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Improvement of Lake Water Quality by Paying Farmers to Abate Nonpoint Source Pollution

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ABSTRACT

Improvement of Lake Water Quality by Paying Farmers to Abate Nonpoint Source Pollution

To mitigate damages caused by agricultural runoff, private lake owners' associations are paying for inlake and instream pollution abatement measures and onland conservation practices. This phenomenon supports the notion that individuals who benefit from improved water quality should be willing to pay part of the abatement costs.

Our research suggests that onland conservation measures can substantially reduce sediment delivery at low cost. The Sediment Economics (SEDEC) model was modified and then used to select and to site management systems that achieved stated sediment goals at least cost. Other resource policies such as T value, no-till, and contouring were compared with the least-cost frontier and shown to be more costly. Abatement costs decreased substantially and sediment delivery increased only slightly when the same resource policies were applied to cropland areas closest to water channels. The research also pointed out the importance of noncropland areas adjacent to water channels. The noncropland areas substantially reduced sediment delivery to water channels and lowered abatement costs.

Further research is needed for long-range watershed planning models such as SEDEC. More work is needed on the modelling of physical processes, particularly sediment delivery. The model also needs to be repackaged into a user-friendly format.

Key words: watershed management, economic feasibility, water quality, erosion control, hydrologic models, subsidies, cost sharing, cost analysis

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CHAPTER I

INTRODUCTION

General Background

The U.S. Agricultural Sector. The United States is second only to the Soviet Union in the amount of arable and permanent cropland, 471 to 574 million acres. The cropland combined with a highly mechanized and efficient sector has helped make the United States a leading country in the production of food and fiber for the world. In 1985 the food and fiber system employed 21.4 million full-time equivalent workers, 18.5 percent of the total civilian workforce. The United States agricultural sector not only met the food and fiber demands of the United States, but also helped fill world demands. In 1985, a very bad year for farm exports, the United States still exported 37 percent of its wheat crop, 13 percent of its course grains, 15 percent its cotton, and 52 percent of its soybeans (USDA 1986).

On the negative side, the U.S. agricultural sector is experiencing major problems. Plagued by large commodity surpluses, low commodity prices, falling land values, and large swings in farm income, producers and agricultural support industries are experiencing financial distress. On the resource front, excessive soil erosion on agricultural lands is decreasing the nation's soil resource base while water runoff is polluting the nation's waterways and lakes with eroded soil, nutrients, chemicals, and livestock waste.

Soil Erosion and Water Quality Problems. According to the 1982 National Resources Inventory, 5.4 billion tons of soil erodes on nonfederal rural land in the United States every year (USDA 1984). In Illinois, average annual sheet and rill erosion exceeds 200 million tons yearly, about

6.3 tons of eroded soil per year from 33 million acres.

The USDA (1985a) estimated that on-farm crop productivity losses cost U.S. farmers $866 million annually in 1983 dollars (USDA 1985a). In another study Crosson (1986) divided on-farm costs into three categories: costs of applying preventive measures such as conservation tillage and conservation practices, costs of production losses in spite of corrective efforts, and costs of compensating for erosion damages by applying more nutrients and other inputs. He estimated an annual cost of $1.7 to $1.8 billion, which includes yield loss over the next 100 years. Erosion control costs accounted for approximately two-thirds of the total costs ($1.2 billion in 1983 dollars); yield loss, 25 percent ($420 million in 1983 dollars); and added input expenditures, less than 10 percent ($105 to $168 million in 1983 dollars).

Water quality is closely related to soil erosion and is becoming an increasingly important resource issue in society. Over 50 percent of surface water pollution can be attributed to diffuse sources such as water runoff from agricultural land, mining activities, and silvaculture (Chesters and Schierow 1985). This pollution from diffuse sources is called nonpoint source pollution. Agriculture is the major contributor of nonpoint source pollution because of the large amounts of eroded soil and farm chemicals either attached to the eroded soil or dissolved in water that are being deposited in the nation's river systems and water bodies. (Gianessi _et al_. 1986).

The major consequences and estimates of damage caused by nonpoint source pollution were discussed in a study conducted by the Conservation Foundation (Clark II, Haverkamp, and Chapman 1985). Yearly instream and offstream damages range between $3.2 and $13 billion. The Conservation Foundation's best single damage estimate equals $6.1 billion, of which $2.2 billion can be directly attributable to cropland. In a separate study, the USDA estimated nonpoint source pollution damages attributable to agriculture at $2.17 billion in 1983 dollars (USDA 1985a).

Neither the Conservation Foundation's off-farm estimates nor USDA's estimates include damages to aquatic organisms or possible ill health effects to humans. Furthermore, the estimates do not include the costs to avoid or to reduce the damages (Crosson 1986). Hence, damages may be considerably higher.

<u>Public Action</u>. The degradation of soil and water resources poses a serious threat to the health and economic viability of the agricultural sector and the nation. To address this growing problem governments have reaffirmed their prior commitments in the areas of soil conservation and water quality. State and Federal laws such as the Illinois Soil Erosion and Sediment Control Law (Illinois Department of Agriculture 1985) and the Food Security Act of 1985 (P.L. 99-198) (USDA 1985b) set the basic groundwork for public involvement in soil and water conservation. State and federal governments also provide both technical assistance and cost-share funds to help producers pay for conservation practices.

<u>Private Action</u>. Private action is increasing in the area of nonpoint source pollution abatement for several reasons. First, the magnitude of on-farm and off-farm damages caused by soil erosion greatly exceeds current public efforts. Second, public efforts that emphasize the use of onland soil conservation practices do not directly address water quality--the primary concern of private groups. Third, private groups can apply inlake,

instream, and onland pollution abatement practices to intervene in many stages of the nonpoint source pollution process. Finally, cooperative arrangements can be worked out with agricultural producers to help meet water quality goals.

Private groups, such as lake owners associations that are composed of individuals who bought property and housing situated around a lake, are funding pollution abatement activities. The associations know that nonpoint source pollution, regardless of source, can lower water quality, impair recreational activities such as swimming and fishing, shorten the useful life of the lake, and diminish the market value of the property.

The Apple Canyon Lake Property Owners Association is an example of a private group that recognizes that damages from sedimentation exceed the costs of abatement. To mitigate the effects of sediment accumulation in their lake, the Association adopted strict erosion control practices and guidelines for Association property. Riprap, grass seedings, and tree planting have been used to stabilize shorelines, streambanks, and other areas on Association property that contribute to sedimentation. In addition, the Association purchased a dredge to deepen bays and inlets that had accumulated as much as 60 inches of sediment.

The Association also began looking for ways to reduce incoming sediment from agricultural sources. This exploration process led to an innovative cost-share arrangement administered by the Apple Canyon Lake Property Owners Association and the Jo Daviess County Soil and Water Conservation District. Cost-share funds are jointly supplied by the Association, and the Agricultural Stabilization and Conservation Service to help pay for conservation practices applied by producers. The practices include dry dams, sediment basins, grassed waterways, tile drainage, terraces, grade stabilization structures, no-till, and contouring.

Preliminary evidence indicates that the program at Apple Canyon Lake is meeting water quality goals. Lake transparency has improved as shown in Table I.1. In 1987, the lake ranked sixth in Illinois. Further improvements are expected in years to come because it often takes time for the effects of sediment control practices to be realized.

The Apple Canyon Lake Property Owners Association's successful efforts to manage nonpoint source pollution have attracted considerable attention. The Illinois EPA cites the management program at Apple Canyon Lake as an example in its recommendations for the management of other Illinois lakes (Hawes and Hammel 1986). Furthermore, Lake Summerset and Dunlap Lake property owners associations have adopted similar cost-share arrangements with agricultural producers.

Table I.1 Water quality improvements of Apple Canyon Lake measured by transparency data from the Illinois EPA (Hawes, 1988)

		Transparency		
Year	Rank in Illinois[1]	Average Depth	Std. Dev.	# of Obs.
		(inches)	(inches)	
1982	--	56.0	30.7	24
1984	31	64.5	38.9	39
1985	29	61.0	28.9	36
1986	14	80.8	59.1	39
1987	6	105.0	47.0	39

[1] Rank in Illinois in terms of transparency (1 being the most transparent) out of lakes monitored in four or more periods under the Illinois EPA Volunteer Lake Monitoring Program. The number of lakes included in the rankings for 1984-87 are respectively 145, 120, 127, and 134.

Statement of the Problem

The idea that individuals and groups who benefit from cleaner water are willing to help pay for the costs of pollution abatement is important for several reasons. First, part of the nonpoint source pollution abatement costs could be shifted from the general taxpayer to the groups who reap the benefits of higher water quality. Second, the number of available abatement options increases substantially because of a shift from erosion related objectives to water quality objectives. Onland, instream, and inlake pollution abatement measures could be combined to achieve water quality goals at lower costs (Sharp and Bromley 1979). Third, federal involvement may decrease as individuals, communities, and states work together to protect and manage their resources more effectively.

To assist the development of this movement in the private sector, research is occurring in two broad areas: valuing the benefits from pollution abatement and financing pollution abatement. A broad overview and discussion of benefit valuation techniques can be found in Dwyer, Kelly, and Bowes (1977) and in Freeman (1979). A recent report by Braden, Farnsworth, Seitz, and Uchtmann (1988) discusses financing alternatives such as local property taxes, water taxes, recreation fees, income tax checkoffs, recreation equipment and fuel excise taxes, and special property assessments to pay for pollution abatement measures.

An area that needs considerably more research is low-cost abatement strategies. Resource managers need this information to explain and justify their pollution abatement strategies to the people they represent, to other landowners in the watershed, to the communities, and to public agencies.

Objectives of the Study

As mentioned earlier, the Apple Canyon Lake Property Owners Association, as well as other private groups, are using many different abatement strategies to improve water quality. After using several inlake and instream practices, they are examining the use of onland conservation practices to reduce sediment control costs.

In this study, we examine the effectiveness and costs of onland conservation measures to reduce sediment delivery. Specifically, we address the following objectives:

Primary objective: identify and compare the costs and pollution consequences of resource management policies within the Apple Canyon Lake watershed.

Secondary objective: improve watershed management via the modification of a simulation model that links abatement measures, farm profitability, and sediment delivery rates.

To achieve the primary objective, we will evaluate and identify the frontier of least-cost combinations of cropland management systems that achieve all feasible reductions in sediment delivery. This cost frontier will then be used to compare and rank alternative resource policies.

To achieve the secondary objective, we will modify the Sediment Economics (SEDEC) simulation model. Furthermore, we will investigate strengths and weaknesses of the sediment delivery relationship in the model.

CHAPTER II

REVIEW OF WATERSHED MANAGEMENT MODELS

Numerous watershed models have been developed by resource agencies, researchers, and private companies. The primary objective of these models is to predict the environmental and economic implications of different resource management situations so that resource policy makers, planners, or managers can improve their decision making.

For our purposes, the models are grouped into two broad groups: storm event models and average annual models. The major characteristics of the two broad groups are compared to explain our choice of the Sediment Economics (SEDEC) model in the analysis.

Storm Event Models

Storm event models simulate the physical processes that occur in response to individual rainfall events of given intensities and duration. For an in-depth review of the technical relationships that underlie such models, see Hadley (1985). For a more general review of computer-based models see DeCoursey (1985).

Four storm event hydrologic models are ANSWERS (Beasley, Huggins, and Monke 1980), CREAMS (Knisel 1980), AGNPS (Young, Onstad, Bosch, and Anderson 1985), and the IIHR Distributed Parameter Watershed Model (Jain, Kumar, Whelan, and Croley 1982). The major characteristics of storm event models can be grouped into the following six categories.

Elemental Unit. A grid system composed of square cells that are one acre or larger divide a watershed into workable units. Cell size depends on the detail desired by the researcher or resource planner.

A cell is the elemental unit. The necessary physical and economic data needed in any of these models are collected for each cell. The collected data are assumed to be uniform across each cell.

Rainfall, Runoff, and Channel Flow. The movement of water is extensively modeled for each cell. Depending on the specific model used, output may include overland runoff per storm, channel flow, infiltration, evapotranspiration, and peak runoff.

Data requirements are extensive. These models require extremely detailed rain data by storm; slope percent, length, and shape characteristics; soil characteristics that include surface roughness, soil composition, particle size distribution, and hydraulic conductivity; and crop parameters such as leaf area index, root depth, surface cover, and other management factors.

Erosion. The Universal Soil Loss Equation (Wischmeier and Smith 1978) is generally used to estimate sheet and rill erosion. Researchers modify the equation to reflect single storm events. Other forms of erosion, such as ephemeral gully and gully erosion, may be predicted within each cell for single storm events. Data about rainfall, runoff, and channel flow and data about soil erodibility, soil bulk density, management practices, conservation practices, and water channel characteristics are needed to predict erosion.

Transport Equations. After erosion and runoff are calculated, transport equations that link the cells together move sediment, nutrients, and chemicals through the watershed.

Management Systems. Production practices can greatly affect erosion, infiltration, runoff, deposition, and other physical processes included in these models. Hence, for each management system (crop rotation, tillage method, and conservation practice) used in the analysis, the following data are required: input quantities to produce each crop, tillage and its impact on soil characteristics and residue, conservation practices, crop development, and output. Because the models generally examine single storm events, long-term production relationships, such as soil productivity and erosion, are ignored or assumed insignificant. Also, researchers do not consider long-term price relationships.

Comparison of Management Systems. Revenues and costs are compared with erosion rates, sediment load, nutrient load, and chemical load for each management system included in the study. Extensive modeling of the physical processes generally limits the number of management systems that can be compared at one time. Hence, a limited number of management systems either are applied to the entire watershed or specific areas within the watershed.

Average Annual Models

The second category of watershed models use long-run weather and economic trends and conditions to simulate physical and economic processes. Justification for this approach is based on the following rationale. From the perspectives of farmers, policy makers, and watershed managers, an effective resource management plan should account for the range of possibilities and not individual storm events or other singular happenings (DeCoursey 1985). Though multiple runs of storm event models may accurately reproduce physical and economic results from average annual models, the time could be spent on incorporating other important relationships such as soil productivity and erosion over time and a larger set of management systems.

The complex physical processes were greatly simplified in the early average annual simulation models. One of the following three approaches was generally used: researchers assumed all erosion became sediment (Heady and Miester 1977); researchers reduced erosion by a fixed delivery ratio to determine sediment delivery (Wade and Heady 1978; USDA 1981; Guntermann, Lee, and Swanson 1975; Miller and Gill 1976; Walker and Timmons 1980; and McQueen, Shulstad, and Osborn 1982); or researchers assigned a delivery ratio to each land parcel based on the location of the land parcel in the watershed (Onishi, Narayanan, Takayama, and Swanson 1974; Walter and Black 1982; Seitz, Sands, and Spitze 1975).

With any of these approaches, a percentage of erosion on all fields becomes sediment regardless of the management systems on any of the fields. Furthermore, the delivery ratios cannot account for the beneficial intercepting effects of changing management systems on intermediate fields (Braden, Johnson, Bouzaher, and Miltz 1988).

In more recent models such as the Sediment Economics model, researchers have incorporated more realistic sediment delivery relationships and have greatly expanded economic components (Braden, Johnson, and Martin 1985). We discuss the primary components of the SEDEC model.

Elemental Unit. For the SEDEC model, the watershed is divided into land units with similar physical and management characteristics. Shape and size of each land management unit varies. All the necessary physical and economic information is collected for each land management unit.

Rainfall, Runoff, and Channel Flow. Only average relationships are included. Specific information about rainfall, runoff, and channel flow is not modeled.

Erosion. The Universal Soil Loss Equation (Wischmeier and Smith 1978) is used to estimate sheet and rill erosion. Other forms of erosion are not addressed. Data that relates to factors in the equation are collected.

Transport Equations. After erosion rates are calculated, sediment movement and deposition is routed through the watershed with a transport equation that links land management units together. The transport equation uses data collected for average annual relationships such as erosion.

Management Systems. Production practices can greatly affect erosion, infiltration, runoff, deposition, and other physical processes included in these models. Hence, for each management system used in the analysis (crop rotation, tillage method, and conservation practice) data are collected on input quantities to produce each crop, tillage and its impact on soil characteristics and residue, conservation practices, crop development, and output.

Because these models are used for long-range planning, physical relationships such as soil productivity and erosion and technological change are incorporated. Other algorithms use long-run average prices to calculate annualized average returns for later comparison.

Comparison of Management Systems. Long-term average numbers such as net returns, erosion rates, and sediment load are calculated for each management system on every land unit. The lowest cost management system is placed on each land unit to meet water quality goals set for the watershed.

Model Selection

Both storm event and average annual models have their strengths and weaknesses. According to Renard, Rawls, and Fogel (1982), storm event models perform relatively well in descriptive watershed or stream analyses. Their use to evaluate the environmental and economic impacts of alternative watershed policies is extensive (Park and Shabman 1982; Carvey and Croley

1984; Lee, Lovejoy, and Beasley 1985; Seale, Hubbard, and Kaiser 1985; Setia and Magleby 1988).

For average annual models, research by Davenport (1983) and White (1988), both of whom used SEDEC's sediment delivery component, indicate predicted sediment approximated actual sediment in the two watersheds. Wu, Braden, and Johnson (1986) modified SEDEC and then compared the costs of controlling sediment using average annual data with the costs of controlling sediment using episodic weather event data. Generally, the costs for proportionate reductions in sediment were lower using average annual data rather than episodic data.

Choice of a particular model depends on the research objectives. The average annual models, particularly SEDEC, more closely fit our research objectives and needs for several reasons.

First, SEDEC incorporates long-term relationships and planning. We can account for the yield-erosion relationship, technological change, and multiperiod decision making. Second, the use of an average annual model simplifies the collection of physical data. Third, essential economic concepts are built into SEDEC.

The joint economic concepts of efficiency and marginal costs are SEDEC's strengths. Given the physical and economic data by LMU and the sediment transport equation, SEDEC applies management systems to LMU's and determines the efficient solution: the best mix of management systems that achieve the sediment delivery goal at least cost. In finding the efficient solution for each sediment delivery goal, SEDEC applies marginal cost criteria, that is, SEDEC chooses the management system on each land unit to reduce additional units of sediment at lowest costs (Lupi, Farnsworth, and Braden 1988).

CHAPTER III

THEORETICAL FRAMEWORK

The economic model was developed using previous works on the efficient control of sediment by Braden et al. (1985); Wu et al. (1986); Braden et al (1987); Bouzaher, Braden, and Johnson (1987); Bouzaher, Murley, Johnson, and Braden (1988); and Braden et al. (1988).

Spacial Delineation of Watershed

The relevant area under consideration is the total drainage area of a reservoir or a watershed. A watershed (or any subwatershed) can be further divided into $j=1,\ldots,J$ catchments, or independent drainage areas according to their surface water runoff characteristics. An example of a catchment is shown in Figure III.1.

