Research Technical Completion Report

DEVELOPING AN INTEGRATED MODEL FOR EVALUATING ECONOMIC AND ECOLOGIC EFFECTS OF REDUCING NON-POINT SOURCE POLLUTION IN A PALOUSE WATERSHED

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Merlyn A. Brusven
Plant, Soil and Entomological Sciences

Anthony A. Prato
Agricultural Economics

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

July, 1988

The research on which this report is based was financed in part by the United States Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

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14-08-0001-G1419-03

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Submitted to

U.S. Geological Survey
United States Department of the Interior
Washington, D.C. 20242

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

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Abstract

A linear programming model and the AGNPS model were used to determine those resource management systems that maximized total net farm income and reduced total erosion and nonpoint source pollution in Idaho's Tom Beall Watershed. Erosion decreased and water quality improved significantly with the optimal resource management systems.

DEVELOPING AN INTEGRATED MODEL FOR EVALUATING THE ECONOMIC AND ECOLOGIC EFFECTS OF REDUCING NONPOINT SOURCE POLLUTION IN A PALOUSE WATERSHED

Tony Prato and Merlyn Brusven[1]

Nonpoint source pollution (NSP) is a serious problem for the nation and Idaho. Nationally, about 46% of the sediment, 47% of the total phosphorus, and 52% of the total nitrogen discharged into U.S. waterways comes from agricultural sources (Gianessi et al. 1986). Nitrogen and phosphorus in agricultural runoff result from extensive application of fertilizer. About 85% of Idaho's water quality problems have been attributed to NSP (Moore 1987).

Nonpoint source pollution from soil erosion impairs beneficial uses of water and increases the cost of municipal water treatment, maintenance of navigation channels, irrigation systems and reservoir storage capacity, and flood protection. It also degrades fish spawning and rearing habitat, reducing fish populations and the net economic value of commercial and recreational fisheries. Damages from agricultural NSP have been estimated at between $2 and $6 billion, with a most likely estimate of $3 billion (Ribaudo 1986).

The Palouse region of eastern Washington and northern Idaho is one of the most productive and highly erodible dryland wheat producing

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[1] Tony Prato is Professor, Department of Agricultural Economics and Rural Sociology, and Merlyn Brusven is Professor, Division of Entomology, College of Agriculture, University of Idaho, Moscow, Idaho.

regions of the world. Due to steeply-sloped landscape and the occurrence of major storm events during periods of low residue cover, soil erosion on Palouse cropland exceeds 11 million tons per year (USDA 1984). For this reason, the Soil Conservation Service (SCS) has targeted the Palouse region as a critical area for controlling erosion and NSP (USDA 1985, Duda 1985).

Objectives

The primary objective of this study is to develop and test procedures for determining economically efficient and environmentally sound RMSs for controlling soil erosion and NSP in Idaho's Tom Beall watershed. Specific objectives are:

1. To test and evaluate the Agricultural Nonpoint Source Pollution (AGNPS) model for the Tom Beall Watershed.

2. To construct a Geographic Information System (GIS) for the Tom Beall Watershed that integrates, displays and analyzes information on land use, geoclimatic conditions, hydrology, economics and water quality.

3. To develop an integrated resource assessment model for analyzing the effects of alternative resource management systems (RMS) on NSP in the Tom Beall Watershed.

Related Research

Current research is inadequate for determining the economic impacts of reducing erosion and NSP in a Palouse watershed. Few studies have attempted to determined economically efficient RMSs for controlling soil erosion and NSP in a dryland watershed in Idaho. One study of agricultural water pollution abatement in Idaho did not explicitly consider the link between the application of RMSs and improvements in water quality (e.g., Idaho Soil Conservation Commission et al. 1987). Rather, it was implicitly assumed that RMSs which reduce erosion rates to soil loss tolerances result in acceptable water quality.

Previous studies of best management practices (BMPs) for northern Idaho's dryland farming region have been confined to representative farms or fields and have ignored the water quality benefits of BMPs (Brooks and Michalson 1981, Berglund and Michalson 1980, Harker and Michalson 1978). Thomas et al. (1985) evaluated sediment pollution for alternative land treatments in the Mission Creek Watershed in northern Idaho. Treatment units were very large, sediment delivery rates were assumed to be a fixed proportion of erosion rates and constant for all acres in a treatment unit, and nitrogen and phosphorus pollution were not considered. Another study used gross sediment delivery ratios for six major land uses in three northern Idaho sub-basins to estimate sediment delivery to Lower Granite Reservoir (USDA 1986).

Integrated assessment of erosion and water quality have been made in other states. Crowder, et al. (1984) applied the CREAMS model to determine those conservation practices that maximized net farm income on a Pennsylvania dairy farm. Crowder and Young (1985) applied CREAMS to typical fields in the Conestoga Headwaters RCWP to determine the soil, nutrient and chemical losses associated with various conservation practices. Cost effectiveness of these practices was also evaluated. Neither study was at the watershed level because CREAMS is a field-scale model. Frevert and Crowder (1987) used the AGNPS model to evaluate potential water quality improvements from implementing alternative BMPs on dairy farms located in a Vermont watershed.

Finally, Braden and Johnson (1985) developed the SEDEC model to identify land management practices that minimize the cost of reducing sediment deposition in a small agricultural watershed. Their study accounted for the long-term productivity benefits of soil erosion but not NSP.

