, GPCM, and PCGL. Notice that each activity produces only one crop indicated by the last two characters. For example, CGPH produces peanuts using the high input level on the land where cotton and grain sorghum are grown in the previous two years. The objective function sums the returns to the three activities. The land constraint allows no more than the total acreage available, denoted by N in Table 3. The rotational linkages are the key element of the rotation model. Notice that CGPH, GPCM, and PCGL are interconnected by rotational constraints CG, GP, and PC. One acre of CGPH uses one acre of CG and supplies one acre of GP, one acre of GPCH uses one acre of GP and supplies one acre of PC, and one acre of PCGL uses one acre of PC and supplies one acre of CG. Therefore, the rotational constraints (CG, GP, and PC) are satisfied with binding condition. On the other hand, continuous cropping systems do not require rotational linkages since they use and supply the same rotational constraints (e.g. CCC uses CC and supplies CC). Again suppose that we wish the model to yield a two-year rotation system of cotton with the high input level followed by grain sorghum with the low input level (CH-GL). Then the model would choose CGCH and GCGL. Suppose further that we wish the model to produce a five-year rotation system PH-CH-GL-CM-GL. This rotation would be produced by choosing CGPH, GPCH, PCGL, CGCM, and GCGL.

A conventional rotation modeling method that considers explicit sequences of rotations limits the choice of rotation to the combinations that the

TABLE 3

SIMPLIFIED ROTATION MODEL

	PCGH	PCGM	PCGL	CGPH	CGPM	CGPL	GPCH	GPCM	GPCL	
PC	1	1	1				-1	-1	-1	
CG	-1	-1	-1	1	1	1				
GP				-1	-1	-1	1	1	1	
GC										
GG										
CC										
LAND	1	1	1	1	1	1	1	1	1	
	CGGH	**CGGM**	**CGGL**	**GGCH**	**GGCM**	**GGCL**	**GCGH**	**GCGM**	**GCGL**	
PC										
CG	1	1	1				-1	-1	-1	
GP										
GC				-1	-1	-1	1	1	1	
GG	-1	-1	-1	1	1	1				
CC										
LAND	1	1	1	1	1	1	1	1	1	
	CCGH	**CCGM**	**CCGL**	**CGCH**	**CGCM**	**CGCL**	**GCCH**	**GCCM**	**GCCL**	
PC										≤0
CG	-1	-1	-1	1	1	1				≤ 0
GP										≤ 0
GC				-1	-1	-1	1	1	1	≤ 0
GG										≤ 0
CC	1	1	1				-1	-1	1	≤ 0
LAND	1	1	1	1	1	1	1	1	1	≤N

modeler develops. Furthermore, the number of activities required with the conventional modeling method increase exponentially as the number of input levels considered increases. For example, a model that can yield every combination of P-C-G-C-G rotation with three input levels would require 243 (3^5) activities. In this study, it was assumed that nine different input levels are available for production of each crop. In this case, a model considering just a single three-year rotation system in terms of explicit crop sequences would require 729 (9^3) activities, while the above rotation modeling approach requires 27 (9 x 3) activities. This remarkable reduction in the number of required activities is the primary contribution of the above modeling approach. In addition, this modeling approach has the advantage of El-Nazer and McCarl's modeling approach (1986) in that it freely determines the optimal long-run rotation.

The most common tillage practices and pesticides used by study area producers of each crop were identified through personal interviews with the County extension agent (Beerwinkle, 1991, 1992). The nine input use levels for each crop/soil combination were determined using data from numerous EPIC-PST test runs. The nine input use levels are denoted by HH, HM, HL, MH, MM, ML, LH, LM, and LL. HM stands for high irrigation and medium nitrogen application, MH stands for medium irrigation and high nitrogen application, LL stands for dryland and low nitrogen application, and so on. Except for peanuts, HH, MH, and LH use nitrogen levels which approximately equate marginal value product and marginal factor cost of nitrogen fertilizer with respect to each irrigation level, given the relative prices used in this study. Peanut yields do not change in accordance with nitrogen applications since peanuts are a legume crop. Except for peanuts, the differences in nitrogen use between the high and subsequent levels are 15-20 pounds per acre under irrigated conditions, and

10 pounds per acre for dryland. Phosphorus, potassium, and micronutrient application levels are assumed to be fixed for each crop.

For each cropping system, soil, irrigation level, and nitrogen level, a 28-year EPIC-PST simulation run was conducted using daily weather data for the study area. EPIC-PST generates a 28-year distribution of crop yields, soil erosion with runoff (USLE), nitrate loss with runoff (YNO3), mineral nitrogen loss with percolation (PRKN), pesticide (active ingredient) loss with runoff and sediment, and pesticide (active ingredient) loss with percolation for each soil-management strategy combination. The potential of pesticide losses to surface and ground water from each activity is aggregated into a single index number using a method similar to that developed by Hoag and Hornsby (1991). The surface water hazard index (I_s) is calculated as

$$I_s = \frac{\text{pesticide losses (active ingredient) with runoff and sediment}}{\text{Lethal Concentration 50}}$$

and the ground water hazard index (I_g) is calculated as

$$I_g = \frac{\text{pesticide losses (active ingredient) with percolation x 100}}{\text{Lifetime Health Advisory Level (Equivalent)}}.$$

The Lifetime Health Advisory Level or Equivalent is defined by USEPA as the concentration of a chemical in drinking water that is not expected to cause any adverse health effects over a lifetime exposure with a margin of safety. Lethal Concentration 50 is the concentration of a chemical at which 50 % of the test fish species die. In this analysis, mean values of the 28-year distributions of nitrate runoff (YNO3), nitrogen percolation (PRKN), and pesticide movements (I_s, I_g) are used. Among them, YNO3, and I_s are perceived as the potential of surface water contamination, while PRKN and I_g are perceived as the potential of ground water contamination.

To convert EPIC-PST output into the coefficient matrix of the mathematical programming model, several programs written in PASCAL language were used. For the calculation of operating costs, the Expanded Budget Generator developed by Norris (1991) is used. The entire model structure is presented in Table 4. The model contains 1,650 activities and 100 constraints.

TABLE 4

SIMPLIFIED TABLEAU OF MATHEMATICAL PROGRAMMING MODEL

	Production	Crop Sale	Water Pumping	Nitrogen Purchase	Pesticide Purchase	Soil & Chemical Movements	RHS
Objective Function	-A	B	-C	-D	-1	-1 or $-\mu_2^{*}$	
Rotational Linkages	1 or -1						
Soil Acreage Constraints	1						I
Irrigated Land Constraints	1 or 0						J
Crop Production Accounting Rows	-E	1					
Water Pumping Accounting Rows	W		-1				
Nitrogen Application Accounting Rows	F			-1			
Pesticide Cost Accounting Rows	G				-1		
Soil and Chemical Movement Accounting Rows	H					-1	
Water Pumping Constraint			1				K
Nitrogen Application Constraint				1			L
Soil and Chemical Movement Constraints						1	M

CHAPTER IV

DATA AND RELATED CONSIDERATIONS

This chapter specifies the data required for the simulation of crop growth/chemical movements and the formulation of the mathematical programming model. The crop growth/chemical movement simulation model (EPIC-PST) requires information about soil properties, weather, and management practices, including tillage, irrigation, fertilizer and pesticide uses. Output from the EPIC-PST simulation model, such as data on crop yield and environmental consequences of farm management practices, are fed into the economic model. In addition to these data, the economic model requires information about the resource endowment of the representative farm, farm program participation, price assumptions, and costs for production activities.

Production Environment of the Representative Farm

Specifying the resource endowment for the representative farm analyzed in the mathematical programming model for this study requires the determination of the total farm acreage, the nature and distribution of soils, the chemical/physical characteristics of soils, and the extent and nature of dryland and irrigated crop production. Farm operations in Caddo County vary considerably in size. According to the 1987 Census of Agriculture, for example, farms less than 50 acres in size account for 12.9 percent of total farms, while farms more than 1,000 acres account for 13.2 percent of total farms. The average size of farm in Caddo County is 469 acres. Farm types also exhibit considerable variation. In 1987, among 1,530 farms in the County, 345 farms had some irrigated acres, and the rest were strictly dryland operations. The average size of irrigated farms was 725 acres. In most cases, irrigation water is withdrawn from underground sources. The most widely adopted irrigation technology by farmers in Caddo County is the high pressure center pivot system (Beerwinkle, 1991). Considering these, a farm that has 480 acres of total cropland with 260 acres of irrigated cropland is defined as the representative farm for this study. The irrigated acreage is assumed to be covered by two one-quarter mile center pivot irrigation systems. It is difficult to determine which part of the farm can be irrigated because the hypothetical farm is assumed to have four types of soils. Thus, it is assumed that each type of soil can be irrigated.

Physical/chemical properties of soils on a farm have influence not only on crop yield but also on the magnitude of nutrient and pesticide losses. The soil series and the soil phase are the most widely used categories of soil classification (USDA Soil Conservation Service, 1973). Soils that have almost the same profiles make up a soil series. All the soils of one series have horizons that are similar in thickness, arrangement, and other important characteristics. Soils of one series may differ in texture of the surface soil and in slope, stoniness, or other characteristics. Based on such differences, a soil series is divided into several phases. A feature of a soil that affects management is indicated by the name of the soil. For example, Pond Creek fine sandy loam, 1 to 3 percent slopes, is one of several phases within the Pond Creek series. About 30 soil series are found in the Soil Survey of Caddo County. Considering the proportionate extent, suitability for major field crops, and similarity in chemical/physical properties of Caddo County soils, four phases of soils are selected as the soils composing the representative farm: they are 120 acres of Cobb fine sandy loam with 3 percent slope, 120 acres of

Grant loam with 3 percent slope, 150 acres of Pond Creek fine sandy loam with 3 percent slope, and 90 acres of Port silt loam with 3 percent slope. Soil profile characterization data for these soils are presented in Tables 19-22, Appendix.

Historic weather data (Jan. 1, 1948 - Dec. 31, 1975) for Fort Cobb, including daily precipitation, and minimum and maximum air temperatures, were used in EPIC-PST simulations. Fort Cobb is located in southwestern part of Caddo County. Solar radiation was simulated for this location by the weather subprogram in EPIC-PST.

Assumptions on Labor, Capital and Machinery Complement

In some farm-level mathematical programming models, the seasonality of labor requirements and the timing of field operations using the tractor units during critical periods of the year are taken into account. In this analysis, no constraints on seasonal availability of family labor or on the timing of field operations are included in the economic model. Labor availability or timeliness of field operations might be problematic in the case of double crop activities. However, the focus of the mathematical programming analysis is on the relationship between production practices and environmental damage. Thus, it is assumed that required labor above that provided by the operator may be hired at $5.00 per hour. In addition, tillage and other production practices are assumed to be conducted by the machinery complement that consists of a 140 HP tractor, a 90 HP tractor, and accompanying equipment owned by the farm without time conflicts. Operating costs and labor requirements associated with each field operation using machinery complements are calculated by the

Expanded Budget Generator (Norris, 1990). Operating capital is assumed to be available at an interest rate of 12 percent.

Assumptions on Irrigation Strategies

Two different center pivot irrigation technologies, high pressure center pivot and LEPA (low energy precision application) systems, are considered in the analysis. Center pivot irrigation systems are considerably more efficient than furrow irrigation systems on sandy or sandy loam soils where excessive deep percolation occurs under furrow irrigation. Center pivot systems are also capable of irrigating gently rolling land and offer improved control over application rates (Dale et al., 1989). Center pivot systems are used throughout the study area where fine sandy loam soils with up to 3 percent slopes represent the majority of the irrigated cropland.

The LEPA system is a further refinement of the center pivot system. LEPA technology offers the benefits of both high application efficiency and reduced operating pressure. This irrigation technology reduces water evaporation losses due to wind and high air temperatures, and reduces application non-uniformity problems caused by wind. LEPA systems employ drop tubes which hang from the pivot lateral and transport water to nozzles only 12 to 15 inches above the ground. When LEPA irrigation is employed, furrow dikes are often constructed around the pivot and appropriately spaced to allow direct application into the furrow dikes as the sprinkler revolves. To minimize evaporation from the soil surface, the LEPA system may apply water only into alternate furrows while irrigating more frequently (Dale et al., 1989). The furrow dikes also reduce runoff of rainfall.

Major differences between the high pressure center pivot and LEPA systems are application efficiency and energy requirements for pumping water from underground sources. The high pressure center pivot system operates at an average application efficiency of 75 percent, while the LEPA system applies water at an average application efficiency of 95 percent. The relative energy required to deliver an acre inch of water using the high pressure center pivot system is about 1.7 times the energy requirement associated with the LEPA system (Dale et al., 1989). Nevertheless, as mentioned in the preceding section, the high pressure center pivot system is the dominant irrigation technology in the study area.

In general, it is expected that the shift from high pressure center pivot irrigation to more efficient LEPA irrigation technology would reduce not only the volume of irrigation water but also the magnitude of chemical movements. Further, the volume and timing of irrigation applications influence the magnitude of chemical movements as well as crop yield. Thus, it appears that comparing the influence of different irrigation technology/irrigation management strategies on crop yield and chemical movements would provide important economic and water quality implications. Considering these, the two irrigation technologies, high pressure center pivot and LEPA irrigation systems, and the four irrigation management strategies, are combined to formulate four irrigation scenarios: they are (1) high pressure center pivot system-maximum single irrigation volume of 4 acre inches-minimum irrigation interval of 14 days (High 4-14); (2) high pressure center pivot system-maximum single irrigation volume of 3 acre inches-minimum irrigation interval of 7 days (High 3-7); (3) LEPA system-maximum single irrigation volume of 3 acre inches-minimum irrigation interval of 10 days (LEPA 3-10); and (4) LEPA system-maximum single irrigation volume of 2 acre inches-minimum irrigation interval of 5 days (LEPA 2-5).

Among them, the first is assumed to be the base irrigation scenario. To simulate the four irrigation scenarios, four separate EPIC-PST simulation runs with four different sets of parameters that determine the efficiency of irrigation (EFI and EVTRI), the minimum application interval (IRI), and the maximum volume allowed for individual irrigations (ARMX), were conducted. To simulate the high and medium irrigation levels within each irrigation scenario, the water stress factor to trigger automatic irrigation (BIR) was modified. If the plant water stress factor reaches the specified level after the specified minimum application interval, EPIC-PST triggers an irrigation automatically. The daily weather data are used to simulate and replicate various irrigation strategies, thus producing distributions of yields for each crop under each irrigation scenario. Also, the distributions of nitrate and pesticide movements are generated simultaneously. EPIC-PST simulation results associated with each irrigation scenario were incorporated into a separate mathematical program.

Crop Production Systems

Peanut Production Systems

Crop production and pest control benefits accruing from crop rotations are well documented in the literature (Johnson et al., 1975; Kommedahl, 1981; Minton et al., 1981). A well developed crop rotation (1) reduces populations of pathogens and keep them low; (2) aids in productivity and microbial balance in soil; (3) improves pest control, including insects, diseases, and weed pests; (4) preserves the physical condition of soil; (5) aids in reducing soil erosion; and, (6) is practical from agronomic and economic points of view.

There are several factors that should be considered in a peanut rotation system. Peanuts should not be grown on the same land continuously, but should be grown in a rotation system. Peanuts are extremely sensitive to the effects of other crops grown in the rotation, especially the crop which immediately precedes peanuts. Crops such as corn, grain sorghum, millet or small grain should be grown before peanuts for partial control of diseases, nematodes, and weeds. Peanuts should not be planted following peanuts (Henning et al., 1982).

Although much has been said and written about the benefits of rotating peanuts with these crops, only a few results on peanut rotation experiments have been reported. Results of an earlier study (1940-44) at the Georgia Coastal Plain Experiment Station (Anonymous, 1946) shows progressive yield reduction (from 25 to 43 percent in 3-year continuous peanuts) with successive peanut growing. Moor and Hoelscher (1977) attribute the low peanut yield in Comanche County, Texas, to continuous peanut cropping practices. Results from three-year experiments conducted by King et al. (1984) show that higher peanut yields were obtained from plots which had been planted to corn or grain sorghum in the previous two years than from plots with continuous peanuts.

Nickels and Sholar (1991), in the first peanut rotation research done in Oklahoma, reported that plots planted to peanuts for two years (1990 and 1991) yielded about 11 percent less than plots that were planted to grain sorghum or cotton in 1990 and then were planted to peanuts in 1991. This test was conducted on land that had been out of peanut production since 1976. If plots have been planted to peanuts many years, one year out of peanuts makes little difference in yields the next year. After two years out of peanuts, yields the following year are about 25 percent above continuous peanuts. However, three years out of peanuts result in about the same yield as two years out (Sholar, 1992). Considering these, it is assumed that the third year of peanuts in a peanuts-another crop-peanuts rotation yields 10 percent less. Also, the third year of peanuts in an another crop-peanuts-peanuts rotation yields 15 percent less than peanuts in an another crop-another crop-peanuts rotation. Few farmers grow peanuts three consecutive years because of lack of available land for rotations or because alternative fields do not have an irrigation source (Sholar, 1992). Thus, three-year continuous peanuts are not included among the production activities in this study. The rotation systems that involve peanuts were presented in the previous chapter.

In Caddo County, peanut planting generally takes place from early May through early June, and harvesting season ends in November. The period between planting and harvesting is usually 130-170 days. In general, peanut seedbed preparation takes place in March through May. In this study, it is assumed that the tillage system for peanut production is a conventional tillage system using a moldboard plow. The dates and types of tillage activities and other field operations for peanut production are presented in Table 23, Appendix.

Two Spanish type peanuts, Pronto and Spanco, and another two Runner type peanuts, Florunner and Okrun, are popular in the study area. Pronto is more desirable than other varieties since it has the ability to yield relatively well and to grade high when grown in short seasons and with limited soil moisture. Spanco is a high-yielding, early maturing variety with erect growth habits. Spanco may be harvested 10-14 days earlier than other varieties, but later than Pronto. Florunner requires higher moisture level and a longer growing season than Spanish peanuts. However, it also has higher yield potential and generates more income per acre if allowed sufficient time to mature. Okrun is less susceptible to leafspots and podrots, and more drought-tolerant than Florunner. In peanut variety tests conducted at five different locations in

Oklahoma, Runner-type peanuts significantly outperformed Spanish-type peanuts at all test sites (Sholar and Kirby, 1990).

With Spanish varieties, planting 6-7 seeds/ft of row is needed to obtain about 5-6 plants/ft of row. With Runner-type peanuts, planting 5 seeds/ft of row is required to obtain 4 plants/ft of row (Sholar et al., 1990). Assumed seeding rates are 100 lb/A for irrigated peanuts and 75 lb/A for dryland peanuts.

Only 10-20 pounds per acre of starter fertilizer are required for peanut production (Sholar et al., 1990). In EPIC-PST simulation runs, 20 pounds per acre for the high nitrogen level, 15 pounds per acre for the medium nitrogen level, and 10 pounds per acre for the low nitrogen level are assumed to be applied before planting, regardless of the irrigation level or soil. Phosphorus recommendations for peanuts vary from 20 to 80 lb of P_2O_5 per acre, and potassium recommendations vary from 30 to 80 lb of K_2O per acre (Sholar et al., 1990). Assumed application rates for phosphorus are 40 lb/A for irrigated peanuts and 20 lb/A for dryland peanuts. It is assumed that the secondary nutrients (calcium, magnesium, and sulfur) and the micronutrients (iron, zinc, boron, etc.) are sufficient in Caddo County soils. Assumed potassium application rates are 40 lb/A for irrigated peanuts and 30 lb/A for dryland peanuts.

The most commonly used preplant herbicides in peanut production are Dual, Pursuit, Prowl, and Treflan. For controlling annual weeds and grasses, these preplant herbicides are incorporated into the soil immediately after application. The most common insects damaging peanut production in the study area are thrips. Insecticides applied at planting to control thrips are Thimet 20G, Temik 15G, and Di-syston 15G. Malathion, Sevin, and Orthene are commonly applied insecticides to control thrips after emergence. The most serious damage in peanut production is caused by diseases and nematodes.

Common peanut diseases are Southern blight, Sclerotinia blight, and foliar diseases. Foliar diseases may reduce yields by 50 percent or more if not controlled. Commonly used fungicides for peanut disease control are Bravo, Ridomil, Terrachlor, and Vitavax. Furadan, Mocap, Nemacur, Telone, and Temik are commonly used nematicides (OSU Cooperative Extension Service, 1991). Details of assumptions on peanut pesticide applications, including types, rates, and times of application, are presented in Table 30, Appendix.

Grain Sorghum Production Systems

In Caddo County, most sorghums are planted from late April to mid June. Harvesting season extends from late September to early November. In general, tillage practices for grain sorghum seedbed preparation are conducted from January through May. The assumed tillage system for grain sorghum production is conventional tillage without moldboard plowing. The dates and types of tillage and other crop management activities for grain sorghum production are described in Tables 24-25, Appendix.

Grain sorghum hybrids can be grouped into early, medium, and late maturing types. Early maturing types need 45 to 50 days, medium maturing types need 50 to 60 days, and late maturing types require over 60 days to reach the mid-bloom stage under reasonably good conditions for growth. Time required to reach the harvest stage is 95 to 100 days for early maturing types, 110 to 120 days for medium maturing types, and over 120 days for late maturing types (Hawkins et al.).

When the planting date is selected, soil temperature, moisture conditions at planting, available moisture over the growing season, expected harvest date, and the maturity of the hybrid, and the occurrence of sorghum midge need to be considered. If winter wheat follows grain sorghum, early or medium maturing types should be planted as early as possible to allow seed-bed preparation before fall wheat seeding. If grain sorghum follows wheat, a short season type grain sorghum should be planted in order to reach maturity before frost. However, these operations are successful only under irrigation. If soil moisture is not a limiting factor and full growing season is available, a medium or late-maturing type should be planted since yields of later maturing types are generally significantly higher than yields of early maturing ones (Hawkins et al.).

