Soil depletion and water quality: a case study in the conjunctive management of natural resources

James Samuel Shortle
Iowa State University

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SOIL DEPLETION AND WATER QUALITY: A CASE STUDY IN THE CONJUNCTIVE MANAGEMENT OF NATURAL RESOURCES

Iowa State University

Ph.D. 1981

University Microfilms International
300 N. Zeeb Road, Ann Arbor, MI 48106
Soil depletion and water quality: A case study in the conjunctive management of natural resources

by

James Samuel Shortle

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Economics

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1981
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CHAPTER I. ISSUES, OBJECTIVES, AND METHODOLOGY

Introduction

Farming, be it of fish or corn, is an activity in which modifications of natural environments are undertaken for the purpose of enhancing flows of harvestable goods and services from nature and is to be distinguished from the case in which such goods and services are harvested directly as they occur (Shulze, 88). While the enhancement of given flows represents a beneficial outcome of environmental modifications, there may also be adverse consequences in the form of impaired flows of other goods and services and these impairments may be of a temporary or permanent nature. As a case in point, and one to which this research is addressed, consider agricultural farming and soil erosion. Environmental modifications undertaken for the purpose of increasing crop flows result in disturbances which have as a consequence the acceleration of soil erosion relative to natural or geologic rates. Soil loss almost invariably reduces soil productivity, an onsite effect of the farming activity, and also results in the pollution of water bodies, an offsite effect. The former represents an impairment of the ability of the soil resource to provide flows of crops in future periods while the latter effect diminishes flows of water-based goods and services. In addition, gully erosion can result in a loss of
acreages suitable for farming, the loss in this case being the productive services of the land. The dependency of the state of soil conservation and the state of water quality upon the rate of soil erosion makes the management of these resources conjoint to some degree. It is the purpose of this research to investigate issues in this conjunctive management problem.

Background

For much of this century, soil erosion has been a subject of interest as a consequence of the adverse effects of soil loss on soil productivity and the agricultural land base. As with many issues, the level of attention drawn by the problems resulting from cropland erosion has varied over the years. In the decade preceding World War II the erosion of croplands and the consequent damages were highly visible and lead to the widespread perception that measures to promote the conservation of soil resources were in the national interest. Federal legislation enacted in those years created the soil conservation policy structure which has been applicable in the nation to this day. In subsequent years, a number of factors, including technological developments in agricultural production, lessened the general level of concern for the conservation of soil.
But recently, erosion of cropland has again come to be viewed by many as an important threat to the nation's agricultural production that requires attention. Further, there has in the last decade, emerged a substantial and growing concern for the adverse water quality impacts resulting from cropland erosion. The geographic focal point of these concerns is the Corn Belt region of the nation.

With renewed concern for cropland erosion, an interest has arisen in erosion control to promote both soil conservation and water quality. Research has been directed toward gaining a better understanding of the physical processes of erosion, the impacts of erosion on crop production, the transportation of sediments, the water quality impacts of sediment, and the onsite control technologies. There remains, however, much additional basic research to be done in these areas. Economic research has also been stimulated by the rising interest in the onsite and offsite problems of soil erosion. In a recent article, Oscar Burt (20) observes that "... the economics of soil conservation has been a neglected subject in agricultural economics during the last two or three decades. The most obvious reason for this apparent lack of interest in the subject is the view that advances in technology have made soil resource per se of less consequence for agricultural production." Burt
further observes that "... topsoil was transformed by modern technology from primarily a stock resource into a largely renewable resource for the purpose of practical decision." It is clear that the subject of soil conservation is again becoming one of interest, particularly in regard to the problems resulting from accelerated soil erosion. Examples of earlier analyses of the economics of soil management include Bunce's (18) volume on the subject published in 1942 and journal articles by Heady (48, 49) in the 1950s. While these and other contributions were, and remain, of considerable importance, particularly with respect to the implications of various agricultural institutions on soil management, they do not incorporate the advances in analytical methodology which began in the 1930s with the publication of Hotelling's (52) seminal paper on the economics of exhaustible resources. Recent analyses of the problem of soil erosion have been largely associated with nonpoint source pollution control planning efforts and have, as a consequence, focused on erosion control for water quality improvement rather than dealing with the issues of soil conservation. These include studies of farm level impacts (Boggess et al., 13; Boehlje et al., 12; McGrann, 68); watershed and riverbasin level impacts (Alt and Heady, 2; Miranowski et al., 71); regional
impacts, particularly in the Corn Belt (EPA, 111; Taylor and Frohberg, 100); and national impact studies (Crosson and Brubaker, 27; Wade and Heady, 118).

There has been considerable support of applied research in the area of soil erosion control and the control of other residuals by the Environmental Protection Agency (EPA) and the United States Department of Agriculture (USDA). The studies cited above are but a limited listing. There are, however, several common traits in such studies. First of all, these studies largely focus on the impacts of alternative public policies for controlling soil erosion, pesticide usage, and fertilizer usage on the actual levels of these quantities, on crop and livestock production, and on farm prices and/or income. There have been few attempts to ascertain or estimate, no less value, the actual water quality impacts of controls. Of course, a major problem in this area of research is the lack of data on the flow of residuals into water bodies or on the pollution damages.

A second common trait of such studies is that they are performed within the framework of static linear programming models. The use of linear programming has gained widespread acceptance in the analysis of agricultural production and marketing decisions and also in the management of water quality. The problem with static linear programming models
is, however, that they ignore the future effects of soil erosion and thus any onsite costs or benefits arising from soil erosion control policies which occur in future periods. Further, the failure to incorporate the effect of erosion on productivity may result in misleading results concerning the effects of policy measures on agricultural production.

An example of a recent paper which focused on soil conservation per se is Burt's article cited above. Burt develops a simple dynamic programming model of wheat production in the Palouse region of the Northwestern portion of the country. In this model, Burt includes two state variables; the depth of topsoil and the organic matter content of the soil. While Burt does not develop the conceptual framework of the model in any detail, the approach taken suggests the following viewpoint of the problem of soil management: As a composite natural resource, a soil can be described at points in time by a state vector, the elements of which are measurements on the various natural resource stocks which together form the composite. Associated with this state vector is a system of equations of motion which describe the behavior of the state vector in response to those internal and external forces acting upon the soil over time. The soil being so described, the soil management problem can then be described as one of determining the path of the soil state vector which maximizes an
appropriate criterion function. This description of the problem is one which is highly conducive to useful analysis, both at the conceptual and applied levels, of the soil management problem and clearly in accord with the modern theory of natural resources management. Of course, a complete description of the soil resource state vector and the system of equations of motion would be an enormously difficult problem given the complexity of the resource. However, as in Burt's endeavor, appropriate abstractions can advance the understanding of particular problems.

The Objectives and Methodology

The soil management problem is clearly a problem in the management of natural resource stocks and the stock of particular importance when considering erosion is soil depth. There has, however, been little consideration of the economics of managing this stock and soil erosion at the conceptual level. Good applied economic analysis requires a sound theoretical foundation and, thus, one objective of this analysis is to draw upon the analytical techniques that have been developed in natural resources production literature to consider the problem of soil erosion. This analysis offers the basis for an empirical analysis of erosion and erosion control that is also pursued. In
addition, it facilitates an understanding of the determination of erosion in markets and why markets may fail to yield rates of erosion that are considered optimal or efficient. It also facilitates an understanding of appropriate policy measures to achieve efficient levels of erosion. The failure of water quality damages to be priced offers one basis for expecting cropland erosion to be suboptimal and emphasis is given in this analysis to this source. Here, the theory of environmental policy is drawn upon to consider alternative policy measures. It is to be noted that in this analysis the endeavor is not to develop new results, but is, instead, to extend the theory explicitly to the problems at hand, this being something which has not yet been done and which is considered useful not only to provide a theoretical foundation for this research but, also, to provide for the rational and objective analysis of the onsite and offsite problems of cropland erosion.

The remainder of the research is devoted to an empirical analysis of soil erosion and its control in the Four Mile Creek watershed of Tama County, Iowa. Four Mile Creek is a tributary of Wolf Creek which is a small tributary of the Cedar River. The Iowa-Cedar Rivers Basin is of interest because it lies in the heart of the Corn Belt and because of the land and water resource problems experienced within it, the most important of which have been identified as being
associated with cropland erosion (USDA, 107). The Iowa River has been the subject of several economic analyses of soil erosion and its control, the most notable among these being those of Alt and Heady, and of Miranowski et al. (71). Both utilized static linear programming models to consider impacts of erosion control policies. While neither of these two studies analyzed damage costs, Boggess et al. (14) expanded the Alt and Heady model by incorporating damage cost estimates for the Iowa River.

Several objectives are pursued in the empirical analysis of this research. One is to contribute to the advancement of the applied economic analysis of soil management problems; specifically, to the management problems arising as a consequence of cropland erosion. This objective is pursued by developing a model of soils management in the Four Mile Creek watershed to consider how a present value maximizing economic planner would manage agricultural production in the area which can be solved by readily available and efficient computational techniques but which properly treat the problem in a dynamic context. The model is solved for specified assumptions concerning agricultural price expectations and the rate of discount to consider the production patterns which would emerge and the planner's responses to the effect of soil erosion on the productive capacity of the soils.
A second objective of the empirical analysis is to consider the net social losses which occur as a consequence of the failure to abate erosion where these losses arise as a consequence of the water quality damages resulting from flows of sediment into streams and reservoirs. This objective is pursued by estimating damage costs associated with the solutions obtained above. The damage cost estimates are based upon the assumption that marginal damage costs are invariant with respect to the level of residuals flows at points in time and over time. The marginal damage cost figures are hypothesized values based upon estimates available in the literature. The results from the analysis provide a basis for considering the severity of the water quality damages resulting from cropland erosion in the watershed. The final major objective of this analysis is to evaluate several alternative policies for improving water quality by controlling cropland erosion. The basis for evaluation is the diminution in the net present value of agricultural production in the watershed resulting from the pursuit of the policies. The estimates of these losses are obtained by application of the dynamic model of crop production in the study area and in evaluating policy options within this context an additional objective; this being the advancement of the applied economic analysis of
cropland erosion control, is pursued. The results of this component of the research will contribute to the economic evaluation of policies for water quality improvement by soil erosion control.

The Study Area

The Four Mile Creek area has been selected because it is small enough to allow a relatively detailed analysis without requiring a very-large scale model, while having a set of soils with a range of erosion problems sufficient to allow the generation of interesting results. Further, relatively good production data is available for the watershed. Four Mile Creek has been the subject of EPA funded research to develop data for erosion control policy development. This research has involved several relevant disciplines and among the objects of the project was the development of an economic model of the watershed for policy analysis with a sound foundation on basic knowledge. Unfortunately, the project has been terminated and, while useful data has been generated, there remains much to be done before such a model could be developed.

The Cedar River originates in south-central Minnesota and drains an area of 7,819 square miles (USDA, 107). The Wolf Creek drainage area contains 238 square miles and the
study area contains approximately 19 square miles. A study of the basin found the predominant land use to be agricultural with seventy-nine percent of the land allocated to agricultural use in recent years. The principal agricultural land use in the northern two-thirds of the basin, including the study area, is cash-grain farming with the major crops being corn and soybeans. The principal agricultural land use in the remaining area is livestock production. A detailed description of the study area is available in Miranowski et al. (71).

Organization

Chapter II provides an overview of the problems and processes of cropland erosion which facilitate an understanding of the analysis in subsequent chapters by introducing certain relevant technical information and by placing the cropland erosion problems into a broader perspective. Chapter III is devoted to the conceptual analysis of cropland erosion and erosion control. The dynamic linear programming model of crop production in the watershed is presented in Chapter IV and in Chapter V the results from the applications of the model are presented and discussed. The final chapter provides a brief summary of the research and the conclusions obtained.
CHAPTER II. AN OVERVIEW OF THE PROBLEMS AND PROCESSES OF CROPLAND EROSION

Water and Wind Erosion of Soils

Erosion is the wearing away of land surface by wind, water, ice, and other geologic forces, and by processes such as gravitational creep. The rate of erosion which is natural to an area is known as the geologic rate and depends upon climate, vegetation, slope, and soil materials primarily. The geologic rate will vary from location to location as these factors vary. Further, the rate will vary over time in a given location with changes in the primary determinants. Included in considerations of the geologic rate, however, are natural catastrophes such as floods and landslides which cause dramatic changes in the geologic rate. Accelerated erosion of soil is the result of human activities which increase soil exposure, such as tillage, logging, and over-grazing, and cause the erosion rate to be in excess of the geologic rate. Both geologic and accelerated erosion rates can vary from virtually zero to quite substantial magnitudes.

The two major forces at work in soil erosion are wind and water. The principal forms of water erosion are sheet, rill, gully, and streambank erosion. With sheet erosion, a thin layer of soil is removed from a field as raindrops
detach particles which are then transported by runoff water. Rill erosion occurs as runoff water concentrates to create small channels in the field, soil loss occurring along the bed and edges of these channels. The channels created by rill erosion are easily obliterated by normal tillage operations, and, in the long-run, the effects of smoothing rills by field operations is to cause rill erosion to be similar to sheet erosion. Gully erosion occurs as the channels become so large that normal tillage operations will not destroy them. While sheet, rill, and gully erosion are associated with rainfall events, streambank erosion need not be so associated. Streambank erosion is a consequence of the action of streamflow on the bed and banks of the stream.

In order to predict sheet and rill losses from cultivated fields in the area of the United States east of the Rocky Mountains, Wischmeir and Smith (125) developed a gross soil loss prediction model known as the Universal Soil Loss Equation (USLE). This equation predicts the amount of soil which will be detached and transported within a field on the average during a year. The soil may be completely removed from the field, or it may be redeposited in depressions, grassed waterways, or other parts of the field. The equation is:

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]
where:

\[ A = \text{Average gross soil loss (tons per acre)}; \]
\[ R = \text{Rainfall-and-runoff factor}; \]
\[ K = \text{Soil-erodibility factor}; \]
\[ L = \text{Slope-length factor}; \]
\[ S = \text{Slope-gradient factor}; \]
\[ C = \text{Cropping-management factor}; \]
\[ P = \text{Erosion-control and support-practice factor}. \]

The rainfall factor \((R)\) summarizes the erosivity of rainfall events in a given location during an average year. The soil-erodibility factor \((K)\) is determined by properties of given soils which influence the erosion potential or hazard of the given soil. The product of \(R\) and \(K\) is the quantity of soil which would be lost in a field that is 72.6 feet long and has a nine percent slope when that field is continuously fallow and tilled. Slope length is the horizontal distance from the point of origin of overland flow to where the runoff water enters a defined channel or waterway or to where slope decreases to an extent such that sediment deposition begins. With increased slope length, runoff accumulation and thus soil loss per unit of area increases. Increases in the slope of land increase runoff velocity which increases the ability of runoff to detach and transport soil particles. The slope-gradient factor \((S)\) is to account for the influence of the steepness of the slope. The product of the slope-length and slope-gradient factors is the ratio of soil loss per unit of area on a given field
to the loss that would occur from a field having a nine percent slope that is 72.6 feet long.

The product of $R$, $K$, $L$, and $S$ is the estimated average gross soil loss from a continuously fallow field which is tilled. This figure is adjusted downward by the cropping-management factor and the erosion-control and support-practice factor. The erosion-control and support-practice factor ($P$) is the ratio of soil loss with a practice to the loss with uphill and downhill culture. Erosion-control and support-practices include contour tillage, contour strip-cropping, and terrace systems. The cropping-management factor ($C$) is the ratio of soil loss in a field cropped and managed in a specified fashion to soil loss in a continuously fallow and tilled field. The $C$ factor adjusts for the complex and diverse influences of crops, crop sequences, residue management, tillage practices, and other cropping and management considerations, while the $P$ factor adjusts for supporting actions undertaken to reduce the velocity of runoff.

Table 2.1 presents data on sheet, rill, and wind erosion in the forty-eight contiguous states in 1977. The highest regional average rates of sheet and rill erosion are seen to have occurred in the Appalachian, Delta, and Corn Belt states, but the greatest volume of soil losses
Table 2.1. Erosion from cropland in the United States in 1977 (USDA, 108)

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<td>2.1</td>
<td>1,908</td>
<td>4.7</td>
<td>2,799</td>
<td>6.8</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Northeast</td>
<td>n.e.</td>
<td></td>
<td>82.9</td>
<td>5.0</td>
<td>82.9</td>
<td>5.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Lake States</td>
<td>n.e.</td>
<td></td>
<td>117.5</td>
<td>2.7</td>
<td>117.5</td>
<td>2.7</td>
<td>4.2</td>
<td>10.7</td>
</tr>
<tr>
<td>Corn Belt</td>
<td>n.e.</td>
<td></td>
<td>688.3</td>
<td>7.7</td>
<td>688.3</td>
<td>7.7</td>
<td>24.6</td>
<td>21.8</td>
</tr>
<tr>
<td>Iowa</td>
<td>n.e.</td>
<td></td>
<td>261.3</td>
<td>9.9</td>
<td>261.3</td>
<td>9.9</td>
<td>9.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Northern Plains</td>
<td>212.3</td>
<td>2.2</td>
<td>322.4</td>
<td>3.4</td>
<td>534.7</td>
<td>5.6</td>
<td>19.1</td>
<td>22.9</td>
</tr>
<tr>
<td>Appalachia</td>
<td>n.e.</td>
<td></td>
<td>186.3</td>
<td>9.0</td>
<td>186.3</td>
<td>9.0</td>
<td>6.7</td>
<td>5.0</td>
</tr>
<tr>
<td>Southeast</td>
<td>n.e.</td>
<td></td>
<td>111.0</td>
<td>6.3</td>
<td>111.0</td>
<td>6.3</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Delta</td>
<td>n.e.</td>
<td></td>
<td>154.9</td>
<td>7.3</td>
<td>154.9</td>
<td>7.3</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Southern Plains</td>
<td>488.8</td>
<td>11.6</td>
<td>141.4</td>
<td>3.4</td>
<td>630.2</td>
<td>15.0</td>
<td>22.5</td>
<td>10.2</td>
</tr>
<tr>
<td>Mountain</td>
<td>190.3</td>
<td>4.5</td>
<td>70.8</td>
<td>1.7</td>
<td>261.1</td>
<td>6.2</td>
<td>9.3</td>
<td>10.2</td>
</tr>
<tr>
<td>Pacific</td>
<td>n.e.</td>
<td></td>
<td>31.9</td>
<td>1.4</td>
<td>3.19</td>
<td>1.4</td>
<td>1.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>

^n.e. means not estimated.
are indicated to have occurred in the Northern Plains and Corn Belt states. The USDA (108) has estimated that state average sheet and rill erosion rates of cropland in 1977 in the nation ranged from a low of 0.04 tons per acre per year in Nevada to a high of 14.1 tons per acre per year in Tennessee while in the Corn Belt states these rates ranged from 3.6 tons per acre per year in Ohio to 11.4 tons per acre per year in Missouri with the average being 7.7 tons per acre per year. Iowa had the second highest state estimated average rate in this region of 9.9 tons per acre per year, but had the greatest volume of soil lost. Further, Iowa had the most cropland of any state with estimated sheet and rill erosion rates exceeding the amount of five tons per acre per year.

Unlike sheet and rill erosion, there exists no generally applicable model for estimating gully erosion rates. There are, however, methods which can be used to estimate gully erosion rates for given localities and using such methods, the USDA (105) estimated total gully erosion from all nonfederal land in Iowa in 1977 to be 44,211,188 tons. Given 38,844,000 acres of nonfederal land in the state in that year, this implies an average gully erosion rate of 1.14 tons per acre. The data do not give gully erosion for cropland, but assuming that the average cropland gully erosion rate is equal to the state average would_
imply cropland gully erosion to have been 30,107,000 tons or approximately 11.5 percent of the total sheet and rill erosion estimated for 1977. It is implied by these figures that gully erosion is considerably less than sheet and rill erosion. This result is generally true for most humid areas and it would be reasonably assumed that gully erosion in Iowa cropland is generally about ten percent of cropland sheet and rill erosion (EPA, 114; Glymph, 43; Wade and Heady, 118).

Wind erosion occurs when the energy of wind is sufficient to detach and transport soil particles. A model of potential annual soil loss to wind erosion in tons per acre per year has been developed by Skidmore and Woodruff (89) for the Great Plains States. The model does not perform well for areas outside this region, however (USDA, 108). The nature of this model will not be detailed here since wind erosion is not generally a severe problem in the Corn Belt states and because of the limits on its applicability. The USDA (108) has compiled estimates of wind erosion in the Great Plains States (Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming) these being those in which wind erosion represents a significant problem. The range of wind erosion rates of cropland estimated for 1977
in these states is from a low of 1.25 tons per acre per year in Nebraska to a high of 14.9 tons per acre per year in Texas. The most severe wind erosion problems occur in New Mexico and Texas. Estimated wind erosion for crop-land in New Mexico for 1977 is 11.5 tons per acre per year. In Colorado, the estimate is 8.9 tons per acre per year, but in the remaining Great Plains states, the estimates are below five tons per acre per year.

Crop Production Impacts of Soil Erosion

The impacts of soil erosion are commonly divided into onsite impacts, these being composed of damages to the soil and land where the erosion occurs, and offsite impacts, these being composed of the effects of sediments deposited on land or in water resources other than those held by the economic agent upon whose land the sediments originated. There are several onsite impacts of interest (Beasley, 11; Troeh et al., 101). Erosion results in loss of top soil, loss of plant nutrients, and textural and structural damages to the soil which generally diminish the productive capacity of the soil. The effects upon crop yields depend most crucially on the relative properties of the top-soil and subsoil. If the subsoil is more fertile than the top soil, a rare but existent condition, then soil loss may
actually be beneficial. However, the usual case is where the properties of the subsoil are less conducive to crop production. In some cases, the productive capacity of a soil may be totally destroyed by soil loss because the root zone is lost for soils that are shallow to bedrock. Erosion can also diminish the agricultural land base as gully erosion diminishes the cultivatable land area and as soil erosion results in depletion of soil depths. A further effect of erosion on the soil is to increase the erosivity of the soil as soil texture is deteriorated. Finally, the textural and structural damages to the soil can result in increased production costs as seed-bed preparation and other field operations are hindered by the damages to the soil and also as field time is increased by the dissection of fields by gullies.

Agronomic research has focused on the productivity impacts of accelerated erosion as has public interest. The essential property of soils which has received the greatest attention in such research is soil depth. One statistic of interest developed by agronomists is the "Soil Tolerance Value" or "T value" of soils, this being defined as the maximum amount of loss per acre per year of soil that will permit a high level productivity to be sustained economically and indefinitely. The concept was originally suggested by
Stamey and Smith (96). Smith and Stamey (91) report values ranging from 0.5 tons per acre per year to 6.0 tons per acre per year, but recently the Soil Conservation Service (SCS) has established a maximum of 5 tons per acre per year. There are a number of agronomists, however, who consider values within this range to be excessive, one reason being that soil formation rates from consolidated materials is no more than 0.5 tons per acre per year (Larson, 64).

Table 2.2 presents data on sheet and rill erosion in excess of soil tolerance in the United States, exclusive of Alaska and Hawaii for 1977. Of the 413.1 million acres of cropland in the forty-eight contiguous states in 1977, 27.28 percent of these acres had sheet and rill erosion rates in excess of the T values for those acreages. The area with the greatest number of acres with erosion rates in excess of the T value was the Corn Belt. Nearly fifty percent of all Iowa cropland experienced sheet and rill erosion in 1977 at rates in excess of the T values for those acreages. What this data indicates is the amount of land on which long term productivity losses may be expected if conditions present in 1977 are maintained. The problem with T values, even if correctly determined, is that they yield no information useful for economic analysis. Such
Table 2.2. Cropland erosion in excess of T values in 1977 (USDA, 108)

<table>
<thead>
<tr>
<th>Area</th>
<th>Acres of cropland with sheet and rill erosion in excess of T value (10^6) acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appalachian</td>
<td>9.5</td>
</tr>
<tr>
<td>Corn Belt</td>
<td>38.1</td>
</tr>
<tr>
<td>Iowa</td>
<td>12.3</td>
</tr>
<tr>
<td>Delta States</td>
<td>12.4</td>
</tr>
<tr>
<td>Lake States</td>
<td>7.3</td>
</tr>
<tr>
<td>Mountain</td>
<td>3.5</td>
</tr>
<tr>
<td>Northeast</td>
<td>6.0</td>
</tr>
<tr>
<td>Northern Plains</td>
<td>16.2</td>
</tr>
<tr>
<td>Pacific</td>
<td>1.5</td>
</tr>
<tr>
<td>Southeast</td>
<td>7.7</td>
</tr>
<tr>
<td>Southern Plains</td>
<td>10.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>112.7</strong></td>
</tr>
</tbody>
</table>

Information must provide for estimation of just how productivity behaves with soil loss under specified conditions. There have been a number of studies which have considered the effects of erosion on soil productivity and the evidence suggests that losses of 0 to 6 bushels per acre may occur with each inch of topsoil lost (USDA, 108). At an erosion rate of 10 tons per acre per year, it will, as a
rule of thumb, take approximately fifteen years to lose one inch of topsoil. However, the existing state of agronomic knowledge is insufficient to provide precise data on the effects of soil loss on crop yields for varying factor input levels for given soils. This represents a severe data problem in efforts to assess the seriousness of erosion losses.

The Offsite Impacts of Soil Erosion

The offsite impacts of water erosion occur as runoff water moves eroded soil particles from the field which are then deposited on land or in water. When deposited on cropland, sediments may result in the destruction of the current crop, and if these sediments are less fertile than the soil upon which they are deposited, then deposition may diminish soil productivity. However, the deposition of sediments on land is not invariably adverse in its impacts and in some cases can be quite beneficial. In recent years, the focus of national concern has been upon the adverse impacts of sediment deposition in water and these will be the subject here.

The sedimentation of water bodies is a two-step process. The first step is soil erosion which has been discussed above. The second step is the transportation of soil to water bodies.
Erosion results as soil particles are detached by raindrop splash and as a consequence of the action of runoff water. Some particles may be moved from the site to receiving waters during a particular storm while others may be moved from the site to be deposited en route or may simply be moved from one part of the field to another. Thus, the delivery of sediments during any particular storm will be some fraction of the amount of gross erosion. However, the "play fairs" law suggests that sediments deposited in concentrated flow channels will, after many storms, ultimately be moved into streams and lakes (EPA, 112). The ratio of sediment delivered or sediment yield at a given location in a stream system to the gross erosion of the drainage area above that point during a specified period is the sediment delivery ratio. Factors influencing this ratio include those factors determining gross soil erosion, the size of the drainage area and particularly the implication of size on the distance of transport, the texture of the eroded soil, the relief of the drainage area, the sediment transportation systems within the area, and the locations of deposition within the area (EPA, 106). In general, the greater the distance required for delivery, the greater the opportunities for deposition en route. The finer the texture of the eroded soil, the greater will be the sediment
delivery ratio relative to that for coarser textured soils since the former tend to stay in suspension for a greater amount of time. High watershed relief-to-length ratios have been shown to be associated with higher delivery ratios. Further, the efficiency of the sediment transportation systems within the watershed has a substantial effect upon delivery ratios.

Simple models of sediment delivery from sheet and rill erosion involve multiplying the USLE by a sediment delivery ratio (EPA, 114). However, the USLE was not developed to predict single-event storm losses of soil, and sediment delivery is insufficiently understood to have any substantial confidence in its use at present. Alternative models involve statistical methods for prediction such as that developed by Glymph (43) and modifications of the USLE such as the Williams (123) model. This area of research, as with many others related to cropland soil and erosion and the onsite and offsite impacts resulting, is one in which there remains much research to be done.