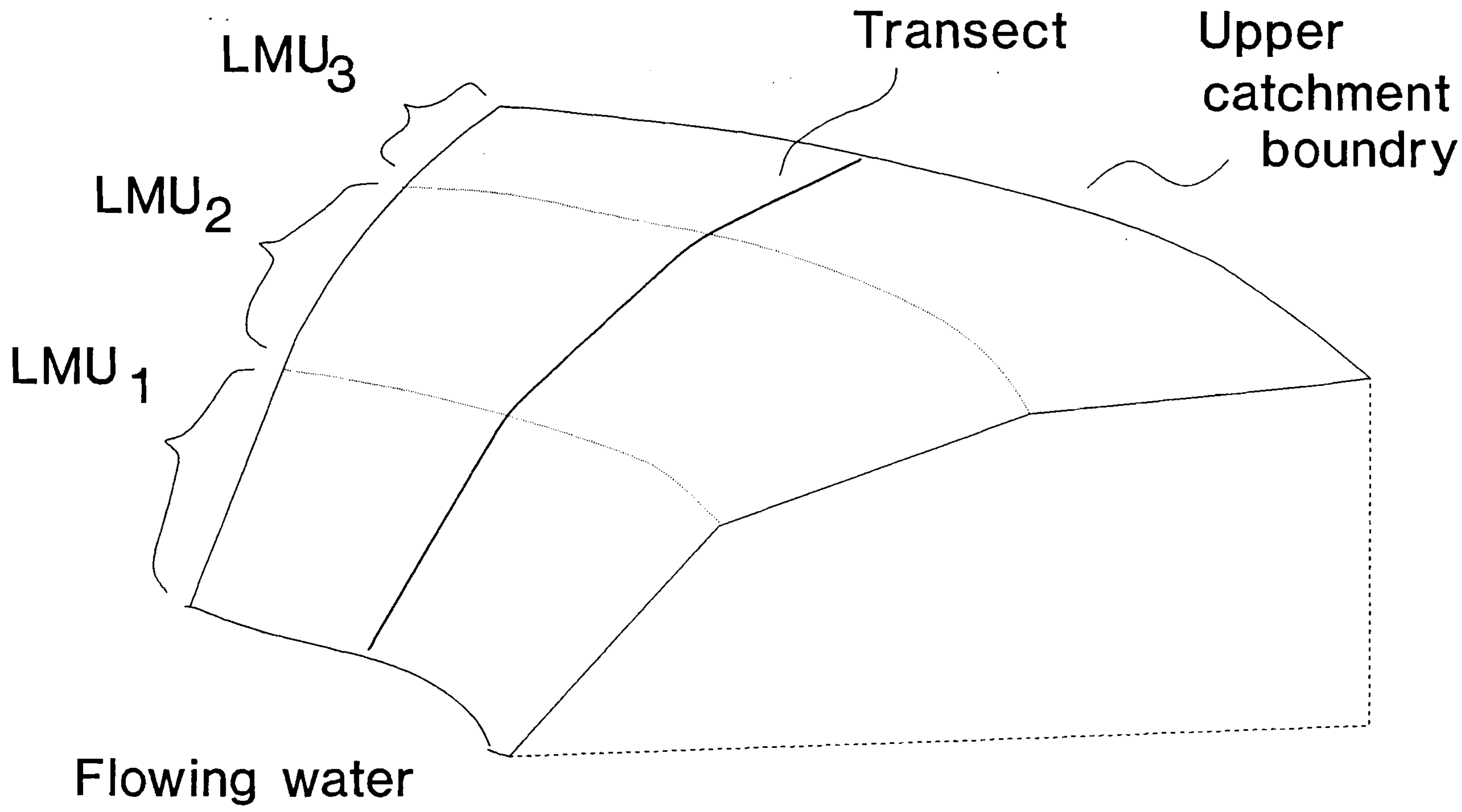
A catchment, j, can be partitioned into a series of $i=1,\ldots,I_j$ land parcels. Each land parcel, which is referred to as a land management unit (LMU), must have a uniform slope and management system.

LMU's are numbered along transects in decreasing order according to direction of surface water runoff. LMU_{Ij} is adjacent to the catchment's upper boundary. LMU_{Ij} drains into $LMU_{I-1,j}$ which drains into $LMU_{I-2,j}$ and so on until LMU_{1j}, the unit adjacent to water, is reached.

The drainage path within catchment j is represented by a transect line j. The transect j begins at a catchment's upper boundary and traverses downslope until reaching a well-defined water channel. Transects must run perpendicular to topographic contour lines and must cross each of the $i=1,\ldots,I_j$ consecutive LMU's one time.

The sediment delivered by each catchment is a complex function of the physical characteristics, management systems, and sediment transport

Figure III.1 An example catchment with a transect and three LMU's



properties of LMU's along transects. For the watershed, the total amount of sediment delivered is the sum of the sediment delivered by each of the j transects. The erosion and sediment delivery processes in SEDEC are fully developed in the next chapter.

Model for the Producer on each LMU

In general, a plausible goal of producers is to maximize net returns (revenues - costs) or profit from production (Beattie and Taylor 1985). For multiperiod decision problems, producers maximize the present value of net returns over time. Furthermore, by formulating the problem over time, the long-term productivity effects of soil erosion can be incorporated into a producer's decisions (McConnell 1983).

The objective of the producer on any LMU is summarized as follows:

$$\max_{\underline{x}_t} \pi = \sum_{t=1}^{T} \{ (1+r)^{-t} [\underline{p}_t \underline{y}_t - C(\underline{y}_t, b_t, \underline{x}_t; \underline{g}_t, \underline{w}_t)] + (1+r)^{-T}(V_T) \} \qquad (2a)$$

$$\text{s.t.} \quad F(\underline{y}_t, b_t, \underline{x}_t; \underline{g}_t) \leqq 0, \qquad (2b)$$

$$b_t = b_t(\underline{x}_t; \underline{g}_t), \qquad (2c)$$

$$g_{d,t+1} = g_{dt} - e(b_t, s), \qquad (2d)$$

$$\underline{x}_t \subset X \subset R^n, \qquad (2e)$$

$$\underline{y}_t, b_t, \underline{x}_t, \underline{g}_t \geqq 0 \text{ , all } t,$$

where:

π = present value of cumulative profits over time,
t = time period where $t=1,\ldots,T$,
r = the discount rate,
$\underline{p}_t$ = row vector of $m=1,\ldots,M$ marketed output prices in time t,
$\underline{y}_t$ = vector of $m=1,\ldots,M$ outputs,
$C(\cdot)$ = total cost function,
$b_t(\cdot)$ = soil erosion associated with production on this LMU,
$\underline{x}_t$ = vector of $n=1,\ldots,N$ inputs,

g_t = vector of k=1,...,d,...,K given physical characteristics,

$\underline{w}_t$ = row vector of n=1,...,N exogenously determined input prices,

V_T = the salvage value of the production operation in the final period of the planning horizon, T.

$F(\cdot)$ = implicit joint production function,

g_{dt} = soil depth at time t,

$g_{d,t+1}$ = soil depth at time t+1,

$e(\cdot)$ = function relating the soil depth g_{dt} to tons of annual soil erosion per acre,

s = natural rate of soil replenishment.

X = the feasible set of input vectors that are contained in a closed and bounded subset of R^n real space.

and assume that all regularity conditions necessary for the first order conditions to identify a unique solution to the problem are satisfied.

The objective function, (2a), states that producers choose inputs to maximize the discounted sum of revenues minus costs over the entire planning horizon plus the salvage value of the land in the final period. Revenues are the vector of prices multiplied by the vector of marketed outputs. Production costs are a function of outputs, inputs, and exogenously given input prices and physical characteristics. By assumption, the producer is competitive in input and output markets; hence, prices are exogenously given. The salvage value of the land is the last term $(1+r)^{-T}(V_T)$ in equation (2a). This term represents the discounted remaining value of the operation in the last period, T.

Equation (2b) represents the joint production process of $\underline{y}_t$, marketable outputs and b_t soil erosion. The outputs are a function of the input vectors $\underline{x}_t$ and g_t, chosen inputs and given physical characteristics.

Equation (2c) explicitly states that erosion on a land management unit is a function of the input vector of management choices and the vector of given physical characteristics such as soil type, climate, and slope. The equation and variables reflect an average annual relationship.

Equation (2d) defines the change in soil depth, the d^{th} element of the vector of physical characteristics. Soil depth equals current depth in time period t minus the net effects of erosion and soil replenishment.

Soil depth is an argument in the cost and production functions that means the level of costs and outputs are affected by cumulative soil erosion. Therefore, farmers maximizing profits will apply conservation practices if the practices improve the present value of profits over time (McConnell 1983). The level of erosion control, though, may not be the socially optimal amount if producers have a different discount rate or planning horizon than society or do not pay for damages caused by sediment in waterways and lakes (Griffen and Bromley 1982).

Efficient Prevention Frontier

The efficient prevention frontier (EPF) can now be constructed by building upon the model of the producer. The EPF is a minimum payment or least-cost frontier. For any given sediment level, the frontier gives the minimum dollar amount that makes producers indifferent between the most profitable management system for an LMU and other management systems that help achieve sediment delivery goals for the watershed.

For ease of exposition assume that all management variables remain constant over time. Recall that subscript ij refers to the i^{th} land management unit on the j^{th} transect. The efficient prevention frontier is characterized by the following formulation:

$$S(z) = \underset{\underline{x}_{ij}}{\text{Min}} \quad \sum_{j=1}^{J} \sum_{i=1}^{I} [\, \pi^{o}_{ij} - \pi_{ij}(\underline{y}_{ij},\underline{x}_{ij};\underline{g}_{ij},\underline{p}_{ij},\underline{w}_{ij}) \,] \tag{3a}$$

$$\text{s.t.} \quad F_{ij}(\underline{y}_{ij},b_{ij},\underline{x}_{ij};\underline{g}_{ij}) \leqq 0 \tag{3b}$$

$$\sum_{j=1}^{J} h_j(b_{1j},\ldots,b_{Ij},\underline{x}_{1j},\ldots,\underline{x}_{Ij};\underline{g}_{1j},\ldots,\underline{g}_{Ij}) \leqq z \quad \text{for all } i=1,\ldots,I_j, \tag{3c}$$

$$\underline{x}_{ij} \subset X \subset R^{n} \tag{3d}$$

$$\underline{y}_{ij},b_{ij},\underline{x}_{ij},\underline{g}_{ij},\underline{p}_{ij},\underline{w}_{ij},z \geqq 0, \text{ all } i,j \;,$$

where:

z = total level of sediment delivered to defined water channels as a result of annual average sheet and rill erosion,

$S(z)$ = optimal value function which gives the minimum total cost of onland sediment control practices or prevention, which are functions of z for all potential levels of z. Thus, S(z) maps out the EPF,

π^{o}_{ij} = the baseline profit maximizing management system for each LMU_{ij} without any sediment constraint as determined in (2a),

$\pi_{ij}(\cdot)$ = the profits on LMU_{ij} of which the total change for all LMU's is minimized to meet the constraint on sediment delivery of z,

$\underline{y}_t$ = vector of m=1,...,M outputs,

$\underline{x}_t$ = vector of n=1,...,N inputs,

$\underline{g}_t$ = vector of k=1,...,K given physical characteristics,

$\underline{p}_t$ = row vector of m=1,...,M marketed output prices in time t,

$\underline{w}_t$ = row vector of n=1,...,N exogenously determined input prices,

$F_{ij}(\cdot)$ = implicit joint production function,

b_{ij} = soil erosion associated with production on this LMU,

$h_j(\cdot)$ = the hydrologic sediment delivery process within a catchment.

Equation 3a gives the total change in profits necessary to achieve the sediment delivery load z for all ij LMU's. This reduction in profits is equal to the sum of the difference between the profit maximizing solution for each LMU and the sediment constrained profit solution for each LMU. The difference in the two profit levels is the minimum amount that farm profits decrease to achieve a sediment constraint of z. The difference is the minimum payment that makes a producer indifferent between the profit maximizing and constrained profit maximizing management systems.

Equation 3b represents the production relationship on LMU_{ij}. The sediment delivery function (3c) sums the sediment delivered by each catchment to obtain the total amount of sediment delivered within the watershed. The sum must be less than or equal to z. Equation 3d restricts the choice of the input vectors to be contained within the feasible set of management systems.

The efficient prevention frontier is constructed by solving function 3a for all feasible levels of z. From the viewpoint of a resource manager, the frontier is analogous to a total cost curve for applying onland sediment control practices. The difference is that the frontier is composed of discrete points which represent sets of efficient management systems. By drawing lines between the points, we obtain the efficient prevention frontier. In accordance with the equal marginal cost rule, the marginal cost of controlling units of sediment delivered will be equal on all LMU's in the optimal solutions to the efficient prevention frontier (3a).

The sediment that results from profit maximizing farming with no sediment constraints can be determined directly from the EPF. This result is the point where

$$\pi^{o}_{ij} = \pi_{ij} , \quad \text{for all } i,j. \tag{3f}$$

The information provided by the EPF may be used to help identify the socially optimal level of sediment delivered from land within a watershed. The social optimum is found where the marginal damages of sediment equal the marginal abatement costs (Baumol and Oates 1975). Unfortunately, from the perspective of an individual resource manager, the information requirements and practical obstacles make the identification of a damage function, the

EPF, and the social optimum a considerable task; particularly in large watersheds. However, the EPF is an extremely useful benchmark for comparing the minimum costs of alternative sediment control policies or other related soil conservation objectives.

Alternative Sediment Delivery Relationships

Recall from the model review chapter that many analyses use erosion as a proxy for sediment. These analyses simplify the sediment delivery function (3c). Under a less sophisticated delivery ratio approach, the sediment delivery function constraint is replaced by

$$\sum_{j=1}^{J} \sum_{i=1}^{I} d_{ij} \cdot b_{ij} \leqq z \qquad (4a)$$

$$\text{If } d_{ij} = \begin{cases} 1 & \text{then sediment equals } 1 \cdot b_{ij} \text{ for } i=1,\ldots,I_j;\ j=1,\ldots J; \\ & \text{all erosion on each field becomes delivered sediment.} \\ \bar{d} & \text{then sediment equals } \bar{d} \cdot b_{ij}\ (0 \leq \bar{d} \leq 1) \text{ for } i=1,\ldots,I_j; \\ & j=1,\ldots J; \text{ the same constant proportion of erosion} \\ & \text{on each field becomes delivered sediment.} \\ d_{ij} & \text{then sediment equals } d_{ij} \cdot b_{ij}\ (1 \leq d_i \leq 1) \text{ for } i=1,\ldots,I_j; \\ & j=1,\ldots J; \text{ a different proportion of erosion becomes} \\ & \text{delivered sediment depending on the location of} \\ & \text{field.} \end{cases} \qquad (4b)$$

The above delivery ratio techniques do not account for the potential sediment transport properties of different management systems. Furthermore, the direction of bias is unknown because we do not know if the delivery ratios are under- or over-estimating sediment delivery.

Additional Management Constraints

Various management constraints can be applied to the model to determine their effectiveness as policy options. For example, a common onland policy is T value, which states erosion rates on soils should to be at or below their tolerance levels. The T value is the maximum yearly amount of sheet and rill erosion that can occur on a soil and still maintain the soil's inherent productivity indefinitely.

It is well documented in economic literature that standards are generally less efficient than other types of pollution controls (Baumol and Oates 1975). In addition, environmental economic theory tells us that any policy that controls emissions (erosion) rather than exposures (sediment) is likely to be inefficient (Nichols 1984). Thus, the T value policy is expected to lie above the EPF. The EPF, therefore, provides us with an effective tool for determining the relative inefficiency of T value and other resource policies.

T value is a constraint that can be incorporated in SEDEC by replacing the sediment delivery function in 3c with the following:

$$b_{ij} \leqq T_{ij}, \text{ for all } i,j. \tag{4c}$$

This type of constraint limits the number of management systems producers can apply to their land. Hence, one can expect an increase in sediment control costs.

Other policies also limit the management choices. For example, consider a policy that states management systems must be the same for all LMU's in a watershed. A constraint of this type would be akin to not letting the $\underline{x}_{ij}$'s and $\underline{y}_{ij}$'s vary by LMU:

$$\underline{x}_{ij} = \underline{x},\ \underline{y}_{ij} = \underline{y} \quad \text{for all } i,j. \tag{4d}$$

Such a policy may restrict the tillage method or conservation practice. For example, a policy that encourages no-till or contouring management systems would impose the following restrictions:

$$\underline{x}_{ij} \subset X_{NT} \subset X \subset R^{n} \quad \text{for all } i,j, \tag{4e}$$

$$\underline{x}_{ij} \subset X_{CN} \subset X \subset R^n \quad \text{for all } i,j. \qquad (4f)$$

where X_{NT} and X_{CN} are subsets of feasible no-till and contouring management systems.

Another policy that constrains the model in a similar fashion is a policy that seeks to place all cropland adjacent to waterways into a permanent vegetative cover. A specific case of such a policy would constrain actions on LMU_{1j} as follows:

$$\underline{x}_{1j} = \underline{x}_1 \subset X_{Hay} \subset X \subset R^n \quad \text{for all } j. \qquad (4g)$$

All of the policies that constrain management choices will be inefficient and lie above the EPF. From a practical viewpoint, these inefficient policies may be easier to implement and administer and not excessively inefficient. Hence we examine and compare EPF with other resource policies in Chapter VI.

CHAPTER IV

THE SEDEC SIMULATION MODEL

Overview of the Model

The SEDEC (SEDiment EConomics) computer simulation and optimization model (Braden et al. 1985; Bouzaher et al. 1987) was used to construct the efficient prevention frontier (EPF) and compare alternative watershed resource policies. The model addresses only average annual sheet and rill erosion and its movement in a watershed. Individual weather events, concentrated flow phenomenon, instream transport, stream bank erosion, and nutrient transport are not incorporated in the model.

The SEDEC model calculates farm profits, average annual sheet and rill erosion, and overland transport and delivery of sediment to well-defined water channels. A large number of management systems can be analyzed on each LMU. In addition, the model accounts for every possible combination of these management systems in the watershed. Another algorithm in SEDEC then uses this information to determine the least-cost combination of management systems that meet various sediment delivery levels for the watershed.

SEDEC is comprised of three subprograms: SOILSED, S-PGEN, and DPOPT. The relevant components of each subprogram are discussed in this chapter.

SOILSED

The economic returns and erosion rates under alternative management systems on each LMU are estimated in the SOILSED subprogram. SOILSED is a modified version of the SOIL EConomics model (SOILEC) (Dumsday and Seitz 1982; Eleveld, Johnson, and Dumsday 1983). For each LMU in the watershed, SOILSED combines physical characteristics, production information, and financial data to estimate long-run net returns and erosion rates associated with every management system applied to each LMU. Relevant components of SOILSED include the Universal Soil Loss Equation (USLE), a discounted net economic returns calculation, and a relationship linking long-run soil productivity to cumulative soil loss.

Universal Soil Loss Equation (USLE). On each LMU, SOILSED estimates an erosion rate for every management alternative using the USLE (Wischmeier and Smith, 1978):

$$A = R \cdot K \cdot LS \cdot C \cdot P, \qquad (5a)$$

where

A = annual average sheet and rill erosion loss in tons per acre,
R = local rainfall factor,
K = soil erodibility factor,
LS = slope length and steepness factor,
C = cropping and management factor,
P = conservation practice factor.

The USLE can be rewritten as follows to match the notation of the theoretical framework adopted in this study:

$$b_{ij}/a_{ij} = R_{ij}(g_{ij}) \cdot K_{ij}(g_{ij}) \cdot LS_{ij}(L_{ij}(g_{ij}), S_{ij}(g_{ij})) \cdot C_{ij}(\underline{x}_{ij}; g_{ij}) \cdot P_{ij}(\underline{x}_{ij}; g_{ij}), \qquad (5b)$$

where b_{ij} is erosion on LMU_{ij}; a_{ij} is acreage; and $LS_{ij}(\cdot)$ is a function developed by Wischmeier and Smith (1978) for generating the LS factor from the site specific values for slope length, $L_{ij}(g_{ij})$, and slope percentage, $S_{ij}(g_{ij})$. The R,K,and LS factors are functions of the physical characteristics g_{ij} on each LMU. Under this formulation, the C and P factors of the USLE change with different management systems. Terraces, a conservation practice, will also change the LS factor of the USLE. Therefore, annual average sheet and rill erosion is controlled through the choice of crop rotations, tillage methods, and conservation practices (i.e., through the choice of management systems previously defined by the input vector $\underline{x}_{ij}$).