Optimum grain sorghum plant population per acre varies quite widely. If soil moisture is not a limiting factor, row spacings from 20 to 28 inches with plant populations of 65,000 to 100,000 plants per acre are necessary for maximum yields. In lower rainfall areas, optimum plant populations for dryland grain sorghum production are 20,000 to 30,000 plants per acre. In this study, it is assumed that grain sorghum seeding rates for the high irrigation level, the medium irrigation level, and the low irrigation level are 8 lb/A, 7 lb/A, and 5 lb/A, respectively (Hawkins et al.).

Grain sorghum requires relatively large amounts of nitrogen fertilizer. Nitrogen requirements are based on a yield goal and the level of nitrogen in the soil. Fertilization decisions for grain sorghum are based on reasonable yield goals, nutrient requirements to achieve the goals, and the soil nutrient level. To produce 40 cwt, 50 cwt, and 70 cwt of grain per acre, for example, about 70 lb/A, 100 lb/A, and 170 lb/A of nitrogen are required, respectively (Johnson and Tucker, 1990). Fertilization decisions for the crop growth/chemical movement simulation were based on results from numerous EPIC-PST test runs. It is assumed that grain sorghum production activities with high nitrogen levels (HH, MH, and LH) use the amount of nitrogen that approximately equates marginal value products and the price of nitrogen. The highest nitrogen level associated with the high irrigation (HH) specified in EPIC-PST simulation ranges from 90 lb/A for Port silt loam soil to 150 lb/A for Cobb fine sandy loam soil. The highest nitrogen level under dryland condition (LH) ranges from 30 lb/A for Port silt loam soil to 70 lb/A for Cobb fine sandy loam soil. The differences in nitrogen use between the high and subsequent levels are 20 lb/A with irrigation and 10 lb/A without irrigation.

Phosphorus recommendations for grain sorghum vary from 20 lb/A of P_2O_5 to 60 lb/A of P_2O_5, and potassium recommendations vary from 30 to 100 lb/A of K_2O (Johnson and Tucker, 1990). Phosphorus rates assumed are 40 lb/A for the high irrigation level, 30 lb/A for the medium irrigation level, and 20 lb/A under the dryland condition. Assumed potassium rates for the high, medium, and low irrigation levels are 50 lb/A, 40 lb/A, and 30 lb/A, respectively.

In the study area, Atrazine, 2,4-d, Banvel, and Basagran are the most commonly used herbicides in grain sorghum production. In most cases, these herbicides are sprayed postemergence after sorghum is about 6 inches tall (Greer and Hawkins). The major insects that damage grain sorghum in the study area are sorghum greenbug and sorghum midge. Insecticides commonly used to control sorghum greenbug are Ethyl Parathion, Di-Syston, Lorsban, and Furadan. Sevin, Di-Syston, Ethyl Parathion, Lorsban, and Cygon are common insecticides used to control sorghum midge (Coppock and Massey). Details of assumptions on grain sorghum pesticide uses, including types, rates, and timing of applications, are presented in Table 31, Appendix.

Cotton Production Systems

There has been much discussion about the benefits of rotating cotton with crops such as small grains and grain sorghum. Bell (1984) indicates that rotations with small grains, rice, grain sorghum, or legumes generally reduce the amount of inoculum of soilborne pathogens of cotton and decrease the incidence and severity of diseases. Williams (1992) recommends that Oklahoma cotton producers rotate cotton with alfalfa, small grain, and grain sorghum for efficient disease management. Chandler (1984), and Greer and Murray (1992) indicate that rotating cotton with grass-type crops often permits the use of additional herbicides or tillage practices on weeds that are difficult to control in continuous cotton production. Further, crop rotation is an efficient way to reduce the soil population density of the target nematode to a level below the economic threshold for cotton (Veech, 1984).

Experimental results from Johnson et al. (1975) show that cotton rotated with other crops has significant yield gains (13 - 24 %) over continuous cotton. On the other hand, experimental results from Keeley et al. (1983) and Motocha and Hopper (1990) reveal that rotated cotton shows only slight yield gains (5 - 10 %) over continuous cotton. Thus, it is assumed that the yield reduction for two-year continuous cotton production is 5 percent below the first year's yield, and that the yield reduction for three-year continuous cotton production is 10 percent below the first year's yield.

In Caddo County, cotton planting generally takes place in May, and most cotton is harvested in November. Tillage for cotton production begins in December and continues through May before planting. A conventional tillage system with moldboard plow is assumed for cotton production. The dates and types of tillage and other field operations for cotton production are presented in Tables 26-27, Appendix.

One of the most important decisions made by cotton producers is cotton variety selection. Long-season, medium-season, and short-season varieties are available, and some varieties provide higher expected net returns than others. Important factors which must be considered are lint yield, maturity length, pest resistance, and fiber properties. Early maturity is important in Oklahoma because the growing season is comparatively short. Under irrigation, however, early maturity is not as critical as it is under dryland conditions (Verhalen and Greenhagen, 1992).

To achieve the maximum yield potential, and for efficient mechanical harvesting, the optimum cotton plant population at the end of the season is in the range of 30,000 to 50,000 uniformly spaced plants per acre. Yield and harvester performance are acceptable with cotton plant populations in the range of 20,000 to 60,000 per acre (Verhalen and Williams, 1992). Assuming 4,500 seeds/lb, an 80 percent germination rate, an 80 percent emergence rate, and a 95 percent survival to harvest, for example, about 22 lb/A of cotton seed must be planted when 60,000 plants/A is the desired plant population at harvest. The seeding rates assumed in the analysis are 22 lb/A for the high irrigation level, 19 lb/A for the medium irrigation level, and 15 lb/A for the low irrigation level.

Fertilizer recommendations for cotton should be based on realistic yield goals under existing soil and climatic conditions. In cotton production, nitrogen is the first limiting nutrient. The estimated nitrogen requirements for producing a bale of cotton per acre is approximately 60 lb/A. If 2 bale/A is the yield goal, then approximately 120 lb/A of nitrogen is recommended (Banks, 1992). Cotton production activities with high nitrogen levels (HH, MH, and LH) also use the amount of nitrogen that approximately equates marginal value products and the price of nitrogen. The highest nitrogen level associated with the high irrigation (HH) specified in EPIC-PST simulation ranges from 40 lb/A for Port silt loam soil to 100 lb/A for Cobb fine sandy loam soil. The highest nitrogen level under dryland condition (LH) ranges from 10 lb/A for Port silt loam soil to 40 lb/A for

Cobb fine sandy loam soil. The differences in nitrogen use between the high and subsequent levels are 20 lb/A with irrigation and 10 lb/A without irrigation. In case of Port silt loam soil, however, the assumed medium and low nitrogen levels under dryland conditions are 5 lb/A and zero, respectively.

Phosphorus recommendations for cotton vary from 30 lb/A to 75 lb/A of P_2O_5, and potassium recommendations vary from 40 lb/A to 110 lb/A of K_2O (Banks, 1992). Phosphorus rates assumed for cotton are 45 lb/A for the high irrigation level, 40 lb/A for the medium irrigation level, and 30 lb/A for dryland cotton. Assumed potassium rates for cotton are 60 lb/A for the high irrigation level, and 50 lb/A and 40 lb/A, respectively, for the subsequent irrigation levels.

Weed management is important in cotton production since weeds reduce yields by competing with cotton for water, nutrients, light, and space. To control annual weeds, grasses, and yellow nutsedge, preplant incorporated herbicides such as Treflan, Prowl, and Lasso are applied. To kill weeds that are not controlled with soil applied herbicides, postemergence herbicides, such as Caparol, Cotoran, Fusilade, and Roundup, are used for directed spray application(Greer and Murray, 1992).

Cotton cannot be produced without insect problems. Highest net returns can be obtained only if insect pests are kept below their economic threshold. When insects are below their economic threshold, however, repeated insecticide applications should be avoided. The most common insects that attack cotton in the study area are boll weevils, bollworms, and cotton fleahoppers. Insecticides recommended for controlling boll weevils are Bidrin, Guthion, Cythion, Marathion, Methyl Parathion, Sevin, and Vydate. Insecticides often recommended to control bollworms are Bolstar, Curacron, Lannate, Orthene, Ambush, Ammo, and Karate. To control cotton fleahoppers, Bidrin, Cygon, Di-Syston, or Lorsban is applied (OSU Cooperative Extension Service, 1991).

The most serious cotton disease in the study area is Fusarium wilt-nematode complex. Although Fusarium wilt can occur without nematodes, the wilt disease itself is not serious unless nematodes are present. To control Fusarium wilt-nematode complex, treatment of soil infested with root-knot or root-lesion nematodes is necessary (Williams, 1992). Nematicides suggested for controlling nematodes are Nemacur, Temik, and Terraclor. These nematicides are applied at planting in furrow or banded over row (OSU Cooperative Extension Service, 1991). Detailed assumptions regarding cotton pesticide applications, including types, rates, and timing of applications, are presented in Table 32, Appendix.

Wheat Production Systems

In Caddo County, wheat is planted from mid-September through mid-October. Optimum planting dates for wheat intended for only grain production are the first two weeks of October. Harvesting season starts in early June and ends in early July. Tillage begins in June after harvest and continues until planting. The objectives of tillage in wheat production are (1) to control weeds; (2) to conserve soil moisture; (3) to recycle nutrient; and, (4) to prepare a seedbed suitable for rapid germination, emergence, and plant development (OSU Cooperative Extension Service, 1985). In this study, a conventional tillage system without moldboard plowing is assumed for wheat production. The dates and types of tillage and other field operations for wheat production are presented in Tables 28-29, Appendix.

One of the most important factors in wheat production is seed quality. Traits that need to be considered when selecting seed are plant maturity, height, straw strength, winter hardiness, and disease and insect resistance. Seeding rates depend on the availability of soil moisture, size of the seed, and the crop's intended use (grain, pasture, or both) (OSU Cooperative Extension Service, 1985). In this study, it is assumed that wheat is grown for grain production only. Assumed seeding rates are 1.25 bu/A under irrigated condition and 1.0 bu/A under dryland condition.

Soil nitrogen requirements for wheat are determined based on a yield goal and the nitrate nitrogen found from a soil test. Soil nitrogen requirements for wheat at the yield levels of 30 bu/A, 40 bu/A, and 60 bu/A are 60 lb/A, 80 lb/A, and 125 lb/A, respectively. Different nitrogen sources do not produce significant differences in wheat yields if equal amounts of nitrogen are applied. However, anhydrous ammonia applied preplant during the fallow period is the most popular form of nitrogen for wheat production in Oklahoma. To avoid seedling injury, anhydrous ammonia needs to be applied at least one week before planting. In winter or spring, nitrogen is topdressed on the soil surface and washed into the root zone by rainfall (OSU Cooperative Extension Service, 1985). The highest nitrogen level associated with the high irrigation level(HH) assumed for EPIC-PST simulation runs ranges from 90 lb/A for Port silt loam soil to 150 lb/A for Cobb fine sandy loam soil. The highest nitrogen level under dryland condition (LH) ranges from 20 lb/A for Port silt loam soil to 70 lb/A for Cobb fine sandy loam soil. The differences in nitrogen use between the high and subsequent levels are 20 lb/A under irrigation and 10 lb/A dryland. Phosphorus recommendations for wheat vary from 20 lb/A of P_2O_5 to 80 lb/A of P_2O_5, and potassium recommendations vary from 20 to 60 lb/A of K_2O (OSU Cooperative Extension Service, 1985). Phosphorus rates assumed for wheat are 40 lb/A for the high irrigation level, 30 lb/A for the medium irrigation level, and 20 lb/A under dryland condition. Assumed potassium rates for wheat are 40 lb/A for the high irrigation level, and 30 lb/A and 20 lb/A, respectively for the subsequent irrigation levels.

Weeds compete with wheat for soil moisture, nutrients, and light. Weeds commonly found in wheat fields are grouped as (1) fall germinating annual broadleaf weeds, such as mustards and henbit; (2) winter annual grassy weeds, such as cheat and wild oats; (3) spring and summer annual broadleaf weeds, such as buckwheat; (4) summer annual grasses; and, (5) perennial weeds such as bindweed. Weed control practices that reduce or eradicate weed infestations are grouped as:(1) preventive control, such as the use of weed-free seeds; (2) cultural control including cover crops and crop rotations; (3) mechanical control removing weeds from the soil, burying weeds, or weakening weeds through root pruning; and, (4) chemical control killing weeds with herbicides (OSU Cooperative Extension Service, 1985). Herbicides commonly applied to control weeds in wheat are Glean, Ally, MCPA, 2,4-D, Banvel, Roundup, and Finesse. The greenbug is the most important insect pest of wheat in the study area. Insecticides used to control greenbug are Marathion, Parathion, Methyl Parathion, Dimethoate, and Di-Syston. Disease problems are not serious in wheat production. Moreover, the cost of applying fungicides for foliar disease control in wheat often exceeds the benefits in increased yields. Thus, it is assumed that pesticide applications for disease control are not required in wheat production. Detailed assumptions regarding wheat herbicide and insecticide applications, such as type, rate, and time of application are presented in Table 33, Appendix.

Government Program Participation

All four crops included in the analysis are program commodities for which price and income support is granted through legislative action. The policy instruments used differ from commodity to commodity. Important policy instruments currently in effect for at least one of the four crops are the acreage reduction program (ARP), farmer-owned reserve (FOR) program, nonrecourse loans, marketing loans, marketing quotas, target prices/deficiency payments, triple-base program, and underplanting provisions (Hallberg, 1992).

The acreage reduction program (ARP), often referred to as setaside, is a voluntary short-term land retirement program in which farmers plant less than their base acreage. In general, it is an unpaid acreage reduction that is required for participation in other farm programs, such as the nonrecourse loan and deficiency payment programs (Hallberg, 1992).

FOR is a producer-held storage program for wheat and feed grains to be accomplished through an extended price support loan of three to five years' duration. Producers receive storage payments and the Secretary of Agriculture adjusts or waives interest charges on farmer-held reserves. The Secretary of Agriculture has the authority to increase the interest rate to encourage redemption of the loan when market price exceeds the release price at which a farmer may sell his/her farmer-owned reserve grain and repay the loan without penalty. This program was designed to protect against production shortfalls and to provide a buffer against wide price fluctuations (Hallberg, 1992).

The nonrecourse loan is a commodity loan made by the government to farmers as a means of providing a floor price for the commodity. The loan is secured by a commodity stored in approved facilities. It is a nonrecourse loan in the sense that if the farmer does not sell the commodity by the due date, the commodity becomes the property of the government in full payment of the loan. The farmer may choose to repay the loan at any time before maturity. When the loan is redeemed, interest and service charges are added to the face value of the loan. Farmers who participate in the program are allowed to gain from any price rise with no risk of loss (Hallberg, 1992).

The marketing loan is a nonrecourse loan which may be paid off by the farmer at a repayment rate less than the announced loan rate. The difference between the announced loan rate and the repayment rate, which is referred to as a marketing loan payment, constitutes an income support payment to the farmer. In general, the repayment rate is some percentage of the loan rate or world market price (Hallberg, 1992).

When supplies of a commodity become excessive, certain means of regulating supplies are needed. A marketing quota is a means of regulating the marketing of a commodity to which the quota is applicable under the law. A national marketing quota for a commodity is set at a level that would provide adequate market supplies. The national quota is apportioned to individual farms based on their past production. Once approved in a producer referendum, marketing quotas are mandatory on all producers (Hallberg, 1992).

The target price is a commodity price guaranteed to farmers who participate in certain farm programs. When the average market price falls below the target price for a specified time period, farmers who meet the eligibility criteria are eligible to receive a direct income support payment. The payment rate is the difference between the target price and the higher of the average market price or loan rate, and is referred to as a deficiency payment. The total deficiency payment to a farm is the product of (1) the payment rate; (2) the base acreage; and, (3) the program yield established for the farm. A base acreage is derived from a 5-year moving average of plantings of the crop on the farm. A program yield is the crop yield of record for an individual farm established at the average yield for the previous five years exclusive of the high and low years (Hallberg, 1992). The triple-base plan is mandated by the Omnibus Budget Reconciliation Act of 1990. Under the triple-base plan, a producer's base acreage is divided into three portions: (1) program acres; (2) flexible acres; and (3) conserving-use acres. The program acres should be planted to a program crop for which deficiency payments are paid. The flexible acres may be planted to any program crop, oilseed crop, or nonprogram crop other than fruits and vegetables, but production on the flexible acres is not eligible for deficiency payment. The conserving-use acres are the acres to be idled by participants, and are subject to the restrictions that normally apply to ARP acres (Hallberg, 1992).

Under an underplanting provision which was authorized by the Food Security Act of 1985, producers who plant between 50 and 92 percent (the 50/92 provision) of their base acres to the program commodity, and devote the remaining 8 percent of base acres to a conserving use, are eligible to receive deficiency payments on 92 percent of the base acreage. This provision has been changed to the 0/92 provision for wheat and feed grains, while the 50/92 provision is still available to cotton and rice producers (Hallberg, 1992).

Current farm programs that apply to peanuts are marketing quotas, a two-price support system, and nonrecourse loans. A quota holder may produce in excess of the quota, but can only receive the higher (quota price) of the two price support levels for peanuts produced up to the quota. For peanuts produced in excess of the quota, referred to as additional peanuts, producers receive the lower of the two price support levels. The marketing quota is transferable within a county. Acreage allotment for peanuts was suspended by the 1981 act (Hallberg, 1992).

Farm programs that are currently available for wheat and grain sorghum producers are (1) nonrecourse loans; (2) acreage reduction program; (3) target price/deficiency payments; (4) farmer-owned reserve program; (5) 0/92 underplanting provisions; and, (6) triple-base provision. Farm programs for cotton that are currently in effect are: (1) nonrecourse loans; (2) marketing loans; (3) acreage reduction program; (4) target price/deficiency payment program; (5) 50/92 underplanting provision; and (6) triple-base provision (Hallberg, 1992). In the analysis, it is assumed that the hypothetical farm has a peanut poundage quota of 300 thousand pounds, and a 100-acre wheat base with a program yield of 35 bushels per acre. A 5 percent set-aside and a 15 percent normal flex acreage rule are assumed as the triple-base for wheat. On the other hand, it is assumed that the farm does not participate in farm programs for either cotton or grain sorghum.

Assumptions on Prices and Costs

The mathematical programming model requires data on operating costs and crop prices. Operating costs include costs for tillage, fertilizer applications, seed, pesticide applications, cultivation, irrigation, harvest, labor, and so on. Among these, outlays for nitrogen fertilizer, pesticides, and the variable cost for irrigation were separated out for easier simulation of various policy scenarios. To determine operating costs by crop, excluding the above costs, the Expanded Budget Generator developed by Norris (1990) was used. The prices for crops and operating inputs used in this study are based on the 1991 expected state prices reported in the OSU Enterprise Budget.

Variable costs of irrigation are based on estimates of fuel, lubrication, repair, and labor costs from Dale et al. (1989). The price of fuel (natural gas) is updated to $3.00/mcf. The assumed depth of the pump lift was 150 feet. The variable costs of irrigation for high pressure center pivot systems are estimated to be $2.73 per acre inch. To estimate the economic consequences of irrigation system conversions from a high pressure center pivot system to LEPA, investment costs for conversion were incorporated in the variable costs for the LEPA system. Conversion from a high pressure system to a LEPA system requires replacing high pressure impact sprinklers with goose necks, flexible drop tubes spaced at 60 inch intervals, and low pressure nozzles. Total investment cost for the conversion, excluding pressure regulators, was estimated to be $8,255 (Earls, 1989). Based on 16 acre-inch annual applications and a 7 year normal accepted life for sprinkler heads, this investment cost was converted to an additional per acre inch irrigation cost, and added to the variable costs for the LEPA irrigation system estimated by Dale et al. (1989). The variable costs of irrigation for the LEPA system calculated using the above method was $2.79 per acre inch.

CHAPTER V

RESULTS AND IMPLICATIONS OF POLLUTION CONTROL POLICY OPTIONS

In this chapter, the mathematical programming model described in Chapter 3 is used to predict optimal agricultural production decisions, net returns to the farm, and effluent discharge levels under alternative pollution control policies. The information obtained from the model is utilized to assess both economic and environmental effects of the optimum behavior of the farm in response to the policy options aimed at controlling agricultural pollution.

The first section of this chapter reviews the policy scenarios for agricultural pollution control tested in this study. The next section reports results obtained from the mathematical programming model and analyzes the impact of various policy options on pollution abatements and net returns to the farm. The last section addresses implications of the results and the prospects of agricultural pollution control. This discussion will provide some insight for policy recommendations.

An Overview of Policy Alternatives

In choosing an agricultural pollution control policy option to be implemented, administration costs and practicality of the option should be considered, along with its estimated effects on water quality. Comparing the economic implications of differing policy options is also important. This section outlines the policy scenarios for agricultural pollution control tested in this study.

Four efficient policy options for agricultural pollution control were discussed in Chapter 2. These were nonpoint standards, nonpoint incentives, management practice standards, and management practice incentives. Once the upper limits of effluent discharges from a farm are determined, then policy parameters for every option are determined simultaneously. Each of these four policy options induces the least-cost rearrangement of production activities to comply with the given policy restrictions. To implement these efficient policy options, detailed information on weather, chemical, hydrologic, and topographical characteristics of the farm land, and on the producer's management practices for crop production, are required. The correct application of this information will provide estimates of effluent production from the farm. However, these efficient policy options inevitably involve high transaction costs due to the data requirements.

Some of the frequently mentioned pollution control policy options may have advantages of less transaction costs since they do not require such detailed information. These policy options include taxes on nitrogen fertilizer and pesticides, restrictions on nitrogen use, taxes on irrigation water use, and restrictions on the amount of irrigation. These may be more acceptable policy options for addressing agricultural pollution problems when transaction costs of implementing policies are considered. An overview of these control policy options is presented below.