Once the sediment has reached the stream, it may be transported within the stream as bed load or suspended load (Johnson and Moldenhauer, 57). The amount of sediment carried downstream to a given point need not equal, however, the amount introduced. For example, flooding may result in the deposition of some proportion back on the land.
Alternatively, stream flow characteristics may result in sediments being deposited in areas along the stream bed. The ratio of sediment yield in a watershed to the amount of sediment transported to a given point is the sediment transportation ratio.

There are numerous impacts of sediment in water, some resulting from sediment accumulation over long periods of time, others being a consequence of current sediment loads. These impacts occur as a consequence of sediments diminishing the capacities of water bodies, settling out on the bottoms of water bodies, increasing the turbidity of waters, and as a consequence of chemical substances which have been absorbed by sediments (EPA, 112). Sediments may reduce the capacity of stream and other channels, lakes, reservoirs, harbors, and coastal areas. Diminution of stream channel capacity can increase flooding and hamper boat traffic while reduction in the capacity of other channels, for example, irrigation channels, may reduce the flow of services from these as well. Sedimentation of lakes and reservoirs will, unless they are dredged, reduce the life and capacity of such. Lakes and reservoirs provide many kinds of services, including flood control, power generation, recreation, and water supply. Sedimentation of harbors is a long and persistent problem in the United States. Turbidity can reduce the quality of water for drinking, cleaning, and recreation,
as can the association of chemicals with sediments. By reducing light transmission in water and dissolved oxygen levels, sediments can adversely affect aquatic plant and animal habitats. Further, high levels of suspended sediments can kill fish outright and the settling of sediments on spawning beds can destroy the fish eggs.

Table 2.3 presents estimates of the relative contribution of various sources to sediment yields in the United States in 1977. These data suggest agricultural activities to be clearly the most important source. Table 2.4 presents data on sediment delivery for various regions of the United States for 1977. These estimates suggest that problems arising from cropland erosion may be particularly severe in the Corn Belt states.

While there are some instances of point source water pollution from agriculture, agricultural production activities generally result in nonpoint source pollution. Nonpoint sources have been shown by the General Accounting Office (115) to account for over half of all pollutants entering the nation's waterways in recent years and it was noted in the same study that unless nonpoint sources are brought under control, the 1982 "fishable and swimmable" water quality standards set forth by Congress in the 1972 Federal Water Pollution Control Act Amendments will be unobtainable. Data given in Table 2.5 show that agriculture
Table 2.3. Percentage contribution to total sediment flow by source (USDA, 108)

<table>
<thead>
<tr>
<th>Sediment source</th>
<th>Contribution (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>40</td>
</tr>
<tr>
<td>Streambanks</td>
<td>26</td>
</tr>
<tr>
<td>Pasture and rangeland</td>
<td>12</td>
</tr>
<tr>
<td>Forest lands</td>
<td>7</td>
</tr>
<tr>
<td>Urban</td>
<td>4</td>
</tr>
<tr>
<td>Roadsides</td>
<td>3</td>
</tr>
<tr>
<td>Mining</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>7</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 2.4. Sediment delivered to water bodies in the United States (Crosson and Brubaker, 27)

<table>
<thead>
<tr>
<th>Region</th>
<th>1977 (million/tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>26.6</td>
</tr>
<tr>
<td>Lake States</td>
<td>45.7</td>
</tr>
<tr>
<td>Corn Belt</td>
<td>250.9</td>
</tr>
<tr>
<td>Northern Plains</td>
<td>141.7</td>
</tr>
<tr>
<td>Appalachia</td>
<td>57.7</td>
</tr>
<tr>
<td>Southeast</td>
<td>41.9</td>
</tr>
<tr>
<td>Delta</td>
<td>73.8</td>
</tr>
<tr>
<td>Southern Plains</td>
<td>69.3</td>
</tr>
<tr>
<td>Mountain</td>
<td>29.5</td>
</tr>
<tr>
<td>Pacific</td>
<td>11.2</td>
</tr>
<tr>
<td><strong>Nation</strong></td>
<td><strong>748.3</strong></td>
</tr>
</tbody>
</table>
Table 2.5. Percentage of basins wholly or partly affected by nonpoint source pollution, by source (USDA, 108)

<table>
<thead>
<tr>
<th>Regions</th>
<th>Urban runoff</th>
<th>Construction</th>
<th>Hydrologic modification</th>
<th>Silviculture</th>
<th>Mining</th>
<th>Agriculture</th>
<th>Solid waste disposal</th>
<th>Individual disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast (40)</td>
<td>70</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>55</td>
<td>35</td>
<td>63</td>
</tr>
<tr>
<td>Southeast (47)</td>
<td>57</td>
<td>2</td>
<td>21</td>
<td>30</td>
<td>15</td>
<td>62</td>
<td>9</td>
<td>40</td>
</tr>
<tr>
<td>Great Lakes (41)</td>
<td>54</td>
<td>7</td>
<td>2</td>
<td>15</td>
<td>41</td>
<td>59</td>
<td>15</td>
<td>39</td>
</tr>
<tr>
<td>North Central (35)</td>
<td>54</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>40</td>
<td>39</td>
<td>9</td>
<td>29</td>
</tr>
<tr>
<td>South Central (30)</td>
<td>50</td>
<td>0</td>
<td>23</td>
<td>13</td>
<td>53</td>
<td>87</td>
<td>13</td>
<td>40</td>
</tr>
<tr>
<td>Southwest (22)</td>
<td>23</td>
<td>0</td>
<td>18</td>
<td>5</td>
<td>36</td>
<td>73</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>Northwest (22)</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>27</td>
<td>23</td>
<td>55</td>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>Islands (9)</td>
<td>67</td>
<td>67</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>78</td>
<td>22</td>
<td>89</td>
</tr>
<tr>
<td>TOTAL</td>
<td>52</td>
<td>9</td>
<td>15</td>
<td>15</td>
<td>30</td>
<td>68</td>
<td>14</td>
<td>43</td>
</tr>
</tbody>
</table>
represents the most widespread source of nonpoint source pollutants in the United States. Several comments are warranted in regard to the figures presented in Table 2.5. First of all, the figures indicate only the percentage of basins affected by agricultural pollutants but not the magnitude of residual flows from various sources. There is, however, little available data on volumes. Secondly, even if the volume of agricultural pollutants is equal to or in excess of those from other sources, there are several reasons to expect that agricultural nonpoint source loadings may have lesser environmental impacts than equivalent point source loadings (USDA, 108). These loadings can be better assimilated than point source loadings which are highly concentrated and agricultural nonpoint source pollutants are received by waters in pulse loads so that water quality impacts are intermittent rather than persistent.

The USDA (108) has identified five agricultural pollutants which are potentially problematic. These are pesticides, nutrients, bacterial and organic matter, sediment, and salinity. Table 2.6 gives the number of basins affected by these. The question which arises at this point is the severity of these impacts. A definitive answer to this question does not exist at present. Crosson and Brubaker (27), in their recent analysis of the environmental
Table 2.6. Percentage of basins wholly or partly affected by nonpoint source pollution, by pollutant (USDA, 108)

<table>
<thead>
<tr>
<th>Region (number of basins)</th>
<th>Bacteria</th>
<th>Oxygen depletion</th>
<th>Nutrients</th>
<th>Suspended solids</th>
<th>Dissolved solids</th>
<th>pH</th>
<th>Oil and grease</th>
<th>Toxics</th>
<th>Pesticides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast (40)</td>
<td>70</td>
<td>53</td>
<td>63</td>
<td>65</td>
<td>10</td>
<td>18</td>
<td>15</td>
<td>33</td>
<td>18</td>
</tr>
<tr>
<td>Southeast (47)</td>
<td>66</td>
<td>74</td>
<td>57</td>
<td>34</td>
<td>4</td>
<td>9</td>
<td>4</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>Great Lakes (41)</td>
<td>51</td>
<td>54</td>
<td>44</td>
<td>56</td>
<td>27</td>
<td>37</td>
<td>20</td>
<td>34</td>
<td>15</td>
</tr>
<tr>
<td>North Central (35)</td>
<td>69</td>
<td>66</td>
<td>63</td>
<td>80</td>
<td>51</td>
<td>20</td>
<td>0</td>
<td>51</td>
<td>37</td>
</tr>
<tr>
<td>South Central (30)</td>
<td>53</td>
<td>43</td>
<td>63</td>
<td>37</td>
<td>70</td>
<td>23</td>
<td>3</td>
<td>47</td>
<td>40</td>
</tr>
<tr>
<td>Southwest (22)</td>
<td>36</td>
<td>14</td>
<td>45</td>
<td>32</td>
<td>68</td>
<td>14</td>
<td>14</td>
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<td>0</td>
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<tr>
<td>Northwest (22)</td>
<td>64</td>
<td>18</td>
<td>55</td>
<td>64</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>Islands (9)</td>
<td>89</td>
<td>44</td>
<td>44</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td>TOTAL</td>
<td>61</td>
<td>51</td>
<td>56</td>
<td>54</td>
<td>30</td>
<td>18</td>
<td>9</td>
<td>32</td>
<td>22</td>
</tr>
</tbody>
</table>
impacts of erosion, commercial fertilizer usage, and pesticides usage, note two reasons why this is the case. The first is that there is a notable lack of basic knowledge about the behavior of residual flows from agriculture and precise information on the impacts of agricultural pollutants. The second is that there are difficulties which arise when valuing certain kinds of impacts such as the illness or death of humans resulting from pesticides. The region of the country with which this study is concerned is the Corn Belt states region and in this area the problem of dissolved solids or salinity can safely be said not to be of major concern since this problem arises largely in connection with cropland irrigation in arid and semi-arid areas. However, fertilizer and pesticide usage, soil erosion rates, and livestock operations levels are all quite high in this region suggesting that there exists a significant potential for substantial water quality problems. Crosson and Brubaker (27) argue persuasively, based upon a review of available data and literature, that the major threat to water quality in the nation from agricultural production arises in connection with soil erosion and sedimentation. Based upon their analysis and upon data presented above, one is led to conclude that, to the extent that this is true, the threat may be particularly severe in the Corn Belt
states. This conclusion finds support elsewhere. In an earlier paper published in the Journal of Soil and Water Conservation, Crosson (26) comes to much the same conclusions. Wauchope (121), based upon a survey of expert opinion, has argued that with the possible exception of a few compounds, currently registered pesticides do not at present cause water quality problems.

In the final analysis, conclusions regarding the relative severity of alternative agricultural nonpoint source pollutants must be based upon sound scientific analysis in which the availability of basic knowledge allows economic analysis of costs and benefits of abatement. Most concern is at present focused, however, on the water quality impacts of erosion and, without suggesting that other impacts are necessarily of lesser concern, the remainder of this study will be given to the economic analysis of these and onsite impacts of erosion.

Public Policy and Soil Erosion

Soil erosion began to be recognized as a resource conservation problem in the late 1920s, and, as a consequence of the interest in the problem, Federal Government research projects were initiated. During the Great Depression, unemployment problems and perceived soil and water resources
conservation problems led to the creation of the Civilian Conservation Corps in 1933. In this year, the Soil Erosion Service was also created to develop erosion control projects. However, the rise in public concern over soil erosion in a substantial way and the initiation of modern soil conservation policy dates back to the mid-1930s. During the severe droughts of the years from 1931 to 1938, wind erosion became a severe problem in the Great Plains States. Dust storms in 1934 and 1935 made history as dust was carried from the Great Plains to the eastern seaboard and beyond. These erosion problems resulted in the passage of the National Soil Conservation Act of 1935. There have been subsequent developments in conservation policy. The interest in soil erosion as a source of water quality problems is more recent. Public concern for environmental quality problems resulted in Federal Government actions beginning in the latter part of the 1950s and has evolved considerably since. The focal point of water quality policy was for many years on more noticeable types of point source pollutants. However, recently a greater interest in nonpoint source and agricultural nonpoint source pollution control has emerged.
Soil conservation policy

There are three principal soil conservation programs operating at present in the United States. The SCS, which was created by the National Soil Conservation Act of 1935, provides farmers with soil and water conservation technical advice and conservation plans. A special program administered by the SCS that was mandated by Congress in 1956 is the Great Plains Conservation program in which the SCS encourages farmers in the region to enter contracts to perform agreed upon soil and wind erosion control plans. Participation in the Conservation Operations Program of the SCS, this being the program in which technical assistance and conservation plans are provided, is strictly voluntary, the initiative lying with the farmer. The General Accounting Office (116) has been critical of this program, arguing that the SCS is not aggressive in seeking out and concentrating efforts on severe erosion problem areas, for devising plans which are too elaborate and which go unimplemented by farmers, and for little follow-up, concluding that the program has little impact upon soil loss. The General Accounting Office has also been critical of the Great Plains Conservation Program. This program has been implemented on only one-fourth of the intended acreages, priority has not been given to problem areas and to effective practices, and strong grain
prices have led farmers to decline contracts or to return lands to cultivation when contracts expire.

The third program initiated by the Federal Government is the Agricultural Conservation Program which provides funds to farmers on a cost-sharing basis for conservation practices. The program is administered by the Agricultural Stabilization and Conservation Service (ASCS) in cooperation with local committees of farmers. The service has its origin in the Agricultural Adjustment Administration which was created in 1933 to control agricultural production. The emphasis of the service on payments to farmers for soil conservation practices is the result of the Soil Conservation and Domestic Allotment Act of 1936. The SCS provides the ASCS with technical assistance as a consequence of an agreement made between the agencies in 1931. While the share of conservation practices costs paid by the ASCS is usually half, the percentage may vary with the particular practice. The review of this program by the General Accounting Office also pointed out several problems. First of all, less than half of the available funds were allocated to activities primarily of soil conservation character, the remainder providing farmers with funds for measures primarily in the farmer's own interests. Further, local committees have shown a tendency to support structural measures over non-structural but effective measures such as conservation
tillage.

In addition to these principal agencies, there are also other federal, state, and local conservation agencies. States were encouraged by the Federal Government to enact a "Standard States Soil Conservation Districts Law." All states had done so by 1947. These laws established districts, frequently called "Soil and Water Conservation Districts," "Conservation Districts," and "Soil Conservation Districts." The SCS acts in support of these. The role of districts is uniformly educational, but some states provided districts with taxation and enforcement powers. The districts are managed by elected boards.

Concern for the effectiveness of soil and water conservation policies rooted in the experience of the Depression led Congress to enact the Soil and Water Resources Conservation Act (RCA) in 1977. This act required the Secretary of the Department of Agriculture to provide to Congress, an appraisal of soil, water, and related resources on non-federal lands in the nation and to develop effective soil and water conservation programs which would be responsive to change by 1980. In addition, the act requires annual evaluation reports and a repetition of the process in 1985.

A number of alternative strategies have been suggested in the RCA appraisal (USDA, 108). Two of these involve
modifications of the existing system. The first would entail a redirection of existing programs to increase their effectiveness with a minimum of disruption to existing activities. The second would involve a cross-compliance strategy which would require considerable rules and procedures changes and diminish the voluntary nature of the programs. A third approach would involve yielding planning and implementation authorities to states subject to USDA approval and oversight, while a fourth would involve the initiation of a regulatory strategy administered by the USDA. Two strategies suggested involve monetary incentives. In one, farmers would receive bonuses for voluntary conservation efforts. The second would entail "natural resources contracts" which would be entered into by farmers and the USDA or its agencies. Farmers would receive payments for the performance of conservation practices.

Water quality policy

The goals of United States water quality policy are set for in the Federal Water Pollution Control Act Amendments of 1972. The national goal is the elimination of all discharges of pollutants into navigable waters by 1985. An interim operational goal was also set forth by Congress, this being "fishable-swimmable" waters by 1983. With respect to point sources, the means by which the goals are
to be obtained are technology-based effluent standards established by the Administrator of the EPA. These standards are to be achieved, according to the enactment, in two stages. First of all, industrial discharges were to meet effluent standards by 1977, based upon the "best practicable control technology" currently available, while publicly owned treatment works were to initiate secondary treatment. By 1983, "industrial dischargers" effluent standards were to be based upon "best available technology economically achievable" while publicly owned treatment works are to meet effluent standards based upon "best available waste treatment technology." In addition to these requirements, the amendments called for the EPA to establish effluent standards based upon the "best available demonstrated control technology."

The technology-based effluent standards do not apply to nonpoint pollution sources. Under Section 208 of the Federal Water Pollution Control Act Amendments of 1972, the EPA delegated nearly all planning and control of nonpoint source pollution to the states, subject to EPA approval. States were required to identify agriculturally and silviculturally related nonpoint sources of pollution and to devise procedures and methods by which to control such sources. In 1977, Congress amended Section 208 with the Rural Clean Water Act. This amendment directed the Secretary of Agriculture,
with the concurrence of the Administrator of the EPA, to establish and administer a program in which five to ten year contracts with rural landowners and operators are entered to promote the installation of best management practices to control water pollution from nonpoint sources. The program provides technical and financial assistance on a cost-sharing basis for those practices that improve water quality and are consistent with the areawide waste treatment management plans devised by states under Section 208.

The EPA has provided financial assistance with administrative guidelines for the preparation of 208 plans. Because the plans are new and mostly voluntary and because completion of plans has been lagging, there is no considerable record of implementation as yet. The emphasis in 208 planning has been upon so-called "Best Management Practices" (BMP's) which involve measures which can be adopted by farmers to control erosion and runoff. There has also been some emphasis on measures to inhibit sediment delivery. Most plans contemplate making use of existing conservation agencies such as the Soil Conservation Districts and envision the use of SCS personnel to provide technical assistance. Thus, in practice, 208 programs have to some extent become extensions of existing soil conservation programs. Beyond providing financial assistance, planning guidelines, review of state plans, and
approval of BMP's, the role of the EPA has not been substantial; responsibility and initiative have fallen to the states. Crosson and Brubaker (27) suggest, however, that state performance has been unworthy of praise, although there is much variation in performance.

Conclusion

There is at present, a high level of public concern for the damages to soil and water quality in the United States. This survey of the processes and problems of water erosion has suggested some of the motivation for these concerns and has identified the Corn Belt states, and Iowa in particular, as warranting particular attention. Dissatisfaction with current soil conservation policies and a change in focus in water quality concerns from the more obvious point sources to nonpoint sources has led to a situation in which both soil and water conservation policies are being evaluated in order to develop an effective public strategy for maintaining or enhancing the quality of these resources. Economic analysis should play an important role in policy developments, however, in order to direct policy deliberations in a direction such that the costs of policy initiatives are warranted by the benefits from those initiatives, and the time is ripe for providing such direction given the
current state of flux in policy development. Past soil conservation and water quality policy in the United States has been subject to criticism by economists and others for failure to weigh costs and benefits. Yet, if the problems are real, it is important that adjustments proceed for several recent predictions of agricultural production suggest that erosion will not diminish from current levels in coming years (Crosson and Brubaker, 27; USDA, 108). That is, if the damages to soil and water quality are significant, they will, under projected future circumstances, remain so unless some actions are taken.
CHAPTER III. AN ABSTRACT ECONOMIC ANALYSIS OF CROPLAND EROSION AND EROSION CONTROL

Introduction: Soil Resources and Soil Management

Students of natural resource management have devised a variety of systems for classifying natural resources for the purpose of management. Commonly, these systems are based upon characteristics of the natural occurrence of the resource. One of the most widely accepted systems of classification based upon characteristics of the natural occurrence of resources is Ciriacy-Wantraup's (23). The resources are broadly classified as renewable or nonrenewable depending upon the economic significance of the rate of regeneration of the resource stock, and then further classified within each of these broad groupings depending upon other attributes of the resource. One common variant of this system is to further distinguish resources as to whether or not they are biological natural resources (Barlowe, 5). Soils, however, represent a more complex case because they are a mixture of biological and nonbiological resources and renewable and nonrenewable resources. Ciriacy-Wantraup chooses to classify resources with such a character as composite natural resources.

The purpose in classifying resources is generally to focus attention upon the crucial aspects of the natural
resource management problem and thus the appropriate principles of resource management. The economic theory of the exploitation of particular types of resource stocks is well-developed. The theory of composite resource management is not so well-developed. To a large extent, however, problems in composite resource management involve only an extension of existing principles since it represents a problem in the conjunctive management of several interrelated renewable and/or nonrenewable resources stocks as demonstrated, for example, in a paper on the conjunctive management of ground and surface water resources by Cummings and Winkelman (30). As a composite of natural resource stocks the soil resource management problem is one of the conjunctive management of natural resources and it is a fundamental proposition of this research that the theory of extraction from renewable and nonrenewable resource stocks can be brought to bear appropriately and usefully upon issues in soil management including soil erosion. But, as noted in Chapter I, this theory has not to date been drawn upon to consider such issues in any significant way and thus an objective of the analysis of this chapter is to demonstrate the applicability of the theory to the soil management problem. This demonstration is provided as other objectives of this chapter are pursued. The first of these is to acquire some understanding of the economic
determination of soil erosion on particular soils as a farmer endeavors to maximize the net present value of the soil resource. The second is to consider issues in the economics of erosion control policy. The framework of analysis is one in which soil depth is treated as an exhaustible resource stock which is depleted by erosion and which may be renewable or nonrenewable depending upon the rate of soil genesis. A final objective of the analysis in this chapter is to provide a theoretical foundation for the empirical analysis of issues in the economics of crop-land erosion and erosion control in the Four Mile Creek watershed. Before proceeding directly to the application of the theory, it is useful to develop the nature of the analytical framework, some useful terminology, and to develop some results of interest. This is done in the following section where a brief review of the theory of extraction is given.

A Review of the Theory of Optimal Extraction

The economic literature in this area can be divided into two basic categories (Smith and Krutilla, 90). The first category includes models in which natural resource inputs are included in models of reproducible capital accumulation primarily for the purpose of investigating
issues in economic growth in the presence of exhaustible resources. Important examples of the literature in this area include contributions by Dasgupta and Heal (32), Stiglitz (98), and Solow (93). The second category is composed of models of extraction of specific resources or types of resources at the level of the firm or industry, or at other levels of aggregation such as a river basin. These models have been developed to consider the properties of optimal extraction of specific resources or types of resources and to investigate positive issues such as the behavior of resource scarcity indices, and the effects of taxation on extraction. Important examples of literature in this area include Hotelling's (52) seminal paper on economics of exhaustible resources, extensions of Hotelling's analysis by Gordon (44), Cummings (28), and Shulze (88), Scott's (86) analysis of the theory of the mine under conditions of certainty, Burness's (19) work on the effects of severance taxes, and developments in the theory of fisheries (renewable resource) management by Schaefer (84), Plourde (79) and Clark (24). The literature in both areas has grown substantially in the last decade as a consequence of the interest in natural resource problems arising from the energy and environmental resources issues which emerged during this time. An extensive, though not highly detailed, survey of this literature is provided by Peterson
and Fisher (77). In the next several pages the basic models of optimal exploitation of renewable and nonrenewable resource stocks found in the second category of literature are briefly outlined. There are a number of variants and extensions of these models and a number of issues in the theory that will not be dealt with here. The purpose of this outline of the basic theory is to establish the structure of such models and to establish some of the basic propositions about optimal management found in the literature.

The first issue to consider is what is meant by optimal exploitation. Treatments of optimal exploitation in the second category of literature commonly posit an optimal extraction path for a particular resource to be one associated with a particular Pareto optimum. It is assumed that the conditions for a first best optimum are otherwise satisfied within the economy and that wealth is distributed equitably both intratemporally and intertemporally. Then, as long as producers and consumers discount at the same rate, the optimal path of extraction will be that path that maximizes the flow of discounted consumers plus producers surpluses. This formulation was used by Hotelling and has been extensively used in subsequent contributions. It is to be noted, however, that while this formulation is fairly well-received by resource
economists, there remains some controversy over just what constitutes optimality of resource use. Page (76) in his recent book on materials policy, compares what he labels the "Present Value Criterion" of resource use, this being the criterion just given, and what he labels the "Conservationist Criterion", the latter being composed of a series of loosely formulated propositions about the "wise" use of resources which can be found in a survey of conservationist literature over the years. In a series of articles, Sandler and Smith (82, 83) have questioned the efficiency of discounting while Solow (92) in his address to the American Economic Association meetings in 1973 expressed concern over the equity implications of discounting when doing so leads to resource exhaustion and the extinction of mankind. The equity and efficiency issues arising from the present value criterion are also considered by Krutilla and Fisher (62), particularly as they occur in relation to irreversible development of unique natural environments.

Turning now to the basic model of optimal nonrenewable resource exploitation, let the benefits from extraction be given at any time by

$$B(q^*) = \int_0^{q^*} P(q)\,dq$$  \hspace{1cm} (1)$$

where $P(q)$ is the inverse of the market demand for $q$. Now,
let \( C(q) \) be the long run cost of extraction function for the homogeneous resource where it is assumed that \( C' > 0 \). Defining an optimal extraction path as a Pareto optimal path, a particular optimum can be obtained by maximizing

\[
\int_0^\infty (B(q) - C(q))e^{-rt}dt
\]  

subject to the restriction that

\[
\int_0^\infty q dt = S_0
\]

where \( r \) is the social rate of discount, which is assumed constant, and \( S(t) \) is the resource stock at time \( t \) so \( S(0) = S_0 \). The problem described here is an isoperimetric problem in the calculus of variations and may be solved by maximizing the function

\[
\int_0^\infty [B(q) - C(q)]e^{-r(t) - \lambda q}dt
\]

where \( \lambda \) is a Lagrangian multiplier. The Euler equation for determining the optimal path of \( q(t) \) is simply

\[
(B' - C')e^{-rt} - \lambda = 0
\]

and where \( B' = P \), this result implies that

\[
P = C' + \lambda e^{rt}
\]
A property of the optimal program is then that at any point in time, the marginal willingness to pay or price of the product must equal marginal extraction cost plus an imputed cost. Let \( V^* \) be the net present value of the optimal program and \( \lambda^* \) be the value of the Lagrangian multiplier in this program. The value of \( \lambda^* \) is

\[
\lambda^* = \frac{dV^*}{ds_0} = P(0) - C'(q(0))
\]

and thus \( \lambda^* \) gives the marginal scarcity value of the resource or the amount society would be willing to pay at the margin for an additional unit of the resource at \( t = 0 \). The multiplier also gives the marginal cost to society of a reduction in the resource stock at time \( t = 0 \) and \( \lambda^*e^{rt} \) gives the marginal cost of a reduction of the stock at time \( t \). This imputed cost is termed the marginal user cost of extraction (Scott, 86; Peterson and Fisher, 77) and rises at the rate of discount in the optimal program.

A complication of the model is to introduce stock effects by defining the long-run extraction cost curve as \( C(q,S) \) where \( C_s \) denotes the partial derivative with respect to \( S(t) \) and is assumed negative. The resource management problem can now be expressed as one of maximizing

\[
\int_0^\infty (B(q) - C(q,S))e^{-rt} dt
\]
subject to the restriction that \( \dot{S} = -q \) and \( S(0) = S_o \). This problem may be solved by use of the maximum principle technique. The Hamiltonian is

\[
H = e^{-rt}[B(q) - C(q,s) - \theta q]
\]

where \( \theta \) is the costate variable. The necessary conditions of interest are

\[
(B' - C_q - \theta)e^{-rt} = 0
\]

and

\[
C_s - \theta + r\theta = 0
\]

where \( C_q \) denotes the partial derivative of the cost function with respect to \( q(t) \). The first of these two conditions can be written

\[
P = C_q + \theta
\]

again, implying that a property of the optimal program is that price equals marginal extraction cost plus the marginal user cost. The second condition may be written alternatively as

\[
\frac{\dot{\theta}}{\theta} = r + \frac{C_s}{\theta}.
\]

Where \( C_s < 0 \), this result implies that the marginal user cost does not rise at the rate of interest but instead at a lesser rate. This result is reasoned to occur because when there is a stock effect, the gain from holding the resource
in situ is composed of a cost savings as well as capital gains and thus the rate of appreciation need not equal the rate of discount (Cummings, 28).