Study Area

Tom Beall Watershed is located in the Lapwai drainage (Figure 1). The mainstem of Tom Beall Creek is formed by the confluence of the north and south forks, 1.5 miles east of Tom Beall's confluence with Lapwai Creek. The creek is projected to flow at 2,029 cubic feet per second and has a runoff volume of 0.71 inches during a 25-year, 24-hour storm event. The watershed contains 11,267 acres of cropland and grazing land in the following categories:

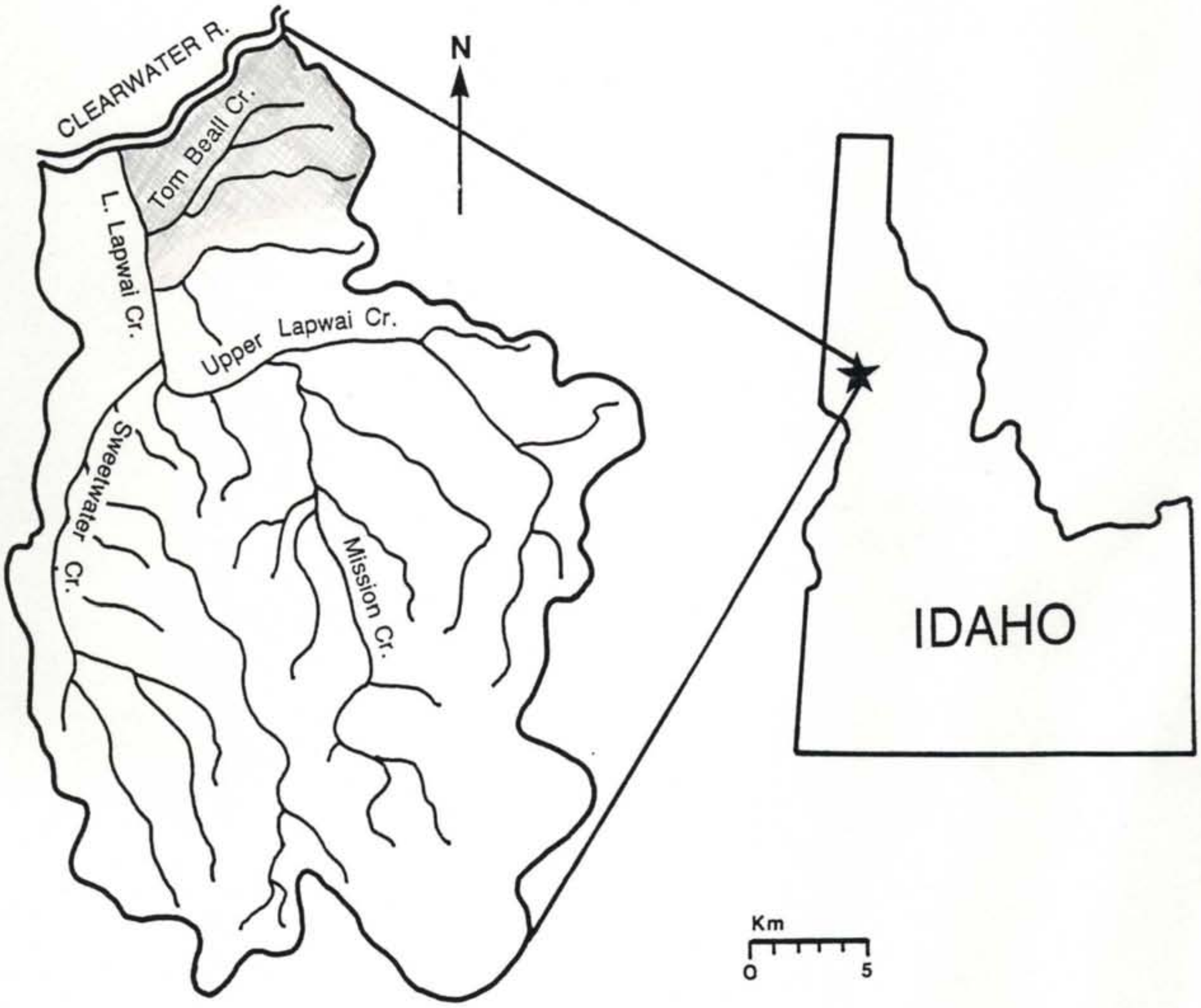

Figure 1. Tom Beall Watershed

Land Use	Acres	Percent
Pasture-Grass-Hay	3,361	29.8
Winter Wheat	3,259	28.9
Fallow	2,062	18.3
Spring Peas	1,412	12.5
Spring Barley	580	5.1
Austrian Winter Peas	202	1.8
Lentils	149	1.3
Winter Barley	106	0.9
Turnips for Seed	80	0.7
Grass for Seed	56	0.5
Total	11,267	99.8

About one-third of the land in the watershed is Indian allotment land and two-thirds is privately owned. Most of the arable land in the watershed is owned by the Nez Perce Tribe and is leased to approximately 16 farm operators. Average farm size is about 1,000 acres.

Due to the watershed's steep and undulating topography (Figure 2), about 75% of the cropland in the watershed has an erosion rate in excess of 5 tons per acre per year (Figure 3). Extensive use of conventional tillage leaves little residue on the land after planting. Most of the erosion in the watershed is caused by snow melt runoff and warm winter rains in January and February. Since the soil is usually frozen at this time of year, surface water cannot percolate into the soil. Runoff