Imposing Taxes on Polluting Inputs

One of the most frequently mentioned control mechanisms to protect water quality is the imposition of excise taxes on inputs that cause pollution. As discussed in Chapter II, imposing a tax on pollution-generating inputs is equivalent to forcing the marginal social cost of pollution to be reflected in the cost of the input. The response of farmers to this control mechanism depends on the ratio of marginal value product to the price of the input including the tax. Thus, a substantial tax rate may be required to induce a significant reduction in pollution-generating input use.

The major advantage of an input tax would be the ease of implementation and relatively low administrative costs. A drawback of the input tax policy is the difficulty in determining farmers' response in the input use to a given tax rate and its adverse economic impact on the farm sector. A low tax rate would not result in significant reductions in the use of polluting inputs. On the other hand, an excessively high tax rate would be met by strong opposition from the farm sector and agricultural chemical industry (Francis, 1992). For the empirical analysis, a policy scenario imposing a 100 percent excise tax on nitrogen fertilizer and pesticides and another scenario imposing a tax on irrigation water use are tested.

Restricting Total Input Use

An example of this control mechanism is restricting total nitrogen applications. This scenario represents a policy in which each farmer is granted a certain amount of nitrogen based on crop needs and in proportion to the number of acres of historic crop production. Additional information, such as soil type, residual soil nitrogen, or the availability of manure, could be used in determining the total nitrogen use. However, the farmer is free to allocate the nitrogen across crops and soils as he/she desires. One approach to implementing this policy would be to issue annual coupons or certificates to each farmer allowing the purchase of a given quantity of nitrogen fertilizer

(Francis, 1992). For the empirical analysis, this policy scenario involves restricting total nitrogen use to 50 percent of the benchmark result.

Another example of a control mechanism is restricting total volume of irrigation water use. Using less irrigation water reduces chemical movements, especially chemical losses with deep percolation. This policy could induce a shift in irrigation technology from a less efficient to a highly efficient system. To implement the restriction on total irrigation water applications, the maximum amount of irrigation was set at 50 percent of the total quantity of irrigation water applied in the benchmark solution.

Restricting Per Acre Nitrogen Application

Pollution control policies that restrict the total amount of input use do not control the intensity of input use. The policy goal of reducing total input use does not address the problems of misuse and mismanagement. An alternative to the policy restricting the total amount of nitrogen application is a restriction on per acre nitrogen applications. If high levels of nitrogen fertilizer use on certain crops cause unacceptable levels of pollution, then a policy restricting per acre nitrogen application could be more effective in reducing pollution. A reasonable degree of compliance could be attained with strict penalties combined with random spot checks. To achieve an acceptable degree of compliance with lower enforcement costs, an approach that shifts the burden of proof of compliance to the producer could be used (Francis, 1992). A disadvantage of this policy option is that administrative and enforcement costs would be higher than those with the policy restricting the total amount of nitrogen application.

Results and Analysis

In this section, analyses of results obtained under the base (current) situation and under various water quality policy measures are conducted. The analyses focus on both economic and environmental consequences of the producer's optimizing behavior to comply with the various policy scenarios. In addition, four different irrigation scenarios described in Chapter 4 are evaluated under each policy scenario. Analyses related to imposing water quality policy options are conducted after the benchmark solution is established.

EPIC-PST Simulation Results

EPIC-PST simulations provide detailed data on the effects of different agricultural practices on crop yield, nutrient and pesticide losses with surface runoff, sediment movement, and leaching below the crop root zone. EPIC-PST simulation results of crop production activities most relevant to this study are reported in Table 5. These EPIC-PST simulation results include crop yield, nitrate runoff, nitrogen percolation, toxicity index of pesticides moved with runoff water (PST runoff index), and health hazard index of pesticides leached below the crop root zone (PST percolation index) associated with a set of selected crop production activities. Notice that the values in Table 5 represent the means of 28 year simulation runs.

In the name of each crop production activity, the first character identifies the soil for each production activity: (1) C denotes Cobb fine sandy loam soil; (2) G denotes Grant loam soil; (3) N denotes Pond Creek fine sandy loam soil; and, (4) P denotes Port silt loam soil. The second character identifies the crop: (1) P denotes peanuts; (2) G denotes grain sorghum; (3) W denotes wheat; and (4) C denotes cotton. The third character (number) represents the rotational effect.

TABLE 5

EFFLUENT LEVELS AND CROP YIELDS
FOR SELECTED ACTIVITIES

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
High 4-14 (Peanuts)	CP1HL	2.02	-	2,550	71.69	3,115 lb
	CP1ML	2.02	-	1,920	46.71	2,776
	GP1HL	2.43	-	2,005	0.22	3,195
	GP1ML	2.43	-	1,572	0.22	2,856
	NP1HL	2.43	0.40	1,679	0.11	3,249
	NP1ML	2.43	0.40	1,277	0.09	2,829
	PP1HL	2.43	0.81	1,528	0.07	3,302
	PP1ML	2.43	0.81	1,107	0.06	2,740
High 4-14 (Cotton)	CC1HH	6.48	-	1,416	36.68	766 lb
	CC1HM	4.86	-	1,416	36.59	744
	CC1HL	3.64	-	1,423	37.25	671
	CC1MH	5.26	-	1,175	30.07	646
	CC1MM	4.05	-	1,175	30.37	612
	CC1ML	2.43	-	1,185	25.39	505
	GC1HH	8.91	0.40	1,010	0.01	780
	GC1HM	6.88	-	1,010	0.01	758
	GC1HL	4.45	-	1,001	0.01	702
	GC1MH	6.48	0.40	957	0.01	715
	GC1MM	4.45	-	957	0.01	676
	GC1ML	2.43	-	960	0.01	576
	NC1HH	7.69	1.21	905	0.34	783
	NC1HM	6.07	0.81	899	0.34	756
	NC1HL	4.05	0.40	891	0.25	688
	NC1MH	6.48	0.81	656	0.25	690
	NC1MM	4.45	0.40	665	0.27	649
	NC1ML	2.43	0.40	654	0.27	537
	PC1HH	4.05	0.40	811	-	793
	PC1HM	3.24	0.40	807	-	778
	PC1HL	2.02	-	819	-	749
	PC1MH	3.24	0.40	556	-	690
	PC1MM	2.43	0.40	557	-	676
	PC1ML	1.21	-	560	-	649
	CC2HH	6.88	-	1,416	36.65	739
	CC2HM	5.26	-	1,416	36.60	719
	CC2HL	3.64	-	1,423	37.27	654
	CC2MH	5.67	-	1,167	30.91	622

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
High 4-14 (Cotton)	CC2MM	4.05	-	1,167	31.13	593 lb
	CC2ML	2.43	-	1,177	26.08	495
	GC2HH	9.31	0.40	1,010	0.01	751
	GC2HM	6.88	-	1,010	0.01	734
	GC2HL	4.86	-	1,001	0.01	683
	GC2MH	6.48	0.40	935	0.01	690
	GC2MM	4.45	-	957	0.01	654
	GC2ML	2.83	-	960	0.01	566
	NC2HH	8.10	1.21	899	0.34	754
	NC2HM	6.07	0.81	899	0.34	732
	NC2HL	4.45	0.40	891	0.29	671
	NC2MH	6.48	0.81	654	0.25	668
	NC2MM	4.45	0.40	660	0.26	629
	NC2ML	2.83	0.40	656	0.27	527
	PC2HH	4.05	0.40	820	-	766
	PC2HM	3.24	0.40	823	-	754
	PC2HL	2.43	0.40	811	-	727
	PC2MH	3.64	0.40	563	-	668
	PC2MM	2.43	0.40	563	-	656
	PC2ML	1.62	0.40	556	-	629
High 3-7 (Peanuts)	CP1HL	2.02	-	2,592	40.67	3,231 lb
	CP1ML	2.02	-	1,941	41.52	2,785
	GP1HL	2.43	-	2,072	0.04	3,302
	GP1ML	2.43	-	1,522	0.04	2,776
	NP1HL	2.83	0.40	1,665	0.05	3,311
	NP1ML	2.43	0.40	1,226	0.06	2,829
	PP1HL	2.43	-	1,560	-	3,240
	PP1ML	2.43	0.40	1,108	0.01	2,749
High 3-7 (Cotton)	CC1HH	6.88	-	1,914	16.82	821 lb
	CC1HM	5.26	-	1,861	17.02	785
	CC1HL	3.64	-	1,863	17.27	690
	CC1MH	5.26	-	1,401	17.00	673
	CC1MM	3.64	-	1,403	19.25	632
	CC1ML	2.43	-	1,420	16.59	510
	GC1HH	7.69	-	1,512	-	829
	GC1HM	6.07	-	1,460	-	805
	GC1HL	4.05	-	1,532	-	736
	GC1MH	6.88	-	1,040	-	739

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
High 3-7 (Cotton)	GC1MM	4.86	-	1,045	-	690 lb
	GC1ML	2.83	-	1,043	-	583
	NC1HH	8.10	0.40	1,088	0.06	815
	NC1HM	6.07	0.40	1,087	0.06	788
	NC1HL	4.05	0.40	1,107	0.06	707
	NC1MH	6.48	0.40	854	0.05	719
	NC1MM	4.45	0.40	831	0.05	668
	NC1ML	2.83	-	820	0.06	549
	PC1HH	4.05	-	1,097	-	815
	PC1HM	3.24	-	1,101	-	797
	PC1HL	2.02	-	1,093	-	768
	PC1MH	3.24	-	670	-	693
	PC1MM	2.43	-	672	-	683
	PC1ML	0.40	-	672	-	654
	CC2HH	6.88	-	1,914	16.87	790
	CC2HM	5.26	-	1,914	16.81	761
	CC2HL	4.05	-	1,915	17.30	676
	CC2MH	5.67	-	1,415	16.39	649
	CC2MM	4.05	-	1,402	16.23	612
	CC2ML	2.43	-	1,415	16.77	500
	GC2HH	8.10	0.40	1,512	-	797
	GC2HM	6.07	-	1,502	-	778
	GC2HL	4.05	-	1,512	-	717
	GC2MH	6.88	-	1,018	-	710
	GC2MM	4.86	-	1,070	-	673
	GC2ML	2.83	-	1,046	-	571
	NC2HH	8.10	0.81	1,100	0.07	785
	NC2HM	6.07	0.40	1,095	0.07	761
	NC2HL	4.45	0.40	1,098	0.06	690
	NC2MH	6.48	0.40	854	0.05	695
	NC2MM	4.45	0.40	785	0.05	651
	NC2ML	2.83	0.40	825	0.06	539
	PC2HH	4.45	-	1,089	-	785
	PC2HM	3.24	-	1,097	-	773
	PC2HL	2.43	-	1,093	-	746
	PC2MH	3.64	-	667	-	671
	PC2MM	2.43	-	667	-	661
	PC2ML	1.62	-	682	-	636

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
LEPA 3-10	CP1HL	1.21	-	723	49.25	3,249 lb
(Peanuts)	CP1ML	1.21	-	576	52.82	2,829
	GP1HL	1.62	-	716	0.31	3,338
	GP1ML	1.21	-	638	0.31	2,991
	NP1HL	1.62	0.40	603	0.33	3,383
	NP1ML	1.62	0.40	456	0.28	2,892
	PP1HL	1.62	0.40	599	0.05	3,369
	PP1ML	1.21	0.40	476	0.03	2,767
LEPA 3-10	CC1HH	3.64	-	333	38.21	826 lb
(Cotton)	CC1HM	2.83	-	333	38.18	800
	CC1HL	2.02	-	342	40.24	717
	CC1MH	3.24	-	276	34.67	695
	CC1MM	2.43	-	277	35.08	656
	CC1ML	1.62	-	275	30.59	532
	GC1HH	4.45	0.40	327	0.01	841
	GC1HM	3.64	-	327	0.01	822
	GC1HL	2.43	-	331	0.01	756
	GC1MH	3.64	-	230	0.01	749
	GC1MM	2.43	-	232	0.01	712
	GC1ML	1.62	-	226	-	602
	NC1HH	4.45	1.21	217	0.48	846
	NC1HM	3.24	0.81	225	0.65	816
	NC1HL	2.43	0.40	225	0.41	736
	NC1MH	3.64	0.81	162	0.33	736
	NC1MM	2.43	0.40	161	0.32	688
	NC1ML	1.62	0.40	157	0.26	568
	PC1HH	2.43	-	286	-	841
	PC1HM	1.62	-	286	-	822
	PC1HL	1.21	-	287	-	785
	PC1MH	2.02	-	148	-	724
	PC1MM	1.21	-	148	-	707
	PC1ML	0.81	-	148	-	673
	CC2HH	3.64	-	333	38.14	795
	CC2HM	2.83	-	333	38.13	773
	CC2HL	2.02	-	342	40.30	700
	CC2MH	3.24	-	270	31.39	668
	CC2MM	2.43	-	281	32.93	639
	CC2ML	1.62	-	273	32.40	522

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
LEPA 3-10 (Cotton)	GC2HH	4.45	0.40	327	0.01	810 lb
	GC2HM	3.64	-	259	0.01	793
	GC2HL	2.43	-	330	0.01	736
	GC2MH	3.64	0.40	233	0.01	719
	GC2MM	2.43	-	236	0.01	690
	GC2ML	1.62	-	230	-	593
	NC2HH	4.45	1.21	217	0.48	815
	NC2HM	3.24	0.81	219	0.48	790
	NC2HL	2.43	0.81	224	0.64	722
	NC2MH	3.64	0.81	162	0.35	710
	NC2MM	2.83	0.40	162	0.33	671
	NC2ML	1.62	0.40	157	0.28	556
	PC2HH	2.43	0.40	287	-	810
	PC2HM	2.02	-	286	-	795
	PC2HL	1.21	-	286	-	766
	PC2MH	2.02	0.40	152	-	702
	PC2MM	1.62	-	158	-	683
	PC2ML	0.81	-	149	-	656
LEPA 2-5 (Peanuts)	CP1HL	1.21	-	644	37.53	3,151 lb
	CP1ML	1.21	-	583	37.58	2,687
	GP1HL	1.62	-	690	0.04	3,249
	GP1ML	1.21	-	551	0.01	2,758
	NP1HL	1.62	0.40	529	0.04	3,249
	NP1ML	1.21	0.40	432	0.04	2,749
	PP1HL	1.21	-	557	-	3,124
	PP1ML	1.21	-	449	-	2,669
LEPA 2-5 (Cotton)	CC1HH	4.05	-	347	15.78	817 lb
	CC1HM	3.24	-	346	16.18	795
	CC1HL	2.43	-	352	16.26	715
	CC1MH	3.24	-	264	14.09	668
	CC1MM	2.43	-	262	11.99	636
	CC1ML	1.62	-	260	10.96	527
	GC1HH	4.45	0.40	288	-	827
	GC1HM	3.24	-	287	-	815
	GC1HL	2.43	-	280	-	758
	GC1MH	3.24	-	190	-	715
	GC1MM	2.43	-	194	-	693
	GC1ML	1.62	-	200	-	600

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
LEPA 2-5 (Cotton)	NC1HH	4.45	0.81	213	0.05	819 lb
	NC1HM	3.23	0.40	216	0.05	805
	NC1HL	2.43	0.40	224	0.05	734
	NC1MH	3.64	0.40	163	0.04	707
	NC1MM	2.43	0.40	159	0.04	676
	NC1ML	1.62	-	158	0.04	568
	PC1HH	2.02	-	207	-	778
	PC1HM	1.62	-	210	-	771
	PC1HL	1.21	-	210	-	749
	PC1MH	1.62	-	159	-	676
	PC1MM	1.21	-	160	-	666
	PC1ML	0.81	-	159	-	644
	CC2HH	4.45	-	347	15.83	785 lb
	CC2HM	3.24	-	345	17.10	768
	CC2HL	2.43	-	350	17.13	697
	CC2MH	3.24	-	259	11.58	644
	CC2MM	2.43	-	264	11.53	617
	CC2ML	1.62	-	261	13.32	517
	GC2HH	4.45	0.40	287	-	795
	GC2HM	3.24	-	287	-	785
	GC2HL	2.43	-	288	-	739
	GC2MH	3.64	0.40	190	-	685
	GC2MM	2.43	-	196	-	673
	GC2ML	1.62	-	198	-	588
	NC2HH	4.45	1.21	219	0.05	788
	NC2HM	3.64	0.40	219	0.05	775
	NC2HL	2.43	0.40	216	0.05	719
	NC2MH	3.64	0.81	163	0.04	680
	NC2MM	2.43	0.40	164	0.03	656
	NC2ML	1.62	-	157	0.04	556
	PC2HH	2.43	-	212	-	751
	PC2HM	1.62	-	211	-	744
	PC2HL	1.21	-	210	-	727
	PC2MH	2.02	-	160	-	649
	PC2MM	1.21	-	160	-	644
	PC2ML	0.81	-	159	-	627

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
Dryland (Peanuts)	CP1LL	0.81	-	179	16.77	1,651 lb
	GP1LL	0.81	-	177	-	1,651
	NP1LL	0.81	0.40	159	-	1,741
	PP1LL	0.81	-	169	-	1,660
Dryland (Cotton)	CC1LH	1.21	-	131	0.90	376 lb
	CC1LM	0.81	-	131	0.90	351
	CC1LL	0.81	-	131	0.90	295
	GC1LH	1.21	0.40	126	-	380
	GC1LM	0.81	-	126	-	371
	GC1LL	0.40	-	126	-	332
	NC1LH	1.21	0.81	94	-	393
	NC1LM	0.81	0.40	94	-	366
	NC1LL	0.40	-	95	-	307
	PC1LH	0.40	-	106	-	383
	PC1LM	0.40	-	106	-	374
	PC1LL	0.40	-	106	-	360
	CC2LH	1.21	-	131	0.90	363
	CC2LM	0.81	-	131	0.90	344
	CC2LL	0.81	-	131	0.89	290
	GC2LH	1.21	0.40	126	-	368
	GC2LM	0.81	-	126	-	358
	GC2LL	0.40	-	126	-	324
	NC2LH	1.21	0.81	94	-	378
	NC2LM	0.81	0.40	94	-	356
	NC2LL	0.40	0.40	95	-	302
	PC2LH	0.81	-	106	-	368
	PC2LM	0.40	-	106	-	359
	PC2LL	0.40	-	106	-	347
Dryland (Sorghum)	CG1LH	2.02	0.40	3	0.66	33.2 cwt
	CG1LM	1.62	-	3	0.66	32.1
	CG1LL	1.21	-	3	0.66	30.4
	GG1LH	2.43	2.02	5	-	33.1
	GG1LM	2.02	1.21	5	-	32.5
	GG1LL	1.62	0.81	5	-	31.1
	NG1LH	2.43	1.21	5	-	37.3
	NG1LM	1.62	0.81	5	-	36.2
	NG1LL	1.21	0.40	5	-	34.0
	PG1LH	1.21	-	5	-	37.7

TABLE 5 (Continued)

Irrigation Scenario	Activity Name	NO_3 Runoff (Kg/A)	N Percol. (Kg/A)	PST Runoff Index	PST Percol. Index	Yield
	PG1LM	1.21	-	5	-	36.5 cwt
	PG1LL	0.81	-	5	-	34.8
Dryland (Wheat)	CW1LH	3.24	-	-	0.05	34.8 bu
	CW1LM	2.83	-	-	0.04	33.6
	CW1LL	2.43	-	-	0.04	30.1
	GW1LH	2.83	-	-	-	36.1
	GW1LM	2.43	-	-	-	34.7
	GW1LL	2.02	-	-	-	31.7
	NW1LH	2.83	-	-	-	36.9
	NW1LM	2.43	-	-	-	35.1
	NW1LL	2.02	-	-	-	31.8
	PW1LH	2.43	-	-	-	36.0
	PW1LM	2.02	-	-	-	34.8
	PW1LL	1.62	-	-	-	32.7

The number 1 indicates that there are no adverse rotational effects. In the names representing cotton production activities, the number 2 represents the second year of cotton in a two-year continuous cotton production activity, and the number 3 represents a three-year continuous cotton production activity.

In peanut production activity names, the number 2 indicates that the peanut production activity is practiced in a soil which was planted to peanuts two years ago but planted to other crops a year ago; the number 3 represents the second year of peanut in a two-year continuous peanut production activity. As was described in the previous chapter, the last two characters represent the irrigation level and the nitrogen application level, respectively. Most three-year rotation systems appearing in the following analysis are composed of activities in Table 5. For example, a three year rotation system cotton(HH)-cotton(HH)-grain sorghum(LH) practiced in Port silt loam soil is composed of PC1HH, PC2HH, and PG1LH. Among them, PC1HH stands for cotton production in Port silt loam soil at high level of irrigation and nitrogen with no rotational effects; PC2HH stands for cotton production in Port silt loam soil at high level of irrigation and nitrogen but with a 5 percent less yield; PG1LH stands for grain sorghum produced in Port silt loam soil under dryland condition at the high level of nitrogen with no adverse rotational effects. Another example of a three-year rotation system peanuts(HL)-cotton(HH)-grain sorghum(LH) practiced in Pond Creek fine sandy loam soil is composed of NP1HL, NC1HH, and NG1LH. Notice that results of individual dryland production activities are identical regardless of irrigation scenarios.

Results indicate that peanut and cotton production activities produce relatively large amounts of pesticide runoff and percolation. The intensive pesticide applications in peanut and cotton production appear to be the major reasons for the large amount of pesticide losses through runoff and percolation.

On the other hand, both grain sorghum production activities and wheat production activities create only a negligible amount of pesticide movement. Contrarily, both wheat production activities and grain sorghum production activities generate larger amount of nitrate runoff than peanut or cotton production activities. Grain sorghum production activities create the largest amount of nitrogen percolation.

The amount of pesticide percolation is quite different across soils. Under a given crop management practice, the magnitudes of pesticide percolation depend largely on the organic carbon content of the soil (Rao et al., 1983). For example, Cobb fine sandy loam soil which has the lowest organic carbon content generates the maximum amount of pesticide percolation. Port silt loam soil which has the highest organic carbon content generates the minimum amount of pesticide percolation, given the crop and the input use level. Crop yields also differ across soils. In most cases, Port silt loam soil produces the highest yield while Cobb fine sandy loam soil produces the lowest yield, given the crop and the input use level. Differences in the soil organic matter content appear to be responsible for the differences in crop yields. Soils high in organic matter have a high cation exchange capacity and hold vast quantities of nutrients as exchangeable ions which are partially available for plant growth (Gardener et al., 1985, pp. 101-2).