The distinction between the basic renewable resource model and the basic nonrenewable resource model is the physical constraint set, which is given by

\[ \dot{S} = R - q \]  

(14)

and

\[ S(0) = S_0 \]  

(15)

where \( R \) is the regeneration of the resource stock. In the nonrenewable resource case \( R = 0 \). For this outline, let \( R = g(S) \). Whereas the literature on the theory of nonrenewable resources typically uses cost functions as above, much of the literature on the theory of the fishery or other biological populations formulate the analysis in terms of production functions. Thus, let

\[ q = f(E, S) \]  

(16)

where \( E \) is effort and \( f_E > 0, f_{EE} < 0, f_S > 0, f_{SS} < 0 \) and \( f_{ES} > 0 \) are the partial derivatives and their assumed signs. The management problem is again to maximize

\[ \int_0^\infty (B(q) - wE) e^{-rt} dt \]  

(17)

where \( w \) is the opportunity cost of effort, subject to the
technology and physical constraint set described above. This problem may be solved by application of the maximum principle technique. Let the Hamiltonian function be

$$H = \{B(q) - wE + \Gamma(g(S) - q)e^{-rt}\}$$  

(18)

The necessary conditions of interest are, where $B' = \mathcal{P}$,

$$(Pf_E - w - \Gamma f_E)e^{-rt} = 0$$  

(19)

and

$$(-\Gamma f_S - \Gamma g' + \Gamma f_S) + \Gamma r - \dot{r} = 0.$$  

(20)

The first condition may be rewritten as

$$P = \frac{w}{f_E} + \Gamma$$  

(21)

which is the condition that price equal marginal extraction cost plus the marginal user cost. The second condition may be rewritten as

$$\dot{r} = \dot{r} + Pf_S + \Gamma g' - \Gamma f_S$$  

(22)

which states that the opportunity cost of holding the resource stock must equal the appreciation of the stock plus the value of the stock in production plus the value of the stock in propagation less the user cost of additional output resulting from an increase in the stock.

Plourde (79) has shown that for fixed values of $P$, $W$, and $r$, renewable resource models will tend to a steady state
in which the resource stock is constant. Two important points are that extinction can be optimal and that the maximum sustainable yield solution, which may arise when conditions in which biological growth laws are applicable, would arise only by accident. These two points have been demonstrated by a number of contributors (Peterson and Fisher, 77).

To summarize, the fundamental feature of models of optimal natural resource production is the physical constraint set which describes the restrictions on resource extraction arising from the characteristics of the physical occurrence of the natural resource. The presence of the physical constraint set requires that models be dynamic. That is, the physical constraint set causes the problem to be one of the management of a capital stock over time and as in all models of optimal management of a capital stock, the appropriate models are dynamic. The problem of optimal natural resource management is to obtain that pattern of natural resource use which maximizes a specified criterion function subject to the technology of resource production and the physical constraint set. Defining an optimal management program as one in which resource use is Pareto optimal, there exist two basic conditions which must be satisfied for a particular Pareto optimum to be obtained under the assumption that the allocation of resources within the
economy otherwise satisfy the conditions for a "first best" optimum. These two conditions are:

1) **The Flow Condition**: The rate of natural resource extraction at any point in time must be such that the marginal willingness to pay for the flow of extractive output is equal to the marginal opportunity cost of the resources used in extraction plus the marginal user cost.

2) **The Stock Condition**: The stock of natural resource held at any point in time must be such that the opportunity cost of holding the stock is equal at the margin to the marginal benefit of holding the stock.

Stiglitz (97) has outlined the conditions under which a market economy will obtain efficient resource usage. These conditions are that the market be perfectly competitive, that there exists a complete set of perfectly competitive futures markets and risk markets, that there be no external effects or common property resource problems, and that there exist no distortion of the market as a consequence of government intervention. It is to be noted, in addition, that if resources are allocated intratemporally and intertemporally in an equitable fashion, the Pareto optimum obtained in such an economy will also be a social optimum.
A Model of Erosion of a Soil

Cropland erosion is no less a form of mining than is the extraction of coal from a coal deposit or the extraction of groundwater from an aquifer. It follows that the theory of extraction has direct applicability to the economic analysis of cropland erosion. In this section, the soil management problem faced by a present value maximizing economic agent operating in an environment characterized by perfect information is considered in order to gain an understanding of how the decision-making of that agent is influenced by erosion and the impacts of erosion on the flow of productive services from the soil. To facilitate the analysis, a simple and highly abstract model of agricultural production from an individual soil resource occurrence is developed. The "soil mine" is conceptualized here as a uniquely located and specialized resource which has a given land surface area and a given and uniform soil depth at points in time. It is assumed that the soil mine is technologically independent of adjacent soil resources in order to simplify the analysis.
The technology of production and the physical constraint set

Assume that but one commodity can be produced from the soil resource and let the output of this commodity at time \( t \) be denoted \( Y_t \). The output of the commodity at time \( t \) is assumed to depend upon the utilization of hired factors of production, the depth of soil at time \( t \), the stock of "soil constituents" present in the soil at time \( t \), and external environmental conditions at time \( t \). The quantity of the \( i \)-th hired factor of production utilized at time \( t \) is denoted \( X_{it} \). Soil depth at time \( t \) is denoted \( S_t \) and the stock of constituents at time \( t \) by \( N_t \). External environmental conditions are measured by the index \( H_t \) at time \( t \). The production function is written at time \( t \) as

\[
Y_t = f_t(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t).
\]  

To simplify the analysis, it is assumed that land surface area is constant and thus that gully erosion occurs at trivial economic rates. It is further assumed that the entire land surface area is utilized in production in any period. This assumption is reasonable if the land area of the soil resource is thought of as being small. The partial derivatives of the function with respect to the hired inputs and the elements of the soil resource state vector included in the production function are assumed positive. The values taken by the external environmental
conditions index are assumed to be known but beyond human control.

Soil depth is assumed to behave over time in accordance with the transition equation

\[ S_{t+1} = S_t + R_{st} - E_t \]  \hspace{1cm} (24)

where \( R_{st} \) is the formation of soil depth at time \( t \) and \( E_t \) is the loss of soil depth to erosion at time \( t \). If for all time it is the case that \( R_{st} = 0 \) then the soil resource is nonrenewable. A strong argument can be made to the effect that soil formation occurs in many cases at rates of trivial economic importance (Larson, 64; USDA, 109). However, it is of some interest to allow for the possibility that soil formation may occur at economically significant rates and that the rate of formation may be influenced by crop production activities. Thus, it shall be assumed here that \( R_{st} \) is given by the function

\[ g_{1t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t). \]  \hspace{1cm} (25)

The value of \( E_t \) is taken to be given by the function

\[ g_{2t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t, K_t) \]  \hspace{1cm} (26)

where \( K_t \) is an erosion control capital stock. The behavior of the erosion control capital stock is assumed to be described by the transition equation
where $I_{kt}$ is investment in the stock in time $t$ and $\delta$ is a depreciation factor. The transition equation describing the behavior of the stock of soil constituents over time is assumed to be

$$N_{t+1} = N_t - R_{NT} + I_{NT}$$

where $R_{NT}$ is the diminution of this stock due to production and erosion and $I_{NT}$ is the replenishment of the stock by investment. The value of $R_{NT}$ is taken to be given by the function

$$g_{3t}(X_{1t}, X_{2t}, \ldots, X_{nt}, S_t, N_t, H_t)$$

The soil resource state vector in this simplified and abstract model thus contains but three elements at any point in time, these being the depth of the soil, the stock of soil constituents, and the land area of the soil resource. The land area is assumed to be constant and to be fully utilized in all time periods. The stocks of soil depth and soil constituents are assumed to change from period to period in accordance with "laws of nature" summarized in the transition equations. The transition equations show how the stocks will change from one period to the next with these changes depending upon the existing
stocks, the use of factors of production, external environment conditions, the stock of erosion control capital in the case of changes in soil depth, and investments to augment the stock of soil constituents. The stock of erosion control capital is not assumed to affect soil genesis or the depletion of soil constituents directly and investments to augment the stock of soil constituents are not assumed to directly affect soil genesis or erosion. The change in erosion control capital from period to period is assumed to depend only on the passage of time and upon investments to augment the stock.

The management problem

Now consider an economic agent who wishes to maximize the present value of the cash flow from exploiting the soil for T periods plus the present value of the amount for which the resource could be sold in period T+1. The returns from soil exploitation are at time t

\[ \pi_t = p_{yt} - \sum_{i=1}^{n} p_{xit} x_{it} - p_{nt} n_t - p_{kt} k_t \]  

(30)

where \( p_{yt} \) is the market price of output in period t, \( p_{xit} \) is the market price of the i-th hired input at time t, \( p_{nt} \) is the market price of additional soil constituents in period t, and \( p_{kt} \) is the market price of increments to the
erosion control capital stock at time \( t \). Where \( r \) is the market rate of discount, which is assumed constant for all time, the present value of the cash flow is given by the quantity

\[
PV_1 = \sum_{t=1}^{T} \pi_t (1+r)^{-(t-1)}.
\]  
(31)

The amount for which the soil (mine) may be sold in the market at time \( T+1 \) will be, if the market for resource rights operates efficiently, equal to the present value of the cash flow from soil explanation that can be obtained in period \( T+1 \) with the resource stocks available at that time. Let this value be given by the terminal value function

\[
V(S_{T+1}, N_{T+1}, K_{T+1}).
\]  
(32)

Where \( \pi^*_t \) is the value of returns obtained in an optimal program beginning in period \( T+1 \) with capital stocks \( S_{T+1}^*, N_{T+1}^*, \) and \( K_{T+1}^* \) it will be the case that the present value of the program is given by the quantity

\[
PV_2 = \sum_{t=T+1}^{\infty} \pi^*_t (1+r)^{-(T-t)}
\]  
(33)

and also by the quantity given by the terminal value function evaluated with the stocks \( S_{T+1} = S_{T+1}^*, N_{T+1} = N_{T+1}^* \) and \( K_{T+1} = K_{T+1}^* \).

The management objective of the economic planner may now be expressed mathematically as maximizing the quantity
subject to the physical constraint set and the technology of agricultural production for the resource. Given the definition of the terminal value function and Bellman's (54) "Principle of Optimality" it follows that the management objective can be expressed equivalently as:

\[
\sum_{t=1}^{\infty} \pi_t (1+r)^{-(t-1)} \quad \text{(35)}
\]

subject to the same restrictions. The implication of this equivalence is that the length of the farmer's planning horizon is of no consequence to soil management. This result is important when considering reasons why farmers may fail to optimally conserve soils.

The management problem can be formally expressed for the T period planning horizon case as:

\[
\max_{t} \sum_{t=1}^{T} \left\{ p_{yt} \gamma - \sum_{i=1}^{n} p_{xit} x_{it} - p_{nt} I_{nt} - p_{kt} I_{kt} \right\} (1-r)^{-(t-1)}
\]

\[
+ V(S_{T+1}, N_{T+1}, K_{T+1}) (1+r)^{-T}
\]

subject in any period 1 \leq t \leq T to

\[
y_t = f_t (x_{1t}, x_{2t}, \ldots, x_{nt}, s_t, n_t, h_t),
\]
\[ S_{t+1} = S_t + g_{1t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t) \]

\[ - g_{2t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t, K_t), \]

\[ N_{t+1} = N_t - g_{3t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t) + I_{Nt}, \]

\[ K_{t+1} = K_t(1-\delta) + I_{kt}, \]

\[ X_{1t} \geq 0, X_{2t} \geq 0, \ldots, X_{nt} \geq 0, I_{kt} \geq 0, I_{Nt} \geq 0, \]

and subject in any period \( 1 \leq t \leq T+1 \) to

\[ S_{t+1} \geq 0, K_{t+1} \geq 0, N_{t+1} \geq 0, \]

and finally subject to the initial resource and capital stocks

\[ S_1 = S_1^0, N_1 = N_1^0, K_1 = K_1^0. \quad (36) \]

The Lagrangian function for the problem is given by:

\[ L = \sum_{t=1}^{T} P_t f_t(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t) \]

\[ - \sum_{i=1}^{n} P_{xit} X_{it} - P_{Nt} I_{Nt} - P_{kt} I_{kt} (l+r)^{(t-1)} \]

\[ + V(S_{T+1}, N_{T+1}, K_{T+1})(1+r)^{-T} \]

\[ - \sum_{t=1}^{T} \lambda_{t+1}(S_{t+1} - S_t - g_{1t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t)) \]

\[ + g_{2t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t, K_t)) \]

\[ - \sum_{t=1}^{T} \rho_{t+1}(N_{t+1} - N_t + g_{3t}(X_{1t}, X_{2t}, \ldots, X_{nt}; S_t, N_t, H_t)) \]

\[ + I_{Nt}) \]
A solution to the problem, if one exits, is characterized by the Kuhn-Tucker (63) conditions. In any period $1 \leq t \leq T$ these are:

\[
\frac{\partial L}{\partial X_{it}} - (P_{yt} \frac{\partial f_t}{\partial X_{it}} - P_{xit}) (1+r)^{-(t-1)} - \lambda_{t+1} \left( \frac{\partial g_{it}}{\partial X_{it}} - \frac{\partial g_{2t}}{\partial X_{it}} \right) - \rho_{t+1} \frac{\partial g_{3t}}{\partial X_{it}} \leq 0, \quad (\partial L/\partial X_{it})X_{it} = 0, \quad (38)
\]

and \( X_{it} \geq 0; \)

\[
\frac{\partial L}{\partial I_{nt}} = -P_{nt} (1+r)^{-(t-1)} + \rho_{t+1} \leq 0, \quad (\partial L/\partial I_{nt})I_{nt} = 0, \text{ and } I_{nt} \geq 0; \quad (39)
\]

\[
\frac{\partial L}{\partial I_{kt}} = -P_{kt} (1+r)^{-(t-1)} + \beta_{t+1} \leq 0, \quad (\partial L/\partial I_{kt})I_{kt} = 0, \text{ and } I_{kt} \geq 0; \quad (40)
\]

\[
\frac{\partial L}{\partial \lambda_{t+1}} = -S_{t+1} + S_t + g_{1t}(\cdot) - g_{2t}(\cdot) = 0; \quad (41)
\]
\[ \frac{\partial L}{\partial \rho_{t+1}} = -N_{t+1} + N_t - g_3(t) + I_{Nt} = 0; \quad (42) \]

\[ \frac{\partial L}{\partial K_{t+1}} = -K_{t+1} + K_t(l-\delta) + I_{Kt} = 0; \quad (43) \]

\[ \frac{\partial L}{\partial S_t} = P_yt \frac{\partial f_t}{\partial S_t} (1+r)^{-t} - (t-1) + \lambda_{t+1} (1 + \frac{\partial g_{1t}}{\partial S_t} - \frac{\partial g_{2t}}{\partial S_t}) - \lambda_t \]

\[- \rho_{t+1} \frac{\partial g_{3}}{\partial S_t} \leq 0, \quad (\partial L/\partial S_t)S_t = 0, \quad \text{and} \quad S_t \geq 0; \quad (44) \]

\[ \frac{\partial L}{\partial N_t} = P_yt \frac{\partial f_t}{\partial N_t} (1+r)^{-t} - (t-1) + \lambda_{t+1} (\frac{\partial g_{1t}}{\partial N_t} - \frac{\partial g_{2t}}{\partial N_t}) \]

\[ + \rho_{t+1} (1- \frac{\partial g_{3t}}{\partial N_t}) - \rho_{t+1} \leq 0, \quad \text{and} \quad N_t \geq 0. \quad (\partial L/\partial N_t)N_t = 0, \quad \text{and} \quad N_t \geq 0 \]

The conditions for the stocks in period \( T+1 \) are:

\[ \frac{\partial L}{\partial K_t} = -\lambda_{t+1} \frac{\partial g_{2t}}{\partial K_t} + \beta_{t+1} (l-\delta) - \beta_t \leq 0 \]

\[ (\partial L/\partial K_t)K_t = 0, \quad \text{and} \quad K_t \geq 0. \quad (46) \]

\[ \frac{\partial L}{\partial S_{T+1}} = \frac{\partial V}{\partial S_{T+1}} (1+r)^{-T} - \lambda_{T+1} \leq 0 \]

\[ (\partial L/\partial S_{T+1})S_{T+1} = 0, \quad S_{T+1} \geq 0. \quad (47) \]

\[ \frac{\partial L}{\partial N_{T+1}} = \frac{\partial V}{\partial N_{T+1}} (1+r)^{-T} - \rho_{T+1} \leq 0, \]

\[ (\partial L/\partial N_{T+1})N_{T+1} \geq 0, \quad \text{and} \quad N_{T+1} \geq 0. \quad (48) \]
Assume that the optimal soil depth is positive in all periods \(1 \leq t \leq T+1\). With this assumption condition (44) yields a recursion which may be iterated to obtain the result:

\[
\lambda_{t+1} = P_{yt+1} \frac{3f_{t+1}}{3s_{t+1}} (1+r)^{-t} \\
- \rho_{t+2} \frac{3g_{3t+1}}{3s_{t+1}} \\
+ \sum_{i=t+2}^{T} \{P_{yi} \frac{3f_{i}}{3s_{i}}(1+r)^{-(i-1)} \\
- \rho_{it+1} \frac{3g_{3i}}{3s_{i}} \prod_{j=t+1}^{i-1} (1 + \frac{3g_{1j}}{3s_{j}} - \frac{3g_{2j}}{3s_{j}}) \\
+ \prod_{j=t+1}^{T} (1 + \frac{3g_{1j}}{3s_{j}} - \frac{3g_{2j}}{3s_{j}}) \lambda_{t+1} \}.
\]

Making similar assumptions about the stock of constituents and the erosion control capital stock and proceeding with conditions (45) and (46) in a similar manner allows the following results to be obtained:
Let $PV^*$ denote the present value yielded by an optimal soil management program and $\lambda^*_{t+1}$, $\rho^*_{t+1}$, and $\beta^*_{t+1}$ be the values of $\lambda_{t+1}$, $\rho_{t+1}$, and $\beta_{t+1}$ in that program. Then it must be true that

$$\frac{\partial PV^*}{\partial S^*_{t+1}} = \lambda^*_{t+1}, \quad \frac{\partial PV^*}{\partial N^*_{t+1}} = \rho^*_{t+1}, \quad \text{and} \quad \frac{\partial PV^*}{\partial K^*_{t+1}} = \beta^*_{t+1}. \quad (53)$$

That is, the multipliers give the change in the value of the program resulting from marginal changes in the stocks in period $t+1$. Since a stock change in period $t+1$ is a consequence of an action in period $t$, it follows that the multipliers are the marginal user costs of the stocks in period $t$ discounted to period one. It is to be noted that
the multipliers $\lambda_{T+1}$ and $\rho_{T+1}$ in Equation (50) may, under the assumptions made here, be replaced by the present marginal terminal value of the soil stock and stock of constituents respectively, as can be ascertained from conditions (47) and (48). The same may be done with the multipliers in Equations (51) and (52). The implications of conditions (47), (48), and (49), under the assumption that the resource stocks are positive, is that the marginal user costs of the stock in period $T$ are simply the present marginal terminal value of these stocks in period $T+1$. This result is clearly consistent with the definitions of the marginal user cost of resources and the terminal value function given above.

Equations (50), (51), and (52), permit an understanding of the determination of the marginal user costs in the solution to the program. Consider first the marginal user costs of the soil depth and soil constituents stocks. Assuming that these stocks have positive marginal products it follows that a reduction in these stocks in some period $t$ will result in a loss of output, ceteris-paribus, in all subsequent periods. If these stocks were not arguments in the transition equations, the marginal user costs would simply be the discounted sum of the value of the marginal products forgone in each period, ceteris-paribus, to period $T$ plus the discounted marginal terminal values of the resource stocks. However, because the stocks do enter
the transition equations a change in these stocks in one period will cause further changes in all subsequent periods. For example, soil loss in period \( t \) reduces the stock available in period \( t+1 \). Assuming that \( \partial g_1^t/\partial S_t > 0 \) and that \( \partial g_2^t/\partial S_t > 0 \) in any period \( t \), and assuming also that \( \partial g_2^t/\partial S_t > \partial g_1^t/\partial S_t \), it follows that reduction of soil depth in period \( t \), by reducing the stock in period \( t+1 \), causes a further reduction, ceteris-paribus, in the stock of soil depth in period \( t+2 \). Further, assuming \( \partial g_3^t/\partial S_t > 0 \) in any period \( t \), the reduction in the stock of soil depth in period \( t+1 \) results in a loss of soil constituents, ceteris-paribus, in period \( t+1 \). Consequently, the marginal user costs reflect not simply the flow of value forgone by the reduction of the stocks occurring in a given period plus the loss in terminal value due to that loss. Instead, they reflect that flow and the values of the effects of the stock change on stock changes in all subsequent periods.

The marginal user cost of the stock of erosion control capital is observed to be the present marginal terminal value of the stock plus a discounted sum of the marginal user cost of soil depth multiplied by the partial derivative of the erosion function with respect to the capital stock. This sum gives the present value of the flow of benefits derived from increasing the depth of soil, ceteris-paribus, by reducing erosion by increasing the capital
stock. The marginal terminal value gives the change in the price of the soil resource resulting from installing erosion control capital.

Let \( \hat{\lambda}_{t+1} = \lambda_{t+1}(1+r)^{(t-1)} \) and \( \rho_{t+1} = \rho_{t+1}(1+r)^{(t-1)} \).

From conditions (44) and (45), it follows that if \( S_t \) and \( N_t \) are to be positive in the optimal program then there must be values of \( S_t \) and \( N_t \) such that the following conditions are satisfied:

\[
\alpha \hat{\lambda}_t = p_y t \frac{\partial f_t}{\partial S_t} + (\hat{\lambda}_{t+1} - \hat{\lambda}_t) + \hat{\lambda}_{t+1} \left( \frac{\partial g_{1t}}{\partial S_t} - \frac{\partial g_{2t}}{\partial S_t} \right) - \hat{\rho}_{t+1} \frac{\partial g_{3t}}{\partial S_t}
\]

\[\tag{54}
(54)
\]

\[
\alpha \hat{\rho}_t = p_y t \frac{\partial f_t}{\partial N_t} + (\hat{\rho}_{t+1} - \hat{\rho}_t) - \hat{\rho}_{t+1} \frac{\partial g_{3t}}{\partial N_t}
\]

\[
+ \hat{\lambda}_{t+1} \left( \frac{\partial g_{1t}}{\partial N_t} - \frac{\partial g_{2t}}{\partial N_t} \right).
\]

\[\tag{55}
(55)
\]

The first of these conditions requires that if the stock of soil depth is to be positive in period \( t \) in the optimal program, then it must be the case that the stock chosen is such that the opportunity cost of holding the stock \( (r\hat{\lambda}_t) \) is equal to the marginal value of the stock in production \( (p_y t \cdot \partial f_t/\partial S_t) \) plus the appreciation in the value of the stock \( (\hat{\lambda}_{t+1} - \hat{\lambda}_t) \) plus the value of the stock in producing additional soil depth \( (\hat{\lambda}_{t+1} \cdot (\frac{\partial g_{1t}}{\partial S_t} - \frac{\partial g_{2t}}{\partial S_t})) \) plus the value of
the stock in producing soil constituents \((-\hat{\beta}_{t+1} = \partial g_{3t}/\partial S_t^{\prime})\).

The second condition is that which must be satisfied by a positive stock of soil constituents in the optimal program. Its interpretation is analogous. If these two conditions cannot be satisfied by positive resource stocks or if the resource stocks which do satisfy them are zero, then it will be the case that the net present value maximizing program is one which leads to exhaustion of the resource stocks by period \(t\). Defining \(\hat{\beta}_{t+1} = \beta_{t+1}(1+r)^{(t-1)}\), the analogous condition derived from (52) for the erosion control capital stock is given by

\[
\frac{\hat{r}^t}{\hat{\beta}^t} = -\hat{\lambda}_{t+1} \frac{\partial g_{3t}}{\partial K_t^{\prime}} + (\hat{\beta}_{t+1} - \hat{\beta}_t) - \delta \hat{\beta}_{t+1}.
\]  

Before proceeding to a consideration of the choice of control variable levels some comments about the signs of the user costs are warranted. The transition equations are equality constraints and consequently the possibility of negative marginal user costs exists. It would generally be presumed that the user cost of soil depth and soil constituents will be positive given that increases in these stocks are beneficial. However, negative marginal user costs cannot be precluded. Suppose, for example, that the top-soil is less productive than the subsoil and thus that the stock effect is negative rather than positive, i.e., \(\partial f_t/\partial S_t < 0\), for some range. It may be the case, then, that
the user cost is initially negative at the margin and thus, that an incentive exists to erode the soil to reduce soil depth. Similarly, without the possibility of costless disposal of surplus stocks of constituents and erosion control capital, situations could conceivably arise in which the marginal user costs of those stocks are negative in some periods.

**Factor mix and investment decisions**

Now, consider the factor choice decisions of the economic agent. From (49) it follows that if \( x_{it} > 0 \) for any \( 1 \leq i \leq n \) in any period \( 1 \leq t \leq T \) then it must be true that

\[
\frac{\partial f_t}{\partial x_{it}} = \frac{\partial x_{it}}{\partial \lambda_{it}} + (1+r)(t-1)\frac{\partial g_{1t}}{\partial x_{it}} - \frac{\partial g_{2t}}{\partial x_{it}} - \rho t \frac{\partial g_{3t}}{\partial x_{it}}.
\]

The optimal use of a factor thus requires equating the value of the marginal product in any period to the market price of the factor plus an imputed cost. This imputed cost reflects the value of changes in the soil resource stocks resulting from the use of the factor. The factor mix chosen by the present value maximizing farmer at any point in time will, then, reflect not only the current marginal costs and benefits from utilizing those factors but also the effects of the current mix upon the
flow of returns in subsequent periods.

The farmer will invest in erosion control capital in any period \( t \) as to equate the marginal cost of erosion control capital to the marginal user cost of the stock. That is, a positive net investment will be made in any period \( 1 \leq t \leq T \) if and only if there is some value of \( I_k \) such that

\[
P_{kt} = \beta_{t+1} (1+r)^{t-1}.
\]  

(58)

Similarly, positive investments in the stock of constituents will be made if and only if in any period \( 1 \leq t < T \) there is a value of \( I_N \) such that

\[
P_{Nt} = \beta_{t+1} (1+r)^{t-1}.
\]  

(59)

That is, the level of investment in the stock of constituents, if positive in any period, will be that level which equates the marginal cost of amendments to the flow of discounted marginal benefits from the increment to the stock.

Whether a solution exists to the programming problem depends upon the forms of the production functions, the terminal value function, and the constraint functions (Kuhn and Tucker, 63). The conditions that must be satisfied for a global maximum shall not be explored here and it will simply be assumed that such a solution exists for any set of market prices and initial capital stocks. With this assumption it follows
that output supply, and factor and investment demand functions may be derived for all periods in the planning horizon. The arguments of these functions will be commodity prices, factor prices, and the prices of capital goods included in the model in all periods in the planning horizon; and the rate of discount and the initial resource and capital stocks. The form of these functions will reflect the underlying technology of production and the physical constraint set. Clearly then, the behavior of the instrument variables and thus the stocks and flows depending upon the values these instruments take, will depend upon the incentives given the economic agent by the market subject to restrictions imposed by the technology of production and the physical constraint set.