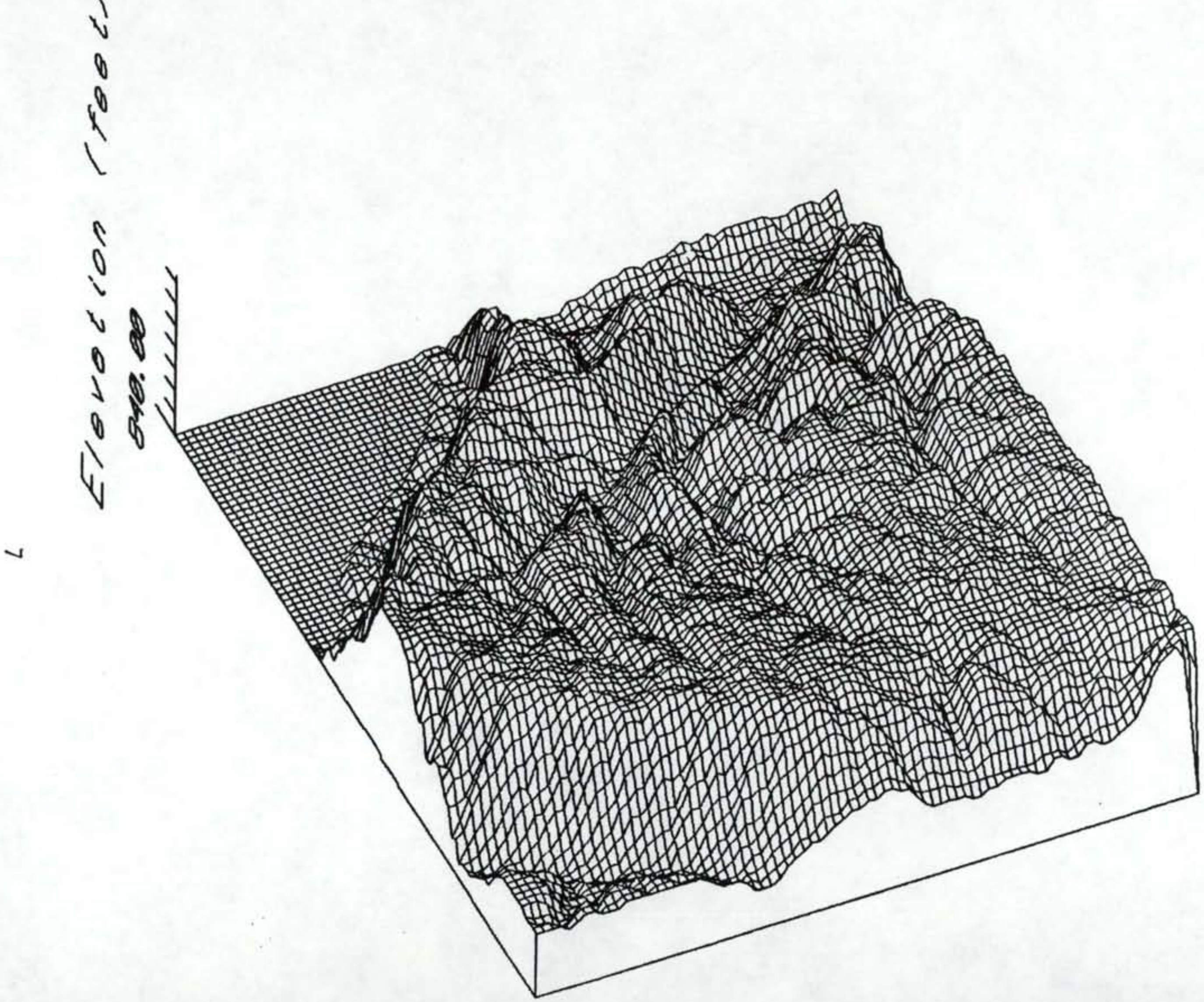

Figure 2. Topography in Tom Beall Watershed (45 degree viewing angle)

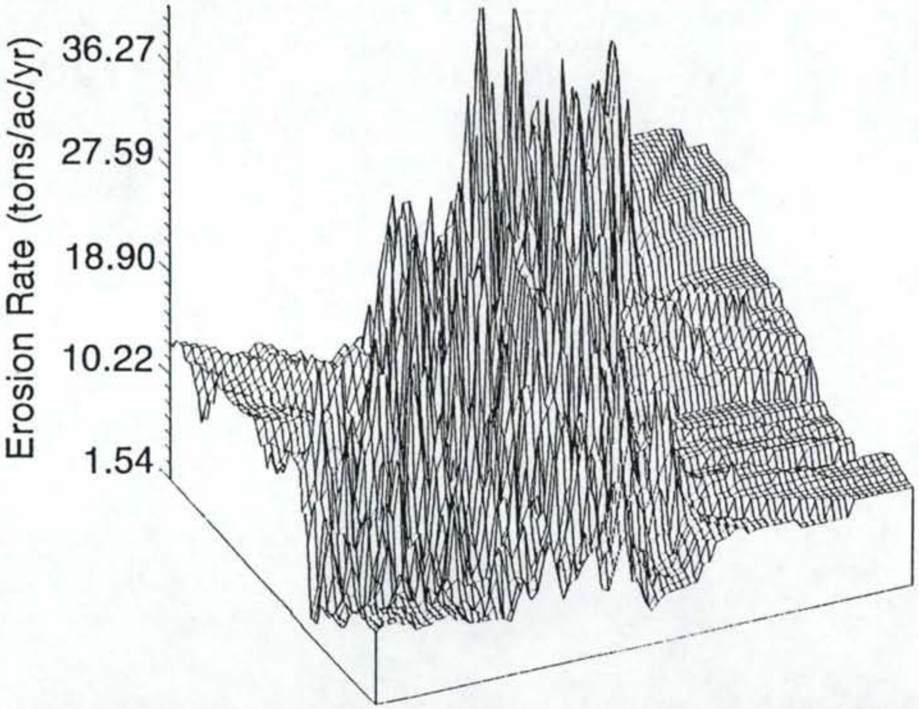

Figure 3. Current Erosion in Tom Beall Watershed

erodes the topsoil down to the frozen layer and carries large amounts of sediment down to lower lands and finally into Tom Beall Creek. Considerable erosion occurs from high intensity rains during the growing season. The average annual erosion rate is estimated at 12.4 tons per acre per year (TAY) based on current land use and farming practices. Erosion rates in the watershed vary considerably because of differences in soil, slope, and land use (Figure 3; Table 1). Many of the riparian areas along Tom Beall Creek are heavily grazed or farmed, increasing the amount of runoff reaching the creek and causing large segments of the watershed to become incised. As a result, average water quality in Tom Beall Creek is poor (Brusven et al. 1986, 1987) and the watershed is contributing large amounts of sediment, nutrients and pesticides to Lapwai Creek.

Methods

Geographic Information System

A computer-based GIS was used to assemble and analyze information on soil type, topography, watercourses, cropping pattern, watershed and field boundaries, conservation practices, and the movement of sediment and nutrients through the watershed.[2] The GIS was used to produce maps of these spatial characteristics and to generate the input data needed to run the physical and economic submodels used in this study.

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[2] The Professional Map Analysis Package was the GIS software system used in this study.