Since water is the medium which transports agricultural wastes from farm land to receiving water bodies, intensive irrigation may produce high levels of agricultural pollution. EPIC-PST simulation results support this point (see Table 5). In this production situation, irrigation has a great influence on the amount of pesticide runoff, pesticide percolation, and nitrate runoff. The amount of nitrogen percolation appears to be affected mainly by the amount of nitrogen applied, soil organic matter content, or crop uptake of nitrogen, rather than irrigation. For example, the differences in nitrogen percolation levels between NC1HH (90 lb; 2.7 lb), NC1HM (70 lb; 1.8 lb), and NC1HL (30 lb; 0.9 lb) can be explained by the amount of nitrogen applications. Notice that numbers in parentheses indicate respective per acre nitrogen application and nitrogen percolation levels. The identical nitrogen percolation levels produced by GC1HH (90 lb; 0.9 lb; 780 lb), GC1MH (70 lb; 0.9 lb; 715 lb), and GC1LH (30 lb; 0.9 lb; 380 lb) may be explained mainly by the differences in crop uptake. Notice that the third number in each parenthesis indicates cotton lint yield. The difference in nitrogen percolation levels between CC1HH (100 lb) and PC1HH (40 lb) can be explained mainly by the differences in soil organic matter content. The stability in nitrogen percolation values, which can be observed in Table 5, appears to be caused by the interaction of those factors.

Results under Current Situation

In Chapter 4, it was assumed that a high pressure center pivot system with the maximum single irrigation volume of 4 acre inches and the minimum irrigation interval of 14 days (High 4-14) represents the current irrigation method. Thus, to be exact, the benchmark results describe the behavior expected under the current production environment involving the High 4-14 irrigation scenario in the absence of water quality control measures. For notational convenience, assume that the baseline scenario is denoted by High 4-14/No policy. Also assume that the other three irrigation scenarios in the absence of pollution control policy options are denoted by High 3-7/No policy, LEPA 3-10/No policy, and LEPA 2-5/No policy. To avoid confusion, assume that results obtained under the High 4-14/No policy scenario are named benchmark results while results obtained under the High 3-7/No policy, LEPA

3-10/No policy, and LEPA 2-5/No policy scenario are named base case results. The benchmark results and the base case results are summarized in Table 6. These results represent the most profitable cropping systems given resources and irrigation scenarios in the absence of pollution control policy measures. Effluent discharge levels are not considered in the decision making process because no policy restrictions are imposed.

Under the High 4-14 scenario, the producer plants 24 percent of the total acreage in a three-year cotton-cotton-grain sorghum rotation (C-C-G), 57 percent of the total acreage in a 3-year peanuts-cotton-grain sorghum rotation (P-C-G), and 19 percent in program wheat. A soil planted to peanuts in a particular year is not going to be planted to peanuts the next two years. Both cotton and peanuts are grown under the high irrigation level, while grain sorghum and wheat are grown under dryland conditions due to the constraint on irrigated acres. Peanuts are grown with the low nitrogen level since peanuts require only a small amount of nitrogen as starter fertilizer. All other crops are grown with the high nitrogen level. Net returns to the farm are estimated to average $193 per acre.

Per acre irrigation applications averaged over the crop mix under the High 4-14 scenario are 20.7 acre inches. The average per acre nitrogen fertilizer application is 56.2 pounds. The average nitrate (NO_3) loss with surface runoff is estimated to be 8.5 pounds per acre, which is about 15.1 percent of the average nitrogen application level. The average nitrogen loss with deep percolation is estimated to be 1.0 pound per acre, which is about 2 percent of the nitrogen application level. These relatively low estimates of the nitrate loss with surface runoff and the nitrogen loss with deep percolation do not necessarily imply that the study area does not have water quality problems caused by nitrogen fertilizer. That is because the nitrogen level in each EPIC-

TABLE 6

OPTIMAL SOLUTIONS IN THE ABSENCE OF POLLUTION CONTROL MEASURES

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use / Effluent Discharges / Net Returns		% of Benchmark Results
			acre					
High 4-14								
C(HH)-C(HH)-G(LH)	114	-	-	-	114	Water (acre inch)	5,393	-
P(HL)-C(HH)-G(LH)	-	36	150	90	276	Nitrogen (lbs.)	26,970	-
Program Wheat(LH)	6	84	-	-	90	NO_3 Runoff (Kg)	1,852	-
						N Percolation (Kg)	222	-
Total	120	120	150	90	480	PST Runoff Index	343,700	-
						PST Percol. Index	2,836	-
						Net Returns	$92,633	-
High 3-7								
C(HH)-C(HH)-G(LH)	26	-	-	90	116	Water (acre inch)	5,455	101.1
P(HL)-C(HH)-G(LH)	94	30	150	-	274	Nitrogen (lbs.)	25,150	93.3
Program Wheat(LH)	-	90	-	-	90	NO_3 Runoff (Kg)	1,806	97.5
						N Percolation (Kg)	137	61.7
Total	120	120	150	90	480	PST Runoff Index	414,000	120.5
						PST Percol. Index	2,127	75.0
						Net Returns	$97,744	105.5
LEPA 3-10								
C(HH)-C(HH)-G(LH)	120	3	-	-	123	Water (acre inch)	4,709	87.3
P(HL)-C(HH)-G(LH)	-	27	150	90	267	Nitrogen (lbs.)	27,160	100.7
Program Wheat(LH)	-	90	-	-	90	NO_3 Runoff (Kg)	1,285	69.4
						N Percolation (Kg)	194	87.4
Total	120	120	150	90	480	PST Runoff Index	104,800	30.5
						PST Percol. Index	3,125	110.2
						Net Returns	$102,761	110.9
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LH)	7	120	150	-	277	Nitrogen (lbs.)	26,690	99.0
Program Wheat(LH)	-	-	-	90	90	NO_3 Runoff (Kg)	1,386	74.8
						N Percolation (Kg)	234	105.5
Total	120	120	150	90	480	PST Runoff Index	105,300	30.6
						PST Percol. Index	1,349	47.6
						Net Returns	$99,220	107.1

PST simulation run was specified at or below the level which equates the marginal value product of nitrogen to the price of nitrogen fertilizer. The indices for both pesticide runoff and percolation indicates that substantial amounts of pesticides are lost into surface water with runoff. For illustration, the toxicity of pesticides moved with runoff from the farm for a year is equivalent to that of 31 pounds of Treflan active ingredient. The degree of health hazard caused by pesticides lost with percolation is equivalent to that caused by approximately 5 ounces of Treflan active ingredient.

The optimal cropping patterns for the other irrigation scenarios are quite similar to the benchmark results. However, the crop mix across the four soils is somewhat different. Changes in relative productivity of soils according to the changes in irrigation scenarios appear to be a reason for the variations in crop mix across soils. Table 7 presents the shadow price of each soil under alternative irrigation scenarios. Each shadow price reflects the marginal profit an additional acre of corresponding soil can generate by rearranging production decisions, under given resource constraints. The differences in shadow prices of the four soils are not uniform across irrigation scenarios. Under the High 4-14, High 3-7, and LEPA 3-10 scenarios, for example, Port silt loam soil has the highest shadow price. Under the LEPA 2-5 scenario, however, the shadow price for Port silt loam soil is lower than that of Pond Creek fine sandy loam soil and Grant loam soil. This result indicates that an irrigation strategy involving more frequent irrigation with lower volume per irrigation is not appropriate for Port silt loam soil. Crop yield data reported in Table 5 support this argument.

The expected returns to the High 3-7 scenario are 6 percent higher than the expected returns to the base irrigation scenario (High 4-14). The nitrate runoff level, nitrogen percolation level, and the pesticide percolation index are lower for the High 3-7 scenario than for the base irrigation scenario. However, the pesticide runoff index of the High 3-7 scenario is 21 percent higher than that of the base irrigation scenario. The greater possibility of coincidental rainfall occurring directly after an automatic irrigation during the period of frequent pesticide application appears to be the cause of the high pesticide runoff level.

TABLE 7

SHADOW PRICES FOR SOILS IN THE ABSENCE OF POLLUTION CONTROL MEASURES

Irrigation Scenario	Soil	Shadow Prices ($)
High 4-14	Cobb fine sandy loam	60.55
	Grant loam	68.39
	Pond Creek fine sandy loam	77.68
	Port silt loam	87.47
High 3-7	Cobb fine sandy loam	63.28
	Grant loam	68.39
	Pond Creek fine sandy loam	73.62
	Port silt loam	74.76
LPEA 3-10	Cobb fine sandy loam	61.10
	Grant loam	68.39
	Pond Creek fine sandy loam	78.06
	Port silt loam	80.90
LEPA 2-5	Cobb fine sandy loam	69.60
	Grant loam	77.50
	Pond Creek fine sandy loam	82.66
	Port silt loam	72.42

Because the application efficiency of the LEPA system is higher than that of the high pressure center pivot system, the expected returns to the two LEPA scenarios are higher than the expected returns to both irrigation scenarios involving the high pressure center pivot system. In addition, the LEPA 3-10 irrigation scenario uses 13 percent less total irrigation water, and the LEPA 2-5 scenario uses 18 percent less total irrigation water than the benchmark result. Both nitrate and pesticide runoff levels are much lower under the LEPA scenarios than under the high pressure center pivot scenarios. These results occur because the application efficiency of the LEPA technology is higher than that of the high pressure center pivot technology. On the other hand, the pesticide percolation level of the LEPA 3-10 scenario and the nitrogen percolation level of the LEPA 2-5 scenario are slightly higher than the benchmark results. Higher application efficiency and a relatively large volume of each irrigation application appear to be responsible for the higher pesticide percolation level under the LEPA 3-10 scenario. The reason for a slight increase in the nitrogen percolation level of the LEPA 2-5 scenario is not obvious.

Excise Tax on Nitrogen Fertilizer and Pesticides

To determine the extent of the farmer's responsiveness to input taxes, a 100 percent excise tax was imposed on both nitrogen fertilizer and pesticides. The influences of this policy on optimal production decisions, net returns, and on nitrogen and pesticide losses are summarized in Table 8. Because the differences in profitability among activities reflected in the model are relatively uniform even with a 100 percent excise tax imposed on both nitrogen and pesticides, this policy option has little impact on the use of these inputs or

TABLE 8

OPTIMAL SOLUTIONS UNDER INPUT TAX POLICY (100% EXCISE TAX ON NITROGEN FERTILIZER AND PESTICIDES)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(HH)-C(HH)-G(LH)	114	-	-	-	114	Water (acre inch)	5,393	100.0
P(HL)-C(HH)-G(LH)	-	-	150	90	240	Nitrogen (lbs.)	26,850	99.6
P(HL)-C(HH)-G(LM)	-	36	-	-	36	NO_3 Runoff (Kg)	1,847	99.7
Program Wheat(LH)	6	84	-	-	90	N Percolation (Kg)	212	95.6
						PST Runoff Index	343,700	100.0
Total	120	120	150	90	480	PST Percol. Index	2,836	100.0
						Net Returns	$59,337	64.1
High 3-7								
C(HH)-C(HH)-G(LH)	26	-	-	90	116	Water (acre inch)	5,455	101.1
P(HL)-C(HH)-G(LH)	94	-	150	-	244	Nitrogen (lbs.)	25,050	92.9
P(HL)-C(HH)-G(LM)	-	30	-	-	30	NO_3 Runoff (Kg)	1,801	97.2
Program Wheat(LH)	-	90	-	-	90	N Percolation (Kg)	129	58.0
						PST Runoff Index	414,000	120.5
Total	120	120	150	90	480	PST Percol. Index	2,126	75.0
						Net Returns	$64,812	70.0
LEPA 3-10								
C(HH)-C(HH)-G(LH)	30	-	-	90	120	Water (acre inch)	4,717	87.5
P(HL)-C(HH)-G(LH)	90	-	150	-	240	Nitrogen (lbs.)	25,170	93.3
P(HL)-C(HH)-G(LM)	-	30	-	-	30	NO_3 Runoff (Kg)	1,229	66.4
Program Wheat(LH)	-	90	-	-	90	N Percolation (Kg)	185	83.5
						PST Runoff Index	107,500	31.3
Total	120	120	150	90	480	PST Percol. Index	3,457	121.9
						Net Returns	$69,877	75.4
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LH)	7	-	150	-	157	Nitrogen (lbs.)	26,290	97.5
P(HL)-C(HH)-G(LM)	-	120	-	-	20	NO_3 Runoff (Kg)	1,369	73.9
Program Wheat(LH)	-	-	-	90	90	N Percolation (Kg)	201	90.9
						PST Runoff Index	105,300	30.6
Total	120	120	150	90	480	PST Percol. Index	1,349	47.6
						Net Returns	$65,960	71.2

cropping patterns. The primary impact of this policy option is to significantly reduce expected net returns.

Under the High 4-14 scenario, the only difference in the optimal cropping system compared to the benchmark result is the shift in 36 acres of Grant loam soil from peanuts(HL)-cotton(HH)-grain sorghum(LH) to peanuts(HL)-cotton(HH)-grain sorghum(LM). This shift indicates that the 100 percent increase in nitrogen fertilizer price made a dryland grain sorghum production activity using the medium nitrogen level (GG1LM) more profitable than an activity using the high nitrogen level (GG1LH). This type of shift did not occur on other soils. The shift described above resulted in a decrease in total nitrogen fertilizer use by 0.4 percent, a decrease in the total nitrate runoff by 0.3 percent, and a decrease in total nitrogen percolation by 4.4 percent from the benchmark levels. The total pesticide runoff and percolation indices did not change.

The results under the High 3-7 scenario, if compared to the corresponding base case results, reveal basically the same type of changes: (1) a shift in 30 acres of Grant loam soil from peanuts(HL)-cotton(HH)-grain sorghum (LH) to peanuts(HL)-cotton(HH)-grain sorghum(LM); (2) total nitrogen use decreased by 0.4 percent; (3) total nitrate runoff decreased by 0.3 percent; and, (4) total nitrogen percolation decreased by 3.7 percent. Again, the total pesticide runoff and percolation levels are same as the base case results.

There are some shifts in the crop mix across soils under the LEPA 3-10 scenario. For example, 90 acres of Port silt loam soil has shifted from peanuts(HL)-cotton(HH)-grain sorghum(LH) to cotton(HH)-cotton(HH)-grain sorghum(LH). EPIC-PST simulation results reveal that Port silt loam soil requires the least amount of nitrogen to produce a same amount of crop among the four soils, and that cotton(HH)-cotton(HH)-grain sorghum(LH) requires more nitrogen than peanuts(HH)-cotton(HH)-grain sorghum(LH). It appears that the increase in the price of nitrogen fertilizer provided an incentive to shift the nitrogen saving Port silt loam soil from peanuts(HL)-cotton(HH)-grain sorghum(LH) which requires a lesser amount of nitrogen to cotton(HH)-cotton(HH)-grain sorghum(LH) which requires a greater amount of nitrogen. Another major change is the shifting of 90 acres of Cobb fine sandy loam soil from cotton(HH)-cotton(HH)-grain sorghum(LH) to peanuts(HL)-cotton(HH)-grain sorghum(LH). It appears that the 100 percent excise tax imposed on nitrogen fertilizer provided an incentive to shift Cobb fine sandy loam soil from a rotation system cotton(HH)-cotton(HH)-grain sorghum(LH) to peanuts(HL)-cotton(HH)-grain sorghum(LH) since Cobb fine sandy loam soil requires a larger amount of nitrogen to attain a given yield. Consequently, compared to the corresponding base case results, total nitrogen use decreased by 7.4 percent, total nitrate runoff decreased by 3.0 percent, and total nitrogen percolation decreased by 3.9 percent. On the other hand, total pesticide runoff (the pesticide runoff index) increased by 0.8 percent and total pesticide percolation (the pesticide percolation index) increased by 11.7 percent. The shift of 90 acres of Cobb fine sandy loam soil from cotton(HH)-cotton(HH)-grain sorghum(LH) to peanuts(HL)-cotton(HH)-grain sorghum(LH) is responsible for the increase since peanuts(HL)-cotton(HH)-grain sorghum(LH) produces greater amounts of pesticide runoff and percolation.

Changes in results under the LEPA 2-5 scenario are (1) the shifting in 120 acres of Grant loam soil from peanuts(HL)-cotton(HH)-grain sorghum(LH) to peanuts(HL)-cotton(HH)-grain sorghum(LM); (2) total nitrogen use decreased by 1.5 percent; (3) total nitrate runoff decreased by 0.9 percent; and, (4) total nitrogen percolation decreased by 14.6 percent. No changes occur in the total pesticide runoff and percolation levels since the change (1) above does not affect pesticide movement.

In summary, neither cropping patterns nor effluent discharge levels are affected much by the 100 percent excise tax imposed on nitrogen fertilizer and pesticides. The only major change is approximately a 36 percent decrease in net returns from the base case results under all irrigation scenarios. Even with these large reductions in net returns, the advantage of two LEPA scenarios over the two High scenarios is maintained. Higher tax rates may induce major changes in the cropping pattern and higher reductions in effluent discharge levels. However, the political acceptability of this policy option with excessively high tax rates is questionable due to the expected strong resistance from the group of affected farmers.

Restricting Total Nitrogen Use

This policy option imposes limits on the total quantity of nitrogen fertilizer that can be applied on the entire farm. To determine the extent of the farmer's responsiveness to this policy alternative, the maximum allowable nitrogen application was set at 50 percent of the benchmark result. The farmer is free to allocate the total quantity of nitrogen to any crop or crop rotation under dryland or irrigated crop production within the limit. The results of this policy option are summarized in Table 9.

To meet the limit on total nitrogen applications, the crop mix and the input use levels are altered under all irrigation scenarios. A major change in the optimal crop mix is the exclusion of the acreage for program wheat. Another change is 29 acres of continuous irrigated cotton appeared in the optimal crop mix of the LEPA 3-10 scenario. The major portion of the reduction in nitrogen use is met by removing from 19 to 24 percent of total acreage from crop production and by lowering nitrogen application levels in cotton and grain

TABLE 9

OPTIMAL SOLUTIONS UNDER TOTAL NITROGEN APPLICATION LIMIT (50% OF THE BENCHMARK RESULT)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
	acre							
High 4-14								
C(HM)-C(HM)-G(LL)	-	-	-	5	5	Water (acre inch)	5,271	97.7
C(HM)-C(HL)-G(LL)	-	-	-	85	85	Nitrogen (lbs.)	13,485	50.0
C(MM)-C(MM)-G(LL)	-	20	-	-	20	NO_3 Runoff (Kg)	1,115	60.2
P(HL)-C(HM)-G(LL)	30	--	150	-	180	N Percolation (Kg)	137	61.8
P(HL)-C(MM)-G(LL)	-	100	-	-	100	PST Runoff Index	329,200	95.8
						PST Percol. Index	1,120	39.5
Total	30	120	150	90	390	Net Returns	$82,756	89.3
							($60,196)	(65.0)
High 3-7								
C(HL)-C(HL)-G(LL)	-	-	-	90	90	Water (acre inch)	5,359	99.4
C(HM)-C(MM)-G(LL)	-	18	-	-	18	Nitrogen (lbs.)	13,485	50.0
P(HL)-C(HM)-G(LL)	20	102	150	-	272	NO_3 Runoff (Kg	1,140	61.6
						N Percolation (Kg)	92	41.7
Total	20	120	150	90	380	PST Runoff Index	369,300	107.4
						PST Percol. Index	402	14.2
						Net Returns	$86,653	93.5
							($60,870)	(65.7)
LEPA 3-10								
C(HM)-C(HL)-G(LL)	-	-	-	78	78	Water (acre inch)	4,761	88.3
C(HL)-C(HL)-C(HL)	-	17	-	12	29	Nitrogen (lbs.)	13,485	50.0
P(HL)-C(HM)-G(LL)	15	103	150	-	268	NO_3 Runoff (Kg)	722	39.0
						N Percolation (Kg)	108	48.8
Total	15	120	150	90	375	PST Runoff Index	106,300	30.9
						PST Percol. Index	509	17.9
						Net Returns	$91,650	98.9
							($64,046)	(69.1)
LEPA 2-5								
C(HL)-C(HL)-G(LL)	-	-	-	90	90	Water (acre inch)	4,265	79.1
C(HM)-C(HL)-G(LL)	-	22	-	-	22	Nitrogen (lbs.)	13,485	50.0
P(HL)-C(HM)-G(LL)	30	22	150	-	202	NO_3 Runoff (Kg)	702	37.9
P(HL)-C(HL)-G(LL)	-	76	-	-	76	N Percolation (Kg)	92	41.7
						PST Runoff Index	96,320	28.0
Total	30	120	150	90	390	PST Percol. Index	550	19.4
						Net Returns	$89,302	96.4
							($65,906)	(71.1)

sorghum production. The acreage removed from production is dryland acres under all irrigation scenarios. The nitrogen application level in all dryland production activities (grain sorghum) is lowered to the low level. The nitrogen application level in irrigated cotton production activities is lowered to the medium or low level. Under the High 4-14 and High 3-7 scenarios, the irrigation level also is reduced from the high level to the medium level in part of the cotton production activities. Under every irrigation scenario, the reduction in planted acreage occurs solely on Cobb fine sandy loam soil which requires the largest amount of nitrogen among the four soils. Port silt loam soil, which requires the least amount of nitrogen, is planted solely to cotton-cotton-grain sorghum (C-C-G) which requires relatively large amounts of nitrogen.