Comments on time paths

There are several comments which can be made of a general nature regarding the soil management problem without further complicating the analysis. It was shown above that the optimal or present value maximizing time path of soil depth is that path which, given prices, technology, and the physical constraint set, yields an equality of the marginal benefits of holding soil to the opportunity cost of the capital stock. The path satisfying condition (54) is jointly determined with the time paths of all other
variables in the model. In general, rising product prices, falling factor prices, and technical advances which increase the value of holding soil depth in future periods, will give incentives to save soil for future periods. Also, the lower the rate of discount the greater will be the incentive to conserve soil depth relative to economic states in which the rate of discount is higher since in the latter case, the future returns from holding the stock are given less weight than current and near future returns. This assumes of course, that the marginal product of soil is positive.

If there is in any period no positive soil depth that satisfies (54) or if the depth that does satisfy this condition is zero, then the soil depth will be exhausted by that period in time. This is true, whether the soil is renewable or not. If nonrenewable, the depletion of soil depth will require that agricultural production activities which require the soil be forever forgone. If renewable, and if the natural rate of formation is significant, production from the soil may simply be deferred in time until sufficient soil is generated to resume production. If the natural rate is trivial but if the rate of formation is accelerated by crop production activities, then the exhaustion of soil depth will result in soil use being forgone
forever since those activities which accelerate the rate of formation to nontrivial rates can no longer be pursued.

The irreversibility of soil exhaustion which is suggested to arise above must be qualified by the possibility of specific investments to augment soil depth. If such investment activities are technologically feasible the soil depth transition equation can be appropriately modified and from the analysis of investments to augment soil constituents it can be inferred that the optimal investment in soil depth in any period, if positive, must be such that the cost of the resources used is equal to the marginal user cost of soil depth in the period the investment is undertaken. If in all periods there is no such level of investment then the exhaustion of soil, while technologically reversible, is economically irreversible (Cummings and Norton, 29). A situation of some interest would be one in which soil depth is naturally nonrenewable and exhausted at some point in time but in which the path of resource costs and technological advance changes the state from one in which it is either technologically or economically infeasible to reverse exhaustion to one in which it is economic to reverse the state of exhaustion.

It is not the physical stock of a resource that is of importance but instead it is the economic scarcity of the
resource. Depleting soil depth, just as the depleting of any exhaustible resource, does not imply an increasing economic scarcity of the resource. There are numerous factors which have been observed to operate to mitigate real economic scarcity and it is to be expected that these operate in response to soil depth depletion as they do in response to the depletion of other resources. These mitigating factors include recourse to lower grade resources as higher grades are exhausted, technological advances which reduce resource requirements, and substitution of resources of lesser economic scarcity for resources of increasing scarcity (Barnett and Morse, 6; Howe, 53; Rosenberg, 81).

Erosion in the model is in any period determined by the capital stocks present in that period, the crop production decisions made in that period, and external environmental conditions which occur in that period. Soil formation is treated in an analogous manner. The time paths of erosion and formation in the present value maximizing program will be those which yield the optimal soil depth path. Again, outcomes are jointly determined for all values so that this statement takes as given the time paths of all other variables. In general, the greater the marginal user cost or economic scarcity of soil depth the greater
the incentive will be to choose crop production practices which conserve soil and encourage formation. If the scarcity value of soil depth is increasing over time, then the incentive to conserve soil and encourage formation will also be increasing. The scarcity value of soil depth will vary as those economic, technological, and physical factors influencing it behave over time and so too will vary the incentive to save soil or disincentive to erode.

Erosion control within a period can, in this model, be undertaken only by choosing a crop mix to achieve the desired level. But with the passage of time stocks in the soil resource state vector may be varied to influence the erosivity of the soil and investments in erosion control capital may be undertaken. The level of investment in any period will be undertaken to equate the cost of the resources required to the marginal benefits of increments in the capital stock. These marginal benefits will, however, reflect the optimal time paths of all variables in the model and clearly there will be trade-offs between obtaining control by adjustments in crop mix, factor input mix, augmenting the stock of constituents, and obtaining control by investing in control capital.

The present value maximizing path of soil constituents, like the soil depth time path, must equate the marginal
benefits of holding the stock to the opportunity cost of capital. If there is no stock level that satisfies condition (55) this stock, despite its renewability, will be exhausted. Those factors noted above which influence the time path of the stock of soil depth will also affect the time path of the stock of constituents as they give incentives for more or less conservation of the stock at points in time. Beyond introducing this generalized stock to further the demonstration of the applicability of the theory of extraction to the economics of soil management, the stock is included to consider the implications of erosion induced losses of soil resources. The stock of constituents is assumed in the transition equations to be depleted in production in any period with this depletion depending upon among other things the depth of soil. Assuming \( \frac{\partial q_t}{\partial S_t} > 0 \) then erosion in period \( t \) diminishes the stock of soil depth available for use in period \( t+1 \) and in subsequent periods but also results in a depletion of soil constituents as soil is lost. Whether the lost constituents are replaced depends upon the time path of the stock. If the present value maximizing path is diminishing, erosion serves to further the desired results. If the path is increasing or constant, then the losses must be replaced. As with erosion control, there is a mix of methods by which to
augment and investment represents but one method.

Of importance in dynamic resource allocation models, is whether a steady state solution will emerge. If the resources in the soil state vector are renewable and if prices, technology, and the discount rate are constant, there is some basis for considering the possibility that a steady state solution exists (Plourde, 79). If, however, there are nonrenewable resources in the state vector which are depleted by production, then it is impossible to have such a steady state since production necessarily depletes and thus diminishes those stocks.

The efficiency of soil exploitation

It is observed above that the soil exploitation program chosen by the price-taking present value-maximizing economic agent will depend, given the physical circumstances in which production takes place, upon the incentives given by the market. The efficiency or optimality of the program from a societal standpoint thus depends upon the information provided the farmer by the market. If there are no market failures, it is to be concluded that the program yields the optimal state of conservation of the soil resource. Any deviation from that state, be it one of underconserving or overconserving will result in a real social loss. But, if markets do not operate to provide the "correct informa-
tion," the program chosen by the farmer may result in either overconservation or underconservation relative to the socially optimal state. Those potential sources of market failure which have found prominence in the literature on natural resources were noted above. Of these, failure due to lack of competition is generally not to be considered of importance in soil resources conservation since agriculture is regarded as competitive. However, failure to obtain the optimal state of conservation as a consequence of the absence of perfectly competitive futures markets, perfectly competitive markets for contingent commodities, the presence of externalities and common property resources, and finally, the pervasive intervention of government in agriculture all warrant consideration and investigation. The issues involved are complex, particularly those arising as a consequence of the absence of complete sets of perfectly competitive futures and risk markets. In this analysis, considerations will be limited to the implications of external water quality damages resulting from erosion in a watershed and to measures by which water quality improvements may be obtained.
Conjunctive Management of Soils and Water Quality

In this section, the analysis is extended to the simultaneous exploitation of several soils and to the conjunctive management of soils and water quality. In order to facilitate this analysis, a model which is considerably simpler than that developed above is utilized. Let the maximum profit attainable from the exploitation of the i-th soil in period t be given by the function

$$\pi_{it}(E_{it}, S_{it})$$

(60)

It is assumed that $$\frac{\partial \pi_{it}}{\partial E_{it}} \geq 0$$, this representing the assumption that more erosive crop practices will be more profitable and that restrictions on production to control erosion are costly. It might be assumed as well, though, that

$$\frac{\partial \pi_{it}}{\partial E_{it}} > 0 \text{ for } 0 \leq E_{it} < \alpha_1$$

(61)

$$\frac{\partial \pi_{it}}{\partial E_{it}} = 0 \text{ for } \alpha_1 \leq E_{it} \leq \alpha_2$$

$$\frac{\partial \pi_{it}}{\partial E_{it}} < 0 \text{ for } E_{it} > \alpha_2$$

which would imply that both highly erosive and minimally erosive crop practices would be less profitable than moderately erosive practices. It is assumed that
\( \frac{\partial \pi_{it}}{\partial S_{it}} \geq 0 \), implying that reductions in soil depth reduce profit possibilities. It is again assumed that

\[
S_{it+1} = S_{it} + R_{sit} - E_{it}.
\]  

However, to simplify the analysis, it is now assumed that \( R_{sit} \) is a nonnegative constant.

Let it be assumed that there are \( m \) soils in a watershed and that the volume of watershed production does not affect product or factor prices. Let it further be assumed that each of the \( m \) soils is technologically independent. Consider first the problem of maximizing the discounted flow of profits from exploitation in the absence of offsite costs. So long as the profit functions are based upon market prices that reflect the marginal social values of commodities produced and used in production, this solution will represent a social optimum. The problem may be represented formally as:

\[
\max_{t=1}^{\infty} \sum_{i=1}^{m} \pi_{it}(E_{it}, S_{it})(1+r)^{-(t-1)}
\]

subject to \( m \) restrictions in each period \( t \) of the form

\[
S_{it+1} = S_{it} + R_{sit} - E_{it}
\]

\( E_{it} \geq 0, S_{it} \geq 0. \)  

A solution to this problem, if one exists, is characterized
by the Kuhn-Tucker conditions. The Lagrangian function is

\[ L = \sum_{t=1}^{\infty} \sum_{i=1}^{m} \pi_{it}(E_{it}, S_{it})(1+r)^{-(t-1)} \]

\[ - \lambda_{it+1}(S_{it+1} - S_{it} - R_{sit} + E_{it}) \]  

(64)

The Kuhn-Tucker conditions are for soil \( i \) in period \( t \):

\[ \frac{\partial L}{\partial E_{it}} = \frac{\pi_{it}}{E_{it}} (1+r)^{-(t-1)} - \lambda_{it+1} \leq 0 \]

(65)

\[ \frac{\partial L}{\partial S_{it}} = \frac{\pi_{it}}{S_{it}} (1+r)^{-(t-1)} + \lambda_{it+1} - \lambda_{it} \leq 0 \]

(67)

\[ (\frac{\partial L}{\partial S_{it}})S_{it} = 0, \text{ and } S_{it} \geq 0 \]

(68)

\[ \frac{\partial L}{\partial \lambda_{it+1}} = -S_{it+1} + S_{it} + R_{sit} - E_{it} = 0 \]

Defining \( \hat{\lambda}_{it+1} = \lambda_{it+1}(1+r)^{t-1} \), then it can be ascertained from condition (65) that if erosion is positive in period \( t \), then it must be true that

\[ \frac{\partial \pi_{it}}{\partial E_{it}} = \hat{\lambda}_{it+1} \]  

(69)

which implies that the level of erosion yielded by the crop production activities in period \( t \) on soil \( i \) must be such that the profits gained at the margin from additional
erosion, or conversely the profits forgone at the margin from reducing erosion, equal the marginal user cost of the resource stock. Condition (66) yields the result that if a positive soil depth is to be chosen in period $t$ on soil $i$, then it must be true that

$$r\hat{\lambda}_{it} = \frac{\partial \pi_{it}}{\partial S_{it}} + (\hat{\lambda}_{it+1} - \hat{\lambda}_{it}).$$

(70)

This implies that the marginal opportunity cost of holding the stock in period must equal the marginal value of the stock in production plus the appreciation of the stock. This condition is identical in economic content to those derived above. It differs as a consequence of the simplification of the model. Again, if the stock condition cannot be satisfied by a positive value of soil depth or if it is satisfied by a zero stock level, then the resource will be exhausted by time $t$.

The erosion path and timing of soil exhaustion, if it occurs, in the optimal program will depend upon the behavior of agricultural commodities prices, factor prices, the discount rate and technology over time. In general, the more profitable future production can be, the less will be current erosion levels. The sequence of development of alternative soils will also depend upon the behavior of prices, the discount rate, and technology over time. If, for example, the change in the profit possibilities over time
is generally upward, then one may expect better soils to be
developed first with poorer soils developed as it becomes
profitable to do so.

Now assume that sediments from the m soils flow into a
river and then into a reservoir where virtually all sediments
are filtered out. Assume further that sediment is the sole
water pollutant and that the m soils are the sole source of
sediments. Let sediment production from soil i at time
t be given by

$$SD_{it} = \beta_{i}E_{it}$$  \hspace{1cm} (71)

Assume that m-n soils deliver sediments to the upper reach
of the river and let sediment delivery to that reach be
given by

$$SD_{u}^{t} = \sum_{i=1}^{m-n} \beta_{i}E_{it} - H_{u}(K_{1t})$$  \hspace{1cm} (72)

where $H_{u}^{t} > 0$ and $K_{1t}$ is a sediment delivery control located
offsite. Let the water quality damage costs be given at
time t in the upper reach by

$$D_{t}(SD_{u}^{t})$$  \hspace{1cm} (73)

where $D_{t}^{u} > 0$. Let sediment delivery to the lower reach of
the river be given by

$$SD_{l}^{t} = \gamma SD_{u}^{t} + \sum_{i=n+1}^{m} \beta_{i}E_{it} - H_{l}(K_{2t})$$  \hspace{1cm} (74)
where \( H_L^0 > 0 \). Finally, assume that sediment delivery to the reservoir is given by

\[
SD_t^R = \Omega (SD_t^L + \gamma SD_t^U).
\]  

(75)

Note that \( \beta_i \) is the sediment delivery factor for soil \( i \) under the assumption that \( K_{lt} = 0 \) multiplied by some factor which converts inches of soil loss \( i \) into a flow of sediment. The parameter \( \gamma \) is the sediment transportation factor for upper reach soils to the low reach and it is assumed that \( 0 < \gamma < 1 \). The parameter \( \Omega \) is the sediment transportation factor for the second reach to the reservoir and is also assumed to be such that \( 0 < \Omega < 1 \). The damage cost function for the reservoir is assumed at time \( t \) to be

\[
D_t^R(SD_t^R, Z_t).
\]  

(76)

where

\[
3D_t^R/3SD_t^R > 0 \text{ and } 3D_t^R/3Z_t > 0, \text{ and where}
\]

\[
Z_t = \sum_{i=1}^{t-1} SD_t^R.
\]  

(77)

This specification of the problem is clearly a substantial simplification of the process. First of all, sediment delivery from any given soil need not be a function of current erosion alone, but will depend upon past erosion as well. Secondly, while accumulated sediment delivery is assumed to cause reservoir damages, the same is
not allowed in rivers. Third, there is no reason to assume that transportation and delivery ratios are constant over time. These will vary with the nature of storms and as changes in those features of the land which affect delivery change over time. Finally, offsite controls are sediment delivery controls. There may be other forms of control as well which do not affect sediment delivery but, instead, enhance assimilative capacity or otherwise exploit the assimilative capacity of the stream and variations in it over time. However, the model does capture crucial aspects of the problem as it is commonly considered and serves as a useful vehicle for discussing water quality policy in the next section in that it does reflect most elements of discussion of the control of water quality found in the recent literature on the problem.

Where agricultural commodities prices and factor prices reflect the marginal social values of the goods, and where the damage cost function reflects the willingness to pay for water quality improvements, the problem for the social planner is to maximize the quantity

$$\sum_{t=1}^{\infty} \sum_{i=1}^{m} \pi_{it} (E_{it}, S_{it}) - D_{U_t}(SD_{t}) - D_{L_t}(S_{L_t}) - D_{R_t}(S_{R_t}, z_{t})$$

$$- C_{1t}I_{1t} - C_{2t}I_{2t}(1+r)^{-(t-1)}$$

subject to the physical constraint set for each soil, the
transition equations for the sediment delivery control stocks, which are assumed to take the form,

$$K_{it+1} = K_{it}(1-\delta_i) + I_{it}$$

and to the nonnegativity of erosion, the soil stocks, and the capital stocks. Letting $\lambda_{it+1}$ be the Lagrangian multiplier for the stocks of soil depth ($i = 1, 2, \ldots, m$) and $\theta_{it+1}$ ($i=1,2$) be the Lagrangian multipliers for the erosion control capital stocks, the Kuhn-Tucker conditions are:

$$\frac{\partial L}{\partial E_{it}} = \left\{ \begin{align*}
\frac{3\pi_{it}}{\partial E_{it}} - \beta_i (D_{it}^t + \gamma D_{it}^L + \gamma \Omega \frac{3D_{t}^R}{3SD_{t}^R}) (1+r)^{-(t-1)} \\
- \sum_{j=t+1}^{\infty} \beta_i \gamma \Omega \frac{3D_{j}^R}{3Z_{j}} (1+r)^{-(j-1)} - \lambda_{it+1} & \leq 0,
\end{align*} \right.$$  

$$(\frac{\partial L}{\partial E_{it}})E_{it} = 0, \text{ and } E_{it} = 0 \quad (80)$$

for all $1 \leq i \leq m-n$ and $1 \leq t < \gamma$;

$$\frac{\partial L}{\partial E_{it}} = \left\{ \begin{align*}
\frac{3\pi_{it}}{\partial E_{it}} - \beta_i (D_{it}^t + \Omega \frac{3D_{t}^R}{3SD_{t}^R}) (1+r)^{-(t-1)} \\
- \sum_{j=t+1}^{\infty} \beta_i \Omega \frac{3D_{j}^R}{3Z_{j}} (1+r)^{-(j-1)} - \lambda_{it+1} & \leq 0,
\end{align*} \right.$$  

$$(\frac{\partial L}{\partial E_{it}})E_{it} = 0, \text{ and } E_{it} = 0 \quad (81)$$

for all $m-n+1 \leq i \leq m$ and $1 \leq t < \gamma$. 
\[ \frac{\partial L}{\partial S_{it}} = \frac{\partial \pi}{\partial S_{it}} (1+r)^{(t-1)} + \gamma_{it} - \gamma_{it}^2 \leq 0, \]

\[ (\frac{\partial L}{\partial S_{it}}) S_{it} = 0, \text{ and } S_{it} \geq 0 \]

for all \( 1 \leq i \leq m \) and \( 1 \leq t \leq \infty \); (82)

\[ \frac{\partial L}{\partial I_{it}} = -c_{it} (1+r)^{(t-1)} + \theta_{it} \leq 0, \]

\[ (\frac{\partial L}{\partial I_{it}}) I_{it} = 0, \text{ and } I_{it} \geq 0. \] (83)

for \( i = 1,2 \) and for all \( 1 \leq t \leq \infty \);

\[ \frac{\partial L}{\partial K_{lt}} = H_u (D_t^u + \gamma D_t^l + \gamma \Omega \frac{3D_t}{3S^R}) (1+r)^{(t-1)} \]

\[ + \sum_{j=t+1}^{T} H_u \gamma \Omega \frac{3D_t}{3S^R} (1+r)^{(j-1)} + \theta_{it} + (1-\delta_2) - \theta_{it} \leq 0, \]

\[ (\frac{\partial L}{\partial K_{lt}}) K_{lt} = 0, \text{ and } K_{lt} \geq 0 \]

for all \( 1 \leq t \leq \infty \); (84)

\[ \frac{\partial L}{\partial K_{2t}} = H_L (D_t^L + \Omega \frac{3D_t}{3S^R}) (1+r)^{(t-1)} \]

\[ + \sum_{j=t+1}^{\infty} H_L \Omega \frac{3D_t}{3S^R} (1+r)^{(j-1)} + \theta_{2t+1} (1-\delta_2) - \theta_{1t} \leq 0, \]

\[ (\frac{\partial L}{\partial K_{2t}}) K_{2t} = 0, \text{ and } K_{2t} \geq 0 \]

for all \( 1 \leq t \leq \infty \); (85)
\[ \frac{\partial L}{\partial \lambda_{it+1}} = -S_{it+1} + S_{it} + R_{sit} - E_{it} = 0 \]

for all \(1 \leq i \leq m\) and \(1 \leq t < \infty\); \hspace{1cm} (86)

\[ \frac{\partial L}{\partial \theta_{it+1}} = -K_{it+1} + K_{it}(1-\delta_i) + I_{it} = 0 \]

for \(i = 1, 2\) and for all \(1 \leq t < \infty\). \hspace{1cm} (87)

In condition (83), \(C_{it}\) denotes the per unit cost of increments to the sediment delivery control stocks.

The interpretation of these results is analogous to those above. The multiplier \(\lambda_{it+1}\) is again the user cost of soil depth in soil \(i\) and is defined in an identical fashion. Condition (80) implies that the optimal rate of soil erosion for an upper reach soil is that rate at which the marginal profit from erosion, less the marginal damage cost occurring in the current period in the upper river reach, the lower river reach, and the reservoir, and, finally, less the flow of discounted marginal costs of cumulative sedimentation of the reservoir, must equal the user cost of the soil. Condition (83) has similar implications for lower reach soil except that erosion of these soils has no effect upon the upper reach of the river, but, on the other hand, have a greater effect, per ton of erosion, than upper reach soils on sedimentation of the reservoir given \(\gamma < 1\). The effect of offsite costs is to diminish the profitability.
of erosion in any period and, thus, to reduce erosion. The introduction of offsite costs will influence the path of soil exploitation then for each soil and will also affect the sequence of soils development and the timing of exhaustion. Again, the character of the solution will depend upon how prices behave and upon the value of the discount rate as well as upon the physical constraint set and productive technology. But, in addition, the processes of sediment delivery and transportation, and the behavior of the damage costs functions over time must be considered in analyzing exploitation paths for given soils and the sequence of soils development.

Sediment control investments will be made, if positive, in a manner such that the user cost of the capital stocks are equal to the marginal costs of these stocks, as implied by condition (84). Iterating (86) and (87) yields expressions for the marginal user costs of the control stocks under the assumption that these stocks are always positive. In the optimal program these are:
It is seen that the marginal user costs are discounted flows of the reductions in damage costs afforded by the capital stocks and that they depend upon the discount rate and the behavior of the damage costs functions over time.

Erosion Control Policy

It was observed in the preceding chapter that there is, at present, a considerable interest in developing public erosion control measures. The objective of this chapter is to consider some of the proposals which have been made and some others as well. Perhaps the appropriate point to begin this discussion is with some consideration of the motives for public intervention. Accepting Musgrave's (73) theory of multiple budget determination, public measures to control soil erosion would be indicated if
markets fail to provide an efficient or equitable allocation of soil resource stocks over time or an allocation which would be consistent with stabilization objectives. The strongest argument for government intervention most certainly would be made on the basis that agricultural markets fail to yield efficient levels of erosion for one or more of the reasons previously outlined, given this normative viewpoint. While depletion of soils may have some implication for sustained economic growth, it is difficult to see how adjustments would be called for so long as erosion rates are efficient and equitable since any deviation from such a path would result in a real welfare loss. Further, it is difficult to argue that an inequitable allocation of intergenerational welfare would require that adjustments to erosion rates be made for the explicit purpose of achieving equity given that welfare is far more likely to be a function of the distribution of all sources of wealth over time and since adjustments to an otherwise efficient allocation of soils resource stocks over time may cause real welfare losses to present and future generations. But it is not so difficult to argue that market failures which may result in inefficient allocation of soil resource stocks are present and, thus, that government intervention on these grounds may be warranted. Beyond Musgrave's normative
justifications, government intervention may clearly arise as a consequence of other motives. However, there is little the economist can say about these beyond indicating their impacts on efficiency and distribution. In particular, if intervention is motivated by considerations other than efficiency, equity, or growth, then the action falls outside the realm of justifications based upon normative economic reasoning in a market economy in which consumer sovereignty prevails. It will be assumed for the remainder of this analysis that erosion control measures are proposed to secure a more efficient allocation of resources. Such measures fall into Musgrave's allocative function of government as distinguished from the distribution and stabilization functions.

The test for the existence of a market failure is whether, given the distribution of welfare, there exists a reallocation of erosion levels over time that will result in a net increase in social welfare, the reallocation being relative to the market solution. However, to find that such a reallocation does exist is not sufficient to establish the efficiency of government intervention. There may exist a variety of alternative measures by which potential Pareto improvements may be secured, the appropriateness of which will vary with the source of the problem. The test for the
desirability of government intervention on efficiency grounds is whether there exists a government measure which, with its attendant resource costs, results in a net social gain. If there are several such measures, then the appropriate measure and the appropriate degree to which it is pursued, will depend upon the relative net gains of the alternatives.

Consider again the area including the m soils and suppose that the only potential source of market failure is the degradation of water quality by sedimentation. Given that the upper reach, lower reach, and reservoir are common property resources, there exists no functioning private market mechanism by which to price the use of these resources as receptacles for erosion and, thus, farmers will initially erode freely into them. Note two problems that arise. The failure of the external effects to be priced may result in a misallocation of resources in which erosion is excessive and in which, as a consequence, water quality is less than socially optimal and the stock of soil resources is depleted at a rate in excess of that which is socially optimal (Bator, 7; Buchanan and Stubblebine, 16; Meade, 69). Measures taken by the public sector to obtain an improvement in resource allocation by reducing soil erosion rates may be considered then as environmental improvement policies and as soil
Students of the problem of externalities are generally agreed that if the number of parties affected by the externality and if the number of parties generating the externality are small, then negotiations among these parties will generally be expected to result in a socially optimal solution. In Buchanan and Stubblebine's (16) terminology, bargaining converts a Pareto relevant externality into simply a relevant but non-Pareto relevant externality, meaning that initially there are gains from trade to be had changing the level of erosion and that after negotiations these gains are exhausted, although the externality remains. Such a solution corresponds to the Coase Theorem (25), that if property rights are well-delineated and if there are no transactions costs, then the socially optimal level of externality will be obtained by negotiations among the parties involved. While qualifications to this theorem have been noted by a number of contributors, the major problem is that if there are large numbers, then transactions costs and free-rider problems can circumvent the process.

The existence of transactions costs do not necessarily preclude the achievement of an efficient solution by private negotiations. Mishan (72), for example, has considered the
implications of lump-sum transactions costs on the existence of, and bargaining to a solution under alternative distributions of rights. If, however, government intervention is costless, or if the costs of government intervention are less than the private transactions costs, and if the benefits net of these costs are positive, then government intervention is called for. This point is made by Calabresi (22) who goes on to stress that the objective of government intervention should be to choose that measure of set of measures that allows the solution which would obtain in the market if negotiations were costless to be most closely and cheaply approximated, given that the benefits of intervention exceed the costs. It is further stressed, however, that the costs of a measure or set of measures will make not the costless market solution, but some alternative solution the social optimum, which is clearly true if costs are not only lump-sum in nature, as considered by Mishan, but also composed of variable costs. This has also been noted by Miranowski and Alt (70) who consider the implications of information, administration, and enforcement costs on the levels of control and choice between alternative pollution control policies.

The public policy measures found most frequently in the economic literature for obtaining improvements in
resource allocation when misallocation is a consequence of technological externalities are Pigovian taxes, pollution abatement subsidies, pollution rights markets, and residuals restrictions or regulations (Davis and Kamien, 33). These and other policies are considered below.

**Pigovian tax or user charge policy**

The taxation of externalities was originally proposed by Pigou (78). The approach has received considerable support by a number of students of environmental economics, most particularly Kneese and Bower (61), as well as others, with a notable defense of the approach against the negative arguments put forth by Coase and others being offered by Baumol (8). Suppose that the tax policy has associated with it no information or policy costs of any kind. The objective is to tax sediment delivery from each source at a rate equivalent to the marginal damage costs at the optimum. Thus, the tax placed on sediment delivery to the upper reach is equal at time $t$ to $D'_u(SD^*_{u,t})$ where $SD^*_{u,t}$ is the socially optimal level of sediment delivery. The tax placed upon sediment delivery to the lower reach is equal to $D'_L(SD^*_{L,t})$ at time $t$ where $SD^*_{L,t}$ is the optimal amount of sediment delivery at time $t$ to this reach. Finally, the tax placed upon sediment delivery to the reservoir at time $t$
will be equal to

\[
\frac{\partial D_t^R(SD_t^*)}{\partial SD_t^R} + \sum_{j=t+1}^{\infty} \frac{\partial D_j^R(Z_j^*)}{\partial Z_j} (1+r)^{-(j-t)}
\]

(90)

where SD_t^R* and Z_j^* are the socially optimal values of SD_t^R and Z_j at time t.