Table 1. Current Erosion in the Tom Beall Watershed

Erosion Rate (tons/ac/yr)	Acres	Percent (%)
0 - 5	1,480	17.8
6 - 10	2,304	27.7
11 - 15	1,764	21.2
16 - 20	1,294	15.5
21 - 25	847	10.1
26 - 30	381	4.5
31 - 35	199	2.4
> 35	53	0.6
Total	8,321	100.0

To optimize resolution and use the GIS to determine watershed boundaries, the GIS data base was set up as an 85x100 matrix. This procedure resulted in a cell size of approximately 3.3 acres with 3,145 cells in the watershed. The basic topographic features of the watershed were obtained from the Lapwai and Culdesac North 7.5 minute USGS quadrangles. Topographic information was entered into the GIS by digitizing all elevation contours (40 ft. interval) from the topographic maps that fell within predetermined data base coordinates. The locations of streams, roads and dwellings were entered in a like manner from the topographic maps. Soil types were digitized from Nez Perce SCS field photos and associated with their respective erodibility (K) factors using the GIS. Intermediate maps (such as slope) were determined analytically by the GIS. Three-dimensional topographic maps were created from GIS data using Golden Graphics software (Figure 2). Land use information was obtained from 7.5 minute aerial photographs of the watershed and ASCS crop records. A farm survey was used to verify land use and field boundaries.

Soil Erosion and Water Quality Models

Soil erosion was calculated by inputting the USLE factors for each cell into the Universal Soil Loss Equation, USLE, (Wischmeier and Smith 1978). Figure 4 illustrates how the GIS was used to generate the soil, topographic, meteorologic, and conservation practice factors in the USLE. The soil erosion rate for an individual field or farm is a

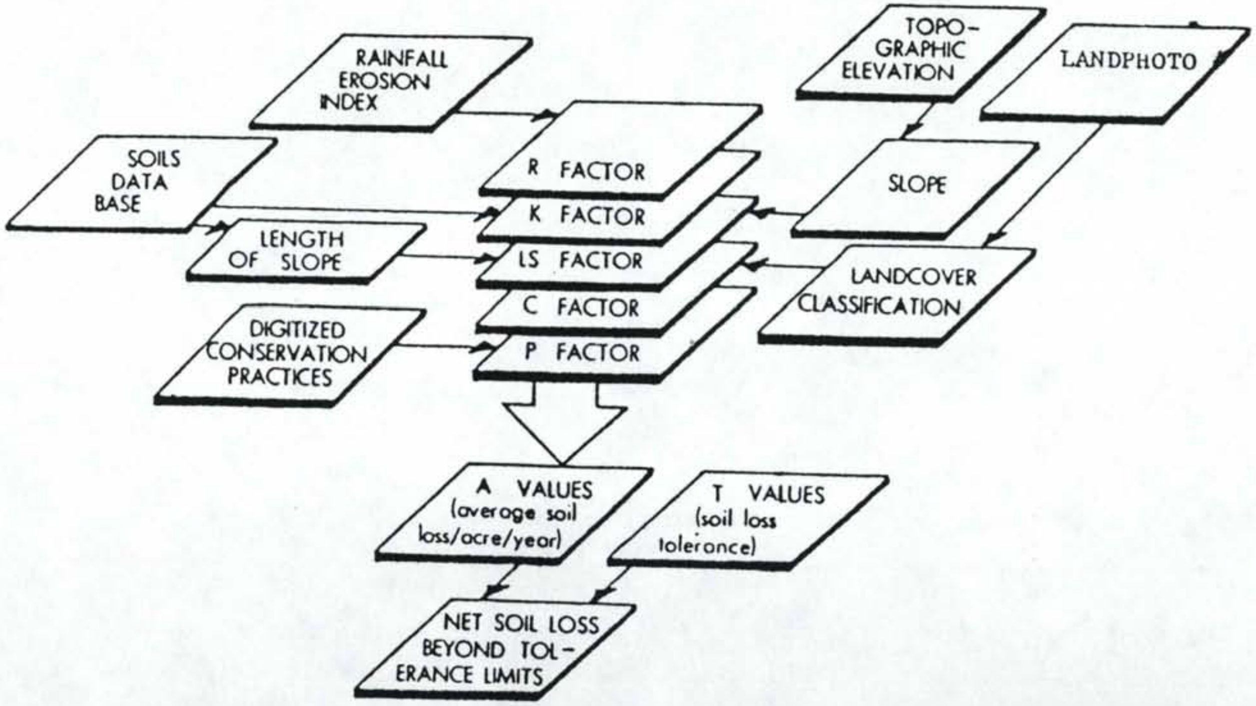

Figure 4. Integrating GIS and USLE (adapted from Pelletier)

weighted average of the rates for all cells included in the field or farm.

AGNPS was used to determine the effects of RMSs on water quality at the outlet of the watershed for individual storm events (Young et al. 1985). This computer simulation model was developed by the Agricultural Research Service to predict erosion, runoff, eroded and delivered sediment, nitrogen, phosphorus and chemical oxygen demand in runoff for individual storm events and land use practices. Erosion, runoff and sediment-nutrient routing are estimated with respect to a cellular grid pattern specified by the user. Four storm events were simulated: 10, 25, 50 and 100 years, each lasting 24 hours. Figure 5 shows how the GIS was used to generate the input parameters used in the AGNPS model. Since AGNPS is an event model and the USLE is an annual average model, the erosion losses predicted by each are not comparable. No attempt was made to aggregate the event-based erosion and pollution levels given by AGNPS to annual average amounts.