Net Economic Returns. The discounted profit function in SOILSED is a standard present value of cumulative profits calculation as shown earlier in equation (2a). The function can be characterized as follows:

$$\pi = \sum_{t=1}^{T} \{ (1+r)^{-t} [\underline{p}_t \underline{y}_t - C(\underline{y}_t, b_t, \underline{x}; \underline{g}_t, \underline{w}_t)] + (1+r)^{-T}(V_T) \} \qquad (5c)$$

recall that

π = present value of cumulative profits over time,
t = time period where $t=1,\ldots,T$,
r = the discount rate,
$\underline{p}_t$ = row vector of $m=1,\ldots,M$ marketed output prices in time t,
$\underline{y}_t$ = vector of $m=1,\ldots,M$ outputs,
$C(\cdot)$ = total cost function,
$b_t(\cdot)$ = soil erosion associated with production on this LMU,
$\underline{x}$ = vector of $n=1,\ldots,N$ inputs which do not vary over time in SOILSED,
$\underline{g}_t$ = vector of $k=1,\ldots,d,\ldots,K$ given physical characteristics,
$\underline{w}_t$ = row vector of $n=1,\ldots,N$ exogenously determined input prices,
V_T = the salvage value of the production operation in the final period of the planning horizon, T.

Equation 5c is used within SOILSED to calculate the present value of cumulative profits for each management system. The difference in profits between each management system and the profit maximizing management system is calculated to determine the cost of choosing an alternative management system. Output from SOILSED expresses the cost differences among management systems as the equivalent annualized average cost over the planning horizon. The cost difference can be thought of as the minimum payment a producer would accept to change management systems.

Yield-Erosion Relationship. Changes in crop yields that correspond to decreases in soil depths due to cumulative erosion are estimated using a procedure presented by Bost (1980). The relationship between soil depth and cumulative soil erosion was previously characterized in 2d as:

$$g_{d,t+1} = g_{dt} - e(b_t, s), \tag{2d}$$

where

$g_{d,t+1}$ = soil depth at time t+1,
g_{dt} = soil depth at time t,
$e(\cdot)$ = function relating the soil depth g_{dt} to tons of annual soil erosion per acre,
$b_t(\cdot)$ = soil erosion associated with production at time t,
s = natural rate of soil replenishment.

The technique used by Bost combines soil bulk density and erosion rates to estimate $e(\cdot)$. The new soil depth is then substituted into the output relationship to determine yield response in the next year.

The relationship between soil depth and yield is calculated by linear interpolation between yields at four user-defined erosion stages. The yields and erosion stages used in this analysis are presented and discussed in the next chapter.

S-PGEN

The Sediment-Path GENerator (S-PGEN) (Bouzaher et al. 1987) combines the information provided by SOILSED with a sediment delivery function to determine the cost and tons of sediment delivery associated with every path, different combination of management systems along each transect. S-PGEN determines the least-cost combination of management systems for different sediment delivery levels on each transect in the watershed in the following manner:

1. Links together LMU's along a transect.
2. Determines all the possible combinations of management systems on all the LMU's along a transect.
3. Calculates the cost of each combination of management systems along a transect based on SOILSED output for the management system on each LMU.
4. Uses the Clarke-Waldo relationship to predict sediment delivery associated with the different combinations of management systems along a transect.
5. Determines the cost effective (nondominated) combinations of management systems for achieving different sediment delivery loads along each transect.
6. Stores the nondominated combinations of management systems by transect and passes the file on to the DPOPT algorithm.

Nondominated Paths. The fifth step is an important part of the operation of S-PGEN and requires elaboration. The paths (combinations of management systems on LMU's along transects) that are considered cost effective (nondominated) yield the lowest costs for any given sediment level. For example, a nondominated path would have the lowest cost of all paths along that transect with the same level of sediment delivery. Likewise, a nondominated path would have the lowest level of sediment delivery of all paths with the same cost along that transect. Only the nondominated paths are moved through to DPOPT.

Sediment Delivery Function. The sediment transport relationship embedded within S-PGEN is based on a procedure developed by C.D. Clarke and P.G. Waldo of the U.S. Soil Conservation Service (1983). The Clarke-Waldo relationship models the movement of eroded soil within catchments. It identifies potential points and amounts of deposition along transects. Deposition may occur when LMU's (defined as land units along a transect that have uniform slope, S, and uniform management, C and P) change along transects.

Specifically, the Clarke-Waldo relationship defines transport capacity along transects to be inversely proportional to deposition. Sediment transport capacity decreases at points of deposition due to any or all of the following factors: decrease in slope (S_{ij}), increase in crop and residue cover (lower C factor value), and increased application of conservation practices (lower P factors). Sediment transport capacity remains the same when a downslope LMU has a higher C,P, or S factor than an upslope LMU (all erosion from the upslope LMU will pass through the downslope LMU). However, if a downslope LMU has a lower C,P or S factor than an upslope LMU, sediment transport capacity decreases proportionally (an inversely proportional amount of the erosion from the upslope LMU is deposited and does not pass through the downslope LMU).

A sediment transport efficiency ratio can be calculated for each LMU boundary along transects as follows:

$$d_{ij} = d(\underline{x}_{i-1,j}, \underline{x}_{ij}; g_{i-1,j}, g_{ij}) = \frac{C^*_{i-1,j}}{C_{ij}} \cdot \frac{P^*_{i-1,j}}{P_{ij}} \cdot \frac{S^*_{i-1,j}}{S_{ij}} , \qquad i=2,\ldots,I_j, \text{ all } j, \tag{6a}$$

such that, for $i=2,\ldots,I_j$:

$$C^*_{i-1,j} = \begin{cases} C_{i-1,j} & \text{if } C_{i-1,j} \leq C_{ij} \\ C_{ij} & \text{if } C_{i-1,j} > C_{ij} , \end{cases}$$

$$P^*_{i-1,j} = \begin{cases} P_{i-1,j} & \text{if } P_{i-1,j} \leq P_{ij} \\ P_{ij} & \text{if } P_{i-1,j} > P_{ij} , \end{cases}$$

$$S^*_{i-1,j} = \begin{cases} S_{i-1,j} & \text{if } S_{i-1,j} \leq S_{ij} \\ S_{ij} & \text{if } S_{i-1,j} > S_{ij} , \end{cases} \tag{6b}$$

and $d_{1j}=1$ for all j, (6c)

where d_{ij} is the sediment transport efficiency ratio between $LMU_{i-1,j}$ and

LMU_{ij}; $\underline{x}_{ij}$ are chosen inputs; $\underline{g}_{ij}$ are physical characteristics; C and P are the USLE factors; and S is the percent slope.

These equations describe soil transport and deposition across LMU boundaries along transects. The last equation, 6c, states that all sediment reaching the lower boundary of the LMU adjacent to water is deposited in the channel or water body. For all other boundaries, the ratio in equation 6a applies subject to the truncations presented in equation 6b.

The truncations built into the calculation of the transport ratio do not affect the amount of sediment generated on $LMU_{i-1,j}$. The truncations prevent the amount of upslope sediment that passes through LMU_{i-1} from exceeding the amount that entered it. When these ratios are less than one, sediment transport capacity decreases and some deposition occurs.

Given these transport relationships, the total sediment delivered from all LMU's in catchment j is:

$$h_j(\cdot) = \sum_{i=1}^{I_j} \prod_{n=1}^{i} d_{nj} \cdot b_{ij} , \qquad n=1,\ldots,i \text{ for each } i=1,\ldots,I_j, \text{ for all } j, \tag{7}$$

where $h_j(\cdot)$ is total sediment delivered to a channel, b_{ij} is erosion, Π is the product operator, and d_{nj} is the transport efficiency ratio from (6a).

The formulation in equation 7 indicates that sediment delivered by catchments is not simply a function of management systems and physical characteristics on each LMU. Overland transport and delivery of sediment also depends on the management systems and physical characteristics of intervening LMU's for all LMU_{ij}, $i \neq 1$. Thus, the relationship generally takes into account spacial and management interdependencies in the overland flow of sediment. These management interdependencies are implicit since the transport efficiency ratios, d_{ij}, depend on management systems in the downslope $LMU_{i-1,j}$ in addition to systems on LMU_{ij}. In the same respect, management actions on LMU_{ij} affect transport efficiency ratios d_{ij} and $d_{i+1,j}$ (Bouzaher et al. 1987; Braden et al. 1988).

Certain idiosyncracies in the formulation of the Clark-Waldo relationship, however, can result in a situation where changes in management systems have no effect on delivered sediment. Appendix A presents a detailed discussion of how the Clark-Waldo sediment delivery relationship performs under numerous situations.

DPOPT

The Dynamic Programing Optimizer (DPOPT) is an algorithm for generating the least-cost solutions (Bouzaher et al. 1987). DPOPT utilizes output from S-PGEN on the cost-effective management combinations for each transect to determine both the achievable levels of sediment delivery for the watershed and the lowest cost, best management system combinations for each level of sediment delivery. The function for determining the sediment delivered to the watershed is the sum of sediment delivered by each catchment. Thus, from equation (7), total sediment for the watershed becomes $\Sigma_j h_j(\cdot)$. Unlike some models, DPOPT applies the efficiency criteria to determine the efficient combinations of management systems that meet sediment goals.

Summary

In summary, the SEDEC model is designed to achieve the following four primary goals: calculate the cost of alternative management systems in terms of forgone profits (net returns to land) on each LMU, estimate the USLE erosion rates associated with each management system on each LMU, determine the sediment consequences of all combinations of management systems, and find the least-cost combination of management systems for various levels of watershed sediment delivery. The SEDEC model employs three subroutines to achieve these goals. SOILSED combines economic and physical data to determine profits and erosion for all management systems on each LMU. S-PGEN links LMU's along transects to determine sediment delivery (according to the Clarke-Waldo relationship) and cost for every combination of management systems for each transect. S-PGEN then gives cost-effective paths along each transect. Finally, DPOPT uses the cost-effective sediment control paths to determine the least-cost combinations of management systems that meet various sediment delivery levels for the entire watershed.

CHAPTER V

APPLICATION TO APPLE CANYON LAKE

Problem Setting and Description

The analysis was conducted on a portion of the Apple Canyon Lake (ACL) watershed in Jo Daviess County, Illinois. Figure V.1 shows the Apple Canyon Lake watershed and it's location in Illinois. The 1,300-acre northeastern-most subwatershed that was modelled is also depicted in Figure V.I.

Apple Canyon Lake was formed in 1969 by damming Hell's Branch of the Apple River. The 480-acre lake is privately owned by the Apple Canyon Lake Property Owners Association. ACL is one of the deepest lakes in Illinois, reaching depths of 70 feet with an average depth of 30 feet.

The lakes primary uses are recreational and aesthetic. Recreational uses include fishing, boating, waterskiing, camping, swimming, picnicking, and wildlife observation. The lake's fishing quality is rated as excellent (Hawes and Hammel 1986).

The ACL watershed contains 13,000 acres of rolling terrain with slopes ranging from 3 to 25 percent. Approximately 25 percent of the land within the watershed is owned by members of the lake association. Agricultural producers own the remaining 75 percent (NALCO 1978).

The agricultural land is the primary source of sediment entering the lake. Over half of the agricultural land is currently in intensive row crop production. The slopes on cropland generally fall between 3 and 13 percent. The average cropland slope is approximately 8 percent. The slopes generally increase when moving toward watershed tributaries, that is, the steepest land is adjacent to waterways.

The analysis was conducted on the 1,300-acre northeastern subwatershed

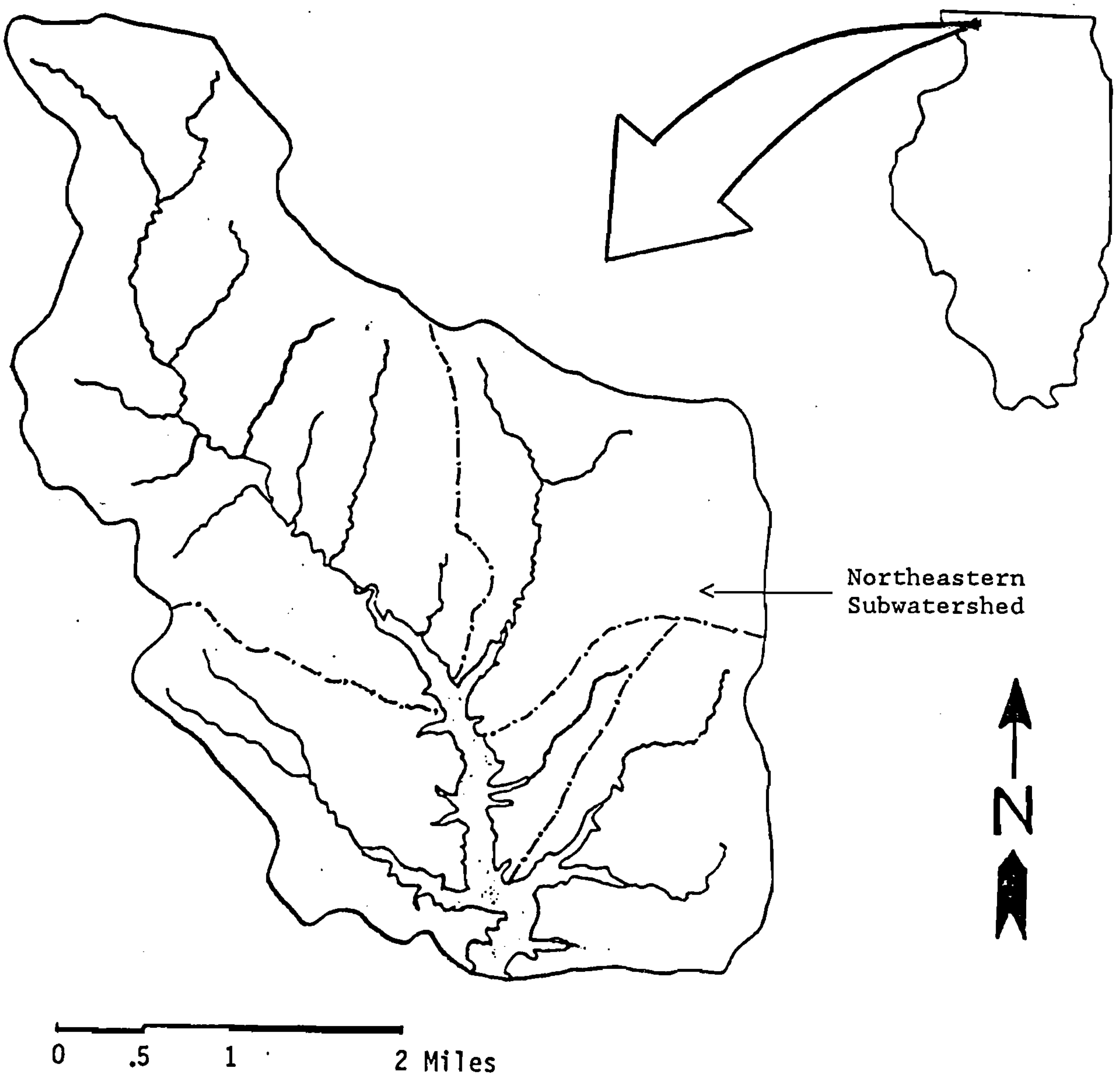


Figure V.1: Location and map of Apple Canyon Lake Watershed of Apple Canyon Lake. Only 955 of the 1,300 acres are actually in agricultural production. The noncropland areas, 345 acres, consist of wooded and grassed areas adjacent to water channels. Almost all cropland in the study area is separated from tributaries by noncropland. These noncropland areas adjacent to tributaries act as natural buffers or filter strips to reduce sediment delivered from cropland.

The remainder of this chapter discusses the data and associated procedures required to implement the SEDEC model on the 1,300-acre subwatershed. The first section describes the procedure and data necessary for constructing transects. The physical data required for each LMU and for the entire watershed is covered in subsequent sections. The final section covers the economic data requirements of SEDEC.

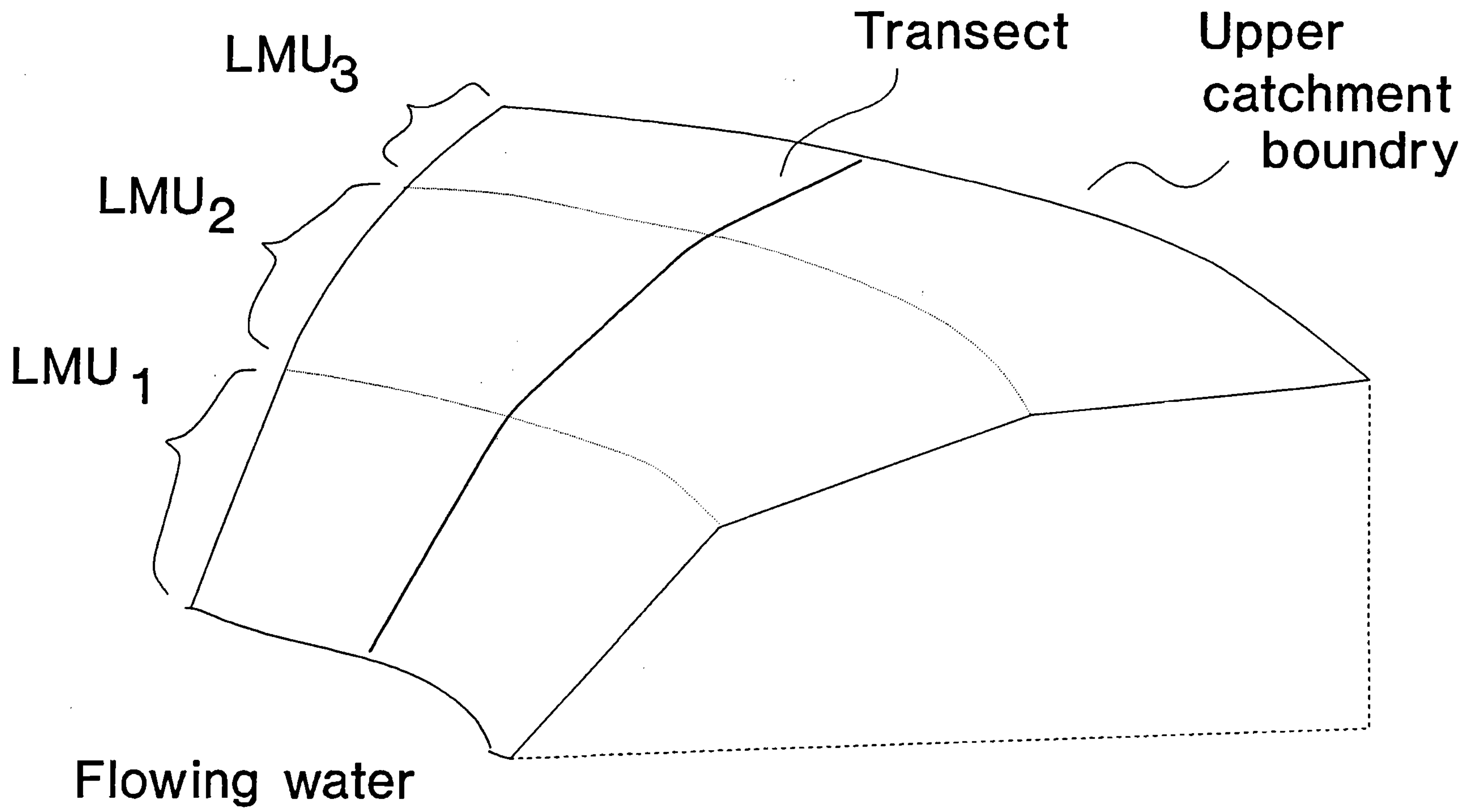
Constructing Transects and LMU's

The basic foundation of the SEDEC model rests upon LMU's and their interactions along transects within independent catchments of a watershed. Figure V.2 depicts some features of an example catchment. Recall that catchments are watershed subdivisions that are independent in their surface water hydrologies; that is, the area within a catchment drains into a common, well-defined water channel or water body, and no additional areas drain into the catchment.