It is to be observed that the three taxes on sediment delivery from an upper reach soil can be reduced to a single tax of the amount, at time t,

\[
UC_{tu}^S = D_t^u'(SD_t^*) + \gamma D_t^l'(SD_t^*)
\]

\[
+ \frac{\partial D_t^R(SD_t^*)}{\partial SD_t^R} + \sum_{j=t+1}^{\infty} \frac{\partial D_j^R(Z_j^*)}{\partial Z_j} (1+r)^{-(j-t)}.
\]

(91)

Similarly, the two taxes on sediment delivery from a lower reach soil can be reduced to a single tax of the amount, at time t,

\[
UC_{tL}^S = D_t^l' + \Omega\left\{\frac{\partial D_t^R(SD_t^*)}{\partial SD_t^R} + \sum_{j=t+1}^{\infty} \frac{\partial D_j^R(Z_j^*)}{\partial Z_j} (1+r)^{-(j-t)}\right\}.
\]

(92)

Note that the two taxes differ between reaches as the effective marginal damage costs of sediment delivery differ and that they will both vary over time. To observe the efficiency of the solution requires simply observing that if there is subtracted from the maximand for the first problem
considered above, the discounted sum of the product of these tax rates and sediment delivery over the time horizon, conditions for sediment delivery identical to those obtained in the second problem will be yielded. Note, further, that where sediment delivery is a function of erosion, the Pigovian tax, which is placed on the externality, translates to a tax on erosion. The tax on erosion of the i-th upper reach soil will be

$$U_{C_{tu}}^E = \beta_i U_{C_{tu}}^s.$$  \hspace{1cm} (93)

The tax on erosion of a lower reach soil is obtained in a similar manner. It is to be observed that, although there are only two sediment delivery tax rates at any point in time, there could be as many as m soil erosion tax rates. But, without knowledge of sediment delivery, there cannot be information about the optimal sediment or erosion tax rates. The problem of monitoring residual flows is one of considerable importance in considering environmental policy alternatives and becomes partially complex when dealing with nonpoint source pollution. Absence of information and other policy cost considerations will, however, be considered further below.
Sediment abatement subsidies

An alternative to the taxation of externalities is subsidization of the reduction of such. To illustrate, consider the following problem. A firm produces a commodity \( q \) and also in fixed proportions an externality \( z \). Let \( z = \beta q \). The Pigovian tax strategy would impose a tax equal to the marginal damage cost at the optimum. Let this tax be denoted \( t^* \). The problem of the firm is, then, to

\[
\max_q Pq - C(q) - Zt^*. \quad (94)
\]

The first order condition for an extremum is

\[
P - C' - \beta t^* = 0. \quad (95)
\]

The abatement subsidy policy is as follows: Let \( A \) be the "base" level of externality and let the firm receive a subsidy of

\[
S = (A-Z)t^*. \quad (96)
\]

Note that \( A-Z \) is the level of abatement of the externality, and that the subsidy rate is equal to the Pigovian tax which is equal to the marginal damage cost at the optimum. The problem of the firm is now to

\[
\max_q Pq - C(q) + (A-Z)t^* \quad (97)
\]
and the first order condition for an extremum is

\[ P - C'(q) - \beta t^* = 0. \]  

(99)

Thus, the firm's output of product and of externality will be equivalent under the two control strategies. There are, however, certain problems that arise and the apparent symmetry of a Pigovian tax policy and abatement subsidy policy vanishes. This symmetry is complete if and only if the firms producing prior to the imposition of the tax are the same as those after imposition. Considering a single soil, imposition of a tax may result in a nonpositive present value so that the soil will be withdrawn from production. This withdrawal, however, may not occur under the abatement subsidy program since under this program the firm receives subsidy payments rather than tax payments. For the subsidy to be neutral with respect to decisions of whether or not to produce, it must be true that farmers will receive the subsidy if they do withdraw and further that all potential entrants are eligible for the subsidy as well so that their decisions as to whether or not to enter are unaffected by the institution of the program (Baumol and Oates, 10). If potential entrants are not eligible then, depending upon how the subsidy bases are chosen, the possibility emerges that the subsidy will give incentives to bring land
which was not previously in use so that the aggregate level of erosion flows may exceed pre-policy levels even though farms previously producing are yielding lesser sediment loads. These implications follow under the assumption that product and factor prices are unaltered by the imposition of the policy. If prices do change, the symmetry between the policies which appears to obtain by making potential entrants eligible is not forthcoming. Indeed, it is to be expected that residuals flows will exceed those that would have occurred in the absence of the policy measure if the industry is competitive (Baumol and Oates, 10).

**Sedimentation rights market**

Dales (31) originally proposed the auctioning of pollution rights as a solution to environmental quality problems. This policy involves having the public authority auction off rights to utilize common property resources, primarily air and water, as waste receptacles. As long as the supply of rights is equivalent to the optimal level of pollution, the result is perfectly symmetric with that of a Pigovian tax. In the problem at hand, the authority would sell rights for upper reach sedimentation, rights for lower reach sedimentation, and rights for reservoir sedimentation. An upper reach farmer would need to acquire all three types
while a lower reach farmer would need to acquire only lower reach and reservoir sedimentation rights. The rights prices established in these markets would equal the Pigovian tax or abatement subsidy rates.

Other policies for onsite control of erosion

The three policies discussed above have all been mentioned by various contributors as potential erosion control measures. It is not difficult to conceive of a variety of others and a number of alternatives can be found in the literature. Examples include restrictions on erosion levels from farms or from parcels of land, land use restrictions such as prohibition of farming on more erosive soils, restrictions on crop rotations and cropping practices, and charges and/or subsidies to give farmers incentives to install erosion control structures and to utilize crops and cropping practices which are soil conserving.

In a world of perfect information in which there are no direct resource costs associated with policy measures, any policy approach which yields the same allocation of resources that is obtained by a Pigovian tax policy is as efficient and in such a world there exists no economic basis for choosing among those policies which yield the efficient solution (Fisher and Peterson, 37). The set of efficient
policies will, of course, only be some subset of the set of all possible erosion control policies.

There is virtually no question that many of the poli­
cies emphasized to date would not be included in this subset since, as with the thrust of environmental quality policy on the whole in the nation, these approaches generally stress the use of control technologies with little consideration of the costs and benefits incurred (Portney, 80).

Government provision and offsite controls

It has been recognized that in some cases, returns to scale, property rights problems, and other considerations make government production an important aspect of efficient pollu­tion control. The Environmental Protection Agency has placed considerable emphasis upon the utilization of onsite erosion controls and little attention has been given to offsite controls. Students of environmental economics, most notably Kneese, Ayres, and d'Arge (59), stress the concept of materials balance in considering the control of pollu­tion. Among other implications of the concept, as applied by economists, are that environmental degradation problems can be dealt with by reducing production of goods and services, by reducing the flow of residuals from producing a
given amount of goods and services, by recovering and re-
cycling residuals, by altering the composition of output, 
by controlling the timing and location of discharges to 
utilize the assimilative capacity of the environment to its 
fullest, and by investing in the assimilative capacity of 
the environment (Freeman et al., 41). All of these have 
some applicability to the sedimentation control problem and 
also have significant implications for government production 
or provision. Greenbelts along rivers and offsite sedimen-
tation impoundments offer measures by which to diminish 
residuals flows for given volumes of production and also 
to control the timing and location of residuals flows. A 
"down-gully" landowner or an owner of riverfront property 
may have no incentives to make such investments which are 
of social value but which may be of little personal value. 
By acquiring property to build impoundments or by acquiring 
riverfront property or offering riverfront property owners 
incentives to develop natural filters, an alternative to 
onsite control is obtained.

The possibility of government investments in offsite 
controls to reduce sediment delivery motivated the in-
clusion of the two offsite erosion control capital stocks 
in the model developed above. It was observed that in-
vestments in these offsite measures ought to be made to the 
extent that the flow of discounted benefits of these controls,
these being the reduction in damage costs allowed, warranted the social costs of the measures. It is to be observed, then, that an optimal solution to the sedimentation problem will have some mix of onsite and offsite control measures and that this mix will vary over time and space. It is to be further noted that where damage costs are strictly increasing with sedimentation levels, reduction in sediment delivery by offsite measures will diminish the Pigovian taxes. In addition to offsite sediment delivery measures, there may be other offsite public control measures which affect damage costs by, for example, enhancing the assimilative capacity of waters. To the extent that such measures exist, their inclusion in considerations of efficient control is required.

Further Analysis of Water Quality Improvement Policies

The discussion of policy in the preceding section has assumed perfect information and has ignored a number of important policy considerations. These will be discussed in this section.

Information

A major problem in the application of theoretically derived policy propositions in the real world is the absence of information on damage costs. Without this information, it
is impossible to identify an optimal Pigovian tax, abatement subsidy rate, regulation levels and so on. Baumol (8) has suggested, it lieu of information on damage costs, a policy which is variously known as the "Targets with Taxes" policy and the "Standards and Charges" policy. This policy involves the specification of some environmental quality standard which is then achieved at least cost by the imposition of residuals charges. For example, suppose that on upper reach, lower reach, and reservoir standards are imposed and that the standards involve limitations on total sediment delivery to each of the bodies of water. The solution found by maximizing the present value of the flow of profits from soil exploitation subject to these restrictions would yield a solution in which a unique set of charges would be placed upon sediment delivery, or, equivalently, an alternative but still unique set of charges could be placed upon erosion levels from each of the soils. The problems created by absence of information go beyond those created by the absence of damage cost information. If damage cost information were available but abatement cost information were not, the problem of identifying the optimum still exists, and, moreover, a least cost abatement policy cannot be identified. Perhaps more importantly, given fairly good information on agricultural production costs, is the previously noted absence of infor-
mation on sediment delivery. To tax a firm on the residuals flow from it requires that this flow can be identified and, without this information, taxes, marketable rights, and efficient regulation policies cannot proceed to yield the social optimum. Considerations of this sort, assuming that it is somehow known to be socially desirable to reduce erosion levels, may give some basis for subsidies to utilize control practices and construct control structures, to impose technical specifications on production, or to provide programs in which farmers are made to make payments to the public authority which are placed in deposit and returnable to the operator upon proof of meeting specified performance standards (Baumol and Oates, 9).

Stochastic considerations

The quality of water will depend not only upon sediment loadings but also upon variations in the volume and rate of stream flow as well as upon other factors. Damage costs will fluctuate not only with fluctuations in water quality, but also with variations in fish populations and other factors which attract people to water, and with fluctuations in the demand for water. Clearly, then, fairly predictable seasonal variations as well as not so predictable random variations in water quality damages, may be expected. On the abatement cost side, there will also be some predictable seasonal
variations and some not so predictable random variations due, for instance, to predictable and random variations in weather conditions. The Pigovian tax, or any other efficient control mechanism, would then have to be adjusted as marginal abatement and damage costs fluctuate. There are, however, two major problems with frequent rate variations. The first is identifying changes in the appropriate rates and implementing them, and the second is that farms will be unable to respond instantly to such changes even if feasible. The latter is of particular importance. Suppose that stream flow falls to very low levels and that a rainstorm occurs which does not affect stream flow above the reach in which sediments are delivered. The introduction of runoff waters with high sediment concentrations may have critical impacts upon stream quality, yet a tax increase of any magnitude would have no effect and nor would virtually any other onsite control. Note here, also, that even if "quick response" onsite control methods existed, sediments accumulated in runoff delivery channels as well as erosion from other sites may have a substantial impact, both of which were ignored in the model developed above.

It was noted in the previous chapter that sediments are delivered in pulse loadings associated with rainfall events. For situations in which there are random variations in
residuals flows with critical levels, Baumol and Oates (10) have suggested the utilization of taxes to achieve desired control levels during normal times. Taxes are a measure which cause adjustments which take time to achieve the desired effect and with frequent changes, nonoptimal responses will occur. The tax rates could alternatively be set at levels which diminish the probability of critical levels to some acceptable level, but in normal times the cost of such a policy may be quite high. Thus, they suggest, instead, the use of standby controls for use at critical times. The appropriate mix of tax and regulation controls would be that mix which minimizes the expected cost of residuals control.

The problem with such a mixed or hybrid strategy in the case at hand is the virtual impossibility of quick-response control mechanisms as noted above. The farmer's fields are tilled and crops planted, slopes, slope length, and soil erosivity given at the time of the rainfall event so that the onsite determinants of erosion are given. Some might suggest that this would, thus, require stringent measures to reduce the probability of critical levels to an acceptable level even though the need for controls may be negligible during most of the time. I would suggest, however, that it most likely implies the need for public investment in impoundments or other methods which allow the control of timing and magnitude of sediment delivery.
Policy cost considerations

There will be associated with the various potential control strategies administration and enforcement costs, and these costs will vary among control programs. These costs must be incorporated into an analysis of the alternatives to no less an extent than any other costs and benefits of these alternatives and the inclusion of such costs in the analysis may result in a rearrangement of the rankings of these relative to the case in which they are not included. There has not been, however, any extensive research on these costs and to a large extent, it will be the case that these costs are dependent upon local conditions. For example, if damage costs are composed solely of water treatment costs, then abatement benefits may be more readily identified and estimated than when damages include diminished recreation values. As a further example, physical conditions in one area may be considerably more conducive to monitoring residual flows, as is required for a pure Pigovian tax, an abatement subsidy, or any other policy in which the levels of residuals flows from particular sources are controlled, than in other areas. It is to be noted that, as in most cases of nonpoint source pollution, monitoring of residuals flows is a complex if not impossible task and may be quite costly. This suggests that there may be some considerable policy cost advantages to measures which do not require the accurate measurement of such flows.
Political acceptability and equity

The history of pollution control in the United States and the nature of many of the current proposals reflect the greater acceptability of regulation and subsidization policies over the charge and marketable rights policies to a considerable degree. In an interesting paper, Buchanan and Tullock (17) show, for the case of residuals regulation, that those affected will have an incentive to be regulated rather than charged and that, in general, the balance of political interests will result in the greater political acceptability of such a control measure. And clearly, those to whom policies are directed, would prefer subsidization to taxation. An additional consideration, which is again related to political acceptability, is the real and perceived distribution of burdens and benefits of controls. These will vary with the measure. While these considerations do not bear upon the analysis of the efficiency of alternative measures, they are of considerable importance to the real world feasibility of implementing control measures.
Conclusion

This chapter has considered soil conservation for individual soils and groups of soils and the conjunctive management of soils and water quality. It is emphasized that the soil management problem is a dynamic problem in the conjunctive management of the resource stocks that together form the composite soil resource, a point which has been explicitly recognized in few of the recent analyses of erosion control. It is further emphasized that the economic theory of natural resource extraction is applicable to the problem of erosion, and, in general, to the management of soils. This, too, has been recognized by but a few students of soil conservation as the developments in this theory which have been widely accepted for their usefulness in considering problems in minerals extraction, the fishery, forestry, and other renewable and nonrenewable resource problems have, as yet, not been incorporated to any substantial degree in the analysis of agricultural problems. It is noted that there may be a variety of sources of failure to achieve the optimum state of conservation. To the extent soil conservation is not optimal, due to water quality damages, it will be the case that those policies which are designed to obtain environmental quality improvements efficiently will also result in appropriate levels of erosion, given that there
are no other sources of failure. There are, however, several areas requiring detailed investigation necessary to the design and implementation of efficient erosion control policies. These include research relating to the generation, transportation and damage costs of sediments, the costs of offsite control measures and onsite control measures, and the information, administration, and enforcement costs of alternative policy measures.
CHAPTER IV. THE WATERSHED PROGRAMMING MODEL

Introduction

This chapter presents the linear programming model of crop production developed to investigate economic issues in cropland erosion and erosion control in the Four Mile Creek watershed. The first section below provides a generalized mathematical description of the model and subsequent sections discuss certain features of the model in greater detail. Results from the applications of the model are presented and discussed in the following chapter.

Agricultural production is quite complex and in many respects too little understood to allow an exact representation of the physical and economic processes involved (Heady, 47). The difficulties in modelling which arise as a consequence are further complicated when, as in this investigation, the analysis is concerned not just with the present state but also with the future. This is due to the problems inherent in forecasting future economic and technological conditions. Because of these difficulties and because of problems which emerge in developing an efficient computational technique for generating quantitative results, a number of simplifying assumptions and abstractions are made to both facilitate and focus the analysis. These include the assumptions that product and factor prices,
production technology, and environmental conditions are invariant over time. It is further assumed that the soil resource state vectors for the soils considered, contain only two elements; the stock of land and stock of soil depth. The former is again assumed constant. These assumptions are noted at this point to facilitate the discussion that follows.

The Structure of the Model

The objective function

The objective function of the model is present value of the cash flow from production activities for a period of fifty years less the present value of penalty function and other adjustments. The penalty function is constructed to reflect the costs imposed on future years by the soil losses resulting from production during the period under consideration. This formulation allows an investigation of the first fifty years of the crop production plan that would be developed by an unspecified private economic planner charged with maximizing the net present value of production in the entire watershed.
The soil management groups

In order to facilitate the derivation of inferences of interest to this research, soils present in the watershed are classified by management characteristics, particular emphasis being given to topsoil and subsoil depths and erosivity of soils, into four relatively homogeneous groups. The characteristics of these soil management groups relevant to construction of the model are obtained as weighted averages of the characteristics of the component soils. This treatment of soils is comparable to treatments found in a number of watershed studies (Frohberg and Swanson, 42; Guntermann et al., 45; Narayanan et al., 74; Narayanan and Swanson, 75; Seitz et al., 87; Swanson, 99). Table 4.1 lists the soils in each of the four groups and the total acreage of the groups. Table 4.2 presents weighted average indicators of the erosivity of the soils in the groups and weighted average topsoil depths. The value RKLS1 in Table 4.2 is the product of the R, K, L, and S factors of the Universal Soil Loss Equation for unterraced land. The value RKLS2 is that product for terraced land.

The watershed production model is divided into four independent submodels. These submodels are associated with the soil management groups and are constructed with allowance for the management characteristics of the component soils.
<table>
<thead>
<tr>
<th>Management group</th>
<th>Acreage</th>
<th>Soils</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2545</td>
<td>118</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td></td>
<td>133</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td></td>
<td>428B</td>
<td>933B</td>
</tr>
<tr>
<td>II</td>
<td>4385</td>
<td>008B</td>
<td>011B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120B</td>
<td>162B</td>
</tr>
<tr>
<td>III</td>
<td>4822</td>
<td>120C2</td>
<td>162C2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>377C2</td>
<td>120D2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>179D2</td>
<td>377D2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>763D2</td>
<td>120D3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>179D3</td>
<td>192D3</td>
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<td></td>
<td></td>
<td>683D3</td>
<td>763D3</td>
</tr>
<tr>
<td>IV</td>
<td>601</td>
<td>162E2</td>
<td>162E3</td>
</tr>
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<td></td>
<td></td>
<td>162F3</td>
<td>179E2</td>
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<td>192E3</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>763F3</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.2. Group soil depths and erosivity

<table>
<thead>
<tr>
<th>Soil management group</th>
<th>RKLS1&lt;sup&gt;a&lt;/sup&gt; (tons/acre yr.)</th>
<th>RKLS2&lt;sup&gt;b&lt;/sup&gt; (tons/acre yr.)</th>
<th>Average top soil depth&lt;sup&gt;c&lt;/sup&gt; (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6.46</td>
<td>6.28</td>
<td>more than 20</td>
</tr>
<tr>
<td>II</td>
<td>22.25</td>
<td>19.06</td>
<td>16.39</td>
</tr>
<tr>
<td>III</td>
<td>114.39</td>
<td>70.62</td>
<td>6.34</td>
</tr>
<tr>
<td>IV</td>
<td>357.65</td>
<td>215.97</td>
<td>less than 3</td>
</tr>
</tbody>
</table>

<sup>a</sup>RKLS1 is the weighted average of the products of the R, K, L, and S factors of the USLE of the soils in the group for unterraced land.

<sup>b</sup>RKLS2 is the weighted average of the products of the R, K, L, and S factors of the USLE of the soils in the group for terraced land.

<sup>c</sup>Soil depths are determined for individual soils by assuming that soils in erosion phases zero and one have the maximum soil depth indicated in the Four Mile Creek Soil Survey (38). Soils in erosion phase two are assumed to have seven inches which is the typical maximum for a soil to be in erosion phase two. Soils in erosion phase three are assumed to have depths of three inches which is the typical maximum depth for a soil in phase three.
The structure of the watershed model is most easily illustrated by considering the submodels separately.

**The Group I Submodel**

The soils in the first management group either have no erosion hazard or have negligible erosion hazard and very deep topsoils. For this reason, there will be no significant depletion of soil depth and no significant stock effects and it is therefore expected that these soils have zero user costs. With the assumptions outlined above, it follows that the same production plan will be chosen in every year.

Let $A_{lj}$ be the acres allocated to the $j$-th crop production activity in any year. The per unit cost of the activity is denoted $C_{lj}$, the output of the $r$-th crop per unit of the activity is denoted $\phi_{lj}$, and the annual erosion per unit of the activity is denoted $\Phi_{lj}$. Let $P_r$ be the price of the $r$-th crop and $L_1$ be the land area of the soil management group. It follows that the cash flow from crop production in any year will be given by

$$R_1 = \sum_{j=1}^{m_1} \sum_{r=1}^{n_1} P_r \phi_{lj} A_{lj} - \sum_{j=1}^{m_1} C_{lj} A_{lj},$$

where $m_1$ denotes the number of permissible activities in the group and $n_1$ the number of crops which can be produced. Let $\delta_{50}$ denote that factor which gives the present value
of one dollar earned annually for fifty years. The present value of cash flow from the group will then be $R_1 \beta_{50}$. The management plan which maximizes this quantity, will also be the management plan which maximizes (1) subject to the land resource constraint:

$$\sum_{j=1}^{m_1} A_{1j} \leq L_1.$$  

(2)

The erosion resulting from the plan in each year will be

$$E_1 = \sum_{j=1}^{m_1} \rho_{1j} A_{1j}.$$  

(3)

It is clear that in the absence of any policies constraining erosion or the selection of crop production activities, the optimal activity will be that activity having the greatest annual cash flow.\(^1\)

The Group II Submodel

The soils in Group II are generally more erosive and have shallower topsoils than those in the first group. Yet, it is still anticipated that the user cost for these soils will be negligible. Based upon USDA (110) estimating procedures, a loss of 4.61 inches of topsoil would be required before any diminution of productive capacity would

\(^1\)If there are two or more activities with equal net returns and if these net returns are in excess of those from the remaining activities, the model will choose some indeterminate linear combination of the most profitable activities.
begin to occur.\(^1\) If the fields were left continuously fallow and tilled, the RKLSI value given in Table 4.2 implies that it would take approximately twenty-nine years to deplete these inches given that one-hundred and forty tons of soil loss are required to lose one inch. With a crop management factor of fifty percent, which is quite high, nearly sixty years of highly erosive management would be required before losses of productive capacity of any magnitude would commence. Further, with such a crop management factor, complete depletion of the topsoil, assuming no soil formation, would require over two-hundred and fifty years of highly erosive management.\(^2\) Yet, the subsoils in this group are rated as being highly favorable for row crop production (Fenton et al., 36). It is expected, then, that with a positive discount rate and with the assumptions made concerning prices and technology, there is little or nothing to be gained by introducing an inter-

1The soils in Group II are indicated by Table 4.2 to have an average soil depth of 16.39 inches. Based on the procedures, mixing of topsoil with subsoil would not be expected with deep tillage until the soil depth has been diminished to twelve inches. Thus, the estimate of 4.61 inches given is obtained.

2The soil lost to erosion is not entirely topsoil since tillage results in mixing of topsoil and subsoil. Consequently, the inches of topsoil which must be lost to deplete the topsoil is in excess of the initial depth of the topsoil. The USDA procedures indicates that approximately eighteen inches of soil loss must occur to achieve a mix of topsoil and subsoil which is predominantly composed of subsoil with deep tillage and once mixing has begun.
temporal interdependence of production possibilities for this management group.

The submodel for this group is essentially the same as that for the first. The only difference between the two models is that contour cultivation is considered for this group. Erosion from the first group's soils is so negligible that there is virtually nothing to be gained by contour cultivation or the installation of terraces. The slopes of the soils in the second group are sufficient to obtain significant reductions in erosion by contouring but are not so steep that terracing would be considered. This allowance for contouring expands the number of activities available in any year. Further modification is required for the cost of laying contours.

To utilize contour cultivation requires that information on how to do so be acquired. This information is considered here as a capital stock and one of the two erosion control stocks included explicitly in the model. The information is acquired at some cost but is assumed to be applicable into perpetuity. Given the assumptions concerning the invariance of prices, technology, and environmental conditions, and given the proposition that the marginal user cost of soil depth is essentially zero for soils in Group II, it follows that if contour cultiva-
tion is utilized it will be utilized in all years in the fifty-year period as the same production plan will be chosen for those years. The information required must be obtained in the first year and is charged against the cash flow in that year.

Let \( A_{2j} \) be the acres allocated to the \( j \)-th crop production activity in any year in the planning horizon, \( C_{2j} \) be the per unit cost of the activity, \( \phi_{2jr} \) be the output of the \( r \)-th crop per acre from the activity, and \( \rho_{2j} \) be the annual soil loss per acre of the activity. Let \( j = 1, 2, \ldots, m_2 \) be the indexes for those crop production activities not associated with contour cultivation and \( j = m_2 + 1, m_2 + 2, \ldots, m_2^1 \) be the indexes for those crop production activities associated with contour cultivation. The cash flow in any year exclusive of capital expenditures is

\[
R_2 = \sum_{j=1}^{m_2^1} \sum_{r=1}^{n_2} P_r \phi_{2jr} A_{2j} - \sum_{j=1}^{m_2} C_{2j} A_{2j}
\]

(4)

Where \( P_c \) is the cost per acre of laying contours. The total contouring expenditures incurred in the first year will be given by

\[
CC = \sum_{j=m_2+1}^{m_2^1} P_c A_{2j}.
\]

(5)

Stocks of machinery and equipment, which may include implements required for conservation tillage activities, are not given explicit treatment in the model. It is essentially assumed that the services of these capital stocks can be rented in the market. However, the services of terraces and contours cannot be had without acquiring the stocks.
Consequently, the present value of crop production from the
soils in the group is \( R_2 \beta_{50} - CC_2 \). The choice of crop pro-
duction activities is constrained by the land available or

\[
\sum_{j=1}^{m_2} A_{2j} \leq L_2
\]

(6)

where \( L_2 \) is the aggregate acreage of the soils in the
group. The annual erosion resulting from these soils
is given by

\[
E_2 = \sum_{j=1}^{m_2} \rho_{2j} A_{2j}.
\]

(7)

As in Group I, the optimal activity is that activity
which yields the greatest annual cash flow and in the
absence of any restrictions on land use or erosion, the
entire average available will be allocated to that
activity.\(^1\)

It is to be noted that maximizing the present value
defined above will result in a bias against investments
in contours because the full costs are charged but the
entire flow of benefits from contour cultivation are not
accounted for. To remove this bias a charge equal to the
present value of the annualized cost of the investment
paid for fifty years can be utilized in place of the actual

\(^1\)See footnote on p. 123.
cost. Thus, at a contouring cost of one dollar per acre and a discount rate of ten percent, the per acre charge for contouring in the model would be $0.005. The cost of laying contours is handled in this manner to eliminate the bias. The adjusted net present value function, where $P_c$ is replaced by $P_c'$, the latter being the adjusted cost, is maximized subject to the restriction in Equation (6). To obtain the actual cash flow in the first period requires modifying the results for actual investment expenditures.