Economic Models

The Microcomputer Budget Management System (MBMS) was used to estimate variable and fixed costs of production for a wheat-pea rotation on a 1,000-acre representative farm in the watershed. The MBMS is an enhancement of the Oklahoma Budget Generator (McGrann 1986). Separate production costs were estimated for conventional, minimum and no tillage. Production costs included machinery, fuel and lube, and repair

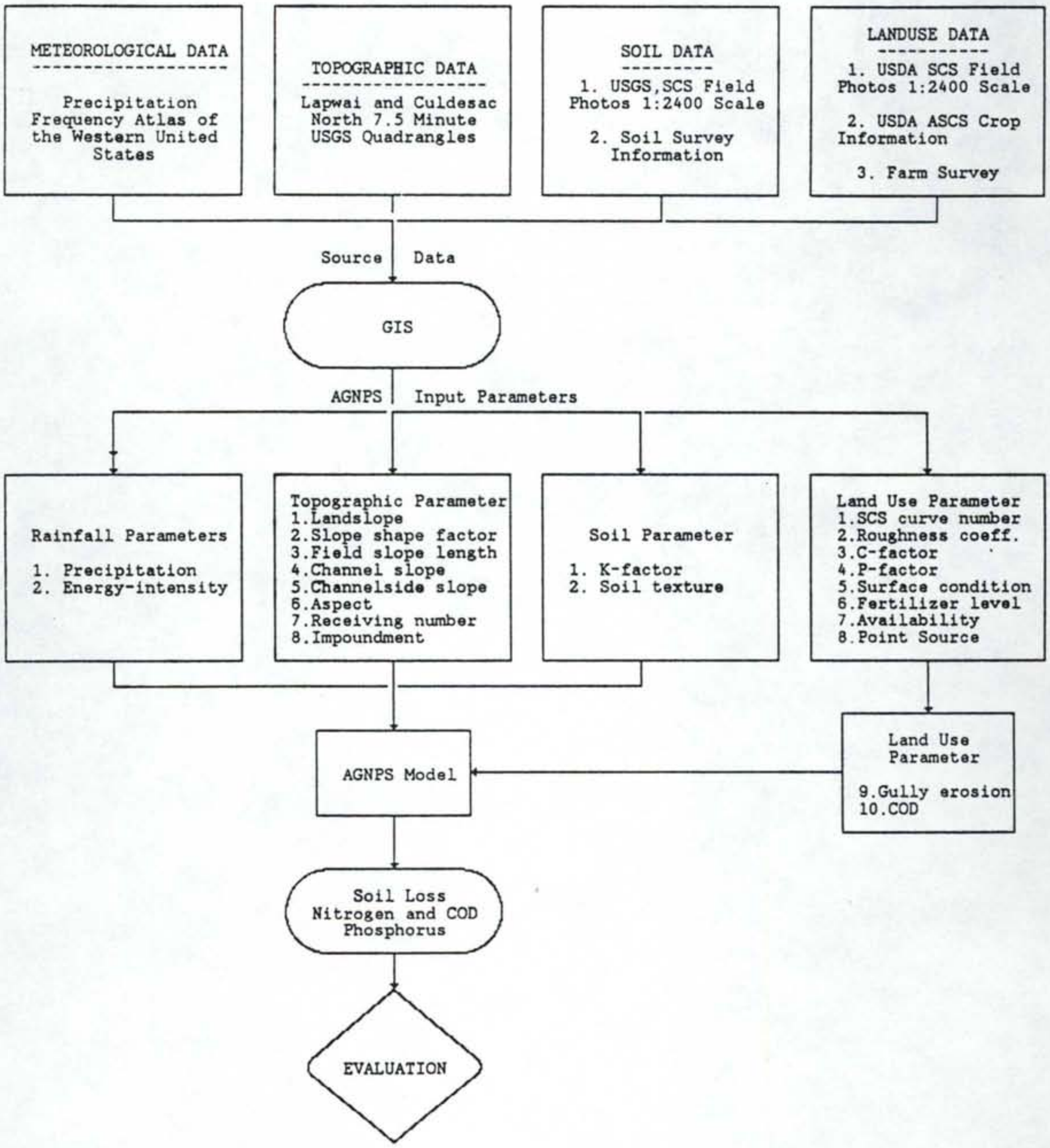

Figure 5. Integrating GIS and AGNPS

costs for specified tillage operations, but excluded the cost of land, owner-operator labor and management. Farming equipment was assumed to be brand new and owned by the farm operator.[3] It was further assumed that each farmer had 100% equity in land and that half the land was planted to winter wheat and the other half to spring peas. Production costs and average yields were estimated from a survey of farm operators in the watershed.

Net returns per acre for each RMS were estimated using the Erosion Planning (EROPLAN) model. EROPLAN estimates the annualized net return per acre which includes the value of the additional yields obtained by reducing erosion. Gross returns per acre equal the wheat and pea yields multiplied by the corresponding prices. The price of wheat equaled the 1987 target price of $4.38 per bushel and the pea price equaled the 1987 market level of $0.08 per pound. Prices and costs were assumed to remain constant in real terms throughout the 20-year evaluation period. A 4% real discount rate was used.

Optimization Model

A linear programming (LP) optimization model was used to determine the RMSs for the 16 farms in the watershed that maximized total net farm income subject to a specified amount of erosion reduction in the watershed. The model is as follows:

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[3] The minimum tillage wheat penalty was estimated from the farm survey and the no tillage wheat penalty is the value used by Taylor and Young (1985).

$$\max Z = \underset{ijkf}{\Sigma\Sigma\Sigma\Sigma}\, A_{ijkf} * C_{ijkf} \tag{1}$$

subject to:

$$\underset{ijk}{\Sigma\Sigma\Sigma}\, A_{ijkf} \leq A_f, \text{ for all } f \tag{2}$$

$$\underset{f}{\Sigma} A_f \leq A \tag{3}$$

$$\underset{ijkf}{\Sigma\Sigma\Sigma\Sigma}\, A_{ijkf} * S_{ijkf} \leq S \tag{4}$$

where:

Z = total net farm income in the watershed;

C_{ijkf} = annualized net returns per acre for crop rotation i, tillage system j, and land treatment k on farm f;

A_{ijkf} = acres in crop rotation i, tillage system j, and land treatment k on farm f;

A_f = acreage in farm f;

S = soil erosion constraint for the watershed;

S_{ijkf} = tons of erosion per acre for crop rotation i, tillage system j, and land treatment k on farm f;

i = 1,....,I is the designation for crop rotation;

j = 1,....,J is the designation for tillage system;

k = 1,....,K is the designation for land treatment practice;

f = 1,....,F is the designation for farm.

The objective function (1) is total net farm income in the watershed. The first constraint (2) prevents the total acreage in RMSs from exceeding the size of the farm. The second constraint (3) ensures that all acreage in the watershed is treated. The third constraint (4) prevents total erosion in the watershed from exceeding the specified level.