Table 10 presents the shadow prices of individual soils under this policy scenario. Each shadow price reflects the additional profit an additional acre of corresponding soil can generate by rearranging production decisions, under given resource and policy constraints. The shadow price of Port silt loam soil is much higher than that of other soils. This indicates that Port silt loam soil requires considerably less nitrogen to attain a given yield. On the other hand, the shadow price of Cobb fine sandy loam soil is zero since this soil has slack acres. These results suggest that the restriction on total nitrogen applications may cause considerable changes in land resource values.

The reduction in total planted acreage and in the nitrogen application levels on cotton and grain sorghum causes reductions in net returns to the farm. However, the reduction in net returns is relatively small because both the acreage and the input use level of the most profitable crop (peanuts) are maintained at previous levels. Compared to the corresponding base case results, net returns under this policy scenario decreased by 12 percent under the High 3-7 and LEPA 3-10 scenarios, and by 11 percent under the High 4-14 and LEPA 2-5 scenarios. As expected, substantial reductions in nitrate runoff and nitrogen percolation are attained under all irrigation scenarios. Reductions in pesticide runoff and percolation are also attained mainly by removing part of the Cobb fine sandy loam soil which has the highest potential of pesticide runoff and percolation from production.

TABLE 10

SHADOW PRICES FOR SOILS UNDER TOTAL NITROGEN APPLICATION LIMITS (50% OF THE BENCHMARK RESULT)

Irrigation Scenario	Soil	Shadow Prices ($)
High 4-14	Cobb fine sandy loam	-
	Grant loam	22.42
	Pond Creek fine sandy loam	26.09
	Port silt loam	96.33
High 3-7	Cobb fine sandy loam	-
	Grant loam	20.56
	Pond Creek fine sandy loam	23.79
	Port silt loam	100.22
LPEA 3-10	Cobb fine sandy loam	-
	Grant loam	23.40
	Pond Creek fine sandy loam	28.98
	Port silt loam	106.60
LEPA 2-5	Cobb fine sandy loam	-
	Grant loam	21.46
	Pond Creek fine sandy loam	24.69
	Port silt loam	81.84

The same level of reduction in total nitrogen applications and the same level of pollution abatement can be attained by imposing a tax on nitrogen fertilizer. The appropriate tax rate for achieving the 50 percent reduction in total nitrogen applications and the same level of pollution abatement is the shadow price of the constraint in the mathematical programming model that imposes the limit on total nitrogen use. Each shadow price reflects the marginal value product of nitrogen fertilizer at the level of the limit on total nitrogen applications, under given resource constraints. Thus, the shadow price is the dual of the corresponding total nitrogen application constraint. The estimated shadow prices of the total nitrogen application constraints are (1) $1.67/lb under High 4-14; (2) $1.91/lb under High 3-7; (3) $2.05/lb under LEPA 3-10; and, (4) $1.74/lb under LEPA 2-5 irrigation scenario. The price of nitrogen fertilizer used for the analysis is $0.16/lb. Notice that extremely high tax rates (over 1,000 %) are required to achieve the same policy goal. If the tax policy is implemented instead of the policy restricting total nitrogen applications, the producer would be subjected to a significantly greater loss in income. The values in parentheses represent net returns obtainable when tax rates, that are equal to the shadow prices of the total nitrogen application constraints, are imposed on nitrogen fertilizer. Notice the substantial difference in net returns caused by the tax policy. Notice also that the highest net return is acquired under LEPA 2-5 scenario, and that there is no considerable difference between the net return associated with the High 3-7 scenario and the net return associated with the High 4-14 scenario under the nitrogen tax policy. These results occur since the tax rates were determined at the margin for each irrigation scenario.

Restricting Per Acre Nitrogen Use

Under this policy, crop land was zoned according to allowable nitrogen application rates. In other words, crop and soil information were combined when determining allowable per acre nitrogen application rates. To implement the per acre nitrogen application limit, crop production activities associated only with the low nitrogen levels were allowed to appear in the optimal farm plan, regardless of the irrigation level. The proportion of the low nitrogen level to the high level varies depending on soil, crop, and the irrigation level. Results of this policy are reported in Table 11. Under all irrigation scenarios, the cropping patterns are almost the same as the corresponding base case results. The acreage planted to cotton-cotton-grain sorghum (C-C-G) ranges from 23 to 25 percent of the total acreage, and the acreage planted to peanuts-cotton-grain sorghum (P-C-G) ranges from 56 to 58 percent of the total acreage, according to the irrigation scenario. The acreage allocated to program wheat is 19 percent of total acreage under all irrigation scenarios.

Large reductions in nitrogen applications are attained under this policy. In every irrigation scenario, there is approximately a 40 percent reduction in total quantity of nitrogen applied. Nevertheless, the high irrigation levels in peanut and cotton production activities are maintained. This result indicates that the complementary relationship between irrigation water and nitrogen fertilizer was not strong enough to lower the irrigation level. Consequently, total irrigation water use remains virtually at the same level as that in the absence of pollution control policy measures. However, the result might be different if the amounts of nitrogen for the low nitrogen level (i.e. HL) were much less than those specified in this study.

TABLE 11

OPTIMAL SOLUTIONS UNDER PER ACRE NITROGEN APPLICATION LIMITS (LIMITED TO THE LOW NITROGEN LEVEL)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(HL)-C(HL)-G(LL)	-	20	-	90	110	Water (acre inch)	5,425	100.6
P(HL)-C(HL)-G(LL)	30	100	150	-	280	Nitrogen (lbs.)	16,240	60.2
Program Wheat(LL)	90	-	-	-	90	NO_3 Runoff (Kg)	1,175	63.4
						N Percolation (Kg)	104	47.1
Total	120	120	150	90	480	PST Runoff Index	331,300	96.4
						PST Percol. Index	1,125	39.7
						Net Returns	$83,614	90.3
High 3-7								
C(HL)-C(HL)-G(LL)	-	27	-	90	117	Water (acre inch)	5,525	102.4
P(HL)-C(HL)-G(LL)	30	93	150	-	273	Nitrogen (lbs.)	16,340	60.6
Program Wheat(LL)	90	-	-	-	90	NO_3 Runoff (Kg)	1,178	63.6
						N Percolation (Kg)	92	41.7
Total	120	120	150	90	480	PST Runoff Index	388,400	113.0
						PST Percol. Index	596	21.0
						Net Returns	$87,349	94.3
LEPA 3-10								
C(HL)-C(HL)-G(LL)	-	32	-	90	122	Water (acre inch)	4,763	88.3
P(HL)-C(HL)-G(LL)	30	88	150	-	268	Nitrogen (lbs.)	16,400	60.8
Program Wheat(LL)	90	-	-	-	90	NO_3 Runoff (Kg)	848	45.8
						N Percolation (Kg)	92	41.7
Total	120	120	150	90	480	PST Runoff Index	107,700	31.3
						PST Percol. Index	952	33.6
						Net Returns	$92,547	99.9
LEPA 2-5								
C(HL)-C(HL)-G(LL)	-	23	-	90	113	Water (acre inch)	4,263	79.0
P(HL)-C(HL)-G(LL)	30	97	150	-	277	Nitrogen (lbs.)	16,270	60.3
Program Wheat(LL)	90	-	-	-	90	NO_3 Runoff (Kg)	849	45.8
						N Percolation (Kg)	92	41.7
Total	120	120	150	90	480	PST Runoff Index	96,680	28.1
						PST Percol. Index	546	19.3
						Net Returns	$90,540	97.7

Reductions in per acre nitrogen applications result in large reductions in nitrate runoff and nitrogen percolation losses. Nitrate runoff levels are reduced from the base case levels by (1) 37 percent under High 4-14; (2) 34 percent under High 3-7; and; (3) 24 percent under LEPA 3-10; and, (4) 29 percent under LEPA 2-5 irrigation scenario. Nitrogen percolation levels are reduced from the base case levels by (1) 53 percent under High 4-14; (2) 20 percent under High 3-7; (3) 46 percent under LEPA 3-10; and, (4) 64 percent under LEPA 2-5 irrigation scenario.

Larger reductions in pesticide percolation levels are attained under all irrigation scenarios. However, these reductions in pesticide losses are not the result of reductions in per acre nitrogen application but the results of shiftings in cropping systems across soils: shiftings of large portions (75 - 79%) of Cobb fine sandy loam soil from peanuts-cotton-grain sorghum (P-C-G) or cotton-cotton-grain sorghum (C-C-G) to program wheat. Although not substantial, reductions in pesticide runoff are also attained.

In summary, this policy option gives the producer less flexibility in using nitrogen fertilizer. However, if high intensity of nitrogen applications in specific crop production or in certain soils is the major cause of nitrogen pollution, this policy could be more effective than the policy restricting the total quantity of nitrogen applied. The influences of this policy are (1) a large reduction in total quantity of nitrogen application; (2) large reductions in nitrate runoff and nitrogen percolation losses; and (3) 10 to 11 percent reductions in the producer's income. The reductions in net returns are relatively small because both the acreage and the input use of the most profitable crop (peanuts) are maintained at previous levels. The profit advantage of the two LEPA systems over the two high pressure center pivot systems is still maintained under this policy.

Tax on Irrigation Water Use

Since water is the main source of nitrate and pesticide movements, abatement in agricultural pollution can be attained by policy alternatives that induce reductions in irrigation water use. Reductions in irrigation water use can be attained by imposing an additional cost on irrigation water use or by imposing a limit on total irrigation water use. To predict the influences of an additional cost of irrigation applications on water quality and producer's income, a tax was imposed on irrigation water use. The tax rate was assumed to be equal to the variable cost per acre inch of irrigation water pumped by the high pressure center pivot system. Results of the water tax policy are summarized in Table 12.

Results obtained under this policy are almost identical with the corresponding base case results, except for producer's income. Because the differences in profitability among activities reflected in the model are relatively uniform even with the tax imposed on irrigation water use, this policy option has little impact on optimal crop production decisions or the quantity of irrigation water use. Hence, little changes occur in nitrogen and pesticide losses. The only notable impact of this policy option is to reduce producer's income. Compared to the corresponding base case results, reductions in producer's income under this policy scenario range from 13 percent to 16 percent. The advantage of the LEPA irrigation scenarios over the High scenarios is more eminent under this policy since LEPA technology uses less water to attain a given yield. Results imply that higher tax rates, or taxes targeted to specific irrigation systems, are required to induce reductions in irrigation water use.

TABLE 12

OPTIMAL SOLUTIONS UNDER A TAX ON IRRIGATION WATER (100% OF VARIABLE COST OF IRRIGATION)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(HH)-C(HH)-G(LH)	114	-	-	-	114	Water (acre inch)	5,393	100.0
P(HL)-C(HH)-G(LH)	-	36	150	90	276	Nitrogen (lbs.)	26,970	100.0
Program Wheat(LH)	6	84	-	-	90	NO_3 Runoff (Kg)	1,852	100.0
						N Percolation (Kg)	222	100.0
Total	120	120	150	90	480	PST Runoff Index	343,700	100.0
						PST Percol. Index	2,836	100.0
						Net Returns	$77,909	84.1
High 3-7								
C(HH)-C(HH)-G(LH)	-	25	-	90	115	Water (acre inch)	5,443	100.9
P(HL)-C(HH)-G(LH)	120	5	150	-	275	Nitrogen (lbs.)	25,050	92.9
Program Wheat(LH)	-	90	-	-	90	NO_3 Runoff (Kg)	1,181	63.8
						N Percolation (Kg)	140	63.2
Total	120	120	150	90	480	PST Runoff Index	415,200	120.8
						PST Percol. Index	2,332	82.2
						Net Returns	$82,862	89.5
LEPA 3-10								
C(HH)-C(HH)-G(LH)	120	3	-	-	123	Water (acre inch)	4,709	87.3
P(HL)-C(HH)-G(LH)	-	27	150	90	267	Nitrogen (lbs.)	27,160	100.7
Program Wheat(LH)	-	90	-	-	90	NO_3 Runoff (Kg)	1,285	69.4
						N Percolation (Kg)	194	87.4
Total	120	120	150	90	480	PST Runoff Index	104,800	30.5
						PST Percol. Index	3,125	110.2
						Net Returns	$89,905	97.1
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LH)	7	120	150	-	277	Nitrogen (lbs.)	26,690	99.0
Program Wheat(LH)	-	-	-	90	90	NO_3 Runoff (Kg)	1,386	74.8
						N Percolation (Kg)	234	105.5
Total	120	120	150	90	480	PST Runoff Index	105,300	30.6
						PST Percolation Index	1,349	47.6
						Net Returns	$87,212	94.1

Restricting Total Irrigation Water Use

To implement this policy, the total volume of irrigation water use is limited to 50 percent of the benchmark level. A summary of results obtained under this policy scenario is presented in Table 13. Several changes occur under this policy. First, a large part of cotton production shifts from the high irrigation level to dryland. These shifts occurred to meet the limit on total irrigation water use. There is also a slight increase (10 acres) in the acreage allocated to program wheat. It appears that the increase in program wheat acreage has occurred since a three-year rotation system cotton-cotton-grain sorghum (C-C-G) becomes less profitable as irrigation water became too scarce to be allocated to cotton production activities within the rotation system. Another portion of the reduction in irrigation water use is met by reducing irrigated acres. The reductions in irrigated acres are (1) 124 acres under High 4-14; (2) 122 acres under High 3-10; (3) 104 acres under LEPA 3-10; and, (4) 90 acres under LEPA 2-5. Under High 4-14, High 3-7, and LEPA 3-10 scenarios, the reductions in irrigated acres occur mainly in Cobb fine sandy loam soil since Cobb fine sandy loam soil requires more water than other soils to attain a given yield. Under the LEPA 2-5 irrigation scenario, on the other hand, the reduction in irrigated acres occurs mainly in Port silt loam soil since, as discussed above, LEPA 2-5 is not an appropriate irrigation strategy for that soil. Interestingly, Cobb fine sandy loam soil is irrigated most intensively under the LEPA 2-5 irrigation scenario. This result indicates that an irrigation strategy involving more frequent irrigation with less per irrigation volume is most appropriate for soils with considerably high sand contents.

In most cases, large reductions in nitrogen and pesticide losses are attained due to the reduction in the irrigated acres and the shifts in a large part

TABLE 13

OPTIMAL SOLUTIONS UNDER TOTAL IRRIGATION WATER USE LIMIT (50% OF THE BENCHMARK RESULT)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(LH)-C(LH)-G(LH)	103	-	-	-	103	Water (acre inch)	2,697	50.0
P(HL)-C(HH)-G(LH)	-	-	20	90	110	Nitrogen (lbs.)	19,330	71.7
P(HL)-C(MH)-G(LH)	-	20	-	-	20	NO_3 Runoff (Kg)	1,105	59.7
P(HL)-C(LH)-G(LH)	17	-	130	-	147	N Percolation (Kg)	192	86.7
Program Wheat(LH)	-	100	-	-	100	PST Runoff Index	208,400	60.6
						PST Percol. Index	500	17.6
Total	120	120	150	90	480	Net Returns	$79,646	86.0
							($65,808)	(71.0)
High 3-7								
C(LH)-C(LH)-G(LH)	-	20	-	85	105	Water (acre inch)	2,697	50.0
P(HL)-C(HH)-G(LH)	-	-	140	-	140	Nitrogen (lbs.)	19,070	70.7
P(HL)-C(LH)-G(LH)	120	-	10	5	135	NO_3 Runoff (Kg)	1,221	65.9
Program Wheat(LH)	-	100	-	-	100	N Percolation (Kg)	137	61.6
						PST Runoff Index	254,300	74.0
Total	120	120	50	90	480	PST Percol. Index	1,695	59.8
						Net Returns	$81,373	87.8
							($64,506)	(69.6)
LEPA 3-10								
C(LH)-C(LH)-G(LH)	92	20	-	-	112	Water (acre inch)	2,697	50.0
P(HL)-C(HH)-G(LH)	-	-	109	90	199	Nitrogen (lbs.)	20,860	77.3
P(HL)-C(LH)-G(LH)	28	-	41	-	69	NO_3 Runoff (Kg)	1,018	55.0
Program Wheat(LH)	-	100	-	-	100	N Percolation (Kg)	18	82.3
						PST Runoff Index	84,040	24.5
Total	120	120	150	90	480	PST Percol. Index	579	20.4
						Net Returns	$87,231	94.2
							($64,981)	(70.1)
LEPA 2-5								
C(HH)-C(LH)-G(LH)	-	9	-	-	9	Water (acre inch)	2,697	50.0
C(LH)-C(LH)-G(LH)	-	-	-	90	90	Nitrogen (lbs.)	20,770	77.0
P(HL)-C(HH)-G(LH)	120	11	90	-	221	NO_3 Runoff (Kg)	1,036	55.9
P(HL)-C(LH)-G(LH)	-	-	60	-	60	N Percolation (Kg)	154	69.7
Program Wheat(LH)	-	100	-	-	100	PST Runoff Index	86,020	25.0
						PST Percol. Index	2,162	76.2
Total	120	120	150	90	480	Net Returns	$86,702	93.6
							($65,827)	(71.1)

of cotton production from the high irrigation level to dryland. There is a large increase in pesticide percolation under the LEPA 2-5 scenario. Intensive irrigation applications on Cobb fine sandy loam soil planted to the peanuts-cotton-grain sorghum (P-C-G) rotation system is responsible for the increase in pesticide percolation. The reductions in net returns range from 14 percent (LEPA 2-5) to 18 percent (High 3-7) relative to the corresponding base case results.

A 50 percent reduction in total irrigation water use and the same level of pollution abatement can be attained by imposing a tax on irrigation water use. The appropriate tax rate for achieving the reduction in total irrigation water use and the same level of pollution abatement is the shadow price of the total irrigation water use constraint. Each shadow price reflects the marginal value product of irrigation water at the level of the 50 percent limit, under given resource constraints. Thus, the shadow price is the dual of the corresponding total irrigation water use constraint. The shadow prices estimated are (1) $5.13 per acre inch under High 4-14; (2) $6.25 per acre inch under High 3-7; (3) $8.25 per acre inch under LEPA 3-10; and, and, (4) $7.94 per acre inch under LEPA 2-5 irrigation scenario. If the tax policy is implemented instead of the policy restricting total quantity of irrigation water use, the producer is subject to a much higher income loss. The values in parentheses represent net returns obtainable when the tax rates, that are equal to the shadow prices of the total irrigation constraints, are imposed on irrigation water use. Notice the difference between the net returns under the tax policy and the net returns under the standard policy. Notice also that the levels of profits are nearly the same for each of the irrigation schemes since the tax rates were determined at the margin for each irrigation scenario.

<u>Restricting Pesticide Percolation</u>

This policy specifies the maximum level of pesticide percolation the farm may generate without penalty. To implement this policy, the maximum allowable pesticide percolation index was set at 50 percent of the pesticide percolation index estimated under the benchmark scenario. Notice that the amount of various pesticide ingredients moved with deep percolation is converted to the percolation index to reflect potential adverse health effects. Notice also that the amount of pesticide ingredients moved with runoff water or sediment is converted to the pesticide runoff index to reflect it's toxicity (see Chapter III). A summary of results obtained under this policy alternative is presented in Table 14.

Because the pesticide percolation constraint is not binding under the LEPA 2-5 scenario, the optimal crop mix and the net return for the LEPA 2-5 irrigation scenario under this policy are not different from the corresponding base case results. This result suggests that the LEPA 2-5 irrigation strategy is the most efficient in reducing pesticide percolation. The optimal crop mixes and net returns for other irrigation scenarios are almost the same as the corresponding base case results. This implies that the 50 percent reduction in pesticide percolation can be attained without difficulty. In general, the reduction in pesticide percolation is attained by shifting part of the rotation systems that generates large amounts of pesticide percolation from Cobb fine sandy loam soil to Grant loam soil.

A policy which targets just one type of pollutant (pesticide percolation in this case) could induce increases in the discharge of other pollutants. Compared to the benchmark results, for example, nitrate runoff and nitrogen percolation for the High 4-14 scenario increase 7 percent and 21 percent,

TABLE 14

OPTIMAL SOLUTIONS UNDER A PESTICIDE PERCOLATION LIMIT (LIMITED TO 50% OF THE BENCHMARK RESULT)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(HH)-C(HH)-G(LH)	56	58	-	-	114	Water (acre inch)	5,391	100.0
P(HL)-C(HH)-G(LH)	-	36	150	90	276	Nitrogen (lbs.)	27,490	101.9
Program Wheat(LH)	64	26	-	-	90	NO_3 Runoff (Kg)	1,976	106.7
						N Percolation (Kg)	268	121.0
Total	120	120	150	90	480	PST Runoff Index	328,200	95.5
						PST Percol. Index	1,418	50.0
						Net Returns	$92,622	100.0
High 3-7								
C(HH)-C(HH)-G(LH)	27	-	-	90	117	Water (acre inch)	5,482	101.7
P(HL)-C(HH)-G(LH)	57		66	150	273	Nitrogen (lbs.)	25,620	95.0
Program Wheat(LH)	36	54	-	-	90	NO_3 Runoff (Kg)	1,841	99.4
						N Percolation (Kg)	156	70.5
Total	120	120	150	90	480	PST Runoff Index	402,700	117.2
						PST Percol. Index	1,418	50.0
						Net Returns	$97,644	105.4
LEPA 3-10								
C(HH)-C(HH)-G(LH)	53	70	-	-	123	Water (acre inch)	4,728	87.7
P(HL)-C(HH)-G(LH)	-	27	150	90	267	Nitrogen (lbs.)	27,760	102.9
Program Wheat(LH)	67	23	-	-	90	NO_3 Runoff (Kg)	1,356	73.2
						N Percolation (Kg)	247	111.6
Total	120	120	150	90	480	PST Runoff Index	104,600	30.4
						PST Percol. Index	1,418	50.0
						Net Returns	$102,725	110.9
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LH)	7	120	150	-	277	Nitrogen (lbs.)	26,690	99.0
Program Wheat(LH)	-	-	-	90	90	NO_3 Runoff (Kg)	1,386	74.8
						N Percolation (Kg)	234	105.5
Total	120	120	150	90	480	PST Runoff Index	105,300	30.6
						PST Percol. Index	1,349	47.6
						Net Returns	$99,220	107.1

respectively, under this policy. Nitrate runoff and nitrogen percolation levels for the High 3-7 and LEPA 3-10 irrigation scenarios are also slightly higher under this policy than for the corresponding base case results. The shifting of irrigated cotton production activities from Cobb fine sandy loam soil to Grant loam soil caused the increase in nitrate runoff and nitrogen percolation. These results suggests the need for a pollution control policy targeting most pollutants simultaneously.