Comments on the Group I and Group II Submodels

The use of linear programming models has come to be widespread in both the analysis of agricultural production decisions and the analysis of environmental quality and residuals management as a consequence of the computational efficiency with which solutions may be obtained and the facility with which such models may be manipulated to obtain alternative solutions (Jensen, 55; Kneese and Bower, 60). The application of such models to the economic analysis of cropland erosion and erosion control has also been widespread and the use of the technique is recommended in an EPA (113) publication concerned with analysis methodology for cropland erosion control. The Group I and Group II models are comparable in their basic structure to many of the
previous models developed for investigating the issue. It is in the structure of the Group III model that the watershed model developed here is innovative. A few dynamic models for the investigation of issues related to cropland erosion have been developed in the past but not all have been true dynamic optimization models (e.g., Narayanan et al., 74) and the erosion control policy analyses contained in the remainder have been quite limited (e.g., Burt, 20; Frohberg and Swanson, 42).

The Group III Submodel

Soil scientists classify the severity of erosion on a soil by erosion phases. A soil in erosion phase zero is uneroded and a soil in erosion phase one is uneroded to slightly eroded. In both cases there is no evidence of subsoil mixing in the plow layer. Soils in erosion phase zero typically have twelve or more inches of top soil while soils in erosion phase one have between seven and twelve inches of top soil. Erosion phase two classifies a soil as moderately eroded with some mixing of topsoil and subsoil while soils in erosion phase three are severely eroded with the plow layer being largely composed of subsoil. The former typically have between three and seven inches of top soil while the latter typically have no more than three remaining inches of top soil.
The soils in the third management group are in erosion phases two and three and consequently some diminution of productive potential is expected to have occurred. This expectation finds support in a recent soil survey of the watershed (Four Mile Creek Soil Survey, 38). Comparison of crop yield estimates in the survey for soils which differ only in erosion phase show that the higher phase soils have consistently lower crop yields. Further, based on the data in the soil survey, and the USDA procedures cited above, it is estimated that under high management conditions yield losses of 0.44 bushels of corn, 0.14 bushels of soybeans, 0.38 bushels of oats, and 0.02 tons of hay will occur with each inch of soil loss. These relatively small losses

The soil survey provides crop yields under high management conditions for various soils in the erosion phases that occur in the area. The USDA procedures indicate that approximately six inches of soil loss are required to move from erosion phase one to erosion phase two and that approximately twelve inches of soil loss are required to move from erosion phase two to erosion phase three. The soils in Group III are moving either from erosion phase two to erosion phase three or from erosion phase three to subsoil. For each soil in the group the yield loss from soil phase two to soil phase three is assumed to be constant per inch of soil loss and this loss is assumed to apply as the soils move from erosion phase three to subsoil. The Group III losses that occur are weighted averages of those occurring on the individual soils. This procedure is analogous to that utilized by Narayanan et al. (74) and a further detailed description may be found there.
can be attributed to the relatively high quality of subsoils available in the area.

In addition to decreasing yield potentials, the reduction of soil depth increases the erosivity of the soils. The gross soil loss estimates utilized in this study are obtained by application of the USLE. The factors of the soil loss model for the soils in the watershed are reported by the USDA (110). Proceeding in a manner analogous to that outlined above for yield losses with loss of soil (see footnote 1, p. 130), it is determined that each inch of soil loss in Group III will bring about an increase in the value of RKLS1 by 2.99 tons per acre per year and an increase in the value of RKLS2 by 1.66 tons per acre per year. The initial values of RKLS1 and RKLS2 are given in Table 4.2.

While these stock effects are not of substantial magnitude, a priori arguments to the effect that current decisions will not be significantly influenced by these impacts cannot be made in this case. It is for the reason that a multi-period model of crop production is warranted for the analysis of this group of soils. The problem which arises at this point is the choice of an appropriate programming method. To consider this problem an "ideal" model
shall first be outlined.

Let $A_{3jt}$ be the acres allocated to the $j$-th production activity in the $t$-th year. Let $\phi_{3jrt}$ be the yield per acre of the $r$-th crop in the $t$-th year and let $\rho_{3jt}$ be the soil loss per acre of the $j$-th activity in the $t$-th period. Based on data and assumptions noted above, it is not unreasonable to postulate that

$$\phi_{3jrt+1} = \phi_{3jrl} - \beta_r \sum_{i=1}^{t} \sum_{j=1}^{m_3} \rho_{3jt} A_{3jt}$$

Equation (8) states that the per acre yield of the $r$-th crop from the $j$-th activity in the $t$-th year is the yield for that crop and activity in the first period less some quantity depending upon cumulative soil loss prior to the $t$-th year. Equation (9) states that the per acre soil loss resulting from the $j$-th activity in the $t$-th year is the per acre soil loss from that activity in the first year plus some quantity depending upon cumulative erosion.

For the purposes of the issues being considered here, the problem of the planner is defined to be:

$$\max_{t=1}^{t-1} \sum_{j=1}^{m_3} \sum_{r=1}^{n_3} \left\{ P_r (\phi_{3jrl} - \beta_r \sum_{i=1}^{t} \sum_{j=1}^{m_3} \rho_{3ji} A_{3ji} ) - C_{3j} A_{3jt} (1+d)^{-(t-1)} \right\}$$
subject in each period $1 \leq t \leq \infty$ to the restrictions that

$$
\sum_{j=1}^{m_3} A_{3jt} \leq L_3
$$

and subject to the restriction, assuming no significant soil genesis, that

$$
\rho_{3jt+1} = \rho_{3jt} - \alpha \sum_{i=1}^{\rho_{3ji}} \rho_{3ji} A_{3ji}
$$

and subject to the restriction, assuming no significant soil genesis, that

$$
\sum_{t=1}^{\infty} \sum_{j=1}^{m_3} \rho_{3jt} A_{3jt} \leq S. \tag{10}
$$

In this description of the problem $m_3$ and $n_3$ are, respectively, the number of crop production activities available and $n_3$ the number of crops available. The cost of the $j$-th activity is denoted $C_{3j}$ and the discount rate is denoted as $d$. The land area available for production is $L_3$ and $S$ is the total amount of soil which may be lost.

Equations (8) and (9) define recursions and if the problem were one of maximizing the cash flow in each period subject to decisions made in previous periods, a recursive programming model utilizing linear programming to solve the allocation problem in each period could be utilized. However, the problem is one of maximizing a flow and consequently recursive programming is inappropriate. Linear programming cannot be used to solve the problem as it is set
forth above because the objective function is nonlinear. However, with appropriate constraints and modifications, solutions can be obtained by linear programming. The advantage of linear programming, as previously noted, is the computational efficiency and facility with which alternative solutions may be obtained. Nonlinear programming algorithms are available and dynamic programming models can be solved by specialized computer programs. However, the cost and complexity of these techniques for models of larger size and in which a number of alternative solutions are to be considered are severely limiting (Hadley and Kemp, 46; Sposito, 94). Consequently, approximate solutions are obtained by developing a linear programming model.

The fifty year period is divided into ten five-year production periods for which crop production activities are selected. Annual real and monetary flows within each period are assumed constant. The initial soil depth is divided into two inch zones and the selection of activities is constrained by the zones in existence in each period. The zones are depleted by erosion. For each zone, a set of crop production activities exist having those per acre yields and soil losses which are estimated to be obtained after cumulative erosion has eliminated the soil depth zones nearer the surface. Thus, activities defined for the first zone have productivities and per acre soil
losses obtained under high management conditions with the initial soil depth. After that zone is exhausted by erosion, these activities are eliminated from the choice set. Activities defined for the second zone have productivities and per acre soil loss coefficients estimated to be applicable after the loss of two inches of soil depth. The soil depth zones which can be obtained in any period are constrained by the maximum cumulative erosion which could have occurred by that period. However, in any period the zones lying above the deepest zone obtainable by that period must be available.

If an activity is constrained by the existence of a soil depth zone, then the use of the activity depletes that zone. Activities depleting zones closer to the surface have greater yields and lower soil losses per acre than activities yielding the same crop mix utilizing the same production practices but which deplete lower zones. Effects upon production beyond losses of high management yields and increases in soil loss rates resulting from erosion are not included in the model. While other effects do occur, they are quite difficult to specify and quantify (Beasley, 11; Troeh et al., 101; 208 Technical Assessment, 103).

Let \( A_{jkt} \) be the acres allocated to the \( j \)-th crop production activity in every year of the \( t \)-th production period which depletes the \( k \)-th soil depth zone. Note that the index
t now refers to five year production periods instead of years. The annual yield per acre of the r-th crop from the j-th activity depleting the k-th soil depth is denoted \( \phi_{3jrk} \) and the annual soil loss per acre of this activity is denoted \( \rho_{3jk} \). It is now assumed that \( \phi_{3jrk} = \phi_{3jrk-1} - \delta_r \) and that \( P_{3jk} = P_{3jk-1} + \alpha_i \) where \( \delta_r \) is the loss in high management yield of the r-th crop per inch of soil loss and where \( \alpha_i \) is equal to the increase in the value of gross soil loss per acre with an inch of soil loss. If \( i=1 \) the activity is defined for nonterraced land and \( \alpha_1 \) is the increase in RKLS1. If \( i=2 \) then the activity is defined for terraced land and \( \alpha_2 \) is the increase in RKLS2.

If \( 1 \leq j \leq m_3 \) let the activities indexed by activities not utilizing contour cultivation or terraced acres. As in the Group II submodel, contour tillage is an appropriate erosion control option. Let the activities utilizing this practice be indexed by those values of \( j \) such that \( m_{3+1} < j \leq m'_3 \). In addition, the Group III soils are such that terracing represents an appropriate erosion control option. The indices for terracing satisfy \( m'_{3+1} < j \leq m''_3 \).

Unlike the models developed for Group I and Group II the selection of activities in the third soil group need not be recurrent in all years. Consequently, transition
equations are required for the two erosion control capital stocks. Let $CA_t$ denote the stock of acres for which information on contour cultivation is available at the end of period $t$. Let $CI_t$ be the number of acres for which such information is obtained in the first year of the $t$-th production period. Again, assuming that once contours are laid they are followed into perpetuity it follows that

$$CA_t = CA_{t-1} + CI_t$$  \hspace{1cm} (11)$$

Terraces are commonly considered to have a twenty-five year life (EPA, 112). However, it is assumed here that once an acre has been terraced it is terraced into perpetuity with the stocks being replaced every twenty-five years. Thus, the transition equation may be written as:

$$TA_t = TA_{t-1} + TI_t$$  \hspace{1cm} (12)$$

where $TA_{t-1}$ is the stock of terraced acres present at the end of period $t-1$ and $TI_t$ is the addition to the stock in the first year of the $t$-th production period. It is assumed that an acre which has been placed in contours can be subsequently placed in terraces. This does not violate the assumption that once contoured an acre is always contoured since terrace farming involves by definition contour cultivation. To allow for the transfer let
\( CI_t = CI_{Nt} - CTT_t \) \hspace{1cm} (13)

where \( CI_{Nt} \) is the quantity of previously uncontoured acres added to the stock and \( CTT_t \) is the transfer of contoured acres into terraces; both in the first year of the \( t \)-th production period. The increments to the stock of terraces in the first year of the \( t \)-th period may then be expressed as

\( TI_t = TI_{Nt} = CTT_t \) \hspace{1cm} (14)

where \( TI_{Nt} \) is the addition of acres which were not previously contoured.

The cash-flow from crop production in any year of the \( t \)-th production period is given by

\[ R_{3t} = \sum_{j=1}^{m^w} \sum_{r=1}^{n_3} \sum_{k=1}^{Z_t} P^j r^k A^j k - \sum_{j=1}^{m^w} \sum_{k=1}^{Z_t} C^j A^j k t \] \hspace{1cm} (15)

where \( Z_t \) denotes the maximum soil depth zone obtainable by period \( t \) and \( C^j \) is the annual per acre cost of the \( j \)-th activity for any year and soil depth zone. Let \( \beta_t \) be the present value of one dollar earned annually for five years beginning in the first year of the \( t \)-th production period. It follows that the present value of the cash flow from crop production for fifty years is given by

\[ PV_1 = \sum_{t=1}^{10} R_{3t} \beta_t. \] \hspace{1cm} (16)
This quantity less the present value of expenditures on the erosion control capital stocks, gives the net present value of the cash flow obtained during the period. Let $P_{c,t}$ be the cost per acre of laying contours in the first year of the $t$-th production period and let $P_{T,t}$ be the per acre cost of installing terraces in that year. Where $\beta_t$ is that factor which discounts one dollar in the first year of the $t$-th production period to the present it follows that the net present value of the cash flow obtained during the fifty-year period is given by

$$PV_{150} = \sum_{t=1}^{T} \left( P_{c,t}C_t + P_{T,t}T_t \right) \beta_t^t.$$  \(17\)

Maximizing (17) subject to restrictions noted below, will not yield the production plan and net present value that would obtain during the fifty-year period for two reasons. The first is that the full costs of contouring and terracing are incurred but the flow of returns from contour tillage and from utilizing terraces installed after the fifth period are not taken into account. To eliminate the bias against terracing the charges for terracing an acre after the fifth period are adjusted downward. The adjusted costs are obtained as the present value of the flow of annualized cost of the investment that would be incurred over the years remaining until the fiftieth year. For example,
at a ten percent rate of discount the payment of $46.69 annually for twenty-five years is equivalent to the payment of $420.00 in the year the terraces are put in place. If the terrace is put in place in the forty-sixth year, the charge placed on terracing is the present value in that year of $46.69 paid annually for five years. This adjustment eliminates the bias noted above but requires, in addition, downward adjustment in the cash flow computed in the solution reflecting the actual amount that would have been paid in the year the investment was made. The per acre terracing cost of $420.00 is obtained from SCS personnel familiar with these costs in the watershed.\(^1\) Terracing costs before the sixth period must also be adjusted to incorporate replacement costs incurred before the fiftieth year. The bias against contouring is eliminated by adjusting the costs in a comparable manner.

Soil erosion in the first fifty years of the planning horizon imposes two types of costs on the remainder of the horizon. First, the use of soil depth in the period deprives the remaining years of the profits that could be obtained from the use of that soil. Secondly, the soil available to the remainder of the horizon will be more

\(^1\)This estimate was provided by Mr. John T. Nicholson of the Tama County Soil Conservation Service Office, Toledo, Iowa, in a letter dated August 27, 1980.
erosive and less productive. If the entire planning horizon were considered here, there would be no reason to look explicitly at these costs, since they are determined in solving the problem. But, since only the first fifty years are investigated, it is required that some accounting for these costs be made.

Recall the model developed in the previous chapter in which profits were expressed as a function of erosion and the stock of soil depth. The marginal user cost of soil depth under the assumption that \( S_{it} > 0 \) for all \( 1 \leq t \leq \infty \) is in period \( t \)

\[
\lambda_{it+1} = \sum_{j=t+1}^{\infty} \frac{\partial \pi_{ij}}{\partial S_{ij}} (1+r)^{-(i-1)}
\]

for the \( i \)-th soil. Thus, the marginal user cost is the flow of profits forgone at the margin into perpetuity as a consequence of erosion in period \( t \). The penalty function developed here is based upon this result.

The function applies only to Group III since with positive discount rates and common cropping practices this is the only group containing soils in which soil loss is expected to be of any significant economic concern. The activity having the greatest per acre profitability in this group is the activity yielding the corn-corn-beans-corn-beans rotation utilizing a fall moldboard tillage system.
and straight-row culture. The loss of net returns per acre per year to this activity per inch of continuous soil loss is $1.23. If this loss were suffered into perpetuity, the present value of the flow of losses in year fifty-one would be $1.23 divided by the discount rate. The value of the penalty function is obtained by multiplying this quantity by the total soil loss in inches which occurs in the first fifty years of the program.

This does not yield an exact estimate. One reason is that the actual cost depends upon the activities which are actually utilized in the years following the fiftieth. Another is that the formulation assumes that soil depth will be positive in all periods in the planning horizon. The first of these deviations implies that the estimate will be an overestimate since all alternative activities will be less profitable. The second source of deviation also implies an overestimate since exhaustion in finite time may be the economic optimum.

The penalty function does not necessarily produce an overestimate, however. In addition to diminished productivity, the loss of soil also increases the erosivity of the activity. Recall now, the first model developed in Chapter II. In that model, the marginal user cost of soil depth was not simply the sum of the discounted forgone net benefits from losing an increment of soil but instead
there was an adjustment in the expression for the marginal
user cost which introduced the effects of soil loss in one
period on soil loss in all subsequent periods. To allow
for this effect in the formulation above would, however,
result in a considerable overestimate of the cost.

Let $P_{ct}'$ be the adjusted cost of laying contours and
let $P_{tt}'$ be the adjusted cost of installing terraces. The
capital costs considered in the model are then

$$PVC = \sum_{t=1}^{10} (P_{ct}' N_t + P_{tt}' T_t) \beta_t.$$  \hspace{1cm} (19)

Let the penalty function be expressed as

$$PF = 5 \cdot \gamma \cdot \sum_{t=1}^{m_3} \sum_{j=1}^{n_3} \sum_{k=1}^{n_3} \rho_{3jkt} A_{3jkt}$$  \hspace{1cm} (20)

where $\gamma$ is the coefficient described above. The quantity
to be maximized in the model for Group III is then

$$PV_{1l} + PVC + PF_{1l}.$$  \hspace{1cm} (21)

By subtracting out the present value of the penalty
function and adjusting for actual expenditures for erosion
control capital, an estimate of the net present value of
the cash flow for the fifty-year period is obtained. If
the capital cost adjustment is made but the penalty
function is not subtracted out an estimate is provided of
the real net economic benefits from production during the
fifty year period accruing to watershed landowners.

Land use by crop production activities must be constrained in each period to not exceed the available stock. In period $t$ the land use constraint is

$$\sum_{j=1}^{m^*} \sum_{k=1}^{Z_t} A_{3jkt} \leq L_3. \quad (22)$$

The use of the stocks of contoured and terraced acres are also constrained in each period by the size of the stocks. The restrictions in the $t$-th period are, respectively, for contour cultivation and terrace utilization:

$$\sum_{j=m_3+1}^{m^*} \sum_{k=1}^{Z_t} A_{3jkt} \leq C_A_t. \quad (23)$$

$$\sum_{j=m_3+1}^{m^*} \sum_{k=1}^{Z_t} A_{3jkt} \leq T_A_t. \quad (24)$$

Total erosion in each of the soil depth zones must be constrained to the total tonnage of soil available in two inches of soil depth. For the $k$-th soil depth zone the constraint is

$$5 \cdot 10 \sum_{t=1}^{m^*} \sum_{j=1}^{Z_t} \rho_{3jk} A_{3jk} \leq S. \quad (25)$$

where $S$ is obtained as the product of $L_3$ and the total quantity of soil in two acre-inches. The latter is estimated to be two hundred and eighty. If the crop production activity having the greatest soil loss coefficient
in each production period is chosen, and if the entire acreage available for use in each period is allocated to that activity, then the total soil loss that could occur by the end of the tenth production period is 13.77 inches. Given that each soil depth zone contains two inches, seven soil depth zones are required and thus seven restrictions on cumulative soil loss, one for each zone, are required. These restrictions apply to the activities which deplete the zones.

In summary, the objective function of the Group III model is given by (21). The value of this function is maximized by choosing values of crop production activities and erosion control investments. The choice of values of these instruments is constrained in each period by restrictions of the types given in (22), (23), and (24) and by seven restrictions of the type given in (25). It is these latter restrictions which bring the stock effects into the model. In each period, sets of production activities depleting each soil depth zone lying above the deepest zone which can be achieved by that period are included in the set of all activities available for use. The seven restrictions constrain the choice of activities depleting each zone to levels such that the total loss of soil from the zones are not in excess of the amount of soil in two acre-inches. The exhaustion of a zone nearer to the surface constrains the choice in periods following that period in which the zone is exhausted to activities depleting
the remaining zones. With sequential exhaustion of the zones, beginning with that having crop yield and soil loss coefficients applicable to the initial soil depth, the set of activities available for use is sequentially limited to activities having lesser productivities and greater erosivities.

The linear programming framework does not allow restrictions on the sequence in which soil depth zones are utilized and an unsatisfactory aspect of this Group III submodel is that illogical sequencing of the use of these zones can emerge in solutions. The model is in fact, formulated in a manner more analogous to the exploitation of multiple grades of a resource than to a pure stock effects model (Herfindahl, 50; Herfindahl and Kneese, 51; Weinstein and Zeckhauser, 122). However, with restrictions on the behavior of prices and technology, the land use constraints and discounting operate to yield logical use sequences and thus permit the use of the model to obtain approximate solutions.

The Group IV Submodel

The soils included in Group IV are steep, shallow, highly erosive, and unproductive. At present, acreages in the group are mostly used for permanent pasture as they are unsuitable for row crop production. In modelling the watershed, it is assumed that the entire acreage of the group is allocated to pasture. Erosion rates from pastured lands even on steep slopes, are so low that no significant
additional depletion of these soils depths is forthcoming. In contrast to the soils in the first group, these soils are considered to have user costs that give very strong incentives for use of highly conservative cropping practices.

The watershed model

The watershed model is obtained by summing the adjusted net present value functions of the submodels. This quantity is maximized by choosing crop production plans for each of the soil management groups that maximizes the adjusted net present values of the groups. The constraints in the watershed model are simply the constraints applying to the submodels.

Crops and Crop Prices

Five crops of current and potential economic interest are included in the model, these being corn, soybeans, oats, hay, and pasture. As observed above, it is assumed that pasture is always grown in Group IV. Groups I, II, and III are allowed three alternative crop mixes or rotations. The first, denoted here as C-C-B-C-B, involves allocating three-fifths of an acre to corn production and the remaining two-fifths to soybean production. The second, denoted here as C-C-O-M-M, involves allocating two-fifths of an acre to corn production, another two-fifths to hay, and the remainder to the production of oats. The final rotation, denoted here as P-P, involves allocating one hundred percent of an acre to permanent pasture.
This selection of crop rotations is considered to allow for the generation of solutions in which the crop mix is fairly representative of current production while allowing flexibility in responses to diminishing productive capacity and to erosion control policies. The C-C-B-C-B mix is, ceteris-paribus, the most erosive of the possibilities while the P-P option is the least erosive. The C-C-B-C-B is also the most profitable and the P-P option least profitable given the assumed output prices and estimated activity costs. Output prices are listed in Table 4.3 and are considered representative of current conditions.

Table 4.3. Crop price assumptions

<table>
<thead>
<tr>
<th>Crop</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>$3.50 per bushel</td>
</tr>
<tr>
<td>Soybeans</td>
<td>$7.50 per bushel</td>
</tr>
<tr>
<td>Oats</td>
<td>$37.50 per ton</td>
</tr>
<tr>
<td>Hay</td>
<td>$15.00 per ton of forage</td>
</tr>
<tr>
<td></td>
<td>yield</td>
</tr>
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</table>
Tillage Practices and Costs

Five alternative tillage systems are allowed in the model for the production of the C-C-B-C-B rotation and four such systems are allowed for the production of the C-C-O-M-M rotation. In this analysis, the tillage systems are differentiated by the primary tillage practice applied to first-year corn ground. These practices are fall moldboard plow, fall chisel plow, spring chisel plow, spring disk, and no-till. The selection of tillage systems is based upon current practices in the area with allowances made to provide for flexibility of response to policy measures and soil loss alternatives discount rates. Table 4.4 gives a summary of current tillage practices utilized in the area for crop rotations considered in the model. Of these, the spring moldboard plow option is not used here after determining that this practice is less profitable and more erosive than the spring chisel plow option and thus it can be eliminated as a viable option in the model. The no-till option is not at present being used in the area but has been included here to provide for flexibility of response for the C-C-B-C-B rotation.

The secondary tillage practices associated with each of the primary tillages options are also based upon actual practices in the area. It is common in economic models
<table>
<thead>
<tr>
<th>Rotation</th>
<th>Number of farmers using practice</th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Moldboard</td>
<td>Fall</td>
<td>Spring</td>
<td>Chisel</td>
<td>Fall</td>
</tr>
<tr>
<td>Continuous corn</td>
<td>5</td>
<td>4</td>
<td></td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Corn after beans</td>
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<td>0</td>
<td></td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Beans after corn</td>
<td>3</td>
<td>11</td>
<td></td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Corn after meadow</td>
<td>4</td>
<td>17</td>
<td></td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
developed to study the effects of erosion control policy measures to assume that secondary tillage activities are conducted at a minimum frequency. But in actual practice, farmers may respond to a reduction in the intensity of primary tillage by increasing the intensity of secondary tillage (Schaller and Amemiya, 85).

Table 4.5 indicates the secondary tillage practices used in the area with each primary tillage practice for each crop in the watershed. Fractional values represent average values over time. Given environmental conditions, such as weather, the farmer may use a secondary tillage practice only once during a particular year but twice the next year with the same primary tillage practice. Generally, secondary tillage operations increase as primary tillage intensity decreases. The exception is with fall chisel plowing. The secondary tillage operations associated with this tillage practice are almost identical to those with fall moldboard plowing. Since the chisel plow requires less time and fuel per acre, the cost-savings of fall chisel tillage would make it more profitable than fall moldboard tillage all other things equal. Fall chisel plowing may result in a later planting date than fall moldboard tillage and could decrease expected yields. Observation shows that the chisel plow is replacing the moldboard through much of the Corn Belt. The cost-savings must be at least equal to if not
<table>
<thead>
<tr>
<th>Crop</th>
<th>Primary tillage</th>
<th>Fall disk</th>
<th>Spring disk</th>
<th>Field cond.</th>
<th>Harrow</th>
<th>Rotary hoe</th>
<th>Cultivate</th>
<th>Planting date (May 1=120)</th>
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<tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1.66</td>
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<td></td>
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<td></td>
<td>Spring plow</td>
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<td>1</td>
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<td>1.75</td>
<td>125</td>
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</tr>
<tr>
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<td>Fall chisel</td>
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<td>1</td>
<td>.5</td>
<td>1.5</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring chisel</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disk only</td>
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<td>1.5</td>
<td></td>
<td></td>
<td>1.3</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>Corn after beans</td>
<td>Fall chisel</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring disk</td>
<td>2</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1.5</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>Corn after meadow</td>
<td>Fall plow</td>
<td>1.5</td>
<td>1</td>
<td>.5</td>
<td>.5</td>
<td>1.5</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring plow</td>
<td>2</td>
<td>1</td>
<td>.5</td>
<td>.5</td>
<td>1.66</td>
<td>127</td>
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<tr>
<td></td>
<td>Fall chisel</td>
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<td>.5</td>
<td>0</td>
<td>1.5</td>
<td>1.5</td>
<td>122</td>
<td></td>
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<tr>
<td></td>
<td>Disk only</td>
<td>2</td>
<td>2</td>
<td></td>
<td>0</td>
<td>1</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Beans after corn</td>
<td>Fall plow</td>
<td>.5</td>
<td>1.5</td>
<td>.5</td>
<td>.5</td>
<td>0</td>
<td>1.5</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Spring plow</td>
<td>2</td>
<td>.75</td>
<td>.5</td>
<td>0</td>
<td>1.5</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall chisel</td>
<td>.5</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring disk</td>
<td>.5</td>
<td>2</td>
<td>1</td>
<td>.25</td>
<td>0</td>
<td>2</td>
<td>135</td>
</tr>
</tbody>
</table>
greater than the yield penalty associated with fall chisel tillage.