Since a farm can have more than one soil type, C_{ijkf} and S_{ijkf} are weighted averages of the corresponding annualized net returns and soil erosion rates, respectively, for all soil types on that farm. The soil erosion coefficients, S_{ijkf}, are the estimated soil loss rates predicted with the USLE. The erosion constraint level, S, was decreased parametrically to determine the change in total net farm income associated with reduced erosion. These income changes can be interpreted as the net social marginal cost of erosion reduction, that is, private marginal cost plus the long-term productivity benefits of erosion reduction.

Since it is more difficult for farmers to change their cropping pattern than their tillage and land treatment practices (Carlson 1985), only a wheat-pea rotation was permitted. Permanent vegetation was introduced as a non-cropping option in order to significantly reduce erosion rates on highly erodible soil for low erosion constraint levels. A 2.6% yield penalty was assumed for minimum tilled wheat and a 15% yield penalty for no tilled wheat.[4] Peas were assumed to be conventionally tilled because minimum tillage and no tillage are generally not used with peas in the Palouse.

The following eleven RMSs were included in the LP model:

CTUD = conventional tillage with up-and-down cultivation

CTCS = conventional tillage with cross slope farming

CTCF = conventional tillage with contour farming

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[4] The minimum tillage wheat penalty was estimated from a farm survey and the no tillage wheat penalty was determined by Taylor and Young (1985).

CTDS = conventional tillage with divided slope farming

MTCS = minimum tillage with cross slope farming[5]

MTCF = minimum tillage with contour farming[6]

MTDS = minimum tillage with divided slope farming

NTCS = no till with cross slope farming

NTCF = no till with contour farming

NTDS = no till with divided slope farming

PV = permanent vegetation

Conventional tillage is an inversion tillage system which clears most of the soil surface of any residue and vegetation. It is the most common tillage practice used in the Tom Beall watershed. Minimum tillage is a form of non-inversion tillage and no till typically involves seeding with a no-till drill. Both minimum and no till leave at least 30% residue cover on the soil surface after planting. Erosion is reduced 50-90% when minimum or no tillage replaces conventional tillage (Poincelot 1987, USDA 1985).

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[5] With cross slope farming, all tillage and planting operations are performed perpendicular to the slope.

[6] With contour farming, all tillage and planting operations are done on the contour.

With up-and-down cultivation, plowing and planting are done in the direction of the slope of the fields. All field operations are done perpendicular to the slope with cross slope farming and on the contour with contour farming. Divided slope farming uses more than one crop or field condition to divide a field. Permanent vegetation involves planting a cover crop such as alfalfa grass. This practice may be the only way to reduce soil erosion rates to tolerable levels on highly erodible land.

A flow chart of the four submodels used in the analysis is given in Figure 6.

Results

Results of two analyses are reported: the optimal RMSs for achieving alternative levels of erosion reduction; and the water quality impacts of the optimal RMSs.

Optimal Resource Management Systems

The LP model determined the RMSs for each farm that maximized net farm income in the watershed subject to alternative soil erosion control levels. Acreages for the optimal RMS and the changes in total net farm income for alternative erosion reduction levels are given in Table 2. Erosion reduction is measured relative to the total erosion that occurs when CTCF is used on all farms in the watershed. As erosion reduction increased, more acreage was shifted from conventional tillage to minimum