Each catchment, j, can be partitioned into $i=1,...,I_j$ land management units (LMU). LMU's are areas of uniform slope and management system.

A transect is a representative drainage path within a catchment. Transects extend from the watershed boundary to a point of flowing water and intersect topographic contour lines at right angles. Within a catchment, each transect must cross each of the consecutive LMU's once and only once.

Figure V.2 An example catchment with a transect and three LMU's



Aerial photos, topographic maps, soils maps, farm boundaries, and field cropping histories for the 1,300-acre study area were used to identify catchments, LMU's, and transects. These items were obtained from Soil Conservation Service (SCS) and the Agricultural Stabilization and Conservation Service (ASCS).

Topographic maps were used to help identify the watershed and subwatershed boundaries. The topographic maps and aerial photos were both useful for dividing the subwatershed into catchments. Soil maps along with the topographic maps were then used to further divide catchments into the following uniform slope groups: A=0-2 percent, B=2-5 percent, C=5-10 percent, D=10-15 percent, E=15-20 percent, F>20 percent. Farm and field boundaries and cropping histories were used to complete the delineation of LMU's within catchments.

Within each catchment, transects were then drawn through LMU's perpendicular to topographic contour lines. In situations where transects would not cross each LMU within a catchment, catchments, LMU's and transects were reevaluated to allow transects to be drawn so that they crossed each LMU within a catchment only once.

Physical Data

The following section describes the physical data needed to implement the framework and methods put forth in previous chapters. The first group of subsections pertain to data requirements for each LMU, while later sections concern data requirements common to all LMU's.

Soil Types and Acreage. The acreage of each LMU was measured using a digitizer. MeasuGraph, 1986, a computer software package by Geographics, was used to compute acreage. In addition, the digitizer was used to determine the acreage of each soil type within a LMU. The soil types were taken from soil maps for the project area. The maps were obtained from SCS personnel stationed in Jo Daviess County. The soil types and slope class for each LMU on every transect can be found in Appendix B.

Other data collected by soil type for the A and B soil horizons include the K factor for erodibility, soil depths, and bulk densities. T values were also collected by soil types. The data were obtained from the Soils-5 computer database (SCS 1987). This database summarizes soil information collected and maintained by SCS personnel.

Crop Yields. Yields for agricultural crops vary by soil types due to differences in soil depth, drainage, fertility, and a host of other factors. Crop yields for uneroded soil types with 0-2 percent slopes were obtained from the Illinois Cooperative Extension Service publication Soil Productivity in Illinois (Fehrenbacher et al. 1978). Yields for soil types in slope class B through G were adjusted using the percentages in Table V.1. The table was also used to adjust yields to account for three erosion stages: uneroded, moderately eroded, and severely eroded.

Table V.1 Percent adjustment in yield by slope and erosion stage[1]

Slope percent	Erosion Stage[2] Uneroded	Moderate	Severe
0-2	100	97	90
2-5	99	96	89
5-10	97	94	87
10-15	93	90	83
15-20	87	84	77
20-25	80	77	70

1 Table adapted from (Fehrenbacher et al. 1978).

2 Erosion stages are defined as follows: moderate--one third of the plow depth consists of soils from the B soil horizon, severe--all of the A horizon is eroded.

Management Systems. A key element to the analysis is that management systems can be used to reduce onland erosion and overland transport of sediment. The management systems analyzed consist of combinations of crop rotations, tillage methods, and conservation practices.

Crop rotations. Crop rotations influence erosion rates on LMU's and the transport of sediment from upslope LMU's. Different crops within a rotation provide different crop canopies, different plant densities, and different amounts of residue following harvest operations. All of these properties are determinants of C factors (see Appendix C). The crop rotations considered are listed in Table V.2 and are based on ASCS records of actual farming practices in the watershed.

Tillage methods. Tillage influences erosion and sediment transport. The effects of tillage operations such as timing and amount of surface residue on erosion are captured in the C factors in the USLE. Furthermore, the ratio of C factors between LMU's help determine sediment delivery. The tillage methods that were analyzed are also listed in Table V.2.

Table V.2 Crop rotations, tillage methods, and abbreviations

Abv.	Crop Rotations	Abv.	Tillage Methods
CC	Continuous Corn	FPL	Fall Moldboard Plow
CS	Corn-Soybeans	SPL	Spring Moldboard Plow
CCS	Corn-Corn-Soybeans	FCL	Fall Chisel Plow
3CO3H[1]	Corn-Corn-Corn-Oats/Hay-Hay-Hay-Hay	SCL	Spring Chisel Plow
		RGTL	Ridge Till
HAY	Continuous Hay	NT	No-Till
COVER	Permanent Cover		

[1] Oats are companion cropped with the first year of hay.

On some soils different tillage methods may affect yields. However, in this analysis, yields were assumed to be unaffected by tillage methods. This assumption is based on the good drainage properties of the soils in the test area, and the existence of conflicting evidence on the effects of tillage methods on yields for soils that are drained moderately well to well (Siemens _et al_. 1980; Doster, Griffith, Mannering, and Parsons 1983; Griffith and Mannering 1985).

Conservation practices. Conservation practices add the third element to the description of a management system. Conservation practices considered include straight and contoured rows. The P factor for straight rows equals 1, which means no erosion or sediment control benefits. The P factors for contouring are found in Table V.3. Values range from 0.5 on B slopes to 0.9 on F slopes. The benefits of contouring decrease as slope increases.

Table V.3 P factor values for contouring on different slopes[1]

	Slope Percentage					
	0-2	3-8	9-12	13-16	17-20	21-25
P value	0.6	0.5	0.6	0.7	0.8	0.9

1 Table adapted from Walker and Pope (1983).

Originally, terraces were included as a structural conservation practice. Preliminary results showed, however, that even those terraces constructed on highly erosive lands were not cost effective. Hence, we dropped terraces from the analysis. These results are consistent with other studies (Johnson, Eleveld, and Setia 1984; English and Krog 1986; Setia and Magleby 1988).

One explanation might stem from the fact that terraces primarily control concentrated water flows and associated erosion problems rather than sheet and rill erosion. Hence, terraces are a prohibitively expensive way of controlling sheet and rill erosion.

Additional Physical Data. The C factor from the USLE represents the erosion benefits from the amount and timing of crop and residue cover as influenced by climate, crops, yields, and tillage. In the Clark-Waldo, C factors help determine sediment delivery through transport ratios between LMU's. C factors must be determined for each crop rotation-tillage method combination. The C factors used were constructed from published procedures and tables (Dickerson 1983). Appendix C details the procedure used to construct C factors for all of the management systems and presents the C factors.

The R factor from the USLE represents the erosive potential of rainfall patterns within a region. The R factor for the watershed equals 180 and can be found in Illinois Cooperative Extension Circular #1220 (Fehrenbacher *et al*. 1978).

Economic Data

The economic data are important because the choice of management systems is guided by the economic goal of controlling sediment at the least cost. Therefore, the discounted profit calculation is an important step in determining which combination of management systems achieves sediment goals at the least cost. The economic information that affects this calculation includes crop prices, yields, production costs, discount rates, and conservation practice costs.

Prices and Discount Rate. Changes in the relative prices of commodities may affect the profitability of alternative crop rotations. Initial tests confirmed this expectation. Relative price changes resulted in significant changes in crop rotations. The chosen long-run crop prices used in this study (see Table V.4) are based on discussions with Agricultural Economists at the University of Illinois (Good and Hinton 1987; Farnsworth 1987).

Table V.4 The per unit price and variable cost by crops within a rotation

CROP	UNITS	PRICE	COST
Corn	($/BU)	2.75	0.594
Soybeans	($/BU)	6.00	0.426
Oats	($/BU)	1.50	0.000
Hay	($/TN)	60.00	16.847
Hay w/oats	($/TN)	60.00	22.072
Cover	($/TN)	0.00	0.000

The discount rate serves the purpose of discounting future returns to reflect their present value. It is an adjustment that is necessary to reflect a producer's time preference of income. The discount rate used in this study is 8 percent.

Production Costs. The costs of production must be determined for each rotation-tillage combination. The data include variable costs per acre per bushel (ton) of each crop and the variable costs per acre for every crop rotation-tillage method. To determine these costs, crop budgets were generated using a computer software package, the Microcomputer Budget Management System (Olson et al. 1985).

The budgets were run for a 350-acre representative farm, $\frac{1}{m}$ the average size farm in the region of the study. Input prices used in the budgets were obtained from the local SCS technical manual (1986) and SCS budgets. Prices from other budgets were adjusted according to published indices (Hinton 1986). Input quantities were obtained from the Illinois Cooperative Extension Service publication Illinois Agronomy Handbook 1986-1987 (1986), and from SCS budgets (SCS 1986).

Input requirements differ among crops within a rotation and among tillage methods. For example, machinery, repairs, labor, herbicides, and insecticides differ among tillage methods. In addition to the inputs that vary by tillage method, fertilizers, seed, and harvest expenses differ among crops within a rotation.

For each of the six tillage methods, budgets were constructed for each crop sequence within a rotation. The crop sequences are as follows: corn after corn, corn after soybeans, corn after hay, soybeans after corn, and oats after corn. In addition, two budgets, hay establishment and hay maintenance, were constructed with generic operations and a fall plow tillage method. Thus, 32 budgets were generated.

Costs per unit of output are presented in Table V.4; costs per acre by rotation-tillage combination are presented in Table V.5 on the following page.

Table V.5 The costs per acre by rotation-tillage combinations

Crop Rotation[1]	Fall Plow	Spring Plow	Fall Chisel	Spring Chisel	Ridge Till	No Till
	$/Acre					
CC	$201.38	$201.81	$195.09	$191.31	$195.74	$194.61
CS	182.49	182.93	176.21	172.42	173.59	173.85
CCS	188.79	189.22	182.50	178.72	180.97	180.77
3CO3H	173.40	173.58	170.70	169.08	n/a	170.50
Hay[2]	155.87	n/a	n/a	n/a	n/a	n/a

1 CC is continuous corn, CS is corn-soybeans, CCS is corn-corn-soybeans, 3CO3H is three years corn-hay with oats cover crop-three years hay.

2 The costs are all the same for hay since the tillage operations for hay do not depend on the tillage used on other crops.

After the data were collected, they were entered into computer files and run through SEDEC. The next chapter describes the results of SEDEC simulation runs that represent a number of resource policies.

CHAPTER VI

ANALYSIS AND MAJOR FINDINGS

The analysis was conducted with SEDEC for the 1,300-acre subwatershed described in Chapter V. The initial run of SEDEC produced the Efficient Prevention Frontier (EPF). The EPF is the total payment or cost frontier. The EPF represents the difference in profits between the profit maximizing management system applied to every land management unit (LMU) and other sets of management systems that help a resource manager achieve specific sediment loads at least cost.

Several other resource policies, such as reducing erosion to T values, encouraging the use of no-till, supporting contouring, or targeting specific locations for treatment, were also simulated using SEDEC. The costs and sediment rates associated with these other resource policies were compared with the EPF and conclusions were drawn.

An important characteristic of the Apple Canyon Lake watershed is the prevalence of noncropland area adjacent to streams. To assess the relative importance of noncropland areas and possible impacts on the rankings of different resource policies, we removed the beneficial filtering effects of noncropland and repeated the entire analysis. The two sets of analyses follow.

The EPF and Other Resource Policies with Effective Noncropland Areas

The Efficient Prevention Frontier (EPF). The EPF is a cost or payment frontier that gives the minimum amount of money a resource manager may pay producers in a watershed for their cooperation in applying management systems that help the resource manager attain specific sediment delivery goals. The EPF for the 1,300-acre watershed is shown in Figure VI.1. As expected, costs steadily increase as sediment delivery decreases.

The point labeled A in Figure VI.1 represents the predicted annual sediment delivery before bargaining begins between a resource manager and producers. At point A, producers apply the most profitable management system to each LMU that results in a total sediment delivery of 1,545 tons annually.

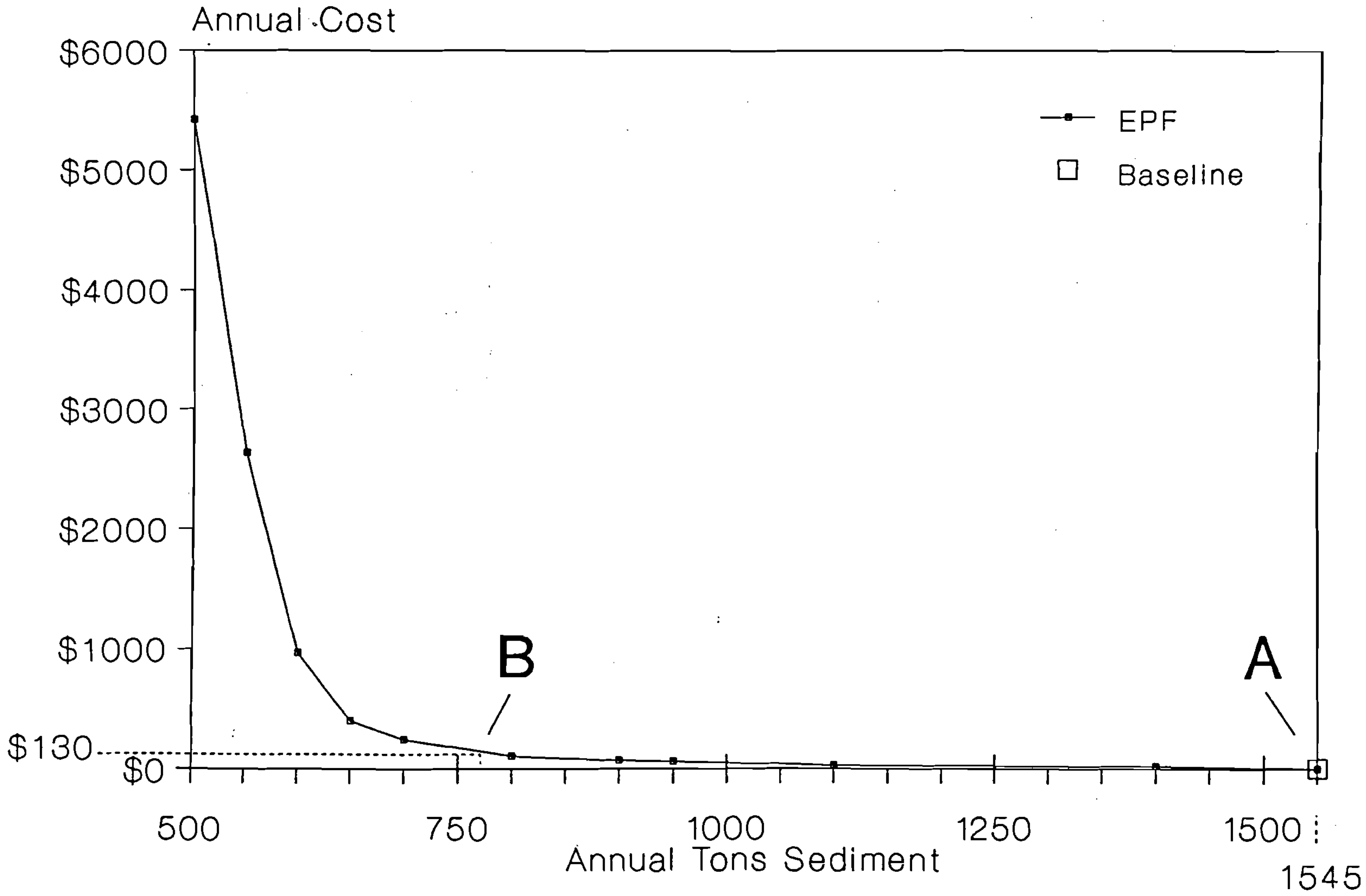
The EPF is relatively flat over a large range of sediment rates. For example, consider point B, which represents a 50 percent reduction in annual sediment delivery (775 tons annually) at a cost to the resource manager of $130 annually. The $130 represents the total difference in profits between the most profitable management systems applied by producers to all LMU's in the watershed and the application of other management systems on selected LMU's to achieve a 50 percent reduction in sediment delivery.

At very low levels of sediment delivery, payments to producers increase rapidly. The management systems needed to achieve these low sediment levels generally produce extremely low profits when compared with the most profitable management systems.

Built into the SEDEC model are farm and field constraints. Researchers may impose the constraints if it is uneconomical either to use multiple tillage methods on a farm or field or to change rotation and tillage on small acreages.

Farm or field constraints limit the set of management systems that can be applied to LMU's. Hence, new EPF's that are generated with these imposed constraints will lie above and to the right of the EPF in Figure VI.1. Research by Lupi (1988) points out these trends and discusses the

Figure VI.1. The efficient prevention frontier (EPF)



limitations of the farm and field constraints. For this report, and given the known diversity of rotations, tillage methods, and field sizes found on farms in the study area, we elected not to impose the constraints.

Alternative Resource Policies. The Efficient Prevention Frontier (EPF) shown in Figure VI.1 represents the least costly set of management systems for any feasible sediment level in the watershed. Other policies and their related sets of management systems that are not part of the efficient frontier are, by definition, inefficient.

SEDEC can be used to simulate many of the policies discussed in resource circles. The costs and sediment rates of these policies can be compared with the EPF to determine their relative desirability.

T values. One policy frequently supported by decision makers is the use of T values or soil-loss tolerance levels. The T value assigned to each soil is the maximum amount of sheet and rill erosion that a soil can incur on a yearly basis and still indefinitely maintain its inherent productivity. In Illinois, T values for soils range between 2 and 5 tons of eroded soil per acre annually (Walker and Peterson 1982).

The use of T values for reducing sediment has received considerable support for several reasons. First, most states use T values in their erosion control guidelines and laws. Second, although not directly addressing sediment delivery, policy makers believe that less erosion means less eroded soil entering waterways and lakes. Third, T values and the Universal Soil Loss Equation (USLE), which predicts average annual sheet and rill erosion, are built on many years of research.

T values target erosion, not sediment. Furthermore, the T value policy does not take into account the marginal cost criteria. That is, management systems are not chosen based on their costs for controlling an additional unit of sediment. Therefore, the T value policy can be expected to lie above the EPF.

For comparison purposes, SEDEC was used to identify the least-cost management system that met T on each LMU and to estimate erosion and sediment delivery. The total erosion associated with the T value policy is 3,115 tons per year. This rate is much less than the baseline erosion rate with no controls (5,778 tons per year).

As shown in Figure VI.2, a resource manager that adopted a T value approach would pay producers $844 yearly to achieve 820 tons of sediment delivery per year. The efficient set of management systems represented by the EPF could achieve the same 820 tons of sediment delivered at a cost of $104 per year.