This policy, which imposes an upper limit on pesticide percolation for the farm, is an example of nonpoint standards ($\mathbf{z}_2^*$) discussed in Chapter II. The corresponding nonpoint incentive ($\boldsymbol{\mu}_2^*$), which is the dual of the nonpoint standard, is the shadow price of the pesticide percolation constraint. It is interpreted as the marginal cost for reducing an additional unit of the pesticide percolation index. The optimal nonpoint incentives are: (1) \$0.007 under the High 4-14; (2) \$0.14 under the High 3-7; and (3) \$0.021 under the LEPA 3-10. The nonpoint incentive for the LEPA 2-5 scenario is zero because the pesticide percolation constraint is not binding. These nonpoint incentives can be charged as effluent taxes to each unit of pesticide percolation index. Under this policy, the effluent taxes charged to pesticide percolation would not cause substantial losses in the producer's income since the tax rates are infinitesimal. Under the LEPA 2-5 irrigation scenario, there is no need of imposing a nonpoint incentive because the policy goal has been attained already.

The optimal production decisions represent the management practice standards ($\mathbf{x}^*$) that are interpreted as the farm production activity levels specified by a regulatory agency. In other words, the farmer is forced to adopt those activity levels as a way to achieve the water quality objective. The management practice incentives are tax rates ($\boldsymbol{\mu}_2^{*\prime}\mathbf{G}_2$) imposed on the activity vector ($\mathbf{x}$) chosen by the farmer. Under this policy, $\boldsymbol{\mu}_2^*$ is a scalar since only one pollutant is targeted. $\mathbf{G}_2$ is also a vector composed of the pesticide percolation indices associated with all crop production activities. Notice that the amount of tax paid under the management practice incentive policy is identical with the amount paid under the nonpoint incentive policy. Because $\mathbf{G}_2\mathbf{x}$ represents the total sum of the pesticide percolation generated by crop production activities and μ_2^* represents the optimal nonpoint incentive, $\mu_2^{*\prime}\mathbf{G}_2\mathbf{x}$ is the amount of tax charged to the total sum of pesticide percolation (indices) generated by crop production activities in the farm. Notice that the optimal production decisions ($\mathbf{x}^*$) that result from any of the four policy tools, including nonpoint standards, nonpoint incentives, management practice standards, and management practice incentives, is consistent with each other.

To illustrate, assume that (1) x_1 denotes the level of the activity NP1HL (Table 5); (2) x_2 denotes the level of NC1HH; (3) x_3 denotes the level of NG1LH; (4) g_1 denotes the level of pesticide percolation generated by one unit of x_1; (5) g_2 denotes the level of pesticide percolation generated by one unit of x_2; and (6) g_3 denotes the level of pesticide percolation generated by one unit of x_3. Then the formula for calculating the amount of the management practice incentive charged to $x_1+x_2+x_3$ acres of a three-year rotation system NP1HL-NC1HH-NG1LH is:

$$\mu_2[g_1\ g_2\ g_3][x_1\ x_2\ x_3]' \qquad (5.1)$$

Under the High 4-14 irrigation scenario, equation (5.1) is converted to

$$\$0.007\ [0.11\ \ 0.34\ \ 0][50\ \ 50\ \ 50]' = \$0.158$$

Under the High 3-7 irrigation scenario, equation (5.1) is converted to

$$\$0.140\ [0.05\ \ 0.06\ \ 0][50\ \ 50\ \ 50]' = \$0.770$$

Under the LEPA 3-10 irrigation scenario, equation (5.1) is converted to

$$\$0.021\ [0.33\ \ 0.48\ \ 0][50\ \ 50\ \ 50]' = \$0.851$$

Notice that 150 acres of Pond Creek fine sandy loam soil is allocated to the rotation system NP1HL-NC1HH-NG1LH (Table 14). The values for x_1, x_2, and x_3 are identically 50 because of the rotational linkages established in the mathematical programming model.

In summary, a 50 percent abatement of pesticide percolation can be attained by any of the four types of policies, including nonpoint standards, nonpoint incentives, management practice standards, and management practice incentives. If policy parameters for these policies are set properly, then every result, except producer's income, would be identical. If either of the two incentive policies is implemented, then the producer's income decreases. Preceding discussions on the four types of least cost policy options apply to the following policy scenarios.

The tax rates associated with the incentive policies are infinitesimal under this policy restricting pesticide percolation. Thus, the loss in producer's income is trivial even though one of the two incentive policies is implemented to attain a 50 percent abatement of pesticide percolation.

Restricting Nitrogen Percolation

This policy specifies the maximum level of nitrogen percolation the farm may generate without penalty. To implement this policy, the maximum allowable nitrogen percolation level was set at 50 percent of the benchmark result. Results of this policy are summarized in Table 15. To meet the nitrogen percolation limit, the nitrogen application level in part of the cotton and sorghum

TABLE 15

OPTIMAL SOLUTIONS UNDER A NITROGEN PERCOLATION LIMIT (LIMITED TO 50% OF THE BENCHMARK RESULT)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
	acre							
High 4-14								
C(HH)-C(HH)-G(LH)	-	-	-	90	90	Water (acre inch)	5,428	100.6
C(HH)-C(HH)-G(LM)	17	-	-	-	17	Nitrogen (lbs.)	23,190	86.0
P(HL)-C(HH)-G(LM)	103	-	-	-	103	NO_3 Runoff (Kg)	1,689	91.2
P(HL)-C(HH)-G(LL)	-	106	60	-	166	N Percolation (Kg)	111	50.0
P(HL)-C(HM)-G(LL)	-	14	-	-	14	PST Runoff Index	374,100	108.8
Program Wheat(LH)	-	-	90	-	90	PST Percol. Index	4,184	147.5
						Net Returns	$91,385	98.7
Total	120	120	150	90	480		($88,157)	95.2
High 3-7								
C(HH)-C(HH)-G(LH)	-	-	-	90	90	Water (acre inch)	5,455	101.1
C(HH)-C(HH)-G(LM)	26	-	-	-	26	Nitrogen (lbs.)	24,610	91.2
P(HL)-C(HH)-G(LH)	-	-	136	-	136	NO_3 Runoff (Kg)	1,782	96.2
P(HL)-C(HH)-G(LM)	94	30	14	-	138	N Percolation (Kg)	111	50.0
Program Wheat(LH)	-	90	-	-	90	PST Runoff Index	414,000	120.5
						PST Percol. Index	2,127	75.0
Total	120	120	150	90	480	Net Returns	$97,655	105.4
							($97,053)	104.8
LEPA 3-10								
C(HH)-C(HM)-G(LH)	-	-	-	2	2	Water (acre inch)	4,732	87.7
C(HH)-C(HH)-G(LM)	120	-	-	-	120	Nitrogen (lbs.)	25,490	94.5
P(HL)-C(HH)-G(LL)	-	81	99	88	268	NO_3 Runoff (Kg)	1,204	65.0
Program Wheat(LH)	-	39	51	-	90	N Percolation (Kg)	111	50.0
						PST Runoff Index	108,700	31.6
Total	120	120	150	90	480	PST Percol. Index	3,117	109.9
						Net Returns	$101,983	110.1
							($99,623)	107.5
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LM)	7	-	-	-	7	Nitrogen (lbs.)	23,590	87.5
P(HL)-C(HH)-G(LL)	-	-	135	-	135	NO_3 Runoff (Kg)	1,222	66.0
P(HL)-C(HM)-G(LL)	-	120	15	-	135	N Percolation (Kg)	111	50.0
Program Wheat(LL)	-	-	-	90	90	PST Runoff Index	105,200	30.6
						PST Percol. Index	1,349	47.6
Total	120	120	150	90	480	Net Returns	$98,397	106.2
							($96,581)	104.3

production activities shifts from the high level to the medium or the low level under every irrigation scenario. On the other hand, overall crop mixes are almost identical with the corresponding base case results. Because the high irrigation level is maintained in spite of the low nitrogen application level, the total amount of irrigation water use in every irrigation scenario is almost identical with the corresponding base case result.

Under the High 4-14 irrigation scenario, the total quantity of nitrogen applied decreases by 14 percent. Also the total amount of nitrogen runoff decreases by 9 percent. However, the pesticide runoff index and the pesticide percolation index increase by 9 percent and 48 percent, respectively. Notice the significant increase in the pesticide percolation index. The sift of the rotation system peanuts(HL)-cotton(HH)-grain sorghum(LM) to the Cobb fine sandy loam soil appears to be responsible for the significant increase in the pesticide percolation index since both the rotation system and the soil have high pesticide leaching potential. This result suggests the need for a pollution control policy that focuses on all types of pollutants simultaneously. Although the nitrogen application level in part of the cotton and grain sorghum activities is lowered to the medium or the low level, the reduction in the producer's income is about 2 percent less than the benchmark result.

Under the High 3-7 irrigation scenario, the total quantity of nitrogen applied and the nitrogen runoff level decrease slightly. However, the pesticide runoff and percolation indices remain at the same level. The producer's income also remains at about the same level: there is only a 0.1 percent decrease when compared with the corresponding base case result.

Under the LEPA 3-10 irrigation scenario, the total quantity of nitrogen applied decreases by 6 percent. The reduction in the amount of nitrate runoff is about 4 percent. While the pesticide percolation index decreases slightly, the pesticide runoff index increases slightly. The producer's income declines only 0.8 percent from the corresponding base case result.

Under the LEPA 2-5 irrigation scenario, the total quantity of nitrogen applied decreases by 12 percent. The amount of nitrogen runoff also decreases by 13 percent. On the other hand, both the pesticide runoff index and the pesticide percolation index remain at the same level. As under the other irrigation scenario, the decrease in the producer's income is small: there is only a 0.9 percent decrease from the level of the LEPA 2-5/No policy case.

Under this policy scenario, the nonpoint standard ($\mathbf{z}_2^*$) is the upper limit on the amount of nitrogen percolation. The corresponding nonpoint incentive ($\boldsymbol{\mu}_2^*$) is the shadow price of the nitrogen percolation constraint in the mathematical programming model. Under this policy, $\boldsymbol{\mu}_2^*$ is a scalar since just one type of constraint is imposed. These shadow prices (nonpoint incentives) are (1) \$29.08 under the High 4-14 irrigation scenario; (2) \$5.43 under the High 3-7 irrigation scenario; (3) \$21.26 under the LEPA 3-10 irrigation scenario; and, (4) \$16.36 under the LEPA 2-5 irrigation scenario. Each shadow price is interpreted as the marginal cost incurred to the producer for reducing an additional unit (kg) of nitrogen percolation under respective irrigation scenarios. To attain the nonpoint standard, which is a 50 percent reduction in the amount of nitrogen percolation, these nonpoint incentives can be charged as effluent taxes to each unit of nitrogen percolation. If these effluent taxes are charged to each unit of nitrogen percolation, there would be some reductions in the producer's income. The values in parentheses (Table 15) represent net returns when these effluent taxes are charged to each unit of nitrogen percolation. The reductions in net returns under the effluent taxes range from 0.6 percent to 3.5 percent, depending upon the irrigation scenario.

The management practice standards ($\mathbf{x}^*$) are represented by the optimal production decisions. The management practice incentives ($\boldsymbol{\mu}_2^{*\prime}\mathbf{G}_2$) are tax rates imposed on each unit of various crop production activities. As discussed above, the management practice incentives involve reductions in the producer's income which are equal to the reductions associated with the nonpoint incentives.

In summary, abatement of nitrogen percolation can be attained by shifting the nitrogen application level in part of cotton and grain sorghum activities from the high level to the medium or the low level. Along with the reductions in nitrogen percolation, reductions in nitrogen runoff are also attained. In most occasions, pesticide runoff and percolation levels remain basically at the same level as the corresponding base case results. Under the High 4-14 irrigation scenario, however, pesticide percolation increases significantly. This suggests the need for a policy that focuses on all types of agricultural pollutants simultaneously. The reductions in producer's income are not significant under all irrigation scenarios because quota peanut production, which is considerably more profitable than other crops, remains at the same level.

Restricting Both Pesticide and Nitrogen Percolation

To determine the extent of the farmer's response to a policy that restricts the amount of both pesticide and nitrogen percolation, the upper limits of pesticide and nitrogen percolation are set at the level which is equivalent to 50 percent of the benchmark results. The influences of this policy on optimum production decisions, net returns, and on nitrogen and pesticide losses are summarized in Table 16.

TABLE 16

OPTIMAL SOLUTIONS UNDER PESTICIDE AND NITROGEN PERCOLATION LIMITS (LIMITED TO 50% OF THE BENCHMARK RESULTS)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
High 4-14								
C(HH)-C(HH)-G(LM)	56	-	-	-	56	Water (acre inch)	5,414	104.4
C(HH)-C(HL)-G(LH)	-	-	-	35	35	Nitrogen (lbs.)	22,730	84.3
Continuous Cotton(HM)	-	14	-	-	14	NO_3 Runoff (Kg)	1,621	87.5
P(HL)-C(HM)-G(LL)	-	106	117	-	223	N Percolation (Kg)	111	50.0
P(HL)-C(HL)-G(LH)	-	-	-	55	55	PST Runoff Index	337,100	98.1
Program Wheat(LH)	64	-	33	-	97	PST Percol. Index	1,418	50.0
						Net Returns	$89,631	96.8
Total	120	120	150	90	480		($78,937)	(85.2)
High 3-7								
C(HH)-C(HH)-G(LH)	-	-	-	1	1	Water (acre inch)	5,445	101.0
C(HH)-C(HH)-G(LM)	115	-	-	-	115	Nitrogen (lbs.)	26,390	97.8
P(HL)-C(HH)-G(LH)	-	-	136	89	225	NO_3 Runoff (Kg)	1,867	100.8
P(HL)-C(HH)-G(LM)	5	30	14	-	49	N Percolation (Kg)	111	50.0
Program Wheat(LH)	-	90	-	-	90	PST Runoff Index	407,800	118.6
						PST Percol. Index	1,418	50.0
Total	120	120	150	90	480	Net Returns	$97,546	105.3
							($96,727)	(104.4)
LEPA 3-10								
C(HH)-C(HH)-G(LM)	53	-	-	-	53	Water (acre inch)	4,762	88.3
C(HH)-C(HM)-G(LH)	-	-	-	69	69	Nitrogen (lbs.)	23,260	86.2
P(HL)-C(HH)-G(LL)	-	-	-	21	21	NO_3 Runoff (Kg)	1,147	61.9
P(HL)-C(HH)-G(LL)	-	-	6	-	56	N Percolation (Kg)	111	50.0
P(HL)-C(HM)-G(LL)	-	120	71	-	191	PST Runoff Index	108,300	31.5
Program Wheat(LH)	67	-	23	-	90	PST Percol. Index	1,418	50.0
						Net Returns	$101,099	109.1
Total	120	120	150	90	480		($95,352)	102.9
LEPA 2-5								
C(HH)-C(HH)-G(LH)	113	-	-	-	113	Water (acre inch)	4,399	81.6
P(HL)-C(HH)-G(LM)	7	-	-	-	7	Nitrogen (lbs.)	23,590	87.5
P(HL)-C(HH)-G(LL)	-	-	135	-	135	NO_3 Runoff (Kg)	1,222	66.0
P(HL)-C(HM)-G(LL)	-	120	15	-	135	N Percolation (Kg)	111	50.0
Program Wheat(LL)	-	-	-	90	90	PST Runoff Index	105,200	30.6
						PST Percol. Index	1,349	47.6
Total	120	120	150	90	480	Net Returns	$98,397	106.2
							($96,580)	(104.3)

The optimal crop mixes under this policy present numerous rotation options. However, the dominance of the three cropping systems, peanuts-cotton-grain sorghum (P-C-G), cotton-cotton-grain sorghum (C-C-G), and program wheat, is still maintained under most irrigation scenarios. The only exception is the 14 acres of continuous cotton which appeared under the High 4-14 irrigation scenario. In most cases, the reductions in pesticide percolation are attained by shifting either the peanuts-cotton-grain sorghum (P-C-G) or the cotton-cotton-grain sorghum (C-C-G) rotation system from Cobb fine sandy loam soil to other soils. Under the LEPA 2-5 irrigation scenario, however, the acreage of Cobb fine sandy loam soil allocated to the peanuts-cotton-grain sorghum (P-C-G) and the cotton-cotton-grain sorghum (C-C-G) rotation system remained at the same level since the pesticide percolation limit was already attained. Under all irrigation scenarios, the reductions in nitrogen percolation are attained mainly by lowering per acre nitrogen applications. The high irrigation levels in peanut and cotton production activities are still maintained. The resulting total irrigation water use and profit to the farm are not considerably different from the corresponding base case results. The total nitrogen application levels are significantly lower (well over 10 percent) under all irrigation scenarios except the High 3-7 irrigation scenario. Under the High 3-7 irrigation scenario, the total quantity of nitrogen applied increases by 4.5 percent even though the per acre nitrogen application level in some of the grain sorghum production activities is lowered to the medium level. It appears that 115 acres of Cobb fine sandy loam soil allocated to the cotton(HH)-cotton(HH)-grain sorghum(LM) rotation system is responsible for the increase in the total quantity of nitrogen application since both the soil and the rotation system require relatively a large amount of nitrogen.

Under this policy, the dimension of the nonpoint incentive vector is 2x1 since two types of limits are imposed as the nonpoint standards. The optimum nonpoint incentives for the pesticide percolation are (1) $1.37 under the High 4-14 irrigation scenario; (2) $0.15 under the High 3-7 irrigation scenario; (3) $0.81 under the LEPA 3-10 irrigation scenario; and, (4) zero under the LEPA 2-5 irrigation scenario since the pesticide percolation constraint is not binding under this irrigation scenario. The optimum nonpoint incentives for the nitrogen percolation standard are (1) $78.84 under the High 4-14 irrigation scenario; (2) $5.43 under the High 3-7 irrigation scenario; (3) $41.51 under the LEPA 3-10 irrigation scenario; and, (4) $16.36 under the LEPA 2-5 scenario. Compared to the nonpoint incentives for the corresponding nonpoint standards under the previous two policy scenarios, these nonpoint incentives are considerably higher under the High 4-14 and LEPA 3-10 irrigation scenarios. These results imply the following: (1) additional abatement of pesticide and/or nitrogen percolation over the 50 percent level would entail substantial costs to the producer because of the double constraints; (2) if either the nonpoint incentives or the management practice incentives are employed as pollution control tools, then the costs incurred for the producer will increase significantly; (3) the High 3-7 and the LEPA 2-5 irrigation scenarios have a relative advantage over the High 4-14 and the LEPA 3-10 irrigation scenario for reducing both pesticide and nitrogen percolation at the same time. The values in parentheses (Table 16) represent the reduced profit associated with the two incentive policies.

Restricting Nitrate Runoff, Nitrogen Percolation, Pesticide Runoff, and Pesticide Percolation

This policy targets all types of agricultural pollutants considered in this study: (1) nitrate runoff; (2) nitrogen percolation; (3) the pesticide runoff index;

and, (4) the pesticide percolation index. To implement this policy, the maximum allowable level of these pollutants is set at 50 percent of those levels estimated under the benchmark scenario. A summary of results of this policy is presented in Table 17.

The optimal crop mixes under this policy present the widest set of rotation options. Under the High 4-14 irrigation scenario, the nitrogen application level in many of the grain sorghum and cotton production activities shifts to the medium or low level to abate nitrate runoff and percolation. The irrigation level in some peanut and cotton production activities shifts to the low level (dryland condition) to abate pesticide runoff and percolation. The appearance of a three-year rotation system (peanut-wheat/grain sorghum double cropping-cotton) in the optimal farm plan is a notable change. Total irrigation water use and total nitrogen applications decrease by 56 percent and 39 percent, respectively. Total irrigated acreage decreases by 55 percent. Net returns to the farm decrease by 18 percent.

Under the High 3-7 irrigation scenario, the nitrogen application level in part of the grain sorghum and cotton production activities shifts to the medium or low level to abate nitrate runoff and percolation. The irrigation level in some part of the peanut and cotton production activities also shifts to the low level (dryland condition) to abate pesticide runoff and percolation. Total irrigated acreage decreases by 58 percent. Compared to the corresponding base case result, total irrigation water use decreases by 62 percent. The total quantity of nitrogen applied decreases by 34 percent. The reduction in net returns under the High 3-7 irrigation scenario is even greater than under the High 4-14 irrigation scenario: a 23 percent decrease from the corresponding base case result.