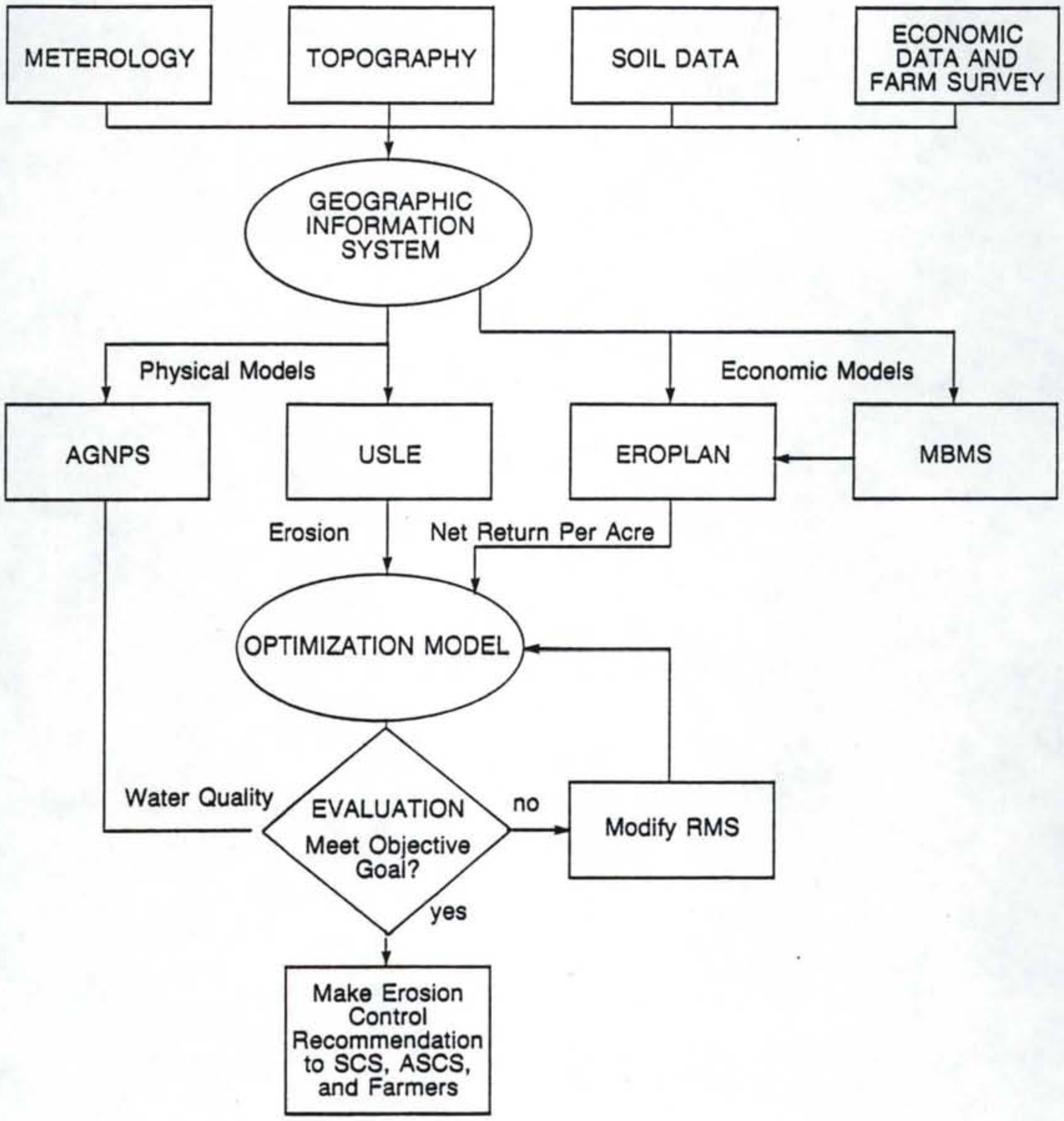

Figure 6. Flow Chart of Integrated Model

Table 2. Optimal Acreage for RMSs Under Different Erosion Control Levels for Tom Beall Watershed

Percent Erosion Reduction Compared to	Net Income ($)		Acreage in Resource Management Systems (RMSs)					
Baseline	Amount	Percent	CTCF	MTCF	MTDS	NTCF	NTDS	PV
Baseline (0)	789958.9	100 %	8769(100%)					
30	802118.9	101.5%	109 (1.2%)	8660 (98.8%)				
40	802117.4	101.5%	283 (3%)	8486 (97%)				
50	749237.8	94.8%		2661 (30%)	4209 (48%)	225 (3%)	1690 (19%)	
60	649243.8	82.2%		1916 (22%)	1672 (19%)	503 (6%)	4331 (49%)	362 (4%)
70	516187.9	65.3%			232 (3%)	2406 (27%)	4972 (57%)	1176 (13%)
80	343720.1	43.5%			232 (3%)	2089 (24%)	2923 (33%)	3542 (40%)
90	103737.3	13.1%				614 (7%)	1440 (16%)	6731 (77%)
91	75349.3	9.5%				234 (3%)	1440 (16%)	7111 (81%)
91.5	55335.2	7.0%				232 (3%)	1166 (13%)	7387 (84%)
92.0	23975.6	3.0%				228 (3%)	740 (8%)	7816 (89%)
92.5	-7722.7	-0.1%				228 (3%)	306 (3%)	8251 (94%)
93.0	-39638.2	-5.0%				100 (1%)		8685 (99%)
93.1	-46131.1	-5.8%				13		8772 (100%
93.11	-47083.6	-6.0%						8785 (100%

The figure in the parentheses is the percent of total watershed acreage in that RMS.

CTCF = conventional tillage and contour farming
CTDS = conventional tillage and divided slope farming
MTCF = minimum tillage and contour farming
MTDS = minimum tillage and divided slope farming

NTCF = No-till and contour farming
NTDS = No-till and divided slope farming
PV = permenant vegetation

tillage, no tillage and permanent vegetation. Although the first run imposed no erosion constraint, it decreased erosion by 30% and increased total net farm income 1.5%. Net farm income increased by the same amounts when erosion was reduced by 40%. For a 70% erosion reduction, total net farm income decreased 34.7%. Total net farm income dropped quickly when erosion reduction exceeded 40% (Figure 7). A 40% reduction in erosion corresponds to an average erosion rate of 2T and a 70% reduction corresponds to an average erosion rate of 1T.

Water Quality Effects of Erosion Control

The water quality effects of current practices and RMSs that maximized total net farm income for the 1T and 2T erosion control levels were determined with the AGNPS model. The Idaho SCS has established 1T as the desired erosion rate and 1.5T as the maximum erosion rate for fields subject to the conservation compliance provision of the 1985 Food Security Act. For analytical purposes, the upper limit was extended to 2T because this erosion control level provides the highest total net farm income.

The total amount of erosion in the watershed and nonpoint source pollutants (sediment, nitrogen and phosphorus attached to sediment, and soluble chemical oxygen demand (COD)) at the outlet of Tom Beall Creek were determined for 10, 25, 50 and 100-year storm events (of 24 hours duration) with current practices and the optimal RMS for reducing erosion to 2T and 1T (Table 3). Sediment and nutrient loadings and COD levels decreased as storm intensity increased, but at a decreasing rate.