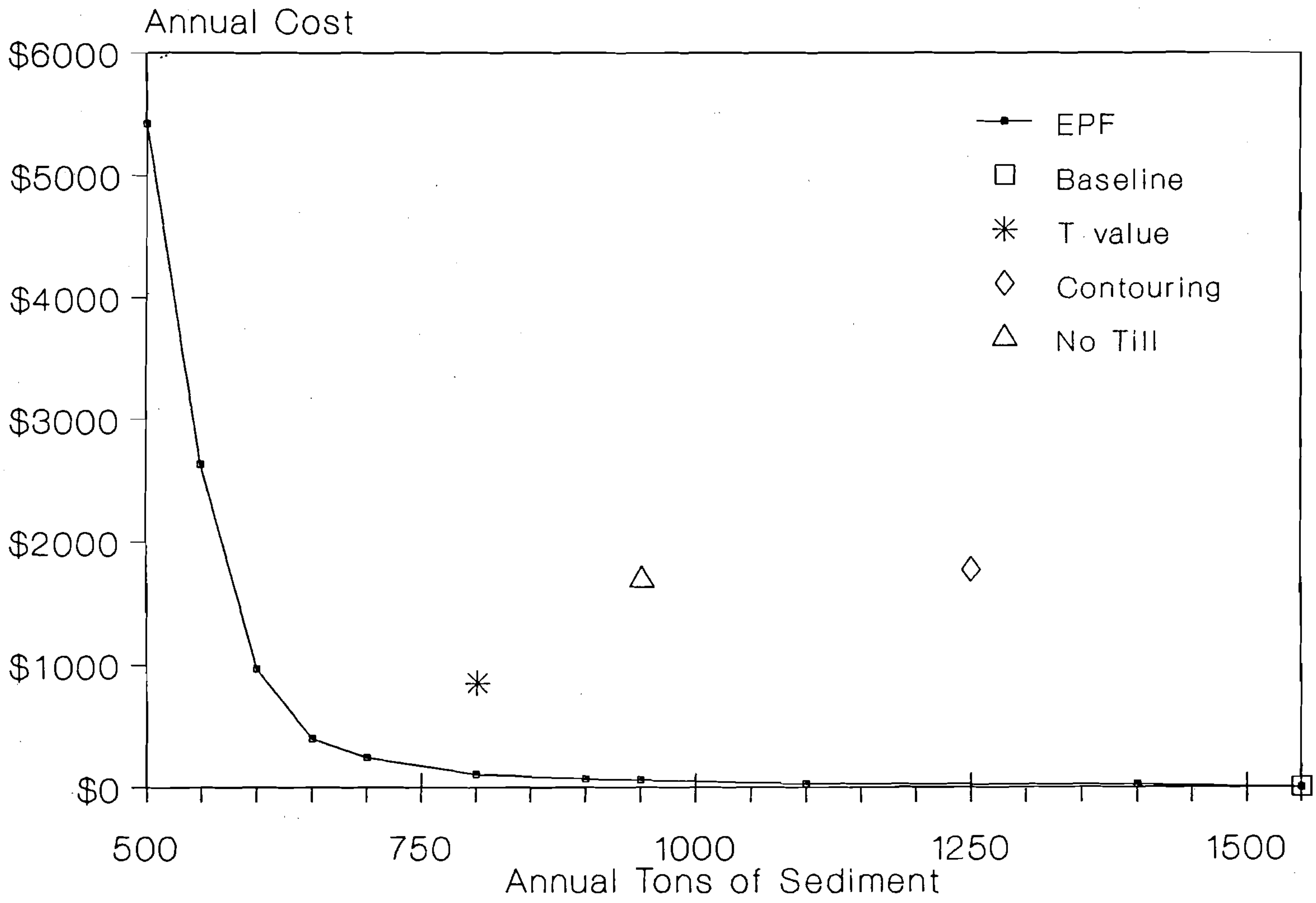
No-till. Another popular resource policy promotes the use of conservation tillage, particularly no-till. To reflect this policy, only no-till management systems were considered in the SEDEC simulations.

The total erosion associated with the no-till policy is 2,200 tons per year. This rate is less than half of the 5,778 tons of erosion per year that accompanies the baseline systems with no controls.

The no-till policy is inefficient because it does not specifically address sediment and ignores marginal cost criteria. The amount of sediment delivered when all LMU's are in no-till management systems equals 920 tons per year and costs $1,693 per year (see Figure VI.2). The cost for the same sediment delivery level using the EPF is $63 per year.

Contouring. Researchers generally consider contouring an effective way of reducing erosion and sediment without incurring excessive costs. Various

Figure VI.2. EPF and alternative watershed policies



estimates of the reductions in sediment that can be achieved with contouring range from 20 to 75 percent (Clark _et_ _al_. 1985).

Again, a policy that encourages contouring on all land in a watershed restricts input choice. The restriction eliminates a large number of feasible management systems that could have been used to achieve the same sediment reduction at lower costs. The contouring policy should be inefficient for the same reasons mentioned for the no-till policy. SEDEC simulations confirm this expectation.

The total erosion associated with the contouring policy is 3,759 tons per year compared with 5,778 tons per year for the baseline systems. Sediment delivered equaled 1,260 tons per year at a cost of $1,762 per year. The cost of the same sediment level on the EPF equals $24 per year (see Figure VI.2).

The contouring policy results in approximately a 20 percent reduction in sediment from the profit maximizing amount of 1,545 tons per year. The reduction is at the low end of the estimates found in Clark _et_ _al_. (1985). Two possible reasons can be given. First, the land in the watershed is fairly steep, and the benefits of contouring decline as slope increases. Second, many of the less productive LMU's are already in hay or permanent cover.

Targeting LMU location. In controlling sediment, a strategically important LMU along any given transect is the LMU adjacent to flowing water. LMU_{1j} is important because all of the sheet and rill erosion on this LMU becomes sediment. LMU_{1j} also serves as a filter for all of the incoming sediment from the upslope LMU's.

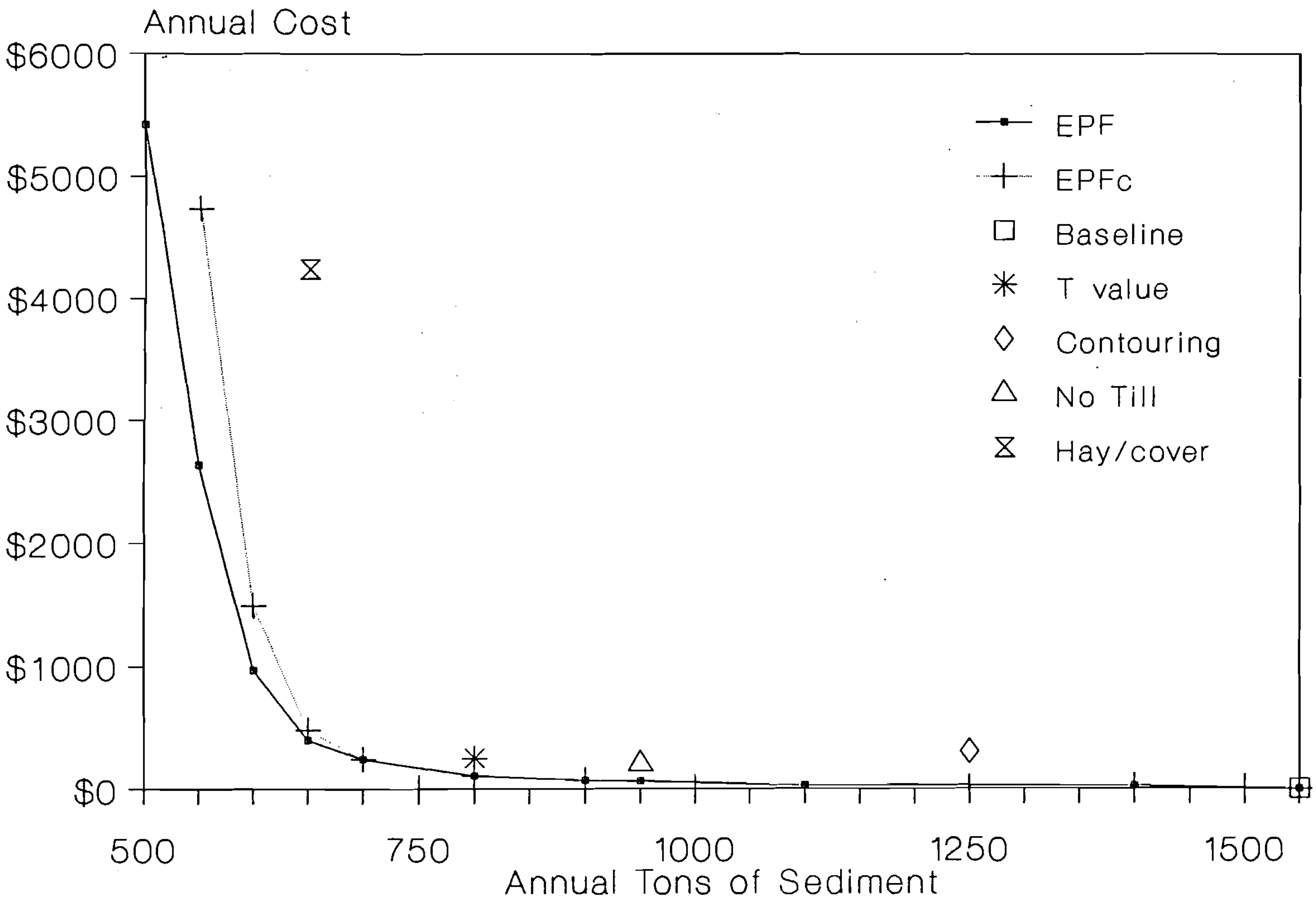
We examined a number of policies that assumed that a water resource manager negotiated with producers to change management systems either on the cropland LMU adjacent to water or the first cropland LMU closest to water. In the latter case, one or more noncropland LMU's lie between water and the first cropland LMU in the transects. On all the other LMU's in every transect, producers apply management systems that maximize profits.

Simulation results from the policies that target only the first cropland LMU for control measures are shown in Figure VI.3. The EPF_c frontier has the same general meaning as the original EPF, but this time, a resource manager only pays producers to change management systems on the first cropland LMU.

For small reductions in sediment, the cost for the EPF and EPF_c frontiers are very close (Figure VI.3). At lower sediment delivery levels, EPF_c becomes more costly. The reason is that ever more costly management systems must be applied to reduce sediment levels. Without the restriction, the resource manager could have negotiated with producers to apply control measures on other LMU's and achieve the same sediment delivery at a lower cost or payment to producers.

The T value, no-till, contouring, and hay/cover policies applied to the first cropland LMU's are more costly. Their costs lie above both the original EPF and EPF_c. All of these policies further restrict the number of management systems that can be applied to the first cropland LMU. For example, the no-till policy states that producers can only apply management systems on the first cropland LMU that have erosion rates below T values. The most restrictive and most expensive policy is hay/cover. Under this policy, the producer has the choice of putting the first cropland LMU in hay or permanent cover. Both hay and cover have similar erosion and sediment

Figure VI.3. EPF and policies applied only to cropland LMU's closest to water



transport characteristics.

Summary. Erosion, sediment, and cost estimates of the policies under consideration and cost estimates from the EPF are shown in Table VI.1. Several interesting observations are discernable.

Table VI.1. Erosion, sediment, and cost comparisons among policies

	Total erosion (tons/yr)	Total sediment delivered (tons/yr.)	Cost of sediment delivered ($)	Cost from EPF_c frontier ($)	Cost from EPF frontier ($)
No controls	5778	1546	0	--	0
T value	3115	819	845	--	104
No-till	2200	920	1693	--	63
Contouring	3759	1261	1762	--	25
Policies that target the first cropland LMU					
T value	4642	820	248	107	104
No-till	4843	926	213	63	63
Contouring	5415	1304	308	25	25
Hay/cover	4298	676	4229	284	265

In general, a resource manager that works with producers and pays them to apply specific management practices on key LMU's will achieve the desired sediment delivery at the lowest cost. Other resource policies that limit the number of management systems or restrict the use of management systems to specific LMU's will increase sediment abatement costs.

From an erosion control perspective, the application of the T value, no-till, or contouring policy when applied to the entire watershed reduces erosion substantially more than the application of same policy to the first cropland LMU. From a sediment abatement perspective, the T value, no-till, and contouring policies when applied to only the first cropland LMU in every transect provide almost equivalent levels of sediment abatement at substantially lower costs than the same policies applied to all the LMU's in the watershed.

Several reasons can be given for this conclusion. First, the LMU's closest to water have an important role in sediment delivery. Proportionately more erosion on these LMU's becomes sediment. Second, well-protected downslope LMU's filter sediment from all upland LMU's. Third, the steepest LMU's in this 1,300-acre watershed typically border water channels, which amplifies their important role. Fourth, the Clark-Waldo delivery relationship, which is an integral part of the SEDEC model, tends to discount erosion and sediment abatement measures on upslope LMU's.

A final result is that a direct relationship does not exist between erosion and sediment control policies. When applied to the entire watershed, the T value policy reduces erosion less (3,115 tons per year) than the no-till policy (2,200 tons per year). Rankings, however, switch when comparing sediment delivery. The T value policy delivers less sediment (819 tons per year) than the no-till policy (920 tons per year). This result points out the importance of accounting for the effects of different management systems on the overland flow of sediment. For example, sediment delivery ratios would not reveal the difference in rankings of the T value and no-till policies in terms of erosion and sediment levels.

Before general conclusions and firm support for specific policies can be given, substantially more analyses must be done on other watersheds. Furthermore, the weaknesses of the Clark-Waldo relationship must be corrected (see Appendix A).

The EPF and Other Resource Policies with Ineffective Noncropland Areas

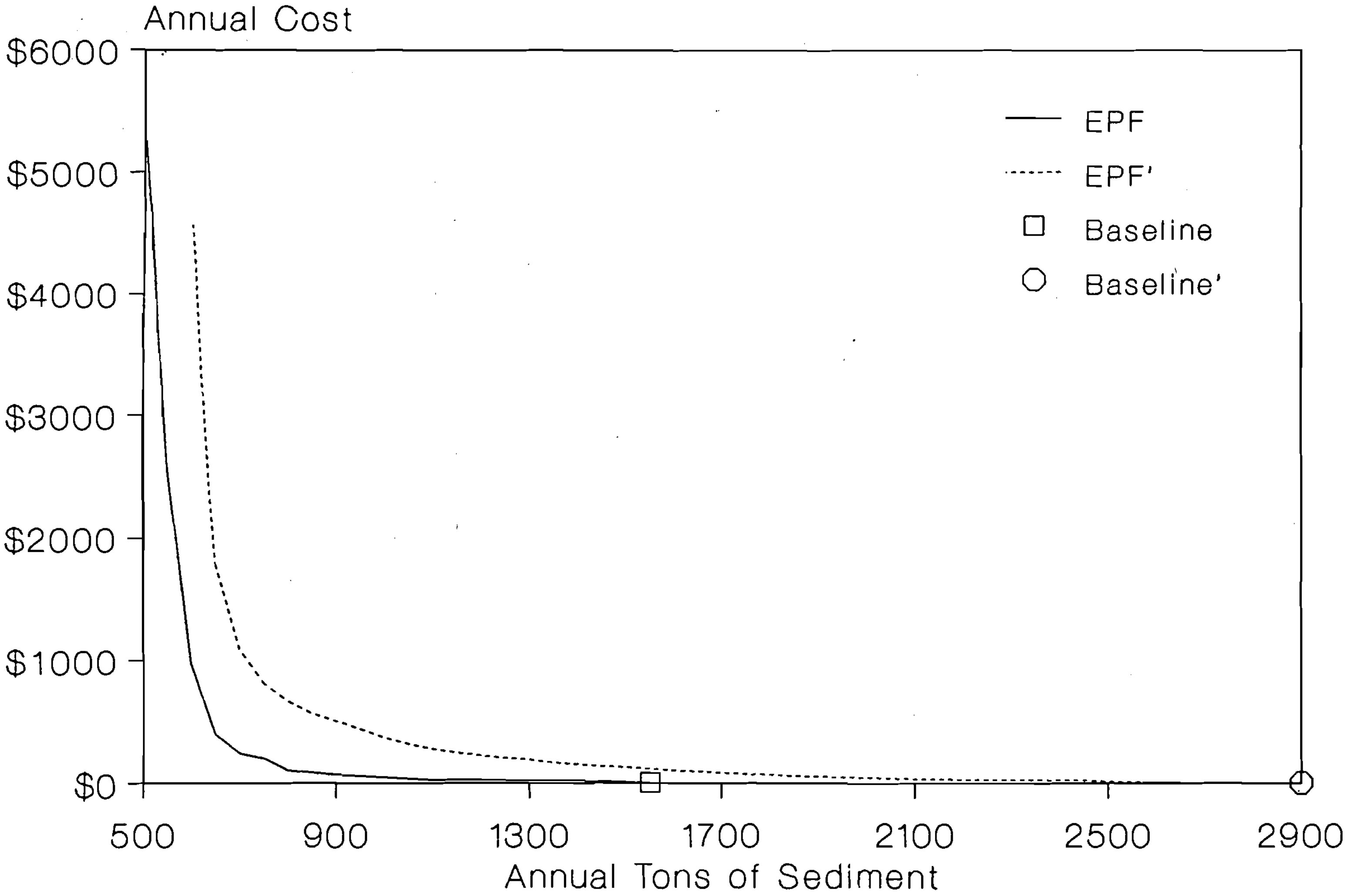
Recall that over 90 percent of the transects in the ACL watershed have natural undisturbed forest and grass areas that occupy the LMU or LMU's adjacent to water channels. The noncropland serves as a natural buffer or filter strip at the base of each transect and significantly reduces the base sediment load.

In the remainder of this chapter, we assume the noncropland LMU's no longer have any beneficial filtering effects on the overland flow of sediment. Either width is inadequate, or ephemeral gullies and gullies cut through these noncropland LMU's and remove their usefulness in trapping sediment.

The Efficient Prevention Frontier (EPF'). The elimination of sediment reduction benefits of noncropland LMU's in the watershed causes a significant jump in the amount of sediment delivered and increases costs to reduce sediment at all levels. The original EPF and EPF' (without the filtering effects of noncropland LMU's) are shown in Figure VI.4. The new least-cost frontier, EPF', maintains the same general properties and shape as the original frontier, EPF, and lies to the right and above the original EPF.

Rather than beginning at 1,545 tons per year, the resource manager must now begin negotiations with producers at a significantly higher sediment rate: 2,915 tons per year. Because sediment delivered is initially higher, use of the same management systems will not achieve the same level of

Figure VI.4. EPF and EPF' (without the filtering effect of noncropland LMU's)



abatement as shown by the original EPF. Hence, costs will increase for each sediment level as shown by the position of EPF'.

Interestingly, a resource manager acquires a new control measure. If costs are not excessive, the resource manager may entice producers to improve the condition or expand the noncropland area. For example, the difference between EPF' and EPF at 1,545 tons per year (the original baseline sediment delivery rate) equals $55 per year. If producers willingly accept $55 or less to make the noncropland areas effective, the resource manager should consider noncropland improvements as a valid policy option.

Alternative Resource Policies. The resource policies examined earlier are repeated. We examine the implications of implementing T value, no-till, and contouring policies on the entire watershed. Then we examine the implications of applying the same policies on the first noncropland LMU.

T value, no-till, and contouring. The results of simulation runs for T value, no-till, and contouring resource policies for the entire watershed and EPF' are exhibited in Figure VI.5. The policies maintain the same relative positions as before. The primary difference is that levels of sediment delivered are higher and abatement costs are higher.

Targeting LMU location. Next, the policies are only applied to the first noncropland LMU in every transect. The first policy that produces the frontier labeled EPF'_c allows the use of any management system on the first noncropland LMU in every transect. The T value, no-till, contouring, and hay/cover policies restrict the use of management systems to only those that meet the requirements of the specific policy.

Results of the location policies, EPF'_c are exhibited in Figure VI.6.