TABLE 17

OPTIMAL SOLUTIONS UNDER LIMITS ON PESTICIDE PERCOLATION, PESTICIDE RUNOFF, NITROGEN PERCOLATION, AND NITRATE RUNOFF (LIMITED TO 50% OF BENCHMARK RESULTS)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench- mark Results
			acre					
High 4-14								
C(HH)-C(HM)-G(LH)	-	-	-	38	38	Water (acre inch)	2,347	43.5
P(HL)-C(HH)-G(LH)	-	-	-	31	31	Nitrogen (lbs.)	6,350	60.6
P(HL)-C(HM)-G(LL)	-	-	10	-	10	NO_3 Runoff (Kg)	926	50.0
P(HL)-C(HL)-G(LH)	-	-	-	21	21	N Percolation (Kg)	111	50.0
P(HL)-C(LH)-G(LL)	-	-	140	-	14	PST Runoff Index	171,850	50.0
P(HL)-C(LM)-G(LL)	-	8	-	-	8	PST Percol. Index	742	26.2
P(LL)-C(LH)-G(LM)	120	-	-	-	120	Net Returns	$76,335	82.4
P(LL)-W(LL)/G(LL)-C(LM)	-	12	-	-	12		($55,276)	(59.7)
Program Wheat(LH)	-	100	-	-	100			
Total	120	120	150	90	480			
High 3-7								
C(HH)-C(HM)-G(LH)	-	-	-	1	1	Water (acre inch)	2,138	39.6
C(HH)-C(MM)-C(LH)	-	-	-	36	36	Nitrogen (lbs.)	16,040	59.5
P(HL)-C(HH)-G(LH)	-	-	-	53	53	NO_3 Runoff (Kg)	926	50.0
P(HL)-C(LH)-G(LM)	-	-	150	-	150	N Percolation (Kg)	109	49.2
P(LL)-C(LH)-G(LM)	120	-	-	-	120	PST Runoff Index	171,850	50.0
P(LL)-C(LH)-G(LL)	-	20	-	-	20	PST Percol. Index	736	26.0
Program Wheat(LH)	-	29	-	-	29	Net Returns	$76,557	82.6
Program Wheat(LM)	-	71	-	-	71		($54,722)	(59.1)
Total	120	120	150	90	480			
LEPA 3-10								
C(HH)-C(HM)-G(LH)	-	-	-	2	2	Water (acre inch)	4,768	88.4
C(HM)-C(HM)-G(LH)	-	-	-	88	88	Nitrogen (lbs.)	20,210	74.9
C(HH)-C(LH)-G(LL)	102	-	-	-	102	NO_3 Runoff (Kg)	926	50.0
C(LH)-C(LH)-G(LL)	18	-	-	-	18	N Percolation (Kg)	111	50.0
P(HL)-C(HM)-G(LL)	-	118	113	-	231	PST Runoff Index	115,800	33.7
P(HL)-C(LH)-G(LL)	-	-	26	-	26	PST Percol. Index	1,418	50.0
P(HL)-C(LM)-G(LL)	-	-	11	-	11	Net Returns	$99,470	107.4
Program Wheat(LM)	-	2	-	-	2		($83,021)	(89.6)
Total	120	120	150	90	480			

TABLE 17 (Continued)

Cropping System	Cobb	Grant	Creek	Port	Total	Resource Use Effluent Discharges Net Returns		% of Bench-mark Results
			acre					
LEPA 2-5								
C(HM)-C(HM)-G(LL)	-	22	-	-	22	Water (acre inch)	4,328	80.3
C(HH)-C(LH)-G(LL)	74	-	-	-	74	Nitrogen (lbs.)	20,230	75.0
C(HM)-C(LL)-G(LH)	-	-	-	90	90	NO_3 Runoff (Kg)	926	50.0
C(HM)-C(LH)-G(LL)	16	-	-	-	16	N Percolation (Kg)	92	41.7
P(HL)-C(HM)-G(LL)	-	98	150	-	248	PST Runoff Index	107,810	31.4
P(HL)-C(HH)-G(LL)	30	-	-	-	30	PST Percol. Index	1,068	7.7
						Net Returns	$96,641	104.3
							($83,326)	(90.0)
Total	120	120	150	90	480			

Under the LEPA 3-10 irrigation scenario, the rotation system cotton-cotton-grain sorghum (C-C-G) replaces most program wheat acreage in order to meet the nitrate runoff constraint. The nitrogen application level in most grain sorghum production activities and some cotton production activities shifts to the medium or low level. Consequently, the total quantity of nitrogen applied decreases by 24 percent. Although part of the irrigated cotton acreage is replaced by dryland cotton acreage, total irrigated acreage remains at the maximum level (260 acres) since most dryland wheat acreage is replaced by the rotation system cotton-cotton-grain sorghum (C-C-G). Consequently, the total amount of irrigation water use increases slightly. The reduction in the producer's income is not as significant as under the preceding two irrigation scenario: a 3.5 percent decrease from the corresponding base case result. Further, net returns are still 7 percent higher than the benchmark result.

Under the LEPA 2-5 irrigation scenario, the optimum farm plan consists of two rotation systems: the peanuts-cotton-grain sorghum (P-C-G) rotation (56%) and the cotton-cotton-grain sorghum (C-C-G) rotation (44%). The nitrogen application level of most grain sorghum production activities and many cotton production activities in these rotation systems is the medium or low level. Consequently, the total quantity of nitrogen applied decreases by 24 percent from the corresponding base case result. The irrigation level in all peanut production activities and most cotton production activities is maintained at the high level and total irrigated acreage remains at the maximum level (260 acres). The resulting total amount of irrigation water use is slightly lower than the corresponding base case result. The producer's income is reduced 2.8 percent from the corresponding base case result, but is still 4 percent higher than the benchmark result.

Not all of the constraints which impose limits on the amounts of the four types of pollutants are binding. Under the High 4-14 irrigation scenario, binding constraints include the nitrate runoff constraint ($9.54), the nitrogen percolation constraint ($18.81), and the pesticide runoff constraint ($0.059). Monetary values in parentheses represent the shadow prices (nonpoint incentives) of the respective constraints (nonpoint standards). Under the High 3-7 irrigation scenario, the nitrate runoff constraint ($10.03) and the pesticide runoff constraint ($0.073) are binding. Under the LEPA 3-10 irrigation scenario, the nitrate runoff constraint ($14,27), nitrogen percolation constraint ($26.25), and pesticide percolation constraint ($0.229) are binding. Under the LEPA 2-5 irrigation scenario, only the nitrogen runoff constraint ($14.38) is binding. If these shadow prices are charged to each unit of pollutants as either nonpoint incentives or management practice incentives, substantial income losses will be incurred to the producer. The values in the parentheses (Table 17) show those reduced net returns to the farm.

Interpretation of the shadow prices estimated under this policy is tedious and unrewarding since four constraints are imposed at the same time. However, comparison of shadow prices under this policy scenario with those under the preceding three policy scenarios (Table 18) provides additional insight. First, High 3-7 is the best irrigation scenario for abating nitrogen percolation, given the quantity of nitrogen applied. This interpretation is drawn from (1) the least profit loss ($89) under policy scenario I; (2) the lowest shadow price ($5.43) for the nitrogen percolation constraint under policy scenarios I and II; and (3) the zero shadow price for the nitrogen percolation constraint under the policy scenario IV. Second, the most efficient irrigation scenario for abating pesticide percolation is LEPA 2-5. The zero shadow price for the pesticide percolation constraint under policy scenarios II, III, and IV support this

TABLE 18

COMPARISON OF SHADOW PRICES OBTAINED UNDER VARIOUS POLLUTION CONTROL MEASURES

	Pollutant				
Scenario (Target)	NO_3 Runoff (YNO_3)	N Percol. (PRKN)	PST Runoff (I_s)	PST Percol. (I_g)	Profit Loss
I. Nitrogen Percolation (PRKN)					
High 4-14	-	$29.08	-	-	$1,248
High 3-7	-	5.43	-	-	89
LEPA 3-10	-	21.26	-	-	778
LEPA 2-5	-	16.36	-	-	823
II. Pesticide Percolation (I_g)					
High 4-14	-	-	-	$0.007	$11
High 3-7	-	-	-	0.140	100
LEPA 3-10	-	-	-	0.021	36
LEPA 2-5	-	-	-	-	-
III. Nitrogen Percolation (PRKN) and Pesticide Percolation (I_g)					
Hi 4-14	-	$78.84	-	$1.371	$3,002
Hi 3-7	-	5.43	-	0.153	198
LEPA 3-10	-	41.51	-	0.806	1,662
LEPA 2-5	-	16.36	-	-	824
IV. Nitrate Runoff (YNO_3), Nitrogen Percolation (PRKN), Pesticide Runoff (I_s), and Pesticide Percolation (I_g)					
Hi 4-14	$9.54	$18.81	$0.059	-	$16,298
Hi 3-7	10.32	-	0.073	-	21,187
LEPA 3-10	14.27	26.25	-	0.229	3,291
LEPA 2-5	14.38	-	-	-	2,579

interpretation. Third, the two LEPA irrigation scenarios are more efficient than the two High irrigation scenarios in abating pesticide runoff. The zero shadow price for the respective pesticide runoff constraints support this interpretation. Fourth, LEPA 2-5 is the most efficient irrigation scenario for abating all types of pollutants at the same time. This interpretation is drawn from the least profit loss ($2,579) and the zero shadow prices for the nitrogen percolation constraint, the pesticide runoff constraint, and the pesticide percolation constraint.

In summary, stricter water quality goals can be attained by changing management practices from high per acre input use levels to lower per acre input use levels without major changes in overall cropping systems. Under the two high pressure center pivot irrigation scenarios, however, more than half of the irrigated acreage is converted to dryland production. Under-utilization of agricultural inputs, such as nitrogen fertilizer and irrigation water, entails substantial profit losses. Contrarily, under the two LEPA irrigation scenarios, neither the irrigated acreage nor the total amount of irrigation water use decreases in order to satisfy the nonpoint standard since the LEPA technology is much more efficient in irrigation water applications than the high pressure center pivot technology. Consequently, profit losses are small under the LEPA irrigation scenarios even for strict nonpoint standards.

Implications of Results and Recommendations

The results obtained under the various policy scenarios provide a number of implications for agricultural pollution control. An overall summary of results and the implications that are drawn from the results of preceding analyses are described in this section.

Summary of Results

1. Pesticide runoff and percolation are caused mainly by the irrigated peanut and irrigated cotton production activities. Nitrate runoff is caused mainly the irrigated cotton production activities. Nitrogen percolation is caused mainly by grain sorghum and cotton production activities.

2. Cobb fine sandy loam soil, which has the lowest organic carbon content and the highest sand content, is extremely vulnerable to pesticide percolation, whether or not it is irrigated. Other soils do not have high pesticide percolation potential. Under the dryland condition, other soils analyzed have very small pesticide percolation potential, regardless of crops grown in those soils.

3. Abatement of nitrogen percolation or pesticide percolation to a certain extent can be attained just by changing irrigation schemes.

4. The LEPA irrigation technology is more profitable than the high pressure center pivot technology, even including the costs for converting the system from a high pressure center pivot system to a LEPA system. This superiority in profitability is maintained under most pollution control policy scenarios considered in this study.

4. An 100 percent tax imposed on agricultural inputs, including nitrogen fertilizers, pesticides, and irrigation water, are not much effective in reducing water pollution. Extremely high tax rates could induce reductions in effluent discharge levels. However, a policy option imposing extremely high input tax rates would be resisted by affected farmers, and probably is not viable.

5. Policy options restricting per acre or total nitrogen applications are effective in reducing nitrate runoff and nitrogen percolation. However, they

entail a substantial profit loss. Furthermore, these policies do not necessarily reduce pesticide runoff and percolation.

6. The policy restricting the total irrigation water use can reduce most types of agricultural pollutants, but with substantial profit losses. A large proportion of irrigated acreage shifts to the dryland production under this policy.

7. A 50 percent abatement of nitrogen percolation and/or pesticide percolation is possible with relatively little profit losses under all irrigation scenarios. In general, shifts in cropping systems across soils or small reductions in per acre nitrogen application levels are sufficient to attain the 50 percent abatement of nitrogen percolation and/or pesticide percolation. When all types of pollutants are targeted, however, substantial profit losses are incurred under the two high pressure center pivot irrigation scenarios. On the other hand, the two LEPA irrigation scenarios can still attain a 50 percent reduction in all types of pollutants with relatively little profit losses.

8. Four efficient pollution control policies, including nonpoint standards, nonpoint incentives, management practice standards, and management practice incentives, are tested under several policy scenarios which target 50 percent abatement of some or all types of pollutants. Standards and incentives result in same crop mix and pollution levels, but incentives entail additional profit losses. Since the optimum incentives are determined at the margin for each irrigation scenario, the additional losses in profit resulting from the incentives sometimes changes the order of profitability among the four different irrigation scenarios.

Implications of Results

1. Each soil has a different potential for creating and/or abating various types of agricultural pollutants. Thus, agricultural pollution control policies should have soil-specific characteristics in order to address the agricultural nonpoint pollution problem effectively. Here, soil characteristics include chemical, physical, and topographical properties.

2. Because relatively small changes in the crop mix across soils, or reductions in per acre input use, can achieve substantial pollution abatement with relatively little cost, changes in crop mixes across soils should be considered for voluntary adoption. These crop management practices could be considered as best management practices (BMPs). Examples are (1) encouraging Cobb fine sandy loam soil be planted to crops other than peanuts or cotton; (2) rotating peanuts and cotton with other crops more intensively; (3) shifting irrigated acreage from highly percolating soils to less percolating soils; (4) changing irrigation strategy in accordance with soil properties; (5) converting to irrigation systems with high application efficiency; and, (6) reducing per acre nitrogen applications. Incentives could be employed, if needed, such as linking these shifts to eligibility conditions for farm program participation or for peanut quota endowments.

3. Input tax policies, including excise taxes on nitrogen fertilizer, pesticides, or water, should probably be avoided since the effectiveness of these policies is questionable. Among the four efficient pollution control policies, nonpoint incentives or management practice incentives should probably be avoided if there is no urgent need of imposing taxes on effluent discharges within the acceptable water quality standards.

4. A policy which focuses on a single type of pollutant may not reduce agricultural pollution as a whole, and may actually exacerbate other pollution problems. Thus, all types of agricultural pollutants should be considered simultaneously when an agricultural pollution control policy is established.

5. A model which connects biophysical processes and farmers' optimizing behavior is quite useful in the evaluation of agricultural pollution control policies, while the process of acquiring data for model construction is tedious and time consuming.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Agricultural production processes generate pollution, such as pesticide and nutrient residuals, which may contaminate both ground water and surface water. In recent years, public concern over possible adverse effects of water pollution on both human health and the environment has been growing. Historical policy prescriptions for improving water quality have focussed primarily on voluntary adoption of recommended crop management practices. But they have not been generally effective in attaining required water quality standards. Agricultural pollution control measures imposing regulations or economic incentives that motivate farmers to make necessary changes for attaining reasonable water quality standards may be needed. It is important to examine regulations and/or economic incentives that may reduce or eliminate agricultural pollution. This study provides insight into the effectiveness of alternative methods of achieving water quality objectives, as well as the associated costs.

Objectives and Procedures

The main objective of this study is to evaluate the effectiveness and distributional effects of pollution control policy alternatives for a Caddo County farm situation. The specific objectives are (1) to identify alternative crop management practices involving various rotation systems, input use levels, and irrigation technologies available to farm operators in the study area; (2) to simulate crop yields and the magnitude of agricultural pollutants generated from alternative farm management practices; (3) to develop a modeling framework that will determine sets of production activities which maximize net returns, subject to both resource, environmental, and policy constraints; and, (4) to analyze both economic and water quality consequences of alternative agricultural pollution control policy measures.

The analytical framework utilized in this study is composed of two parts: a biophysical simulation model and a mathematical programming model. Formulating the analytical framework requires an accurate representation of the production environment, crop yield responses to alternative crop management practices, cost and returns estimates, and determination of the amount of pollution generated by the agricultural production process. A representative farm and the typical crop management practices were identified using combinations of published data available from various sources and interviews with the County Agricultural Extension Agent. To simulate crop growth and the magnitude of agricultural pollutants, EPIC-PST was used. EPIC-PST is able to simulate the effects of alternative crop management practices on crop yields and nutrient/pesticide losses by surface runoff, sediment movement, and leaching below the crop root zone. The mathematical programming model is utilized to predict optimum production decisions and economic and environmental consequences under alternative pollution control policies.

Nine pollution control policy alternatives are analyzed utilizing the mathematical programming model. The first imposes an 100 percent excise tax on nitrogen fertilizer and pesticides. The second limits the total quantity of nitrogen applications to 50 percent of the benchmark result. The third restricts per acre nitrogen application to the low level (see Chapter III for a detailed description). The fourth imposes a tax on irrigation water use which is equal to 100 percent of the variable cost for applying an acre inch of irrigation water using a high pressure center pivot system. The fifth restricts the total amount of irrigation water use to 50 percent of the benchmark result. Four additional policies explained below are intended to achieve a specific set of water quality standards. The sixth intends to attain a 50 percent reduction in pesticide percolation from the benchmark result. The seventh aims to attain a 50 percent reduction in nitrogen percolation from the benchmark result. The eighth intends to achieve a 50 percent reduction in both pesticide percolation and nitrogen percolation from the corresponding benchmark results. The last intends to attain a 50 percent abatement of nitrate runoff, nitrogen percolation, pesticide runoff, and pesticide percolation from the corresponding benchmark results.

Four alternative irrigation scenarios are tested under each policy. Two irrigation technologies (high pressure center pivot and LEPA irrigation), and four irrigation management strategies are combined to formulate four irrigation scenarios: (1) a high pressure center pivot system with the maximum single irrigation volume of 4 acre inches and the minimum irrigation interval of 14 days (High 4-14) ; (2) a high pressure center pivot system with the maximum single irrigation volume of 3 acre inches and the minimum irrigation interval of 7 days (High 3-7); (3) a LEPA irrigation system with the maximum single irrigation volume of 3 acre inches and the minimum irrigation interval of 10 days (LEPA 3-10); and, (4) a LEPA irrigation system with the maximum single irrigation volume of 2 acre inches and the minimum irrigation interval of 5 days (LEPA 2-5). To simulate the four irrigation scenarios, four separate EPIC-PST simulation runs were conducted with three different sets of parameters that determine (1) the efficiency of irrigation; (2) the minimum application interval; and (3) the maximum volume allowed for single irrigations. If the plant water stress factor reaches a certain level after the specified minimum application interval, EPIC-PST triggers an irrigation automatically.

EPIC-PST simulation results associated with each irrigation scenario and policy parameters associated with individual pollution control policy scenarios were combined to formulate a separate mathematical program. Results obtained under the High 4-14 irrigation scenario in the absence of control policy measures were referred to as benchmark results. Results obtained under other irrigation scenarios in the absence of control policies were referred to as base case results. In evaluating individual policy options, results obtained under individual policy/irrigation scenarios were compared with the benchmark results or the base case results.

Results and Conclusions

Results for the Unrestricted Case

Under the High 4-14 scenario, the producer plants 24 percent of the total acreage in a cotton-cotton-grain sorghum rotation, 57 percent in a peanuts-cotton-grain sorghum rotation, and 19 percent in program wheat. Both cotton and peanuts are grown under the high irrigation level, while grain sorghum is grown under dryland conditions. Peanuts are grown with the low nitrogen level, while cotton and program wheat are grown with the high nitrogen level. Per acre irrigation applications average 20.7 acre inches. Per acre nitrogen applications average 56.2 pounds. Per acre nitrate loss with runoff and nitrogen loss with percolation are 8.5 pounds and 1.0 pound per acre, respectively. The pesticide runoff and percolation indices indicate that substantial amounts of pesticides are lost. The toxicity of pesticides lost with runoff, for example, is about the same as the toxicity of 31 pounds of Treflan active ingredient. The degree of health hazard caused by pesticides lost with percolation is equivalent to approximately 5 ounces of Treflan active ingredient. Per acre net returns average $193.

Under other irrigation scenarios, the optimum crop mix is almost identical with the benchmark result. However, the crop mix across soils is somewhat different. Under the High 3-7 irritation scenario, per acre irrigation applications increase by 1.1 percent. Per acre nitrogen applications decrease by 6.7 percent. Compared to the High 4-14 irrigation scenario, this irrigation scenario produces (1) about the same amount of nitrate runoff; (2) less amount of nitrogen percolation; (3) more amount of pesticide runoff; and, (4) less amount of pesticide percolation, given individual crop/input use level combinations. Nitrate runoff and nitrogen percolation decrease by 2.5 percent and 38 percent, respectively. Pesticide runoff increases by 21 percent, while pesticide percolation decreases by 25 percent. Per acre net returns increase 5.5 by percent.

Under the LEPA 3-10 scenario, per acre irrigation applications decrease by 13 percent. Per acre nitrogen applications increase by 0.7 percent. Compared to the High 4-14 irrigation scenario, this irrigation scenario produces (1) less nitrate runoff; (2) less nitrogen percolation; (3) less pesticide runoff; and, (4) more pesticide percolation, given individual crop/input use level combinations. Nitrate runoff decreased by 31 percent. Despite the LEPA 3-10 scenario uses about the same quantity of nitrogen fertilizer, nitrogen percolation decreased by 13 percent since the entire Cobb fine sandy loam soil, which produces a relatively small amount of nitrogen percolation, is planted to the rotation system cotton(HH)-cotton(HH)-grain sorghum(LH) which produces a relatively large amount of nitrogen percolation. Pesticide runoff decreases by

69 percent, while pesticide percolation increases by 10 percent. Per acre net returns increase by 10.9 percent.

Under the LEPA 2-5 scenario, per acre irrigation applications decrease by 18 percent. Per acre nitrogen applications decrease by 1 percent. Compared to the High 4-14 irrigation scenario, this irrigation scenario produces (1) less nitrate runoff; (2) about the same amount of nitrogen percolation; (3) less pesticide runoff; and, (4) less pesticide percolation, given individual crop/input use level combinations. Nitrate runoff decreased by 25 percent. Despite the LEPA 2-5 scenario uses about the same amount of nitrogen fertilizer, nitrogen percolation increases by 6 percent mainly due to the 84 acres of Grant loam soil shifted from wheat production to a three-year rotation system peanuts(HL)-cotton(HH)-grain sorghum(LH). Pesticide runoff and percolation decrease by 69 percent and 52 percent, respectively. Per acre net returns increase by 7.1 percent.

Excise Tax on Nitrogen Fertilizer and Pesticides

Under all irrigation scenario, neither optimum crop mixes nor effluent discharge levels are affected much since the differences in profitability among activities reflected in the mode are relatively uniform even with the 100 percent excise tax imposed on nitrogen fertilizer and pesticides. The only major changes are large reductions in net returns. Compared to the corresponding base case results, reductions in net returns are about 36 percent under all irrigation scenarios. The dominance of the LEPA scenarios in profitability over the High scenarios is still maintained.