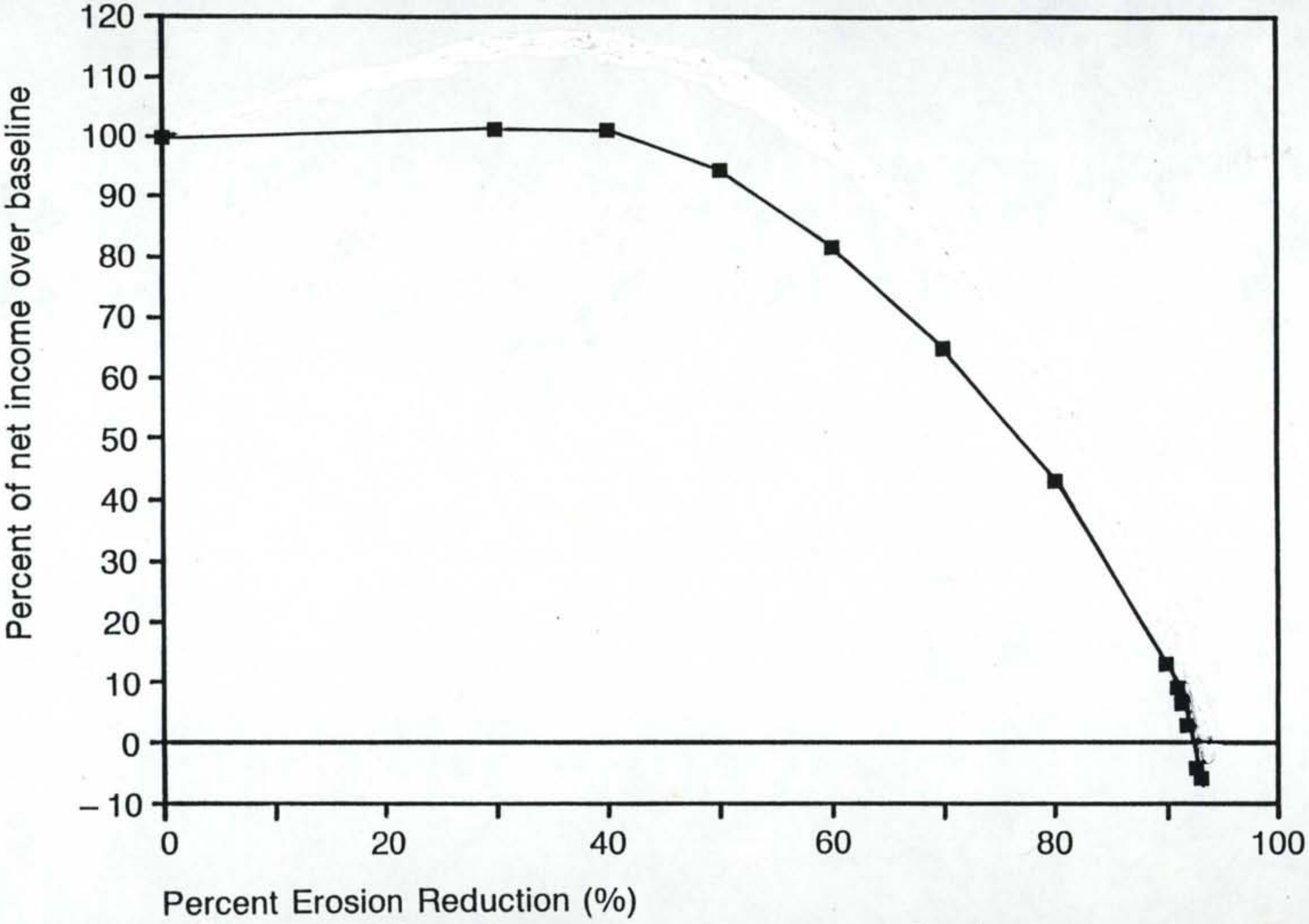

Fig. 7. Total Net Farm Income vs. Erosion Reduction.

Table 3. Nonpoint Source Pollutants for Alternative Erosion Control Levels in Tom Beall Watershed (total amount)

Water Pollutant	Storm Event (year)	Erosion Control Level		
		Current Practice	2T	1T
Erosion[a] (tons)	10	34,559 (37%)[b]	31,238 (21%)	14,841 (20%)
	25	48,465 (41%)	43,795 (25%)	22,209 (24%)
	50	56,456 (43%)	50,956 (26%)	26,464 (26%)
	100	65,278 (44%)	58,947 (28%)	31,030 (27%)
Sediment[c] (tons)	10	12,793	6,560	2,968
	25	19,871	10,745	5,330
	50	23,906	13,249	6,881
	100	28,722	16,293	8,378
Nitrogen[c] in sediment (lbs)	10	39,125	22,935	12,246
	25	55,419	34,040	19,303
	50	64,447	40,474	23,454
	100	74,202	47,427	27,917
Phosphorus[c] in sediment (lbs)	10	19,511	11,520	6,123
	25	27,709	17,020	9,652
	50	32,276	20,237	11,727
	100	37,049	23,766	14,010
Soluble[c] chemical oxygen demand (lbs)	10	92,676	65,070	60,608
	25	134,084	100,770	93,713
	50	156,396	120,489	111,979
	100	179,539	141,348	131,281

a. Total amount of erosion generated on all fields in watershed.
b. Figure in paretheses is the sediment delivery ratio.
c. Total amount of sediment, nitrogen, phosphorus and chemical oxygen demand (COD) released at watershed outlet.

Between current practices and 2T, total erosion fell 10%, sediment declined 43 to 49%, nitrogen and phosphorus dropped 36 to 41%, and soluble COD declined 21 to 30%. The lower limit in each percentage range corresponds to a 100-year storm and the upper limit to a 10-year storm. From 2T to 1T, erosion and sediment declined 50%, nitrogen and phosphorus decreased 41 to 47% and COD fell 7%. Sediment, nutrients and COD decreased from current practices to 2T and from 2T to 1T because cropland erosion and the sediment delivery ratios diminished. Averaged over the four storm events, erosion and losses of sediment, nitrogen, phosphorus and soluble COD decreased by 8, 45, 38, 38 and 24%, respectively, with the optimal RMSs for 2T, and by 33, 72, 64, 64 and 29%, respectively, with the optimal RMSs for 1T. These results indicate that controlling erosion significantly reduces sediment, nutrients and soluble COD at the watershed outlet.

Conclusions

The economic efficiency of improving water quality in the Tom Beall watershed can be increased substantially by reducing erosion on highly erodible cropland. The level of erosion control directly affected the optimal choice of RMSs and total net farm income in the watershed. Maximizing total net farm for a 40% reduction in total erosion required substituting minimum tillage with contour farming for conventional tillage with contour farming. Total net farm income increased 1.5% with minimum tillage because it had a higher net return per acre than conventional tillage. A 40% reduction in erosion corresponds to an average erosion rate for the watershed of 10 tons per acre per year (2T).

Resource management systems that maximized total net farm income subject to a 70% reduction in erosion were predominantly no till with contour farming. This alternative resulted in a 35% decrease in total net farm income. Reducing current erosion by 70% is equivalent to achieving an average erosion rate for the watershed of 5 tons per acre per year (1T).

The optimal resource management systems for reducing erosion to 1T and 2T resulted in substantially lower sediment, nitrogen, phosphorus and chemical oxygen demand at the watershed outlet. Averaged over the four storm events (10, 25, 50 and 100 years), sediment, nitrogen, phosphorus and chemical oxygen demand declined by 45, 38, 38 and 24%, respectively, at the 2T level, and by 72, 64, 64, and 29%, respectively, at the 1T level.

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