Figure VI.5. EPF' and alternative watershed policies: without the filtering effect of noncropland LMU's

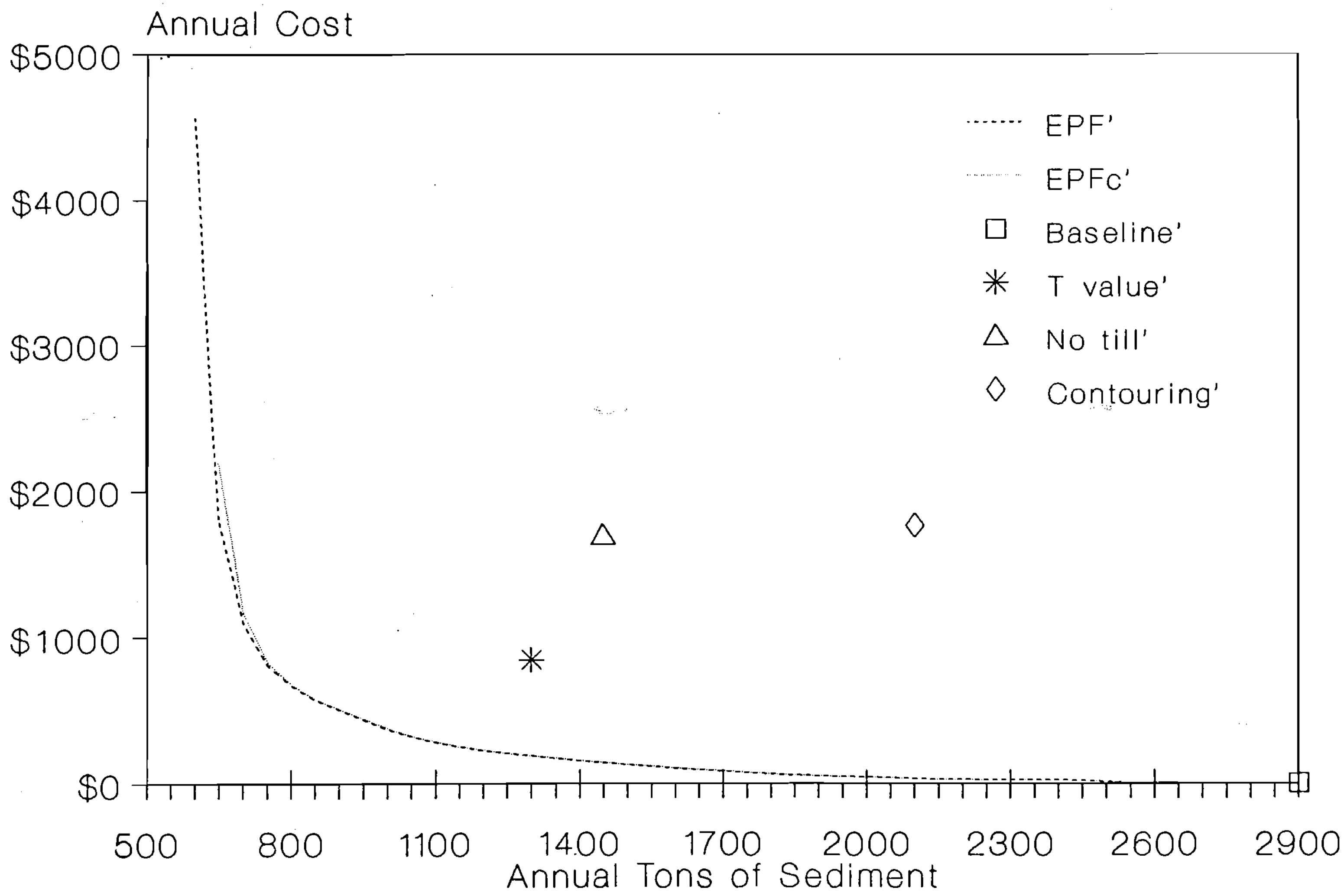
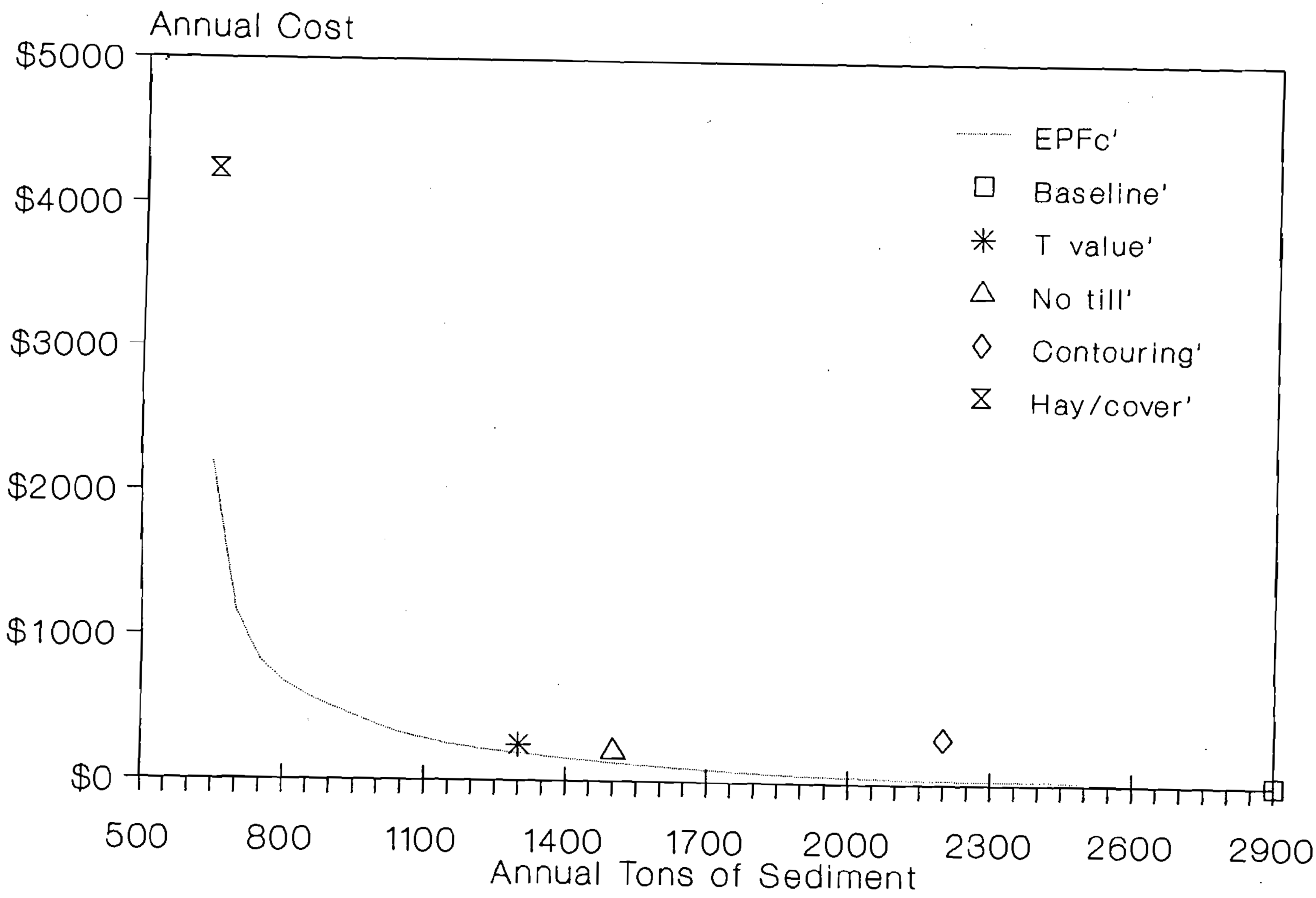


Figure VI.6. Policies applied only to cropland LMU's closest to water: without the filtering effect of noncropland LMU's



The policies maintain their relative rankings though sediment levels and costs are higher. In general, the policies are much closer to EPF'. The frontier EPF_c' is so close to EPF', it is virtually indistinguishable.

Summary. Erosion, sediment, and cost estimates of the policies under consideration and cost estimates from the EPF' and EPF_c' policies are shown in Table VI.2. Though the baseline sediment load is higher, the trends observed earlier in Table VI.1 are evident in Table VI.2. In addition, the resource manager acquired an additional policy option: pay to improve the effectiveness of noncropland areas. We briefly review the major trends and the new policy option.

First, the cost figures in Table VI.2 point out that the management systems that represent points on the efficient prevention frontier (EPF') have the lowest costs. The other policies in varying degrees are inefficient. Second, policies that target only the first cropland LMU on every transect compete effectively with the same policies applied to the entire watershed. This result is partly due to the important role of LMU's close to water channels and the Clark-Waldo relationship that discounts the erosion and sediment properties of management systems on upslope LMU's. Third, policies that effectively reduce erosion may not perform as well for reducing sediment. The switch in rankings between no-till and T value for erosion and sediment point out the importance of choosing an objective and then picking a policy that complements the objective.

Under the assumption that noncropland areas were either too small or not adequately maintained to filter sediment, the resource manager acquired an additional policy option: pay producers to improve the noncropland area. This policy should be seriously considered because producers may be more willing to work with private groups to improve noncropland areas than employ new management systems on cropland.

Table VI.2 Erosion, sediment, and cost comparisons among policies without the filtering effects of noncropland

	Erosion rate (tons/yr)	Sediment delivered (tons/yr.)	Cost of sediment delivered ($)	Cost from EPF'_c frontier ($)	Cost from EPF' frontier ($)
No controls	5778	2915	$0	--	$0
T value	3115	1320	845	--	187
No-till	2200	1424	1693	--	151
Contouring	3759	2095	1762	--	35
Policies that target the first cropland LMU					
T value	4642	1324	248	187	185
No-till	4843	1490	213	132	132
Contouring	5415	2191	308	31	31
Hay/cover	4298	676	4229	1863	1318

CHAPTER VII

PRINCIPLE FINDINGS, LIMITATIONS, AND RECOMMENDATIONS

The observation that private groups who benefit from cleaner water are willing to pay for nonpoint source pollution abatement initiated this research. The cost-share funds provided by the Apple Canyon Lake Owners Association to producers who willingly apply onland conservation measures to reduce sediment delivery focused our interests and objectives.

The primary objective of our study was to identify an efficient cost frontier for controlling sediment and then to use the frontier as a basis to compare other resource policies. Our secondary objective was to modify, use, and critique components of an average annual watershed model called Sediment Economics (SEDEC). To accomplish the two objectives, we collected physical and economic data on a 1,300-acre subwatershed of the Apple Canyon Lake watershed, which is located in Jo Daviess County, Illinois. We used a modified SEDEC to generate a least-cost frontier that we labeled the efficient prevention frontier (EPF). Costs and sediment delivery associated with the T value, no-till, and contouring resource policies were also calculated using SEDEC. Our principle findings, limitations, and recommendations for future work follow.

Principle Findings

First, the integration of physical and economic concepts in an average annual model such as SEDEC suggests that large reductions in sediment delivery can be achieved at modest cost. Furthermore, an efficient cost frontier can be constructed that gives the minimum total payment to producers that would make each of them indifferent between applying their profit maximizing management system and another management system that helped a resource manager meet a specific sediment delivery goal.

Second, other resource policies such as T value, no-till, and contouring cost more to apply because the policies reduce the set of feasible management systems. When these policies are applied to the entire subwatershed, generally T value dominates no-till and contouring policies and no-till dominates contouring.

Third, the application of T value, no-till, or contouring policies to only the first cropland land management unit of every transect almost achieves the same level of sediment delivery as the same policies applied to the entire 1,300 acres. Furthermore, the costs of applying the T value, no-till, or contouring policies to the first cropland unit lie slightly above the efficient prevention frontier. This finding signifies the relative importance of downslope land management units versus upslope land management units. However, discrepancies in the Clark-Waldo sediment delivery relationship warrant a note of caution.

Fourth, noncropland areas adjacent to streams significantly reduced sediment delivery and costs. Resource managers may consider the maintenance of noncropland area adjacent to streams another policy that should be seriously investigated along with the application of conservation measures on cropland.

Fifth, rankings among the inefficient policies change when the objective changes. For the entire watershed, no-till is the preferred policy from an erosion control perspective. However, T value is the preferred policy when the objective is to reduce sediment delivery.

Sixth, the Clark-Waldo relationship sometimes fails to account for the effects on sediment delivery from changing management systems on upslope land management units. Further refinement of the relationship may be necessary to more adequately estimate sediment delivery.

Finally, other restrictions such as the same crop rotation and tillage method on a field or the same tillage method on an entire farm are restrictions that reduce the set of feasible management systems. Though we did not extensively investigate these restrictions because of the small fields and multiple systems used on each farm in the watershed, sediment delivery and abatement costs will be higher under such restrictions.

Limitations

All of the above results are subject to limitations. First, the results apply only to the 1,300-acre Apple Canyon Lake subwatershed. Analyses on other watersheds are needed before general statements and trends can be stated with confidence.

Furthermore, the model only accounts for sediment generated by sheet and rill erosion. Other forms of erosion caused by concentrated flow are not modelled. Instream erosion and transport processes are also not included in the model. In addition, the results are contingent upon the accuracy of the erosion and sediment delivery calculations.

The sediment delivery relationship used in this study had strong and weak points. Numerous management systems could be applied to each LMU and sediment could be predicted by the sediment delivery equation. In some instances though, the effects on delivered sediment from changing management systems was not fully predicted. The direction and degree of the bias appears small, but additional analysis is needed.

The results are also based on the economic assumption that producers maximize profits. The assumption allows the determination of the amount of money that would make a producer indifferent between the most profitable management system and other systems. In reality, producers may follow more complex behavioral rules that may change the amount of money that makes a producer indifferent between management systems.

Recommendations

A complex physical and economic model can be used to help resource managers meet their goals. Substantially more work, however, needs to be accomplished before these models can be part of a manager's set of decision aides. The following recommendations point out areas of needed research.

Future work is needed to develop practical and user friendly models that accurately account for all the effects of management systems on erosion and sediment. The incorporation of concentrated flow, instream, and inlake processes would also be extremely beneficial. The inclusion of nutrient and chemical transport components would also be desirable.

On the economic side, the cost effectiveness of instream and inlake sediment control practices needs to become part of future investigations. These controls will allow the construction of a more general cost frontier for controlling sediment, rather than a cost frontier for controlling cropland sediment with onland practices.

In addition, a damage function for sediment needs to be determined so that the damages and control costs can be used to determine the socially optimal sedimentation levels. Furthermore, formulation of the water quality problem using dynamic optimization over time would allow researchers and managers to examine intertemporal tradeoffs. Finally, by incorporating risk analysis into the problem, researchers would be able to asses whether the types or timing of optimal controls would change under uncertainty.

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APPENDIX A

THE CLARKE WALDO DELIVERY RELATIONSHIP

The primary rational for using a hydrologic model with a sediment delivery relationship is straight forward. All soil that erodes in a watershed will not necessarily become sediment in streams or lakes within that watershed. Therefore, practices that are aimed at controlling sediment will be more cost effective than erosion controls whenever all erosion does not become sediment in waterways. A sediment delivery relationship is a tool that can be used to predict the amount of sediment that occurs under different scenarios. Thus, a sediment delivery relationship enables users to differentiate between onland soil erosion and delivered sediment so that control practices can be more effectively used to reduce sediment.

As such there are certain properties that would be desirable for a delivery relationship to have. The following are just a sample of all these properties: verifiable, accurate, use readily available data, be compatible with economic optimization, be capable of prediction, and account for management intervention in the overland flow of sediment.

Unfortunately the state-of-the-art models do not allow us to do all of these at once. Each model has advantages and disadvantages. The remainder of this appendix will discuss the advantages and disadvantages that were encountered in using the Clarke-Waldo relationship (C-W) in this analysis.

There are many advantages of the C-W. The relationship does not require the extensive and difficult to obtain data necessary for the event based models discussed in the model review. Because C-W is based on annual average sheet and rill erosion, it is also readily compatible with annual economic data and long-run planning needs. The C-W also adopts the LMU as the basis for data collection rather than a square cell. This approach is more compatible with farm and field boundaries, and physical realities. In addition, the C-W functional form is computationally not too demanding to be solved by programs that run on personal computers. Furthermore, the C-W is capable of being combined with large economic optimization routines to allow sediment controls to be targeted in an economically optimal way.

Previous models have not been capable of combining economics with sediment delivery relationships to analyze all the potential combinations of management systems as SEDEC can with the C-W. Event based models are computationally too complex to be effectively combined with economic optimization algorithms within a personal computer format. Even though economics can be incorporated with erosion based delivery ratio techniques, these techniques are too simple to allow management systems to have any intervening effects on sediment delivery. Most importantly, therefore, the primary feature of the C-W was that it offered the promise of being able to combine many of the desired aspects in a workable format.

The remainder of this appendix will explore some aspects of the functional form of the C-W in detail. An example transect is constructed and the C-W is applied to all the possible scenarios that arise. Finally, the effects of changes in management factors on sediment delivered is discussed for these scenarios.

An Example to Show Affects of Management Changes

To fully see what is going on with the C-W, this section will cover all the possible scenarios that can occur on an example transect with three LMU's. The form of the C-W under these different scenarios will be presented. In addition, the C-W will be differentiated with respect to management changes to explore the effects of changes in management systems on delivered sediment.

To begin with, the C-W is presented in its general form, and then for the case of three LMU's prior to the truncation of any transport ratios. Recall that the C-W was characterized by the following function for sediment delivered by each transect j,

$$h_j(\cdot) = \sum_{i=1}^{I_j} \prod_{n=1}^{i} d_{nj} \cdot b_{ij} \text{ , all } j \tag{7}$$

where b_{ij} is the USLE erosion on LMU_{ij}, and d_{nj} is the C-W transport ratio between LMU_{ij} and $LMU_{i-1,j}$. For ease of exposition, let h_j be represented by h and drop the transect subscript j. The relationship will, for a three LMU case, become

$$h = b_1 + d_2 \cdot b_2 + d_2 \cdot d_3 \cdot b_3$$

Substituting in for the appropriate transport ratios, d_n, and the USLE erosion rates, b_i, the function becomes

$$h = R \cdot K_1 \cdot LS_1 \cdot P_1 \cdot C_1 + (S_1/S_2 \cdot P_1/P_2 \cdot C_1/C_2) \cdot R \cdot K_2 \cdot LS_2 \cdot P_2 \cdot C_2 +$$
$$(S_1/S_2 \cdot P_1/P_2 \cdot C_1/C_2) \cdot (S_2/S_3 \cdot P_2/P_3 \cdot C_2/C_3) \cdot R \cdot K_3 \cdot LS_3 \cdot P_3 \cdot C_3$$

where h is total sediment delivered by this transect; R,K,LS,C,P are the USLE factors for erosion on the subscripted LMU; and the ratio's in parentheses are the Clarke-Waldo transport ratios between LMU's.

By assuming that all P factors are equal to 1, and that all the slopes are the same, the mathematics will be greatly simplified without changing the implication of the results. The relaxation of these assumptions is discussed later. Cancelling the P's and S's reduces the equation for sediment delivered to

$$h = R \cdot K_1 \cdot LS_1 \cdot C_1 + (C_1/C_2) \cdot R \cdot K_2 \cdot LS_2 \cdot C_2 + (C_1/C_2) \cdot (C_2/C_3) \cdot R \cdot K_3 \cdot LS_3 \cdot C_3$$

Recall the truncations that occur in calculating the transport ratios. If the C factor on LMU_1, C_1, is greater than the C factor for LMU_2, C_2, then the ratio C_1/C_2 is truncated to 1 to prevent more soil from being transported than actually eroded. Because of these potential truncations, it is necessary to define the relationship between C factors in order to take the partial derivatives of the function with respect to management factor C. The four potential relationships between C factors for the three LMU case with constant P and S factors are as follows:

1. $C_1 \geq C_2 \geq C_3$,
2. $C_1 \geq C_2 \leq C_3$,
3. $C_1 \leq C_2 \geq C_3$,
4. $C_1 \leq C_2 \leq C_3$.