The per acre costs of each tillage practice for each rotation were obtained by use of the Oklahoma State Budget Generator (58) with adjustments made for the additional costs of field operations conducted on contoured and terraced acres. Representative machinery complements for crop production in the area were developed from a survey of machinery inventories in the area by Miranowski et al. (71). The complements were obtained by averaging the size of machinery used in the production of the specified crops by the specified techniques. Fertilizer application rates are based upon recommended uses for soils in the area developed by Voss (117). Herbicide and insecticide application rates are based upon data developed for Iowa soils by Jennings and Stockdale (56) and information contained in a Felco Land O'Lakes (35) guideline. Application methods are based upon actual practices as determined by Miranowski et al. (71).

The cost per acre of tillage systems are inflated on contoured and terraced acres. Contouring increases field time and fuel usage as a consequence of the modifications in field operations relative to straight-row culture. Based upon data developed by Miranowski et al. and Walker
(120), the labor costs obtained from the budget generator were inflated by five percent on B slopes, seven percent on C slopes, and nine percent on D slopes. Fuel costs were similarly inflated for contoured acres on the three slopes. These costs were increased by another thirty percent on terraced acres.

Crop Yields

Basic yield estimates for existing soil depths were obtained from data available in the recent survey of soils in the study area. Based upon data available in Miranowski et al. (71), these estimates were adjusted for tillage practices and rotations. Yield penalties of two percent, four percent, five percent, and ten percent of the yields obtained by fall moldboard primary tillage are applied, respectively, to tillage systems utilizing full chisel, spring disk, spring chisel, and no-till. The study by Miranowski et al. showed that a five percent yield increase is obtained on average for corn following soybeans and a ten percent yield increase obtains on the average for corn following second-year meadow, the basis for comparison being a continuous corn rotation. The study showed that no yield losses were associated with a change from straight-row to contour culture but that a five percent yield loss occurred on the average with a change to farming contoured
acres. The yields for activities in Group III are adjusted for soil loss using the figures for yield losses per inch noted above.
The model is first solved at discount rates of three, five, and ten percent without modification for policy alternatives. These baseline solutions allow a consideration of the production plan that would be developed by the planner in the absence of erosion control policy. A range of discount rates is chosen to provide for analysis of the impacts of alternative discount rates on the production plan. The rates are considered to be real rates and the range provided does permit important inferences to be made.

In the section following, the presentation of the baseline solutions estimates of the water quality damages associated with these solutions are provided. To obtain such estimates using technically appropriate economic procedures, would be a highly complex and costly endeavor (Freeman, 39; Freeman, 40). Such an investigation being beyond the scope of this research, the values developed here are based upon estimates of sediment damage costs found in the applied literature. National estimates include those of the American Society of Civil Engineers (3, 4) and Stall (95). Studies concerned with damages in watersheds include those of Brandt (15), Guntermann et al.
Based upon data contained in the studies by Brandt (15) and Narayanan et al. (74), Boggess et al. (14) derived an estimate of sediment damage costs in the Iowa River above the Coralville Reservoir dam of $5.05 per ton. Alt (1) reports sediment delivery ratios for watersheds in the area considered by Boggess et al. to range between 0.04 and 0.22 and argues that a transportation ratio of one is appropriate. Using these three figures would imply damage costs per ton of erosion ranging between $0.20 and $1.11.

In order to consider potential magnitudes for the values of water quality damages from erosion in the Four Mile Creek watershed, it is assumed that the sediment delivery and transportation ratios for all soils in the area are equal and that damage costs resulting from sediment discharges are invariant with respect to the level of erosion in the watershed. Hypothetical damage cost figures of $0.50, $1.00, $1.50, $2.00, and $3.00 are utilized. These values, based upon data available in the literature, are considered to be within a reasonable range.

The next set of results considered are obtained by solving the model at the three discount rates with annual erosion taxes of $0.50, $1.00, $1.50, $2.00, $2.50, and $3:00 per ton. These solutions can be considered in either of two ways. If it is assumed that these are the marginal
damage costs in an optimal solution, then the results may be interpreted as the optimal solution for the watershed if it is further assumed that all other conditions for a particular Pareto optimum are otherwise satisfied. In such a solution, the taxes may be considered as optimal Pigovian taxes. Alternatively, no assumptions concerning the information carried by the values may be made and the analysis may be viewed simply as an investigation of the effects of erosion taxes on the production program.

The last set of solutions investigated are obtained by solving the model with modifications for alternative policy options which are considered as economically viable options under present circumstances. Based upon the discussions in Chapter II and Chapter III, it is clearly the case that policy measures requiring the measurement of erosion flows cannot be realistically proposed. This eliminates the Pigovian tax, marketable rights, and erosion regulations as these require the observation of erosion flows. In considering the solutions discussed in the previous paragraph, it must be assumed that the USLE accurately measures the tax base, which it does not. Where monitoring of residual flows is infeasible, realistic policy options for environmental quality management generally entail either technical specifications or subsidies for the use of
control practices. The focus in this analysis is upon the first of these two types of approaches. In selecting alternative technical specifications for this investigation emphasis is placed on the efficacy of the control practices or structures and upon the facility with which compliance may be observed. The policies considered are discussed in detail below.

The Baseline Solutions

Presented in Table 5.1 are the present value of cash flow from production in the watershed, the present value of the penalty, and the present value of cash flow less that of the penalty for the baseline solutions. Tables 5.2, 5.3, and 5.4 provide data on cropping practices in these solutions. The abbreviations M-F and C-F in these three tables denotes, respectively, the fall moldboard tillage system and the fall chisel tillage system.

Table 5.1. Baseline present values

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>Cash flow</th>
<th>Penalty</th>
<th>Net economic benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>$51,426,431</td>
<td>$292,521</td>
<td>$51,133,910</td>
</tr>
<tr>
<td>5%</td>
<td>$36,683,724</td>
<td>$115,378</td>
<td>$36,568,346</td>
</tr>
<tr>
<td>10%</td>
<td>$19,981,004</td>
<td>$5,531</td>
<td>$19,975,473</td>
</tr>
<tr>
<td>Table 5.2. Baseline cropping practices: 3% discount rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Group (period)</strong></td>
<td><strong>Rotation</strong></td>
<td><strong>Tillage</strong></td>
<td><strong>Contour</strong></td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>I (All)</td>
<td>C-C-B-C-B</td>
<td>M-F</td>
<td></td>
</tr>
<tr>
<td>II (All)</td>
<td>C-C-B-C-B</td>
<td>M-F</td>
<td></td>
</tr>
<tr>
<td>III (All)</td>
<td>C-C-B-C-B</td>
<td>C-F</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.3. Baseline cropping practices: 5% discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group (period)</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>I (All)</td>
</tr>
<tr>
<td>II (All)</td>
</tr>
<tr>
<td>III (1 to 4)</td>
</tr>
<tr>
<td>III (4 to 9)</td>
</tr>
<tr>
<td>III (9 and 10)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.4. Baseline cropping practices: 10% discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group (period)</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>I (All)</td>
</tr>
<tr>
<td>II (All)</td>
</tr>
<tr>
<td>III (All)</td>
</tr>
</tbody>
</table>
In Groups I, II, and III, the activity having the greatest profitability per acre is the activity yielding the C-C-B-C-B rotation utilizing the fall moldboard tillage system and straight row cultivation. Because there is no intertemporal dependence of production possibilities in Groups I and II this activity is chosen for use at all discount rates in these two groups. However, this activity is never chosen during the period for use on soils in Group III. In addition to being the most profitable activity it is also the most erosive. The interdependence of production possibilities between periods, at all discount rates considered, results in soil conservation incentives sufficient to lead to the selection of less erosive practices. These incentives are greatest at the three percent discount rate and least at the ten percent rate. The rotations and tillage systems chosen for Group III are the same in each period and in each solution. However, contour cultivation is utilized on the entire acreage in the three percent solution, not at all in the ten percent solution, and to some extent, in the five percent solution. In the five percent solution, contour cultivation begins in the thirteenth year with 837 acres and in forty-fifth year the acreage utilizing contour cultivation is expanded to 1,377 acres.
The effect of alternative discount rates on the incentive to conserve soils is most evident in Table 5.1. In the three percent solution, cumulative erosion in Group III is 4,378,871 tons and the value of the penalty function discounted to the present is $292,521. In the ten percent solution, the cumulative erosion by the fiftieth year is 8,150,664 tons but the present value of the penalty is only $5,531. In the three percent solution, depletion of the fourth soil depth zone begins in the ninth period but in the ten percent solution this zone is depleted by the fifth period. In the ten and five percent solutions, all but the seventh depth zone are exhausted.¹

The shadow price of a given soil depth zone is the amount the private planner would be willing to pay for an additional acre depleting that zone during the fifty-year period. These are not the marginal user costs for the zones although they are related. The shadow prices, which are discounted to the present, decrease as the associated zone is deeper reflecting the poorer quality of the soil as soil depth is diminished. The shadow prices of unexhausted stocks are zero because these do not constrain production. These shadow prices are listed in Table 5.5.

¹Soil depth zones are used sequentially in all solutions.
The behavior of erosion in the three groups is given in Table 5.6. Because the same activity is selected in all periods for Groups I and II, it follows that erosion rates are the same in all periods. In all Group III solutions, the trend of erosion rates is upward. There are, however, substantial differences between the rates in the three solutions. Erosion rates in the ten percent solution are nearly twice those of the three percent solution in all periods. While erosion rates in the five percent solution mirror those of the ten percent solution for the first three periods, contour cultivation beginning in the fourth period and the subsequent expansion of this practice results in a moderation of erosion rates in this solution relative to the ten percent solution after the third period.

The land shadow price for a group is the present value of the amount the planner would be willing to pay for an additional acre of the group's land. These shadow prices are listed in Table 5.7. The shadow prices are distinguished by period for Group III because land is not a homogeneous resource in this group as it is in the others under the assumptions made here. As soil quality diminishes the present value of the amount the planner is willing to pay for land in any year is diminished. Table 5.8 lists present values analogous to those given in Table 5.1 for each of the groups.
<table>
<thead>
<tr>
<th>Soil depth zone</th>
<th>Shadow prices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>1</td>
<td>0.187</td>
</tr>
<tr>
<td>2</td>
<td>0.099</td>
</tr>
<tr>
<td>3</td>
<td>0.036</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group (period)</th>
<th>Erosion (tons/acre/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>I (All)</td>
<td>2.32</td>
</tr>
<tr>
<td>II (All)</td>
<td>8.01</td>
</tr>
<tr>
<td>III (1)</td>
<td>18.25</td>
</tr>
<tr>
<td>III (2)</td>
<td>18.25</td>
</tr>
<tr>
<td>III (3)</td>
<td>18.25</td>
</tr>
<tr>
<td>III (4)</td>
<td>19.10</td>
</tr>
<tr>
<td>III (5)</td>
<td>19.18</td>
</tr>
<tr>
<td>III (6)</td>
<td>19.18</td>
</tr>
<tr>
<td>III (7)</td>
<td>20.52</td>
</tr>
<tr>
<td>III (8)</td>
<td>20.52</td>
</tr>
<tr>
<td>III (9)</td>
<td>20.76</td>
</tr>
<tr>
<td>III (10)</td>
<td>21.39</td>
</tr>
</tbody>
</table>
Table 5.7. Shadow prices of land: baseline solutions

<table>
<thead>
<tr>
<th></th>
<th>Shadow prices</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3%</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>I (1)</td>
<td>$5,105.86</td>
<td>3,622.51</td>
<td>1,967.53</td>
</tr>
<tr>
<td>II (1)</td>
<td>4,834.54</td>
<td>3,430.96</td>
<td>1,862.98</td>
</tr>
<tr>
<td>III (1)</td>
<td>668.56</td>
<td>644.50</td>
<td>575.71</td>
</tr>
<tr>
<td>III (2)</td>
<td>573.10</td>
<td>499.44</td>
<td>353.49</td>
</tr>
<tr>
<td>III (3)</td>
<td>490.92</td>
<td>387.74</td>
<td>217.74</td>
</tr>
<tr>
<td>III (4)</td>
<td>421.95</td>
<td>300.23</td>
<td>133.28</td>
</tr>
<tr>
<td>III (5)</td>
<td>362.06</td>
<td>232.71</td>
<td>81.77</td>
</tr>
<tr>
<td>III (6)</td>
<td>310.14</td>
<td>180.72</td>
<td>50.41</td>
</tr>
<tr>
<td>III (7)</td>
<td>263.01</td>
<td>139.93</td>
<td>30.82</td>
</tr>
<tr>
<td>III (8)</td>
<td>227.71</td>
<td>108.51</td>
<td>18.95</td>
</tr>
<tr>
<td>III (9)</td>
<td>194.08</td>
<td>83.99</td>
<td>11.69</td>
</tr>
<tr>
<td>III (10)</td>
<td>166.55</td>
<td>65.04</td>
<td>7.13</td>
</tr>
<tr>
<td>IV (1)</td>
<td>73.33</td>
<td>52.03</td>
<td>28.26</td>
</tr>
</tbody>
</table>

Table 5.8. Present values by soil management groups: baseline solutions

<table>
<thead>
<tr>
<th>Group (discount rate)</th>
<th>Cash flow</th>
<th>Penalty</th>
<th>Net economic benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (3)</td>
<td>$12,994,414</td>
<td>-</td>
<td>$12,994,414</td>
</tr>
<tr>
<td>II (3)</td>
<td>21,199,458</td>
<td>-</td>
<td>21,199,458</td>
</tr>
<tr>
<td>III (3)</td>
<td>17,188,488</td>
<td>$292,521</td>
<td>16,895,967</td>
</tr>
<tr>
<td>IV (3)</td>
<td>44,071</td>
<td>-</td>
<td>44,071</td>
</tr>
<tr>
<td>I (5)</td>
<td>9,219,288</td>
<td>-</td>
<td>9,219,288</td>
</tr>
<tr>
<td>II (5)</td>
<td>15,044,760</td>
<td>-</td>
<td>15,044,760</td>
</tr>
<tr>
<td>III (5)</td>
<td>12,388,412</td>
<td>115,378</td>
<td>12,273,034</td>
</tr>
<tr>
<td>IV (5)</td>
<td>31,269</td>
<td>-</td>
<td>31,269</td>
</tr>
<tr>
<td>I (10)</td>
<td>5,007,364</td>
<td>-</td>
<td>5,007,364</td>
</tr>
<tr>
<td>II (10)</td>
<td>8,169,167</td>
<td>-</td>
<td>8,169,167</td>
</tr>
<tr>
<td>III (10)</td>
<td>6,787,491</td>
<td>5,531</td>
<td>6,781,960</td>
</tr>
<tr>
<td>IV (10)</td>
<td>16,982</td>
<td>-</td>
<td>16,982</td>
</tr>
</tbody>
</table>
Comments on the baseline solutions

The results obtained above are contingent upon the assumptions concerning the economic and technological conditions in the present and in future years, the structure of the model, and the data available for development of the model. There are, however, several interesting implications which may be derived from these results. Despite the relatively modest yield losses associated with soil loss in the area, it is found even at the ten percent discount rate that the incentives to conserve soil are strong enough to lead the present value maximizing private economic planner to choose crop management practices other than those which maximize current returns. Total erosion in the model is constrained, but only to the total amount of erosion that could occur if the most erosive of crop practices is chosen in all periods. However, in none of the solutions for Group III is this practice chosen despite it's being the most profitable on a per acre basis in any year. Consequently, in none of the solutions is the total available soil depth exhausted.

There is considerable flexibility for choosing erosion paths less conserving than that chosen for the ten percent solution but more conserving than choosing the most erosive activity available for use on the entire acreage in all
years. It is suggested that for some set of discount rates in excess of ten percent, solutions with greater husbanding of soil than the least conserving option may result. Similarly, the flexibility remaining for choosing erosion paths more conserving than that obtained at the three percent solution suggests that lower discount rates may lead to solutions in which soil erosion rates are negligible.

The trend in erosion in all three solutions is upwards over time. This movement may be attributed to the effects of soil loss on soil erosivity since in no solution is there a movement towards more erosive crop management practices over time. Indeed, in the one solution in which there are changes in crop management practices during the period the movement is towards more conserving management practices. Such a movement towards practices which are more soil conserving are observed to occur in a number of the tax solutions considered below. Given constant product and factor prices, and given no technological change, a trend towards the greater utilization of conservation practices is to be expected. The discounting of returns gives an incentive to use more profitable and thus generally more erosive practices in earlier periods. Opposing this incentive are the incentives to produce profitably for as long as possible and to do so with high quality soils. In
earlier periods, the more distant losses from depleting are given less weight. But as the "future" is approached, the forgone profits are given greater weight and thus the incentive to conserve increases. The incentive to use soil conservation practices over time is further increased by the imposition of erosion taxes at constant rates.

The choice of practices at points in time and the path of erosion depend upon the behavior of prices, technology, and the dictates of the physical constraint set. Increasing product prices relative to factor costs will give greater incentives to conserve in the near term in comparison to the case in which they are constant. The opposite will be true if product prices are decreasing relative to factor costs.

The results have two important implications for the empirical analysis of cropland erosion. If the soils in Group III were treated equivalently to those in Group I and Group II, the practice predicted would be the fall moldboard tillage option for the same rotation. The soil loss coefficient for this activity is 41.18 tons per acre per year. The average annual erosion rates for the three, five, and ten percent solutions are, respectively, 19.53, 33.60, and 36.37 tons per acre for the fifty year period in
Group III. Thus, such a treatment would overestimate the amount of erosion occurring in each year and the present value of production for the fifty year period. Further, no indication of the time path of erosion would be provided.

Sediment Damage Costs

Table 5.9 provides estimates of the present value of the offsite water quality damages under the assumptions outlined above. Note that while annual erosion rates in the ten percent solution are nearly twice those of the three percent solution, the discounting of the damage costs at the higher rate reduces the present value of the economic damages occurring during the period to nearly one-half the value of those occurring at the three percent rate.\(^1\) For the five percent discount rate, however, the increase in the erosion rates outweigh the effects of increasing the rate of discount so that the estimated damage costs increase relative to the three percent solution.

The damage cost figures listed in Table 5.9 are subtracted from the net present value figures listed in Table 5.1 to obtain those presented in Table 5.10. Assuming

\(^1\)As is evident from this statement, it is assumed that those damaged discount at the same rate as the private watershed planner.
Table 5.9. Estimates of the present value of offsite water quality damages

<table>
<thead>
<tr>
<th>Marginal cost</th>
<th>Present value of damages 3%</th>
<th>5%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.50</td>
<td>$1,629,868</td>
<td>$1,723,364</td>
<td>$942,988</td>
</tr>
<tr>
<td>$1.00</td>
<td>3,259,736</td>
<td>3,446,728</td>
<td>1,885,976</td>
</tr>
<tr>
<td>$1.50</td>
<td>4,889,604</td>
<td>5,170,092</td>
<td>2,828,964</td>
</tr>
<tr>
<td>$2.00</td>
<td>6,519,472</td>
<td>6,893,456</td>
<td>3,771,952</td>
</tr>
<tr>
<td>$2.50</td>
<td>8,149,340</td>
<td>8,616,820</td>
<td>4,714,940</td>
</tr>
<tr>
<td>$3.00</td>
<td>9,779,208</td>
<td>10,340,184</td>
<td>5,657,928</td>
</tr>
</tbody>
</table>

Table 5.10. Estimates of the net benefits of production in Four Mile Creek: baseline solution

<table>
<thead>
<tr>
<th>Marginal cost</th>
<th>Net present value of production 3%</th>
<th>5%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.50</td>
<td>$49,504,042</td>
<td>$34,844,982</td>
<td>$19,032,485</td>
</tr>
<tr>
<td>$1.00</td>
<td>47,874,174</td>
<td>33,121,618</td>
<td>18,089,497</td>
</tr>
<tr>
<td>$1.50</td>
<td>46,244,306</td>
<td>31,398,254</td>
<td>17,146,509</td>
</tr>
<tr>
<td>$2.00</td>
<td>44,614,438</td>
<td>29,674,890</td>
<td>16,203,521</td>
</tr>
<tr>
<td>$2.50</td>
<td>42,984,570</td>
<td>27,951,526</td>
<td>15,260,533</td>
</tr>
<tr>
<td>$3.00</td>
<td>41,354,702</td>
<td>26,228,162</td>
<td>14,317,545</td>
</tr>
</tbody>
</table>
that the only potential source of market failure is the externality associated with sediment flows into offsite water resources, the figures given in Table 5.10 serve as estimates of the net benefits from production in the watershed during the fifty-year period.

In considering these damage cost estimates, the economic issue which arises is the cost of reducing them. It is to this issue that the investigation now turns. Throughout the analysis that follows it is assumed that policy measures have no impacts upon the prices of products or factors of production.

**Tax Solutions**

Tables 5.11, 5.12, and 5.13 summarize relevant data from the tax solutions. The net present values in these tables are the present value of the fifty-year cash flow less the present value of the penalty function. The imposition of the taxes does not affect the returns to Group IV soils since erosion on these is trivial. The taxes considered are not of sufficient magnitude to lead to alterations in the crop management practices utilized on soils in Group I and in Group II. The taxes do, however, reduce the net present values of these soils. All adjustments to the taxes are found to occur on the soils in
Table 5.11. Tax solutions: 3% discount rate

<table>
<thead>
<tr>
<th>Tax rate</th>
<th>Net present value</th>
<th>Cumulative erosion (tons)</th>
<th>Average annual erosion rates (tons/acre)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.50</td>
<td>$49,504,042</td>
<td>6,430,283</td>
<td>2.32, 8.01, 19.53</td>
<td>11.27</td>
</tr>
<tr>
<td>1.00</td>
<td>48,009,313</td>
<td>4,561,333</td>
<td>2.32, 8.01, 11.20</td>
<td>7.99</td>
</tr>
<tr>
<td>1.50</td>
<td>46,863,402</td>
<td>4,443,408</td>
<td>2.32, 8.01, 10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>2.00</td>
<td>45,720,412</td>
<td>4,443,408</td>
<td>2.32, 8.01, 10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>2.50</td>
<td>44,577,422</td>
<td>4,443,408</td>
<td>2.32, 8.01, 10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>3.00</td>
<td>43,434,432</td>
<td>4,443,408</td>
<td>2.32, 8.01, 10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>Tax rate</td>
<td>Net present value</td>
<td>Cumulative erosion (tons)</td>
<td>Average annual erosion (tons/acre)</td>
<td>TOTAL</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>--------------------------</td>
<td>-----------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>$0.50</td>
<td>$35,313,589</td>
<td>6,430.283</td>
<td>2.32  8.01  19.53</td>
<td>11.27</td>
</tr>
<tr>
<td>1.00</td>
<td>34,183,583</td>
<td>5,051,992</td>
<td>2.32  8.01  13.39</td>
<td>8.85</td>
</tr>
<tr>
<td>1.50</td>
<td>33,345,334</td>
<td>4,443,408</td>
<td>2.32  8.01  10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>2.00</td>
<td>32,532,791</td>
<td>4,443,408</td>
<td>2.32  8.01  10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>2.50</td>
<td>31,720,249</td>
<td>4,443,408</td>
<td>2.32  8.01  10.67</td>
<td>7.79</td>
</tr>
<tr>
<td>3.00</td>
<td>30,907,707</td>
<td>4,443,408</td>
<td>2.32  8.01  10.67</td>
<td>7.79</td>
</tr>
</tbody>
</table>
Table 5.13. Tax solutions: 10% discount rate

<table>
<thead>
<tr>
<th>Tax rate</th>
<th>Net present value</th>
<th>Cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.50</td>
<td>$19,235,853</td>
<td>6,430,283</td>
<td>2.32</td>
<td>11.27</td>
</tr>
<tr>
<td>1.00</td>
<td>18,600,459</td>
<td>5,816,293</td>
<td>2.32</td>
<td>10.19</td>
</tr>
<tr>
<td>1.50</td>
<td>18,093,370</td>
<td>4,443,408</td>
<td>2.32</td>
<td>7.79</td>
</tr>
<tr>
<td>2.00</td>
<td>17,636,544</td>
<td>4,443,408</td>
<td>2.32</td>
<td>7.79</td>
</tr>
<tr>
<td>2.50</td>
<td>17,179,718</td>
<td>4,443,408</td>
<td>2.32</td>
<td>7.79</td>
</tr>
<tr>
<td>3.00</td>
<td>16,722,893</td>
<td>4,443,408</td>
<td>2.32</td>
<td>7.79</td>
</tr>
</tbody>
</table>
Group III, these being the most erosive of the soils in the watershed on which row-crops are produced.

**Three percent solutions**

The $0.50 erosion tax has no impact on crop management in Group III although it does result in a reduction in present value. The net present value for this solution is equivalent to the value reported in Table 5.10 for $0.50 marginal damage. Adjustments do occur, however, as the tax is increased to $1.00 and again to $1.50. The increase in the rate to $2.00, $2.50, and $3.00 result in no further modifications relative to the $1.50 solution. In all solutions the C-C-B-C-B rotation is grown and contour cultivation practiced, just as was the case in the baseline solution. The increase in the tax from $0.50 to $1.00 leads in period one to the allocation of 42.3 percent of the acreage to no-till management with fall chisel tillage used on the remainder as in the baseline solution. By the sixth period however, the entire acreage is no-till-farmed and this practice is used in all subsequent periods. While in the baseline solution and in the $0.50 tax solution the third soil depth zone is exhausted by the tenth period, in the $1.00 tax solution the second depth zone is just depleted by the tenth period. Increasing the tax to $1.50 leads to no-till-farming in all periods and by the tenth period
there is soil remaining in the second soil depth zone. No further adjustments are forthcoming, though, as the tax is increased further to $3.00.

**Five percent solution**

At the five percent discount rate, changes in the production plan for Group III soils relative to the baseline solution occur at tax rates of $0.50, $1.00, and $1.50. At the tax rate of $0.50, the production plan is equivalent to that utilized at the three percent discount rate in the baseline and $0.50 tax solutions. Recall that in the five percent baseline solution the rotation and tillage system were identical to those of the three percent baseline but that contour cultivation was utilized initially in the fourth period and its use expanded in the ninth. The moderation of erosion resulting from expanding to contour cultivation is such that the third soil depth zone is depleted and the fourth in use by the end of the fifty year period where as in the baseline solution the sixth zone is depleted by the last year. The increase in the tax rate to $1.00 leads to the use of no-till as it did in the three percent solution. The utilization of this practice begins in the fourth period and by the sixth period the entire acreage is no-till farmed. As in the three percent solution, the increase in the tax rate to $1.50 results in
the exclusive use of the no-till system. Further rate increases up to $3.00 yield no further adjustments in crop management practices. The increase in the rate to $1.00 results in a moderation of erosion such that the third zone is not fully exhausted by the tenth period and the increase in the rate to $1.50 results in the availability of soil in the second zone for use beyond the fiftieth year.

**Ten percent solution**

In the ten percent solution, changes in crop management practices also occur at the tax rates of $0.50, $1.00, and $1.50 and again increases in the tax by $0.50 increments to $3.00 result in no further modifications. The imposition of the $0.50 tax results in no change in rotation or tillage system relative to the baseline but does result in contour cultivation of the entire acreage in each period. Thus, this solution is identical to the three and five percent solutions at the tax rate of $0.50. The solution obtained at a tax rate of $1.50 is also identical to those for the three and five percent discount rate cases. The $1.00 tax rate solution involves a transition to no-till farming beginning in the sixth period and by the ninth period no-till is used exclusively. Since the solutions at $0.50, $1.50, $2.00, $2.50, and $3.00 are
identical to those obtained in the three and five percent solutions, the use of the soil depth zones is identical. In the $1.00 tax solution, the third soil depth zone is just exhausted by the end of the tenth period. In the ten percent baseline solution, the sixth soil depth zone was depleted and in the tenth period production was depleting the seventh zone.