Restricting Total Nitrogen Use

The 50 percent reduction in the total quantity of nitrogen applied is met by lowering the nitrogen application level and by idling 19 to 22 percent of total acres. Program wheat is not part of the optimum farm plan. Per acre nitrogen applications in all dryland production (grain sorghum) are reduced to the low level. Nitrogen applications for all irrigated crops (peanuts and cotton) are reduced to the medium or low level. Consequently, compared to the benchmark results, nitrate runoff decreased by from 40 to 62 percent. Nitrogen percolation decreased by from 40 to 58 percent, depending upon the irrigation scenario. Reductions in pesticide runoff and percolation also were achieved mainly by removing most Cobb fine sandy loam soil from production. Compared to the base case results, reductions in net returns range from 11 to 12 percent depending on the irrigation scenario. The dominance of the LEPA scenarios in profitability over the High scenarios is still maintained.

Restricting Per Acre Nitrogen Use

Although production activities only with the low nitrogen level were allowed to be part of the optimum farm plan, regardless of the irrigation level, optimum crop mixes are almost the same as the benchmark results. The total quantity of nitrogen applied is approximately 60 percent of the benchmark result under all irrigation scenarios. Compared to the corresponding benchmark results, nitrate runoff decreased by 37 to 54 percent, and nitrogen percolation decreased by 53 to 58 percent, depending upon the irrigation scenario. Reductions in pesticide runoff and percolation also are achieved mainly by shifting a large part of Cobb fine sandy loam soil from a cotton-cotton-grain sorghum rotation or a peanuts-cotton-grain sorghum rotation to program wheat.

Compared to the base case results, reductions in net returns range from 10 to 11 percent depending on the irrigation scenario. The dominance of the LEPA scenarios in profitability over the High scenarios is still maintained.

Tax on Irrigation Water Use

Because the differences in profitability among activities in the model are relatively uniform even with the tax, which is 100 percent of the variable cost of high pressure center pivot irrigation, this policy option has little impact on optimal production decisions or on the quantity of irrigation water use. Optimal crop mixes under the High 4-14, LEPA 3-10, and LEPA 2-5 are identical with base case results. Under the High 3-7 scenario, some shifts in cropping systems across soils occur while changes in the optimum crop mix are not notable. Compared to the corresponding base case results, nitrogen runoff decreases by 34 percent. Little change occurs in runoff or percolation of other pollutants. Compared to the base case results, the reductions in net returns due to the irrigation tax range from 13 to 16 percent depending on the irrigation scenario. The dominance of the LEPA scenarios in profitability over the High scenarios is more evident since the LEPA system requires less water.

Restricting Total Irrigation Water Use

Under all irrigation scenarios, the 50 percent reduction in the total irrigation water use is met mainly by changing a large part of the intensively irrigated cotton production activities to dryland production. Irrigated acres decrease by (1) 48 percent under the High 4-14 scenario; (2) 47 percent under the High 3-7 scenario; (3) 40 percent under the LEPA 3-10 scenario; and, (4) 35 percent under the LEPA 2-5 scenario. The high nitrogen application levels are maintained in all cotton and grain sorghum production activities. Most types of pollutants decrease significantly. Compared to the corresponding base case results, net returns decrease by (1) 14 percent under the High 4-14 scenario; (2) 18 percent under the High 3-7 scenario; (4) 16 percent under the LEPA 3-10 scenario; and (4) 13 percent under the LEPA 2-5 scenario.

Restricting Pesticide Percolation

In general, the 50 percent reduction in pesticide percolation is attained by shifting part of the crop rotation systems that generate relatively large amount of pesticide percolation (peanuts-cotton-grain sorghum and cotton-cotton-grain sorghum) from Cobb fine sandy loam soil to Grant loam soil. Under the LEPA 2-5 irrigation scenario, the pesticide percolation limit is met even in the base case. The reductions in pesticide runoff vary depending upon the irrigation scenario. Under every irrigation scenario except LEPA 2-5, both nitrate runoff and nitrogen percolation increase due to the shift of peanuts-cotton-grain sorghum and cotton-cotton-grain sorghum crop rotation systems from Cobb fine sandy loam soil to Grant loam soil. Little changes occur in the total quantity of nitrogen applied and the total amount of irrigation water pumped. Decreases in net returns are trivial under all irrigation scenarios.

Restricting Nitrogen Percolation

In general, the 50 percent reduction in nitrogen percolation is met mainly by lowering the nitrogen application level in most grain sorghum production activities to the medium or low level. Consequently, the total quantity of nitrogen applied decreases by 2 to 14 percent depending on the irrigation scenario and the amount of nitrate in runoff and percolation decreases.

However, there is a 48 percent increase in pesticide percolation under the High 4-14 scenario. The 103 acres of the peanuts-cotton-grain sorghum rotation on Cobb fine sandy loam soil appear to be responsible for the increase in pesticide percolation. This result suggests that a policy which focuses on a single type of pollutant may not reduce agricultural pollution as a whole, and may actually exacerbate other pollution problems. Compared to the base case results, the reductions in net returns are less than 2 percent.

Restricting Both Pesticide and Nitrogen Percolation

Optimum crop mixes under this policy contain many crop rotations. However, the dominance of the two crop rotation systems (peanuts-cotton-grain sorghum and cotton-cotton-grain sorghum) and program wheat acres is still maintained. In general, the pesticide percolation limit is met mainly by removing the peanuts-cotton-grain sorghum or cotton-cotton-grain sorghum rotation systems from Cobb fine sandy loam soil. The nitrogen percolation limit is met by lowering the nitrogen application level in most cotton and grain sorghum production activities from the high level to the medium or low level. The irrigation level in all peanut and cotton production activities remains at the high level. The resulting changes in nitrate runoff and pesticide runoff are small and variable, sometimes increasing a little, and sometimes decreasing a little. Compared to the base case results, the reductions in net returns are less than 4 percent under every irrigation scenario.

Restricting All Types of Pollutants

This policy targets all types of agricultural pollutants considered in this study: nitrate runoff, nitrogen percolation, pesticide runoff, and pesticide percolation. The optimum crop mixes under this policy contain the largest set of crop rotations. The four limits are met by lowering the irrigation level or the nitrogen application level in some peanut and cotton production activities. The reductions in irrigated acres were 55 percent under High 4-14 and 58 percent under High 3-7. Irrigated acres under the two LEPA scenarios remained at the same level. Compared to the base case results, the reductions in net returns are (1) 18 percent under High 4-14; (2) 17 percent under High 3-7; (3) 4 percent under LEPA 3-10; and, (4) 3 percent under LEPA 2-5 irrigation scenario. Nevertheless, net returns for LEPA 3-10 and LEPA 2-5 are still 7 percent and 4 percent higher than the benchmark result, respectively. This result indicates that the LEPA irrigation scenarios are more profitable and environmentally sound than the High irrigation scenarios.

Policy Implications

Similar production practices on different soils will produce different levels of agricultural pollution. Thus, agricultural pollution control policies should perhaps be soil-specific to address the agricultural pollution problem effectively. Relatively small changes in crop mix across soils, or the reductions in per acre input use, can achieve substantial pollution abatement with relatively little cost. Thus, changes in crop mix across soils might be encouraged as part of the approach to reducing agricultural pollution. These crop management practices could be considered best management practices (BMPs). Examples based on this study are (1) removing peanut and cotton production from Cobb fine sandy loam soil (and soils with similar properties); (2) shifting irrigation from soils with high percolation potential to soils less likely to produce percolation; (3) reducing per acre nitrogen applications; and, (4) rotating peanuts and cotton with other crops more intensively. If voluntary adoption of these practices was unsuccessful, eligibility conditions for farm program participation or for peanut quota acquisition could be tied to environmentally-enhancing practices.

In this analysis, abatement of pesticide percolation could be attained by adopting more frequent, lower volume irrigation practices. In addition, the LEPA irrigation scenarios were more profitable and efficient in reducing overall water pollution than the High irrigation scenarios. Nevertheless, high pressure center pivot systems are used much more widely than LEPA irrigation systems in the study area. Extending education programs on the advantages of LEPA irrigation over high pressure center pivot systems, or cost-sharing programs for converting other irrigation systems to LEPA systems, would also reduce runoff and percolation losses of agricultural pollutants.

Input tax policies, including excise taxes on nitrogen fertilizer and pesticides, or a tax on irrigation water, may not be effective in achieving water quality objectives unless tax rates are extremely high. In this analysis, producers' income were reduced substantially under input tax policies. In addition, nonpoint incentives and management practice incentives impose additional costs on the producer who complies with certain nonpoint standards. Nonpoint incentives and management practice incentives are probably politically unacceptable.

A pollution control policy which focuses on just a single type of pollutant will not reduce agricultural pollution as a whole, and may actually exacerbate other pollution problems. Thus, all types of agricultural pollutants should be considered simultaneously when an agricultural pollution control policy is established.

This study suggests that an analytical model which connects biophysical processes and farmers' optimizing behavior may be useful in evaluating agricultural pollution control policies. Furthermore, management practice standards identified in this study might be encouraged as best management practices designed to achieve certain nonpoint pollution standards.

Limitations and Need for Further Research

This research has several limitations that should be addressed. First, the dates for various crop management practices, including tillage, fertilizer applications, planting, and pesticide applications, were fixed from year to year in the multi-year (28 years) simulation. In fact, the dates of individual crop management practices may change year by year in accordance with weather conditions or other factors. Also the dates and types of pesticide applications may change since crop pests vary from year to year.

Second, the location of the representative farm relative to the watershed was not considered, nor was the volume of ground water in the underlying aquifer. In addition, the estimated amount of each pollutant moved in runoff and percolation through the soil profile does not necessarily indicate that the pollutant left the watershed or reached the aquifer.

Third, in the mathematical programming model, it was assumed that irrigated production was limited to 260 acres, put freely among the four soils on the farm. This assumption provided the model more flexibility in choosing soils to be irrigated in order to comply with certain water quality standards. This flexibility may have exaggerated the ability of the farmer to comply with certain water quality standards or incentive policies.

This study was confined to a farm-level analysis. A farm-level analysis may have certain limitations in representing water pollution problems in an area or region. A regional model or a model which incorporates multiple farms with different soil characteristics would likely provide different insight into the problem.

Biophysical simulation models play an important role in identifying optimal solutions to agricultural pollution problems. A more detailed and sophisticated model which is capable of simulating the crop-pest interaction process together with other biophysical processes might provide more detailed information for solving pesticide pollution problems.

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APPENDIXES

APPENDIX A

SOIL PROFILE CHARACTERIZATION DATA

TABLE 19

SOIL PROFILE CHARACTERIZATION DATA
FOR COBB FINE SANDY LOAM

Depth from the Surface to the Bottom of the Soil Layer (m)	0.010	0.203	0.762	1.524
Bulk Density (t/m^3)	1.40	1.40	1.57	1.25
Wilting Point (m/m)	0.081	0.081	0.183	0.010
Field Capacity (m/m)	0.224	0.224	0.296	0.106
Sand Content (%)	67.9	67.9	54.5	100.0
Silt Content (%)	20.1	20.1	17.0	-
Soil pH	6.7	6.7	7.3	7.3
Organic Carbon (%)	0.44	0.44	0.05	0.05

Source: USDA-SCS National Soil Survey Laboratory. 1990. Soil Parameter Preparation Program for the GLEAMS Model. Lincoln, NE.

TABLE 20

SOIL PROFILE CHARACTERIZATION DATA
FOR GRANT LOAM

Depth from the Surface to the Bottom of the Soil Layer (m)	0.01	0.15	0.20	0.41	0.56	0.81	1.07	1.27	1.63	2.00
Bulk Density (t/m^3)	1.40	1.14	1040	1.40	1.55	1.55	1.55	1.55	1.55	1.55
Wilting Point (m/m)	0.106	0.106	0.106	0.130	0.135	0.143	0.153	0.152	0.159	0.140
Field Capacity (m/m)	0.227	0.227	0.227	0.252	0.224	0.232	0.254	0.257	0.255	0.255
Sand Content (%)	21.8	21.8	21.8	18.0	19.6	21.2	37.2	35.2	41.5	39.0
Silt Content (%)	64.8	64.8	64.8	62.8	58.1	54.7	37.5	35.2	41.5	39.0
Soil pH	6.0	6.0	6.0	7.3	7.6	7.6	7.3	7.2	7.3	7.0
Organic Carbon (%)	0.89	0.89	0.89	0.64	0.55	0.48	0.35	0.31	0.30	0.10

Source: USDA-SCS National Soil Survey Laboratory. 1990. Soil Parameter Preparation Program for the GLEAMS Model. Lincoln, NE.

TABLE 21

SOIL PROFILE CHARACTERIZATION DATA
FOR POND CREEK FINE SANDY LOAM

Depth from the Surface to the Bottom of the Soil Layer (m)		
0.010	0.305	1.727
Bulk Density (t/m^3)		
1.450	1.450	1.550
Wilting Point (m/m)		
0.105	0.105	0.191
Field Capacity (m/m)		
0.252	0.252	0.310
Sand Content (%)		
63.0	63.0	36.5
Silt Content (%)		
23.0	23.0	36.0
Soil pH		
6.2	6.2	7.3
Organic Carbon (%)		
1.16	1.16	0.15

Source: USDA-SCS National Soil Survey Laboratory. 1990. Soil Parameter Preparation Program for the GLEAMS Model. Lincoln, NE.

TABLE 22

SOIL PROFILE CHARACTERIZATION DATA
FOR PORT SILT LOAM

Depth from the Surface to the Bottom of the Soil Layer (m)

0.010	0.690	1.830

Bulk Density (t/m^3)

1.410	10410	1.560

Wilting Point (m/m)

0.120	0.120	0.180

Field Capacity (m/m)

0.320	0.320	0.320

Sand Content (%)

16.9	16.9	36.5

Silt Content (%)

65.0	65.0	36.0

Soil pH

6.7	6.7	7.3

Organic Carbon (%)

1.18	1.18	0.39

Source: USDA-SCS National Soil Survey Laboratory. 1990. Soil Parameter Preparation Program for the GLEAMS Model. Lincoln, NE.

APPENDIX B

CROP PRODUCTION SYSTEM DESCRIPTIONS

TABLE 23

FIELD OPERATIONS FOR PEANUT PRODUCTION

Production Activities	Date	Implements
Tillage	March	Moldboard Plow
Tillage	March	Offset Disk
Weed Control	March	Sprayer
Fertilization	April	Fertilizer Spreader
Tillage	April	Tandem Disk
Tillage	April	Tandem Disk
Disease Control	May	Band Applicator
Tillage	May	Springtooth
Planting	May	Peanut Planter
Insect Control	June	Sprayer
Cultivation	June	Row Cultivator
Disease Control	June	Custom Airplane
Disease Control	July	Sprayer
Cultivation	July	Row Cultivator
Disease Control	July	Custom Airplane
Disease Control	July	Sprayer
Disease Control	August	Custom Airplane
Disease Control	August	Custom Airplane
Harvest	October	Shaker-digger, Peanut Combine

TABLE 24

FIELD OPERATIONS FOR IRRIGATED GRAIN SORGHUM PRODUCTION

Production Activities	Date	Implements
Tillage	March	Sweep/Chisel
Tillage	March	Sweep/Chisel
Tillage	April	Offset Disk
Fertilization	April	Fertilizer Spreader
Tillage	April	Springtooth
N Application	April	Anhydrous Applicator
Planting	May	Planter
Weed Control	May	Sprayer
Insect Control	July	Sprayer
Cultivation	July	Row Cultivator
Insect Control	August	Sprayer
Harvest	September	Grain Combine

TABLE 25

FIELD OPERATIONS FOR DRYLAND GRAIN SORGHUM PRODUCTION

Production Activities	Date	Implements
Tillage	March	Sweep/Chisel
Tillage	April	Offset Disk
Fertilization	April	Fertilizer Spreader
Tillage	April	Springtooth
N Application	April	Anhydrous Applicator
Planting	May	Planter
Weed Control	May	Sprayer
Insect Control	July	Sprayer
Cultivation	July	Row Cultivator
Insect Control	August	Sprayer
Harvest	September	Grain Combine

TABLE 26

FIELD OPERATIONS FOR IRRIGATED
COTTON PRODUCTION

Production Activities	Date	Implements
Stalk Destruction	January	Rotary Mower
Tillage	February	Moldboard Plow
Tillage	February	Sweep/Chisel
Tillage	March	Offset Disk
Fertilization	March	Fertilizer Spreader
Weed Control	April	Sprayer
Tillage	April	Offset Disk
Disease Control	May	Band Applicator
Tillage	May	Springtooth
Planting	May	Planter
Cultivation	June	Row Cultivator
Insect Control	July	Custom Airplane
Cultivation	July	Row Cultivator
Insect Control	August	Custom Airplane
Cultivation	August	Row Cultivator
Insect Control	August	Custom Airplane
Insect Control	September	Custom Airplane
Harvest	November	Cotton Stripper

TABLE 27

FIELD OPERATIONS FOR DRYLAND COTTON PRODUCTION

Production Activities	Date	Implements
Stalk Destruction	January	Rotary Mower
Tillage	February	Moldboard Plow
Tillage	March	Offset Disk
Fertilization	March	Fertilizer Spreader
Weed Control	April	Sprayer
Tillage	April	Offset Disk
Disease Control	May	Band Applicator
Tillage	May	Springtooth
Planting	May	Planter
Insect Control	July	Custom Airplane
Cultivation	July	Row Cultivator
Insect Control	August	Custom Airplane
Insect Control	August	Custom Airplane
Insect Control	September	Custom Airplane
Harvest	November	Cotton Stripper

TABLE 28

FIELD OPERATIONS FOR IRRIGATED
WHEAT PRODUCTION

Production Activities	Date	Implements
Tillage	June	Offset Disk
Tillage	July	Springtooth
Tillage	July	Springtooth
N Application	August	Anhydrous Applicator
Tillage	August	Offset Disk
Fertilization	August	Fertilizer Spreader
Cultivation	September	Field Cultivator
Planting	September	Drill Planter
Weed Control	February	Sprayer
N Application	March	Liquid Fertilizer Spreader
Insect Control	March	Sprayer
Harvest	June	Grain Combine

TABLE 29

FIELD OPERATIONS FOR DRYLAND
WHEAT PRODUCTION

Production Activities	Date	Implements
Tillage	June	Offset Disk
Tillage	July	Springtooth
N Application	August	Anhydrous Applicator
Tillage	August	Offset Disk
Fertilization	August	Fertilizer Spreader
Cultivation	September	Field Cultivator
Planting	September	Drill Planter
Weed Control	February	Sprayer
N Application	March	Liquid Fertilizer Spreader
Insect Control	March	Sprayer
Harvest	June	Grain Combine

APPENDIX C

DESCRIPTIONS OF PESTICIDE APPLICATIONS FOR CROP PRODUCTION

TABLE 30

PESTICIDE APPLICATIONS FOR PEANUT PRODUCTION

Pesticide	Rate per Acre	Time of Application	Soil Halflife	Partitioning Coefficient	Target Pest
Prowl	1.5 pt	April	8	5000	Annual Weeds and Grasses
Ridomil G	20-25 lb	May	25	35	Pod Rot
Temik G	17-20 lb	May	40	40	Nematodes
Orthene	0.75 lb a.i	June	2	300	Thrips
Bravo	1.5 pt	June	18	4000	Foliar Diseases
Vitavax	2.5-3 pt	July	7	260	Southern Blight
Bravo	1.5 pt	July	18	4000	Foliar Diseases
Vitavax	2.5-3 pt	July	7	260	Southern Blight
Bravo	1.5 pt	August	18	4000	Foliar Diseases
Bravo	1.5 pt	August	18	4000	Foliar Diseases

TABLE 31

PESTICIDE APPLICATIONS FOR GRAIN SORGHUM PRODUCTION

Pesticide	Rate per Acre	Time of Application	Soil Halflife	Partitioning Coefficient	Target Pest
Atrazine	2 qt	May	18	160	Annual Weeds and Grasses
Furadan 4F	0.5 lb a.i.	July	17	40	Sorghum Greenbug
Sevin	1.5 lb a.i.	August	7	229	Sorghum Midge

TABLE 32

PESTICIDE APPLICATIONS FOR COTTON PRODUCTION

Pesticide	Rate per Acre	Time of Application	Soil Halflife	Partitioning Coefficient	Target Pest
Lasso	3 pt	April	8	5000	Annual Weeds and Grasses
Temik G	5-10 lb	May	40	40	Nematodes
Bidrin	0.2 lb a.i.	July	7	20	Boll Weevil
Curacron	1 lb a.i.	August	8	2000	Bollworms
Lorsban	0.5 lb a.i.	August	12	5300	Fleahoppers
Lannate	0.5 lb a.i.	September	8	160	Bollworms

TABLE 33

PESTICIDE APPLICATIONS FOR
WHEAT PRODUCTION

Pesticide	Rate per Acre	Time of Application	Soil Halflife	Partitioning Coefficient	Target Pest
Glean	0.5 oz	February	160	1	Broadleaf Weeds
Sevin	1 lb a.i.	March	7	229	Grasshoppers

VITA

Suhk-Hyun Kim

Candidate for the Degree of

Doctor of Philosophy

Thesis: A FARM-LEVEL ECONOMIC ANALYSIS OF AGRICULTURAL POLLUTION CONTROL

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Kwang-Joo, Korea, November 18, 1956, the son of Mr. and Mrs. Byung-Gyoon Kim.

Education: Graduated from Kwang-Joo Jeil High School, Kwang-Joo, Korea, in January, 1975; received Bachelor of Science degree in Agricultural Economics from Seoul National University in February, 1984; received Master of Science degree in Agricultural Economics from Seoul National University in February, 1986; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in July, 1993.

Professional Experience: Agricultural Economist, Korea Rural Economic Institute, January, 1986, to December, 1987; Research Assistant, Department of Agricultural Economics, Oklahoma State University, January, 1989, to August, 1993.

Professional Organizations: Korean Agricultural Economics Association, American Agricultural Economics Association, Gamma Sigma Delta.