For scenario 1, where $C_1 \geq C_2 \geq C_3$, C_1/C_2 and C_2/C_3 are truncated and set equal to one. The function for sediment delivered reduces to

$$h = R \cdot K_1 \cdot LS_1 \cdot C_1 + R \cdot K_2 \cdot LS_2 \cdot C_2 + R \cdot K_3 \cdot LS_3 \cdot C_3$$

which is simply the sum of erosion on each LMU. The change in sediment delivered by each LMU with respect to a change in each of the C factors is given as

$$\partial h/\partial C_1 = \partial v_1/\partial C_1 = R \cdot K_1 \cdot LS_1 > 0$$

$$\partial h/\partial C_2 = \partial v_2/\partial C_2 = R \cdot K_2 \cdot LS_2 > 0$$

$$\partial h/\partial C_3 = \partial v_3/\partial C_3 = R \cdot K_3 \cdot LS_3 > 0$$

and all partials with respect to other LMU's equal 0.

Where v_i is the actual amount of sediment delivered by LMU_i ceribus paribus.

The result is that when downslope LMU's have increasing C factors the change in sediment for a change in C factor will equal the change in sediment delivered by the LMU in which C changes, which equals the change in erosion on that LMU. This result is due to the truncation of the transport ratios. In addition, since all of the USLE coefficients are positive in sign and as there are no negative signs in the resulting expressions, the signs of the partials will all be positive. In this situation, the C-W will act as desired. Interestingly, the function under this scenario behaves exactly like a delivery ratio in which all erosion becomes sediment.

Scenario 3

Moving to scenario number 3, where $C_1 \leq C_2 \geq C_3$, the transport ratio for C_2/C_3 will be truncated to 1 as before. However, the ratio C_1/C_2 will not be truncated, and the equation for sediment delivered becomes

$$h = R \cdot K_1 \cdot LS_1 \cdot C_1 + (C_1/C_2) \cdot R \cdot K_2 \cdot LS_2 \cdot C_2 + (C_1/C_2) \cdot R \cdot K_3 \cdot LS_3 \cdot C_3$$

Note that the C_2's in the second expression cancel out leaving the following

$$h = R \cdot K_1 \cdot LS_1 \cdot C_1 + (C_1) \cdot R \cdot K_2 \cdot LS_2 + (C_1/C_2) \cdot R \cdot K_3 \cdot LS_3 \cdot C_3$$

Taking all the partials derivatives of sediment delivered with respect to changes in C factors gives the following:

for changes in C_1,

$$\partial h/\partial C_1 = R \cdot K_1 \cdot LS_1 + R \cdot K_2 \cdot LS_2 + R \cdot K_3 \cdot LS_3 \cdot (C_3/C_2) > 0$$

$$\partial v_1/\partial C_1 = R \cdot K_1 \cdot LS_1 > 0$$

$$\partial v_2/\partial C_1 = R \cdot K_2 \cdot LS_2 > 0$$

$$\partial v_3/\partial C_1 = R \cdot K_3 \cdot LS_3 \cdot (C_3/C_2) > 0$$

for changes in C_2,

$$\partial h/\partial C_2 = R \cdot K_3 \cdot LS_3 \cdot C_1 \cdot C_3 \cdot -1/(C_2)^2 < 0$$

$$\partial v_1/\partial C_2 = 0$$

$$\partial v_2/\partial C_2 = 0$$

$$\partial v_3/\partial C_2 = \partial h/\partial C_2 = R \cdot K_3 \cdot LS_3 \cdot C_1 \cdot C_3 \cdot -1/(C_2)^2 < 0$$

for changes in C_3,

$$\partial h/\partial C_3 = R \cdot K_3 \cdot LS_3 \cdot C_1/C_2 > 0$$

$$\partial v_1/\partial C_3 = 0$$

$$\partial v_2/\partial C_3 = 0$$

$$\partial v_3/\partial C_3 = \partial h/\partial C_3 = R \cdot K_3 \cdot LS_3 \cdot C_1/C_2 > 0$$

The results of the partials under this scenario provide some interesting insights into the actual working of the C-W.

Beginning with changes in C_1, the signs of the partials all have the desired direction. When C_1 is increased, the total amount of sediment delivered by the transect increases, as does the amount of sediment delivered by each LMU. The changes are in the desired direction. If the management system on LMU_1 becomes more erosive, then total sediment should increase, as should the sediment delivered by LMU_1. Furthermore, as desired, the increase in erosion on LMU_1 will increase the transport of sediment through LMU_1 from LMU_2 and LMU_3. Thus, changes that occur due to changes in C_1 are all in the desired direction.

The results for changes in C_2 are not as promising. The sign for the change in total sediment delivered when C_2 changes is negative. Likewise, the sign for changes in sediment delivered by LMU_3 is negative. In addition, there is no change in sediment delivered by LMU_2 and LMU_1 when C_2

changes. When the C factor on LMU_2 changes the amount of sediment delivered by LMU_1 should not change, so the result for $\partial v_1/\partial C_2$ is desirable. However, when C_2 changes the sediment delivered by LMU_2 should increase, not remain constant.

The reason sediment does not increase lies in the formulation of the C-W in this scenario. The C_2's for LMU_2 cancelled out so that C_2 has no effect on the term for LMU_2, that is, an increase in C_2 causes an proportionate increase in USLE erosion for LMU_2, while at the same time it causes a proportionate decrease in the transport ratio. The net effect is that changing C_2 will have no effect on the amount of sediment delivered by LMU_2.

Furthermore, changing C_2 will have a negative effect on the amount of sediment delivered by LMU_3. This result comes about through the transport ratio C_1/C_2. For LMU_2, the decrease in the transport ratio was counteracted by an increase in erosion. However, the decreased transport ratio is multiplied by the erosion on LMU_3 to determine the amount of erosion from LMU_3 that becomes sediment. So when C_2 increased, the transport ratio between LMU_1 and LMU_2 decreased; its effect on LMU_2 is balanced by the increase in erosion, but its effect on LMU_3 is not countered by anything. The decreased transport ratio is multiplied by LMU_3 and the model predict that less eroded soil becomes sediment. The combined effects cause a change in C_2 to have a negative effect on total sediment delivered by the transect. The desired effect would be that an increase (decrease) in C_2 would have an increase (decrease) on total sediment delivered by the transect, on sediment delivered by LMU_2, and on sediment delivered by LMU_3.

In fact, the same results will hold for changes in the P factor. The results for changes in the P factor can be seen by simply substituting P for C. Results for changes in slope would be somewhat different since slope is not a linear term in the USLE. However, slope is not changed by management so it is not as relevant. The effects of changes in delivered sediment under all the scenarios for changes in C factors are presented in Table C.2. The generalized result is that whenever any factor on LMU_{i-1} is less than that factor on LMU_i, and the factor on LMU_i is greater than that factor on LMU_{i+1}, the effect on sediment delivered of changing the factor on LMU_i will be negative.

Table A.1 Desired verses actual signs of partial derivatives of the C-W for changes in sediment delivered with respect to changes in C factors for all four scenarios with three LMU's.

Scenario 1. $C_1 \le C_2 \le C_3$

	Clarke Waldo					Desired			
	∂v_1	∂v_2	∂v_3	∂h		∂v_1	∂v_2	∂v_3	∂h
∂C_1	+	+	+	+	∂C_1	+	+	+	+
∂C_2	0	0	0	0	∂C_2	0	+	+	+
∂C_3	0	0	0	0	∂C_3	0	0	+	+

Scenario 2. $C_1 \le C_2 \ge C_3$

	Clarke Waldo					Desired			
	∂v_1	∂v_2	∂v_3	∂h		∂v_1	∂v_2	∂v_3	∂h
∂C_1	+	+	+	+	∂C_1	+	+	+	+
∂C_2	0	0	-	-	∂C_2	0	+	0	+
∂C_3	0	0	+	+	∂C_3	0	0	+	+

Scenario 3. $C_1 \ge C_2 \ge C_3$

	Clarke Waldo					Desired			
	∂v_1	∂v_2	∂v_3	∂h		∂v_1	∂v_2	∂v_3	∂h
∂C_1	+	0	0	+	∂C_1	+	0	0	+
∂C_2	0	+	0	+	∂C_2	0	+	0	+
∂C_3	0	0	+	+	∂C_3	0	0	+	+

Scenario 4. $C_1 \ge C_2 \le C_3$

	Clarke Waldo					Desired			
	∂v_1	∂v_2	∂v_3	∂h		∂v_1	∂v_2	∂v_3	∂h
∂C_1	+	0	0	+	∂C_1	+	0	0	+
∂C_2	0	+	+	+	∂C_2	0	+	+	+
∂C_3	0	0	0	0	∂C_3	0	0	+	+

APPENDIX B

TRANSECT AND LMU SUMMARY FOR N.E. SUBWATERSHED OF ACL

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
1	1	1	3.33	13	120	4	-	429	D2	1	3.33	100
		2	7.50	8	200	5	-	280	C2	1	7.50	100
		3	17.89	3.4	300	5	-	279	B	1	12.60	70
								278	B	1	5.29	30
2	1	*1	0.52	8	50	4	-	429	C2	1	0.52	100
		2	2.48	8	167	4	-	429	C2	2	2.48	100
		3	8.99	3.8	300	5	-	279	B	2	7.39	82
								278	B	2	0.73	8
								429	B	1	0.87	10
3	1	*1	0.97	12	60	2	-	973	D2	1	0.97	100
		2	1.56	12	116	2	-	973	D2	2	1.56	100
		3	2.81	8	116	5	-	279	C2	1	2.81	100
		4	6.11	3.6	133	5	-	429	B	2	0.28	4
								279	B	3	4.68	77
								278	B	3	1.15	19
4	1	*1	4.09	12	67	2	-	973	D2	3	4.09	100
		2	9.32	8	133	4	-	429	C2	3	4.00	43
								279	C2	2	5.32	57
		3	11.91	4	300	5	-	279	B	4	11.63	98
								278	B	4	0.28	2
5	1	*1	11.60	19	150	4	-	29	E2	1	11.60	100
		2	2.81	13	83	4	-	429	D2	2	2.81	100
		3	16.31	4	500	5	-	279	B	5	16.31	100
6	1	*1	9.46	19	116	4	-	29	E2	2	9.46	100
		2	8.42	12	133	2	-	973	D2	4	8.42	100
		3	3.80	8	83	5	-	279	C2	3	3.80	100
7	1	*1	0.64	13	33	5	-	279	D2	1	0.64	100
		2	0.97	13	67	5	-	279	D2	2	0.97	100
		3	1.59	8	216	5	-	279	C2	4	1.59	100
8	1	*1	1.61	8	20	4	-	547	C2	1	1.61	100
		2	2.93	8	150	4	-	547	C2	2	2.93	100
		3	6.15	4	300	5	-	279	B	6	6.15	100
9	1	*1	1.03	8	20	4	-	547	C2	3	1.03	100
		2	2.35	8	83	4	-	547	C2	4	2.35	100
		3	6.96	4	200	5	-	279	B	7	6.96	100

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
10	1	1	9.10	8	400	3	-	547	C2	5	3.71	41
								417	C2	1	1.35	14
								418	C2	1	4.14	45
		2	11.64	4	400	4	-	547	B	1	5.91	50
								279	B	8	5.73	48
								386	B	1	0.24	2
11	1	1	14.68	8	600	4	-	547	C2	6	9.24	63
								417	C2	2	0.99	7
								418	C2	2	0.78	5
								753	C2	1	3.67	25
		2	9.93	3.9	250	4	-	279	B	9	4.30	43
								386	B	2	2.04	21
								753	B	1	2.00	20
								274	B	1	0.88	9
								36	B	1	0.71	7
12	1	*1	1.95	8	33	4	-	547	C2	7	1.95	100
		2	1.56	8	67	4	-	547	C2	8	1.56	100
		3	6.59	3.8	300	5	-	386	B	3	5.08	77
								36	B	2	1.51	23
		4	8.27	8	500	4	-	279	C2	5	2.25	27
								753	C2	2	6.02	73
		5	2.04	4	133	5	-	279	B	10	2.04	100
13	2	*1	0.71	19	100	4	-	29	E2	1	0.71	100
		*2	2.40	4	300	5	-	386	B	1	2.40	100
		3	10.81	3.2	600	5	-	36	B	1	9.10	84
								386	B	2	1.71	16
14	2	*1	0.46	13	33	5	-	279	D2	1	0.46	100
		2	3.61	8	133	4	-	279	C2	1	2.37	66
								547	C2	1	1.24	34
		3	0.73	4	133	5	-	386	B	3	0.73	100
15	2	*1	0.76	8	85	4	-	547	C2	2	0.76	100
		2	1.37	8	85	4	-	547	C2	3	1.37	100
		3	10.88	4	400	5	-	386	B	4	10.88	100
16	2	1	10.46	4	600	5	-	386	B	5	10.46	100
17	2	*1	1.61	13	67	5	-	279	D2	2	1.61	100
		*2	2.01	8	100	5	-	279	C2	2	2.01	100
		3	5.30	8	116	5	-	279	C2	3	5.30	100
		4	30.11	4	600	5	-	279	B	1	14.87	49
								386	B	6	15.24	51

TRANSECT	FARM	LMU	ACRES^a	S^b	L^c	T^d		SOIL^e	CLASS^f	N^g	AC^h	%LMU^i
18	2	*1	1.79	13	140	5	-	279	D2	3	1.79	100
		2	0.47	13	83	5	-	279	D2	4	0.47	100
		3	2.61	8	150	5	-	279	C2	4	2.61	100
		4	2.35	4	216	5	-	279	B	2	2.35	100
19	2	*1	4.24	13	120	4	-	547	D2	1	4.24	100
		*2	11.08	8	200	5	-	280	C2	1	11.08	100
		3	3.64	8	183	5	-	280	C2	2	3.64	100
		4	6.89	4	300	5	-	279	B	3	6.89	100
		5	6.41	4	167	5	-	279	B	4	6.41	100
*20	2	*1	6.02	19	200	3	-	417	E2	1	6.02	100
		*2	3.64	8	83	4	-	547	C2	4	3.64	100
		*3	7.91	4	300	5	-	280	B	1	7.91	100
*21	2	*1	9.76	19	67	4	-	29	E2	2	9.76	100
		*2	6.05	8	133	5	-	279	C2	5	1.92	32
								429	C2	1	4.13	68
		*3	10.46	4	300	5	-	280	B	2	9.08	87
								386	B	7	1.38	13
22	3	*1	1.22	13	120	4	-	29	D2	1	1.22	100
		2	15.67	8	600	4	-	279	C2	1	6.79	23
								547	C2	1	8.88	77
		3	6.95	3.8	300	5	-	280	B	1	3.20	46
								386	B	1	2.05	29
								36	B	1	1.70	25
23	3	1	29.22	8	600	4	-	279	C2	2	13.63	47
								547	C2	2	10.90	37
								386	C2	1	4.69	16
		2	6.07	3.5	300	5	-	36	B	2	3.08	51
								279	B	1	1.78	29
								280	B	2	1.21	20
24	3	*1	1.27	13	85	4	-	29	D2	2	1.27	100
		2	0.87	13	85	4	-	29	D2	3	0.87	100
		3	13.83	8	600	4	-	547	C2	3	7.72	56
								279	C2	3	3.26	23
								753	C2	1	2.85	21
		4	7.04	13	120	4	-	547	D2	1	4.62	66
								279	D2	1	2.42	34
		5	3.80	19	67	4	-	547	E2	1	3.80	100
25	3	*1	4.30	12	165	2	-	973	D2	1	4.30	100
		2	4.78	8	200	4	-	119	C2	1	2.91	61
								429	C2	1	1.87	39
		3	2.24	4	300	5	-	279	B	2	2.24	100
	4	4	11.05	4	300	5	-	279	B	3	9.96	90
								753	B	1	1.09	10

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
26	4	*1	1.12	12	85	2	-	973	D2	1	1.12	100
		2	7.47	8	185	4	-	279	C2	1	3.79	51
								119	C2	1	3.68	49
		3	6.49	4	250	5	-	279	B	1	6.49	100
27	4	*1	2.57	12	120	2	-	973	D2	2	2.57	100
		2	2.13	12	120	2	-	973	D2	3	2.13	100
		3	11.23	8	300	5	-	279	C2	2	11.23	100
		4	15.01	4	250	5	-	279	B	2	14.67	98
								280	B	1	0.34	2
28	4	*1	5.11	12	165	2	-	973	D2	4	5.11	100
		2	3.33	12	115	2	-	973	D2	5	3.33	100
		3	6.70	8	185	4	-	429	C2	1	6.70	100
		4	4.30	4	125	5	-	279	B	3	2.98	69
								280	B	2	1.32	31
29	4	*1	4.61	12	110	2	-	973	D2	6	4.61	100
		2	1.88	12	120	2	-	973	D2	7	1.88	100
		3	6.70	8	200	4	-	429	C2	2	0.35	5
								119	C2	3	0.92	14
								279	C2	4	5.43	81
		4	4.50	4	300	5	-	279	B	1	4.50	100
30	4	*1	3.29	20	120	1	-	504	E2	1	3.29	100
		2	2.45	8	116	3	-	417	C2	1	2.28	93
								547	C2	1	0.17	7
		3	6.45	4	300	5	-	279	B	5	6.45	100
		4	0.45	8	85	4	-	547	C2	2	0.45	100
31	4	1	12.55	8	600	4	-	547	C2	3	8.33	66
								417	C2	2	2.15	17
								279	C2	4	2.07	17
		2	6.24	8	600	4	-	547	C2	4	6.24	100
		3	0.58	19	67	4	-	547	E2	1	0.58	100
32	4	*1	0.91	20	60	1	-	504	E2	2	0.91	100
		2	3.06	12	200	2	-	973	D2	8	3.06	100
		3	3.18	8	166	4	-	279	C2	5	2.26	71
								429	C2	3	0.66	21
								417	C2	3	0.26	8
		4	2.60	4	265	5	-	279	B	6	2.60	100
33	5	*1	8.10	20	150	1	-	504	E2	1	8.10	100
		*2	5.67	19	120	2	-	973	E2	1	5.67	100
		3	14.22	12	165	2	-	973	D2	1	14.22	100
		4	11.27	8	200	4	-	429	C2	1	7.65	68
								29	C2	1	3.62	32

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
34	5	*1	0.80	19	67	2	-	973	E2	2	0.80	100
		*2	2.91	12	85	2	-	973	D2	2	2.91	100
		3	4.14	12	200	2	-	973	D2	3	4.14	100
		4	3.38	8	200	4	-	429	C2	2	3.38	100
		5	0.96	4	150	5	-	280	B	1	0.96	100
35	5	*1	12.43	30	300	4	-	29	F2	1	12.43	100
		*2	7.56	13	67	4	-	29	D2	1	7.56	100
		3	5.77	13	120	4	-	29	D2	2	5.77	100
		4	8.87	8	266	4	-	429	C2	3	5.22	59
								280	C2	1	3.65	41
		5	1.40	4	200	5	-	280	B	2	1.40	100
36	5	*1	6.50	20	300	1	-	504	E2	2	6.50	100
		*2	2.92	12	60	2	-	973	D2	4	2.92	100
		3	4.88	12	120	2	-	973	D2	5	4.88	100
		4	7.82	8	300	4	-	429	C2	4	4.79	61
								280	C2	2	3.03	39
37	5	*1	21.00	20	250	1	-	504	E2	3	21.00	100
		2	7.77	12	200	2	-	973	D2	6	7.77	100
		3	6.16	8	200	4	-	429	C2	5	5.21	85
								280	C2	3	0.95	15
38	5	*1	2.54	19	100	4	-	29	E2	1	2.54	100
		*2	3.08	12	120	2	-	973	D2	7	3.08	100
		3	3.37	12	120	2	-	973	D2	8	3.37	100
		4	4.87	8	225	4	-	429	C2	6	3.42	70
								280	C2	4	1.45	30
*39	5	*1	7.47	19	85	4	-	29	E2	2	7.47	100
		*2	3.22	13	120	4	-	29	D2	3	3.22	100
40	5	*1	4.27	19	100	4	-	29	E2	3	4.27	100
		2	3.73	19	67	4	-	29	E2	4	3.73	100
		3	4.00	12	120	2	-	973	D2	9	4.00	100
		4	1.68	8	85	4	-	429	C2	7	1.68	100
		5	1.62	4	67	4	-	429	B	1	1.62	100
41	6	*1	17.91	19	67	2	-	973	E2	1	17.91	100
		*2	6.51	12	100	2	-	973	D2	5	5.51	100
		3	23.79	12	120	2	-	973	D2	6	23.79	100
		4	20.70	8	200	4	-	429	C2	1	5.52	27
								279	C2	3	15.18	73
		5	4.78	8	85	5	-	279	C2	4	4.78	100
		6	8.79	4	300	5	-	279	B	3	8.79	100