Comments on the tax solutions

The range of tax rates considered above is relatively narrow although it is considered reasonable for the purposes of this analysis. That there is no response to the increase in the tax rate from $0.00 to $0.50 in the three percent solution implies that no adjustments to lesser tax rates would occur. The strong responses in the five and ten percent solutions suggest that tax rates less than $0.50 will yield adjustments in cropping practices at these discount rates. The magnitude of the response to the imposition of $0.50 tax is particularly noteworthy at the ten percent rate.

The existence of conservation measures which will yield erosion levels greater than those obtained at the $0.50 tax rate and less than those obtained at the $1.00 tax rate at all three discount rates implies that rates between these values will yield solutions differing from those obtained
at the two rates. The same is true for rates between $1.00 and $1.50. Further, in the three soil management groups upon which row-crop production is considered profitable, there exists considerable flexibility for achieving levels of erosion control in excess of those obtained at rates of $1.50, $2.00, $2.50, and $3.00. Indeed, at the limit, erosion in the watershed can be reduced to virtually zero by allocating all land to permanent pasture. Thus, it is not to be concluded that rates in excess of $1.50 will not yield further control.

The trend in erosion in all three solutions is again increasing over time. This can again be attributed to the increasing of the erosivity of the soils in Group III with soil loss for the trend in use of conservation measures is generally upwards over time at the discount and tax rates considered. That the incentive to utilize conservation practices increases over time was noted above. However, in the tax solutions the incentive is further increased because the erosivity of the soils is increasing. That is, erosion control incentives become greater not just because the incentive to conserve increases but also because the potential tax base of any crop production activity is increasing.

Comparing the net present value of production figures
in Table 5.10 to those in Tables 5.11, 5.12, and 5.13 it is to be observed that all discounted marginal damage costs in Tables 5.11, 5.12, and 5.13 exceed the corresponding values in Table 5.10 except at the three percent discount rate with a $0.50 tax rate. If these damage costs can be interpreted as those which obtain in the optimal solution, the results imply in all cases but the one noted that the reallocation of resources brought about by the costless imposition of a Pigouvian tax will represent a potential Pareto improvement.

Technical Restrictions for Erosion Control

Aggregate erosion levels in a watershed may be reduced from a technical standpoint by reducing the number of acres in row-crops and by reducing erosion rates on acres in row-crops. From the standpoint of public policy, reductions in aggregate erosion levels can be obtained by introducing economic incentives for erosion control measures or by imposing restrictions on land use. Environmental quality policy in the United States has largely involved the imposition of technical restrictions to obtain reductions in residuals flows. If this approach is carried over into the control of nonpoint source water pollution from agricultural activities, then the approach would be one in
which farmers are directed to utilize "best management practices" in row-crop production. In this section, the impacts of such directives are considered. The practices included are chosen, as noted previously, for the facility with which compliance may be observed and for their efficacy in controlling erosion.

Three basic potential components of erosion control packages are evaluated. These are bans on fall tillage in row crop production, a requirement that contour cultivation be utilized in row-crop production, and a requirement that row-crop production be done on terraced land. The fall tillage ban can be applicable to any of the three management groups individually or to combinations of the groups. Contour cultivation, however, has little impact upon erosion on the soils in Group I and thus the requirement would be realistically imposed upon production on soils in Group II, Group III, or both. The requirement that terraced land be used in row-crop production would sensibly be imposed only on the use of soils in Group III.

The three components can be combined in a variety of ways to obtain various degrees of erosion control. Fall tillage could be prohibited across the board or on particular soils. Contouring could be required on Group I and Group II or on one or the other. Further, the fall tillage restriction
can be combined with contour restrictions. Clearly there are a number of possible combinations. Some of these will be dominated by others as will be demonstrated below.

**Fall tillage bans**

For soils in all three management groups for which row-crop production activities are defined, the activity yielding the greatest annual profits per acre is that activity yielding the C-C-B-C-B rotation utilizing the spring-disk tillage system and straight-row cultivation. Under the assumptions made here concerning the constancy of product and factor prices, the absence of technological change, and the absence of a significant intertemporal interdependence of production possibilities in soils in Group I and Group II, it follows that imposition of a ban on the use of fall tillage in row-crop production on soils in these groups will result in the choice of this activity. There is no need, then, to solve the submodels for these two groups to ascertain the impacts of bans on fall tillage. The same is not true of soils in Group III. Solutions of the submodel for soils in Group III indicate the use of the spring-disk tillage system to produce the C-C-B-C-B rotation at the three discount rates of three, five, and ten percent. However, straight-row cultivation is found to be exclusively used only in the ten percent solution. In the
three percent solution, contour cultivation is used exclusively in all years in the fifty year period. In the five percent solution, straight-row cultivation is used in the first ten years but beginning in the eleventh year and continuing until the fiftieth, 948 acres are managed with contour cultivation with the remainder managed with straight-row cultivation. These results indicate that despite the greater degree of conservation of soil depth imposed by the imposition of the ban, at discount rates of three and five percent, there remains sufficient incentive to save soil for use in future years to lead to the choice of less profitable but more conserving crop production activities. At the ten percent discount rate, however, the incentive to conserve is not sufficient to lead to conservation beyond that imposed by the ban. The restriction results in approximately one-half inch of soil saved at the three percent discount rate and approximately two inches of soil saved at the five and ten percent discount rate.

Contour cultivation restrictions

The imposition of a restriction that crop production utilize contour cultivation on Group III soils will have no impact on the production plan at the three percent discount rate since this method is voluntarily utilized as indicated in the baseline solution. At the five and ten percent
discount rates, a policy requiring contour cultivation on Group III soils will yield the same results with respect to rotation and tillage system as that obtained in the three percent baseline solution. Consequently, there will be a significant increase in the conservation of soil depth relative to the five and ten percent baseline solutions. That moldboard tillage is not chosen in the five percent solution, and particularly in the ten percent solution is of interest. It has been previously noted, that this activity is more profitable on a per acre basis and it is clear that the contour restriction results in greater conservation at the five and ten percent discount rates than would be chosen by private planner in the unrestricted case. That it is not chosen indicates that the incentive to conserve for production in future periods still outweighs the gains from maximizing current profits despite the imposition of greater soil conservation by the policy. The moldboard tillage system option will be chosen for use in producing the C-C-B-C-B rotation on Group II soils when the contour cultivation restriction is imposed since this is the most profitable crop production activity available.
Fall tillage bans and contour cultivation restrictions

A policy which simultaneously bans the use of fall tillage and requires the use of contour cultivation will at any of the three discount rates result in the selection of a spring-disk tillage system to produce a C-C-B-C-B rotation regardless of whether it is applicable to Group II or Group III. The degree of soil depth conservation resulting from the imposition of this policy measure is considerable, particularly in comparison to the five and ten percent baseline solutions, as the loss of soil depth resulting over the fifty year period is just slightly more than four inches in Group III.

Fall tillage bans and terrace restrictions

If row-crop production is restricted to terraced land on Group III soils the model indicates the selection of a fall moldboard tillage system for use in all periods at all three discount rates in the production of C-C-B-C-B rotation. The degree of soil conservation imposed is again, then, such that the activity which maximizes annual profits is chosen for use. Slightly more than four inches of soil loss occur by the fiftieth year. With the further requirement of spring tillage the spring-disk tillage system is chosen and as a consequence, little more than two inches of soil loss occurs by the end of the tenth period.
Evaluation of the technical restrictions

Ideally the various restrictions and possible combinations of them would be economically evaluated on the basis of the net present value of the resulting abatement benefits. There is, however, insufficient information to permit such an evaluation and consequently an alternative method for comparison is required. In Tables 5.14, 5.16, 5.17, and 5.18 the cumulative reduction in erosion during the fifty year period, the reduction in the net present value of the fifty year cash flow less the present value of the change in the penalty function, and the cost per ton of the reduction in cumulative erosion are listed for the alternative restrictions and soil management groups. The first of these permits consideration of the effectiveness of the restriction in controlling erosion and the second permits consideration of the costs in terms of the forgone present value of watershed production. The cost per ton figure permits a comparison of the total costs of the restrictions relative to the cumulative control resulting.

Table 5.14 presents the results for bans on fall tillage. At all three discount rates the greatest abatement is obtained by imposing the ban on soils in Group III and the least is obtained by imposing the constraint on use of soils in Group I. These results arise because the soils in Group II are more erosive than those of Group
Table 5.14. Fall tillage restrictions

<table>
<thead>
<tr>
<th>Group (discount rate)</th>
<th>Reduction in net present value</th>
<th>Reduction in cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>Cost per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (3%)</td>
<td>$448,913</td>
<td>97,982</td>
<td>1.55</td>
<td>$4.58</td>
</tr>
<tr>
<td>II (3%)</td>
<td>723,220</td>
<td>585,398</td>
<td>5.34</td>
<td>1.24</td>
</tr>
<tr>
<td>III (3%)</td>
<td>438,867</td>
<td>679,023</td>
<td>16.50</td>
<td>0.64</td>
</tr>
<tr>
<td>I (5%)</td>
<td>318,583</td>
<td>97,982</td>
<td>1.55</td>
<td>3.25</td>
</tr>
<tr>
<td>II (5%)</td>
<td>513,221</td>
<td>585,398</td>
<td>5.34</td>
<td>0.88</td>
</tr>
<tr>
<td>III (5%)</td>
<td>430,390</td>
<td>1,254,960</td>
<td>28.00</td>
<td>0.34</td>
</tr>
<tr>
<td>I (10%)</td>
<td>172,984</td>
<td>97,982</td>
<td>1.55</td>
<td>1.76</td>
</tr>
<tr>
<td>II (10%)</td>
<td>278,666</td>
<td>585,998</td>
<td>5.34</td>
<td>0.47</td>
</tr>
<tr>
<td>III (10%)</td>
<td>226,882</td>
<td>1,316,382</td>
<td>30.50</td>
<td>0.17</td>
</tr>
</tbody>
</table>
I and those in Group III are more erosive than those in Group II and because the acreage in Group III exceeds that of Group II which exceeds that of Group I. The total cost of a ban on fall tillage is greatest for Group II at all discount rates but at the rates of five and ten percent the costs of the control for Group III soils exceed those of Group I. The cost per ton of abatement are least at all three discount rates for soils in Group III and greatest for soils in Group I.

Table 5.15 presents the results for the bans on straight-row cultivation. This ban will have no effect upon the use of soils in Group III at the three percent discount rate since this practice is chosen voluntarily by the unrestricted planner in the baseline solution. At the five and ten percent discount rates the ban will yield greater cumulative control with lower total costs and lower costs per ton when placed on the more erosive soils in Group III than when imposed upon the soils in Group II. Table 5.16 presents the results for simultaneously imposing a ban on straight-row cultivation and a ban on fall tillage. The remarks concerning the ban on straight-row cultivation alone apply here except that at the three percent discount rate the measure will lead to a reduction in cumulative erosion relative to the baseline solution. However, the level
<table>
<thead>
<tr>
<th>Group (discount rate)</th>
<th>Reduction in net present value</th>
<th>Reduction in cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>Cost per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>II (3%)</td>
<td>398,328</td>
<td>826,573</td>
<td>4.24</td>
<td>0.48</td>
</tr>
<tr>
<td>III (3%)</td>
<td>0</td>
<td>0</td>
<td>19.53</td>
<td>-</td>
</tr>
<tr>
<td>II (5%)</td>
<td>286,209</td>
<td>826,573</td>
<td>4.24</td>
<td>0.35</td>
</tr>
<tr>
<td>III (5%)</td>
<td>44,762</td>
<td>3,146,689</td>
<td>19.53</td>
<td>0.01</td>
</tr>
<tr>
<td>II (10%)</td>
<td>157,803</td>
<td>826,573</td>
<td>4.24</td>
<td>0.19</td>
</tr>
<tr>
<td>III (10%)</td>
<td>142,130</td>
<td>3,146,689</td>
<td>19.53</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Table 5.16. Contour cultivation and fall tillage restrictions

<table>
<thead>
<tr>
<th>Group (discount rate)</th>
<th>Reduction in net present value</th>
<th>Reduction in cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>Cost per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (3%)</td>
<td>$1,084,047</td>
<td>1,135,715</td>
<td>2.83</td>
<td>$0.95</td>
</tr>
<tr>
<td>II (3%)</td>
<td>443,138</td>
<td>681,916</td>
<td>16.50</td>
<td>0.65</td>
</tr>
<tr>
<td>I (5%)</td>
<td>770,576</td>
<td>1,135,715</td>
<td>2.83</td>
<td>0.68</td>
</tr>
<tr>
<td>II (5%)</td>
<td>434,336</td>
<td>3,832,805</td>
<td>16.50</td>
<td>0.11</td>
</tr>
<tr>
<td>I (10%)</td>
<td>420,434</td>
<td>1,135,715</td>
<td>2.83</td>
<td>0.37</td>
</tr>
<tr>
<td>II (10%)</td>
<td>310,520</td>
<td>4,453,709</td>
<td>16.50</td>
<td>0.07</td>
</tr>
</tbody>
</table>
of control is less than that obtained on soils in Group II by imposition of the same restrictions although it does come at a lower total cost and a lower cost per ton.

Comparing the data given in Tables 5.14 and 5.15, it is clear that a ban on straight-row cultivation generally dominates a ban on fall tillage for Group II and Group III since in all but the three percent case for the third group, the degree of control achieved by the former exceeds that of the latter while the costs of the former are less than those of the latter. Comparing the results given in Tables 5.14, 5.15, and 5.16 it is observed that the simultaneous bans on fall tillage and straight row cultivation will yield a greater level of control at a higher cost than the individual restrictions yield for Groups II and III. However, the costs per ton are less than those of the restrictions on fall tillage but greater than those for the restrictions on straight-row cultivation.

Table 5.17 presents the results for the requirement that row-crop production on soils in Group III be done on terraced acres. Table 5.18 presents the results when there is added to this restriction, an additional restriction that spring-tillage be used. The level of control afforded by these two measures exceed those considered above as do the total costs for Groups II and III. The costs per ton are also
### Table 5.17. Terrace restriction

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>Reduction in net present value</th>
<th>Reduction in cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>Cost per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>$10,029,629</td>
<td>072,673</td>
<td>15.20</td>
<td>$10.31</td>
</tr>
<tr>
<td>5%</td>
<td>7,488,496</td>
<td>4,123,562</td>
<td>15.20</td>
<td>1.31</td>
</tr>
<tr>
<td>10%</td>
<td>4,930,516</td>
<td>4,744,462</td>
<td>15.20</td>
<td>1.04</td>
</tr>
</tbody>
</table>
### Table 5.18. Fall tillage and terrace restrictions

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>Reduction in net present value</th>
<th>Reduction in cumulative erosion (tons)</th>
<th>Average annual erosion (tons/acre)</th>
<th>Cost per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>$10,388,448</td>
<td>2,168,478</td>
<td>9.86</td>
<td>$4.79</td>
</tr>
<tr>
<td>5%</td>
<td>7,716,652</td>
<td>5,319,367</td>
<td>9.86</td>
<td>1.45</td>
</tr>
<tr>
<td>10%</td>
<td>5,124,062</td>
<td>5,940,267</td>
<td>9.86</td>
<td>0.80</td>
</tr>
</tbody>
</table>
in excess of those measures considered above except the ban on fall tillage on soils in Group I at the discount rates of five and ten percent.

Based on the results presented above, some guidance to the efficient design of erosion control policy using technical restrictions is obtained. Consider the results for the three percent discount rate. The measure which yields the greatest degree of control at the lowest total cost and the lowest cost per ton is a ban on straight-row cultivation on soils in Group II. Starting with this measure the public authority could achieve a cumulative control of 826,573 tons at a cost of $0.48 per ton. The measure which yields the next greatest level of cumulative control with the next lowest cost per ton is a ban on fall tillage on soils in Group III. A package of the two measure would yield a cumulative control of 1,505,569 tons at an average cost per ton of approximately $0.55 per ton. It is to be observed, then, that the public authority can obtain increasing levels of control by expanding the package of control measures. The cost of the package and the degree of control obtained will depend upon how it is composed. There will be, however, packages which dominate others because they yield greater levels of control at a lower cost per ton and perhaps even at a lower total cost.
Comments on technical restrictions

Only a limited number of possible technical restrictions have been considered here under a limiting set of assumptions and discount rates. The results demonstrate that increasing levels of erosion control can be obtained by imposing increasingly stringent restrictions on production and that increased control levels will come at higher costs. It is also demonstrated that some packages of restrictions will dominate others. The results suggest that the effectiveness of restrictions will be greater on more erosive soils and that the costs per ton of abatement will be lower for these soils than for less erosive soils. Finally, it is suggested that across the board restrictions will generally be less efficient than control strategies in which restrictions are tailored for soils of specified types.

The major alternatives to a control program in which "Best Management Practices" are imposed by directive is a program in which subsidies are given for utilization of control practices. There is a wide range of alternative subsidy programs for erosion control which can be envisioned and under present circumstances it is difficult to foresee the probable structure of such programs. This makes it difficult to analyze alternative programs since it is not clear what is to be subsidized and what the subsidy rates will
be. It can be said that any subsidy program which yields
the same outcome as a program of technical restrictions
will be no more efficient, however, and if the object of
a subsidy program is to obtain the same results but in a
more politically acceptable manner then there is no economic
basis for choosing between the two approaches.
CHAPTER VI. SUMMARY AND CONCLUSIONS

Introduction

The purpose of this endeavor has been to contribute to the conceptual and applied economic analysis of issues in cropland erosion and erosion control for water quality improvement. The salience of these issues is established in Chapter II and it is observed in that chapter that these issues are particularly relevant in the Corn Belt states. The purpose of this brief chapter is to reiterate some of the more important points which have been developed in this investigation.

Soil Management and Soil Erosion

Chapter III considers soil conservation issues for individual soils and for groups of soils, and the conjunctive management of soils and water quality. It is emphasized that the soil management problem is a dynamic problem in the conjunctive management of resource stocks, a point which has been explicitly recognized in few of the recent analyses of erosion control. It is further emphasized that the economic theory of natural resource extraction is applicable to the problem of erosion, and, in general, to the management of soils. Recent developments in
This theory which have been widely accepted for the analysis of problems in minerals extraction, fisheries, forestry, and other renewable and nonrenewable resources have, as yet, not been widely incorporated in the analysis of soil erosion problems.

It is observed that the soil exploitation program chosen by the price-taking present value-maximizing economic agent will depend, given the physical circumstances in which production takes place, upon the incentives given by the market. The efficiency or optimality of the program from a societal standpoint thus depends upon the information provided the farmer by the market. If there are no market failures, it is to be concluded that the program yields the optimal state of conservation of the soil resource. Any deviation from that state, be it one of under-conserving or overconserving will result in a real social loss. But, if markets do not operate to provide the "correct information," the program chosen by the farmer may result in either overconservation or underconservation relative to the socially optimal state. Market failure, due to lack of competition, is generally not to be considered of importance in soil resources conservation since agriculture is regarded as competitive. However, failure to obtain the optimal state of conservation as a consequence of the absence of futures
markets, risk markets, the presence of externalities and common property resources, and finally, the pervasive intervention of government in agriculture all warrant consideration and investigation. The issues involved are complex, particularly those arising as a consequence of the absence of futures and risk markets. In this analysis, consideration is limited to the implications of external water quality damages resulting from erosion in a watershed and to measures by which water quality improvements may be obtained. To the extent soil conservation is not optimal, due to water quality damages, it will be the case that those policies which are designed to efficiently obtain environmental quality improvements will also result in appropriate levels of erosion, given that there are no other sources of failure.

Comments on Cropland Erosion Control Policy

The test for the existence of a market failure is whether, given the distribution of welfare, there exists a reallocation of erosion levels over time that will result in a net increase in social welfare. However, to find that such a reallocation does exist is not sufficient to establish
the efficiency of government intervention. There may exist a variety of alternative measures ex ante by which potential Pareto improvements may be secured. The test for the desirability of government intervention on efficiency grounds is whether there exists a measure which, with its attendant resource costs, results in a net social gain. If there are several such measures, then the appropriate measure and the appropriate degree to which it is pursued, will depend upon the relative net gains of the alternatives.

The public policy measures found most frequently in the economic literature for obtaining improvements in resource allocation when misallocation is a consequence of technological externalities are Pigovian taxes, pollution abatement subsidies, pollution rights markets, and residuals restrictions or regulations. In a world of perfect information in which there are no direct resource costs associated with policy measures, any policy approach which yields the same allocation of resources that is obtained by a Pigovian tax policy is as efficient. In such a world there exists no economic basis for choosing among those policies which yield the efficient solution. The set of efficient policies will, of course, only be some subset of the set of all possible erosion control policies.
There is virtually no question that many of the policies emphasized to date would not be included in this subset since, as with the thrust of environmental quality policy on the whole in the nation, these approaches generally stress the use of control technologies with little consideration of the costs and benefits incurred. Further, the discussion of erosion control policy in Chapter III stresses that the efficient achievement of water quality improvements by reducing sediment flows will entail some mix of onsite erosion control measures, offsite sediment delivery control measures, and perhaps further offsite measures directed towards enhancing the assimilative capacity of surface water resources. Yet current deliberations focus almost exclusively on obtaining water quality improvements by onsite erosion control measures.

It is also observed in Chapter III that there are several areas requiring detailed investigation necessary to the design and implementation of efficient erosion control policies. These include research relating to the generation, transportation and damage costs of sediments, the costs of offsite control measures and onsite control measures, and the information, administration, and enforcement costs of alternative policy measures. One issue of particular concern is the inability to accurately monitor erosion flows and sediment contributions from particular economic
entities. Those policies which are generally most favored on efficiency grounds by economists involve the measurement of residuals flows. Such policy measures include Pigovian taxes and pollution rights markets. This problem, assuming that it is somehow known to be socially desirable to reduce erosion levels, gives some basis for considering subsidies to utilize control practices and construct control structures, to impose technical specifications on production, or to provide programs in which farmers are made to make payments to the public authority which are placed in deposit and returnable to the operator upon proof of meeting specified performance standards.

The Empirical Analysis

There has been considerable support of applied research in the area of soil erosion control. There are several common traits in such studies. One is that these studies largely focus on the impacts of alternative public policies for controlling soil erosion, on the predicted level of erosion, on crop and livestock production, and on farm prices and/or income. A second common trait of such studies is that they are performed within the framework of static linear programming models which have evolved to have relatively
standardized structures in terms of the types of activities and constraints included. A problem with static models is, however, that the failure to incorporate the effect of erosion on future soil productivity can result in misleading results concerning the effects of policy measures. The contribution which this research endeavors to provide centers to a large extent on the treatment of the soil management problem in a dynamic setting. There have been a few previous studies involving dynamic analysis of soil management but these have been quite limited in their consideration of the impacts of erosion control policy measures.

Chapter IV presents the multi-period linear programming model of crop production developed to investigate economic issues in cropland erosion and erosion control in the Four Mile Creek watershed. In order to facilitate the derivation of inferences of interest to this research, soils in the watershed are classified by management characteristics into four relatively homogeneous groups. Submodels are developed for each group and combined to obtain the watershed model. The soils in two of these (Group I and Group II) management groups either have no erosion hazard or have negligible erosion hazards and relatively deep topsoils. It is argued
that these soils have very small user costs. The submodels developed for these two groups are comparable in structure to many of the previous models developed. The soils in a third management group (Group III) are relatively shallow and have relatively high erosion hazards. It is expected that the quality of these soils has been affected by erosion. It is also expected that further yield losses and increases in the erosivity of these soils will occur with soil loss. A multiperiod model of crop production is required for the analysis of this group of soils. The Group III submodel is constructed in a manner which incorporates the effects of soil loss on future productive capacity and erosivity of the soils in the group. The model is formulated in a manner more analogous to the exploitation of multiple grades of a resource than to a pure stock effects model. The soils included in the final group (Group IV) are steep, shallow, highly erosive, and unproductive. At present, acreages in the group are mostly used for permanent pasture because they are unsuitable for row crop production. In modelling the watershed, it is assumed that the entire acreage of the group is allocated to pasture.

The criterion function of the model is the present value of the cash flow from production activities for a
period of fifty years less the present value of a penalty function and other adjustments. The formulation allows an investigation of the first fifty years of the crop production plan that would be developed by an unspecified private economic planner charged with maximizing the net present value of production in the entire watershed. In developing the model prices and technology are assumed invariant.

The model is first solved at discount rates of three, five, and ten percent without modification for policy alternatives. These baseline solutions allow a consideration of the production plan that would be developed by the planner. A range of discount rates is chosen to provide for analysis of the impacts of alternative discount rates on the production plan. The rates are considered to be real rates and the range provided does permit important inferences to be made. Despite the relatively modest yield losses associated with soil loss in the area, it is found that even at the ten percent discount rate the incentives to conserve soil are strong enough to lead the present value maximizing private economic planner to choose crop management practices other than those which maximize current returns. Total erosion in the model is
constrained, but only to the total amount of erosion that could occur if the most erosive of crop practices is chosen in all periods. However, in none of the solutions for Group III is this practice chosen despite it's being the most profitable on a per acre basis in any year. Consequently, in none of the solutions is the total available soil depth exhausted.

The trend in erosion in all three solutions is upwards over time. This movement may be attributed to the effects on soil loss on soil erosivity since in no solution is there a movement towards more erosive crop management practices over time. Indeed, in the one solution in which there are changes in crop management practices during the period the movement is towards more conserving management practices. Given constant product and factor prices, and given no technological change, a trend towards the greater utilization of conservation practices is consistent with the propositions of the theory of exhaustible resource management.

The results have two important implications for the empirical analysis of cropland erosion. It is demonstrated that if the soils in Group III were treated equivalently to those in Group I and Group II, the model would overestimate the amount of erosion occurring in each year and the present value of production for the fifty year period. Further, no indication of the time path of erosion would be provided.
The next set of results considered are obtained by solving the model at the three discount rates with annual erosion taxes of $0.50, $1.00, $1.50, $2.00, $2.50, and $3.00 per ton. These solutions can be considered in either of two ways. If it is assumed that these are the marginal damage costs in an optimal solution, then the results may be interpreted as the optimal solution for the watershed if it is further assumed that all other conditions for a particular Pareto optimum are otherwise satisfied. In such a solution, the taxes may be considered as optimal Pigovian taxes. Alternatively, no assumptions concerning the information carried by the values may be made and the analysis viewed simply as an investigation of the effects of erosion taxes on the production program. The trend in erosion in all three solutions is again increasing over time. This can again be attributed to the increasing of the erosivity of the soils in Group III with soil loss for the trend in use of conservation measures is generally upwards over time at the discount rate and tax rates considered. That the incentive to utilize conservation practices increases over time was noted above. However, in the tax solutions the incentive is further increased because the erosivity of the soils is increasing and thus because the potential tax base is increasing.
The last set of solutions investigated are obtained by solving the model with modifications for alternative policy options, which are considered as viable options under present circumstances. Where monitoring of residual flows is infeasible, realistic policy options for environmental quality management generally entail either technical specifications or subsidies for the use of control practices. This investigation considers some potential technical restrictions. The results demonstrate that increasing levels of erosion control can be obtained by imposing increasingly stringent restrictions on production and that increased control levels will come at higher costs. It is also demonstrated that some packages of restrictions will dominate others. The results suggest that the effectiveness of restrictions will generally be greater on more erosive soils and that the costs per ton of abatement will be lower for these soils than for less erosive soils. Finally, it is suggested that across-the-board restriction will generally be less efficient than control strategies in which restrictions are tailored for soils of specified types.
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ACKNOWLEDGMENTS

I wish to thank Dr. John Miranowski, my major professor, for his guidance and support in this endeavor. I also wish to thank Dr. Harvey Lapan, Dr. Dennis Starleaf, Dr. Roy Hickman, and Dr. Wallace Huffman for their patience and helpful comments. My greatest debt, however, is to my wife who was not only helpful in preparing this research, but who gave me great support; and to my parents, without whom it would not have been possible.