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
42	6	*1	1.84	19	67	2	-	973	E2	2	1.84	100
		2	0.38	19	100	2	-	973	E2	3	0.38	100
		3	1.82	12	200	2	-	973	D2	1	1.82	100
43	7	*1	3.17	12	100	2	-	973	D2	1	3.17	100
		2	3.50	12	120	2	-	973	D2	2	3.50	100
		3	9.06	8	300	4	-	119	C2	1	7.93	88
								279	C2	1	1.13	12
		4	6.42	3.7	166	5	-	279	B	1	5.17	81
								61	B	1	0.90	14
								386	B	1	0.35	5
44	7	*1	1.28	8	85	4	-	119	C2	2	1.28	100
		2	12.89	8	300	4	-	119	C2	3	2.70	21
								386	C2	1	10.19	79
		3	19.80	3.5	300	5	-	386	B	2	14.60	74
								61	B	2	5.20	26
45	7	*1	0.80	12	35	2	-	973	D2	3	0.80	100
		2	2.70	12	120	2	-	973	D2	4	2.70	100
		3	6.36	8	200	4	-	119	C2	4	6.36	100
		4	4.57	4	133	5	-	279	B	2	4.00	87
								386	B	3	0.57	13
46	7	*1	2.90	12	120	2	-	973	D2	5	2.90	100
		2	0.98	12	35	2	-	973	D2	6	0.98	100
		3	3.90	8	200	4	-	119	C2	5	3.90	100
		4	1.03	4	50	5	-	279	B	3	1.03	100
47	7	*1	1.04	8	100	4	-	119	C2	6	1.04	100
		2	1.67	8	100	4	-	119	C2	7	0.68	41
								279	C2	2	0.99	59
		3	1.12	4	100	5	-	279	B	4	1.02	91
								386	B	4	0.10	9
48	7	*1	0.85	8	200	5	-	279	C2	3	0.85	100
		2	2.50	4	250	5	-	386	B	5	2.50	100
49	7	*1	0.38	8	35	4	-	119	C2	8	0.38	100
		2	3.71	8	200	4	-	119	C2	9	1.21	33
								279	C2	4	2.50	67
		3	9.97	4	300	5	-	279	B	5	4.95	50
								386	B	6	5.02	50
50	7	*1	2.69	12	67	2	-	973	D2	7	2.69	100
		2	3.38	12	85	2	-	973	D2	8	3.38	100
		3	16.29	8	200	4	-	279	C2	5	12.16	75
								119	C2	10	4.13	25
		4	14.92	4	300	5	-	279	B	6	14.92	100

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
51	7	*1	1.60	12	67	2	-	973	D2	1	1.60	100
		2	3.27	12	120	2	-	973	D2	2	3.27	100
		3	11.56	8	200	4	-	279	C2	1	6.36	55
								119	C2	1	5.20	45
		4	9.57	4	300	5	-	279	B	1	8.89	93
								386	B	1	0.68	7
52	7	*1	1.58	12	100	2	-	973	D2	3	1.58	100
		2	1.55	12	120	2	-	973	D2	4	1.55	100
		3	7.10	8	300	4	-	279	C2	2	6.38	90
								119	C2	2	0.72	10
		4	4.86	4	300	5	-	279	B	2	3.79	78
								386	B	2	1.07	22
53	8	*1	1.75	25	67	4	-	29	F2	1	1.75	100
		2	1.40	19	85	2	-	973	E2	1	1.40	100
		3	4.20	12	200	2	-	973	D2	1	4.20	100
		4	2.48	8	165	4	-	429	C2	1	1.34	54
								279	C2	1	1.14	46
54	8	*1	5.48	19	165	2	-	973	E2	1	5.48	100
		2	5.81	12	250	2	-	973	D2	2	5.81	100
		3	2.50	8	150	4	-	429	C2	2	1.37	55
								279	C2	2	1.13	45
55	8	*1	4.03	19	67	4	-	29	E2	1	4.03	100
		2	1.20	19	100	2	-	973	E2	3	1.20	100
		3	4.33	12	150	2	-	973	D2	3	4.33	100
		4	3.45	8	300	4	-	429	C2	3	3.45	100
*56	9	*1	3.24	12	180	2	-	973	D2	4	3.24	100
		*2	1.28	8	200	4	-	429	C2	4	1.28	100
57	9	*1	14.30	12	300	2	-	973	D2	5	14.30	100
		*2	5.06	8	165	4	-	429	C2	5	2.29	45
								279	C2	3	2.77	55
		3	5.08	8	300	5	-	279	C2	4	5.08	100
		4	2.09	4	100	5	-	279	B	1	2.09	100
58	10	*1	1.70	25	60	4	-	29	F2	1	1.70	100
		*2	1.00	19	60	2	-	973	E2	1	1.00	100
		3	0.72	19	50	2	-	973	E2	2	0.72	100
		4	3.94	12	200	2	-	973	D2	1	3.94	100
		5	1.27	4	85	5	-	280	B	1	1.27	100
59	10	*1	3.18	25	120	4	-	29	F2	2	3.18	100
		2	1.02	13	85	4	-	29	D2	1	1.02	100
		3	1.03	8	150	5	-	280	C2	1	1.03	100
		4	0.63	4	150	5	-	280	B	2	0.63	100

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
60	10	*1	2.60	25	85	4	-	29	F2	3	2.60	100
		*2	1.75	13	150	4	-	29	D2	2	1.75	100
		3	1.31	8	166	5	-	280	C2	2	1.31	100
		4	0.38	4	133	5	-	280	B	3	0.38	100
61	10	*1	1.65	19	85	4	-	29	E2	1	1.65	100
		*2	1.88	13	120	4	-	29	D2	3	1.88	100
		3	1.31	13	166	5	-	280	D2	1	1.31	100
		4	10.16	8	200	5	-	280	C2	3	8.89	87
								429	C2	1	1.27	13
		5	12.41	4	300	5	-	280	B	4	2.84	23
								279	B	1	9.57	77
62	10	*1	1.57	13	200	4	-	29	D2	4	1.57	100
		2	4.88	8	600	4	-	279	C2	1	3.25	67
								429	C2	2	1.63	33
		3	3.36	4	270	5	-	279	B	2	3.36	100
63	10	*1	1.01	19	100	4	-	29	E2	2	1.01	100
		2	0.66	19	85	4	-	29	E2	3	0.66	100
		3	1.23	8	300	4	-	429	C2	3	1.23	100
		4	0.37	4	100	5	-	279	B	3	0.37	100
64	10	*1	8.38	30	200	1	-	504	F2	1	3.55	42
								29	F2	8	4.83	58
		2	4.04	8	250	4	-	29	C2	1	2.83	70
								429	C2	4	1.21	30
		3	1.16	4	133	5	-	280	B	5	1.16	100
65	10	*1	18.55	30	300	1	-	504	F2	2	18.55	100
		2	8.07	12.2	120	2	-	973	D2	2	6.58	82
								429	D2	1	1.49	18
		3	6.46	8	120	4	-	429	C2	5	6.46	100
		4	2.65	4	85	5	-	280	B	6	2.65	100
66	11	*1	3.39	19	200	4	-	29	E2	4	3.39	100
		2	5.62	8	300	4	-	429	C2	6	5.62	100
		3	13.79	4	400	5	-	279	B	4	13.79	100
67	11	*1	0.59	19	67	4	-	29	E2	5	0.59	100
		2	0.75	19	67	4	-	29	E2	6	0.75	100
		3	2.44	13	85	4	-	29	D2	5	2.44	100
		4	2.98	8	100	4	-	429	C2	7	2.54	85
								280	C2	4	0.44	15
		5	4.58	4	165	5	-	279	B	5	4.58	100

TRANSECT	FARM	LMU	ACRES[a]	S[b]	L[c]	T[d]		SOIL[e]	CLASS[f]	N[g]	AC[h]	%LMU[i]
68	11	*1	4.95	19	120	4	-	29	E2	7	4.95	100
		2	6.00	13	120	4	-	29	D2	6	6.00	100
		3	8.24	8	165	4	-	280	C2	5	6.33	77
								429	C2	8	1.91	23
		4	7.54	4	205	5	-	280	B	7	3.44	46
								279	B	6	4.10	54
69	11	*1	1.37	19	150	4	-	29	E2	8	1.37	100
		2	1.60	13	67	4	-	29	D2	7	1.60	100
		3	5.33	8	200	4	-	429	C2	9	5.33	100
		4	6.19	4	200	5	-	280	B	8	6.19	100

Totals:

Transects	LMU's	Total acreage	Noncrop acres	Cropland acres
69	246	1300	345	955

* - Indicates that the LMU, Transect, or acreage is not in crop production.
a - The acreage of the LMU.
b - The average slope for the LMU.
c - The representative length of the LMU.
d - The T-value for the LMU.
e - The soil types that make up the LMU which were obtained from SCS soil maps. The numbers correspond to the following soils:

29	Dubuque	36	Tama	119	Elco
61	Assumption	274	Seaton	278	Stronghurst
279	Rozetta	280	Fayette	386	Downs
417	Derinda	418	Schapville	429	Palsgrove
504	Sogn	547	Elroy	753	Massbach
973	Dunbarton & Dubuque Complex				

f - The soil class for each soil where no number represents uneroded soil and the number 2 represents eroded soil. The letters represent general slope catagories: B-2-5%, C-5-10%, D-10-15%, E-15-20%, and F>20%.
g - Indicates the version number used in SOILSED data files.
h - The acreage of the soil type within the LMU.
i - The percentage of the LMU occupied by the soil type.

APPENDIX C

DETERMINING C FACTORS

The C factor, or cropping and management factor, is used in calculating the erosion that occurs on LMU's, and the sediment that is transported through an LMU. The affects of management on sediment delivery occur primarily though the C factors associated with different management systems. C factors depend primarily on the timing and amount of crop cover and residue cover. Each crop within a rotation will have different growth patterns, plant densities, and gross residue production, while each tillage system will reduce residues by different amounts and at different times. The amount of crop cover and residue cover is also influenced by yields since higher yielding soils will produce more cover. Therefore, management systems will affect C factors through the choice of crop rotations and tillage systems.

For SOILSED the C factors must be determined at five yield levels for every crop rotation-tillage system combination. The calculation of C factors is based on the procedure explained by Dickerson in Agronomy Technical Note IL-17 (Rev. 1), Soil Conservation Service, 1983. The process uses C factor tables developed for Northern Illinois rainfall and growth patterns found in the SCS Field Office Technical Guide - Illinois (1986). These tables contain C factors for each crop within a rotation, by tillage system and percent residue cover prior to planting. Thus the percent of residue cover prior to planting is required to calculate C factors. This can be found by multiplying the residue production factor (56 for corn, 60 for soybeans, and 50 for oats) by the yield of that crop. The resulting figure is then multiplied by the residue reduction factor (found in Table

C.1) for the desired tillage system to yield pounds of residue prior to planting. Pounds of residue cover is converted to percent residue cover for each crop using a relationship determined by Wischmeier and Smith (1978). Then for each tillage system, the C factors for an entire rotation can be determined by averaging the C factors for crops within that rotation. Finally, this procedure is followed for five different yield catagories to allow for the differences in C factors by LMU's due to different soil productivities. The C factors for rotation-tillage-yield combinations used in this analysis are presented in Table C.2.

The C factors for hay are assumed to be unaffected by soil productivity and are the same for all tillage systems since they were modelled using the same tillage implements regardless of the tillage system. The C factor for hay is therefore always 0.004. The same factor was used to represent cover and noncropland. This noncropland C factor roughly corresponds with the C factors for 90 percent grass cover or the 50 percent canopy for undisturbed forest land found in Illinois Cooperative Extension Circular #1220 (Fehrenbacher _et_ _al_. 1978). These grass and canopy cover percentages are consistent with those on noncropland in the Apple Canyon Lake watershed. Noncropland C factors do not change because, as modelled in this study, the land is not subject to control by agricultural producers.

Table C.1 Tillage Residue Factors (adapted from Dickerson, 1983)

Tillage[1]		Field Operations[3] (multiply across columns)								Residue
System	Crop[2]	W x	Ch x	D x	D2 x	C x	A x	P	=	Factor
FCL	Corn	.7	.75	.7	.7	.8	.8	.9	=	.148
	Soy	.7	.5	.4	.4	.5	.5	.85	=	.012
SCL	Corn	.7	.75	.7		.8	.8	.9	=	.212
	Soy	.7	.5	.4		.5	.5	.85	=	.030
RGTL	Corn	.7				.8	.8	.85	=	.381
	Soy	.7				.5	.5	.8	=	.140
NT	Corn	.7					.8	.9	=	.504
	Soy	.7					.5	.85	=	.298

1 The FPL and SPL systems leave no residue remaining on the surface of a field prior to planting and were therefore assigned a residue reduction factor of 0.

2 The effects of the field operations within a tillage system have different effects on corn and soybean residues because soybean residues are much more fragile than corn residues.

3 A tillage system is composed of a set of field operations that will reduce residue by the percentages shown in the table. These field operations are defined as follows:

W	Overwintering
Ch	Chisel plow, straight shanks
D	Disking
D2	Second Disking
C	Field cultivation
A	Anhydrous application with knife
P	Planting of the crop

Multiplying together all of the factors for percent residue remaining after each field operation will result in the appropriate residue factor for each tillage system and crop type.

Table C.2 Northern Illinois C factors by rotation-tillage-yield levels

		Yield Level[1]				
Rotation	Tillage	I	II	III	IV	V
CC	FPL	.408	.408	.408	.340	.340
CS	FPL	.450	.410	.375	.375	.375
CCS	FPL	.436	.436	.387	.363	.363
C3OH	FPL	.156	.156	.156	.156	.130
CC	SPL	.348	.348	.348	.290	.290
CS	SPL	.396	.360	.330	.330	.330
CCS	SPL	.380	.380	.337	.317	.317
C3OH	SPL	.131	.131	.131	.109	.109
CC	FCL	.264	.252	.228	.180	.170
CS	FCL	.336	.289	.265	.255	.243
CCS	FCL	.312	.296	.253	.230	.220
C3OH	FCL	.109	.107	.094	.076	.072
CC	SCL	.216	.194	.181	.135	.122
CS	SCL	.294	.246	.225	.219	.212
CCS	SCL	.270	.252	.206	.184	.179
C3OH	SCL	.090	.082	.072	.057	.051
CC	RGTL[2]	.181	.146	.119	.081	.063
CS	RGTL[2]	.265	.218	.194	.169	.158
CCS	RGTL[2]	.233	.212	.167	.146	.127
CC	RGTL[2]	.141	.114	.093	.063	.049
CS	RGTL[2]	.206	.167	.151	.131	.123
CCS	RGTL[2]	.181	.165	.130	.114	.099
CC	NT	.168	.108	.088	.056	.030
CS	NT	.234	.133	.095	.073	.070
CCS	NT	.188	.145	.098	.075	.060
C3OH	NT	.071	.047	.038	.026	.016

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[1] These yield levels are the equivalent of the following bushels per acre yield for continuous corn rotation: I = 50, II = 70, III = 90, IV = 110, V = 130. Linear interpolation is used to determine the C factors for yields between columns.

[2] The second set of RGTL rows are for ridge till on the contour and are in addition to the P factor for contouring (Wischmeier and Smith, 1978). Furthermore, the C3OH rotation is not applicable, since it would be infeasible to maintain ridges with hay in the rotation.

APPENDIX D

SEDEC POLICY ANALYSIS OUTPUT

This appendix presents the data used to construct the figures in the analysis of sediment control policies. The data is in tabular form and presents selected data points for all the different policies. The entire set of data points for all of the policies and scenarios simulated is lengthy and can be summarized without altering the purposes of this study.

Table D.1 Sediment and costs for policies with noncropland buffers[1]

Tons of sediment	EPF	Location	T-value[2]	adjusted T-value[2]	Other[3]
500	$5420.5				
550	2633.2	$4734.0			
600	968.7	1486.6	$4687.9	$3843.4	(all hay)
650	396.2	481.6	1249.8	405.3	9028.4
700	241.8	241.8	982.3	137.8	
750	199.9	207.1	969.5	125.0	
800	107.2	107.2	844.5	0.0	(no till)
900	69.3	71.6	\		1692.8
950	61.0	60.2	(T-value)		
1000	27.8	27.8			
1100	25.4	25.4			(contour)
1250					1762.0
1400	24.2	24.6			
1450	2.4	2.4			
1550	0.0	0.0			

[1] The values shown in this table are selected from SEDEC output from DPOPT. Not all points and sediment levels are given.

[2] The T-value curve represents the total cost and sediment for efficient sets of practices under the assumption that farmers can only use systems that meet the T-value of their soil. The first curve represents the total cost to society, while the adjusted T-value column represents the cost to induce farmers to control to levels under T.

[3] The other column refers to the policies placing the same practices on all LMU's. The practices are indicated in parentheses.

Table D.2 Sediment and costs for policies without noncropland buffers[1]

Tons of sediment[2]	EPF'	Location'	T-value'[3]	adjusted T-value'[3]	Other[4]
600	$4562.5				(all hay)
650	1797.5	$2200.0	$2521.9	$1677.4	9028.4
700	1091.3	1164.1	1715.6	871.1	
750	807.8	825.6	1411.7	567.2	
800	669.3	678.1	1270.8	426.3	
850	570.4	580.3	1176.9	332.4	
900	505.8	510.1	1106.7	262.2	
950	438.8	445.6	1042.3	197.8	
1000	371.2	379.4	972.1	127.6	(no till)
1050	322.5	322.4	916.8	72.3	1692.8
1100	281.2	284.8	881.5	37.0	
1150	252.1	253.3	864.8	20.3	
1200	225.4	227.7	854.3	9.8	
1250	205.1	206.4	846.1	1.6	
1300	191.4	191.8	844.5	0.0	
1400	156.4	157.6	\		
1500	128.8	130.2	(T-value)		
1600	105.3	107.2			
1700	86.9	87.3			(contour)
1750	77.4	78.2			1762.0
1800	69.2	69.6			
1900	54.4	54.5			
2000	48.0	47.9			
2100	34.9	35.0			
2200	30.8	30.8			
2400	26.1	26.3			
2500	16.9	16.9			
2600	7.3	7.3			
2700	4.2	4.2			
2800	2.4	2.4			
2900	0.0	0.0			

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[1] The values shown in this table are selected from SEDEC output from DPOPT. Not all points and sediment levels are given.

[2] The tons have been adjusted to include the erosion from noncropland to make these figures comparable to those with noncropland buffers.

[3] The T-value curve represents the total cost and sediment for efficient sets of practices under the assumption that farmers can only use systems that meet the T-value of their soil. The first curve represents the total cost to society, while the adjusted T-value column represents the cost to induce farmers to control to levels under T.

[4] The other column refers to the policies placing the same practices on all LMU's. The practices are indicated in parentheses.