Sedimentation of Reservoirs: Prevention vs. Cleanup

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Abstract: Soil erosion from cropland contributes significantly to reducing storage capacity in reservoirs. A model is developed for comparing economic desirability of various catchment level soil conservation practices. Results from an illustrative case study show that prevention of sediment accumulation can be much more economical than sediment removal at the reservoir level.

Key Words: soil erosion, sedimentation, watershed management, dams, cost-benefit analysis.

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SEDIMENTATION OF RESERVOIRS: PREVENTION VS. CLEANUP

I. Introduction

Soil erosion has the potential to cause substantial loss of agricultural productivity over time. The eroded soil can also have various negative externalities, including sedimentation of downstream reservoirs that causes gradual reduction of storage capacity. For example, soil eroded from cropland is estimated to account for about 24% of reservoir storage lost annually in the U.S. (Crowder, 1987). A reduction of storage capacity lowers economic benefits of dams in terms of water supply, hydropower, recreational activities, and/or flood control. The lost capacity may be recovered using sediment removal techniques such as mechanical or hydraulic (hydrosuction) dredging and flushing, but these approaches are usually quite expensive.

Alternatively, prevention of excessive sediment inflow may be feasible with soil conservation measures at the watershed level. Agricultural practices, such as terracing, contouring, strip cropping, and crop rotation may be used to control erosion. These practices also help maintain soil productivity, leading to higher crop yields in the future. There exists a controversy, however, regarding the cost-effectiveness of such measures for enhancing reservoir life (Doolette and Magrath, 1990). Our paper contributes to this debate by developing a model that may be used to study the economic trade-off between catchment level soil conservation and reservoir level cleanup.

Our model is unique in terms of its combination of physical realism and interdisciplinary inputs from economics, agricultural science and reservoir engineering. The model is calibrated with a combination of real and synthetic data from a watershed in Connecticut to provide an illustrative case study. Computations are performed with STELLA □ (High Performance Systems) software.

The paper is organized as follows. Section II presents a brief overview of the modeling of soil erosion and its control at the farm level. This section also reviews the limited literature that exists on the economics of reservoir sedimentation. Section III goes over the key ingredients of our dynamic model of watershed management (technical details are relegated to an appendix). Section IV presents case study results and sensitivity analysis. Section V concludes the paper with a summary of the main findings and suggestions for future research.

II. Background and Literature Review

Agricultural Productivity, Soil Erosion, and Control of Soil Erosion.

Topsoil is considered a non-renewable resource, mainly because regeneration takes a long time. The major agents of soil loss are water and wind erosion. Erosion often reduces soil productivity very gradually, making it difficult to detect the effect in time to make necessary amendments.

Quantifying the relation between erosion and agricultural productivity is a complicated matter (Crosson, 1983, Frye, 1987). Some of the erosion effects are irreparable while others are temporary. The yields on eroded lands may possibly be restored by addition of nutrients but this does not affect the regeneration process. The effect of erosion on cropland soil is a function of topsoil thickness/soil depth (Lal, 1985), available water capacity, plant nutrient storage, surface runoff, soil tilth, and soil organic matter. Kiniry et al. (1983) and Lal (1985) are among the many authors who have derived a relationship between soil erosion and productivity loss. The maximum acceptable rate of erosion is defined by soil loss tolerance value (T value) which is a function of soil depth (Skidmore, 1982). Tolerance value for soils in Connecticut is 3 (USDA and SCS, 1976).

The soil productivity can be increased by application of fertilisers and adopting various conservation techniques. Fertilisers reap short-term benefits while conservation methods though expensive initially, has long-term impacts. The basic concept of conservation involves covering the soil to prevent exposure to raindrop impact, increasing soil characteristics to reduce runoff and boosting the stability of the soil (Morgan and Davidson, 1986). The crops presenting greatest erosion problems are those of considerable value either for industrial purposes or as food crop upon which the survival of world's population depends. The challenge is to develop soil conservation strategies that will allow these crops to be grown on a sustained basis. One practice is to change the land use from cropland to pasture or forest. Forestlands provide excellent protection against erosion. They maintain high rates of infiltration, and protect the soil surface; and therefore generate only small quantities of sediment. Rotation methods involve strip cropping and mulching while soil management techniques use conservation tillage. Mechanical methods of conservation are terracing and building structures. In-depth explanation of conservation practices are given by Morgan (1995).

The Universal Soil Loss Equation (USLE) (Wischmeier, et al., 1978) is the primary method of soil loss estimation from rainfall and runoff. Soil loss (A) in tons per acre per year is related to rainfall factor (R), erodibility factor (K), length and slope (LS), cover (C) and land practice (P) as $A=R*K*LS*C*P$. While various soil erosion control practices may be technically effective as determined by the above equation, they typically require significant initial investments while benefits are observed after few years of adoption. A cost benefit analysis of various erosion control techniques should therefore be conducted to ascertain their relative desirability. Economic analysis of several conservation practices have been performed (with varying levels of sophistication) by Countryman and Murrow (2000), Gunatilake and Gopalakrishnan (1999), Mitchell, et al. (1980), among others.

Reservoir Level Impacts and Mitigation

A dam blocks the flow of water resulting in deposition of the sediment on the reach of backwaters. Part of sediment deposited is from land erosion. Human activities within a watershed accelerate or decelerate erosion and can affect the operation of water control structures. The spatial and temporal variability of sediment production, transport and deposition greatly complicates the task of estimating sediment from a watershed [Wigham, 1973 #61]. A comprehensive literature survey by Sloff (1991) addresses issues related to sedimentation processes, impact on riverine morphology and preservation of storage capacity.

Calculation of sediment deposited into a reservoir is divided into two steps, namely estimation of sediment yield and calculation of the proportion of sediment yield that will be deposited in the reservoir, i.e., sediment delivery ratio (Annandale, 1987)**.** Sediment yield is the amount of sediment passing a specified channel location and is typically expressed as the total sediment volume delivered to a specified location in the basin divided by the effective drainage area above that location for a specified period of time. The yield for a given area varies with the changing patterns of precipitation, cover and land use. It also depends on the drainage size and slope of the water shed. Sediment yield can be estimated using various relationships, such as sediment rating curves, gross erosion and sediment delivery ratio, measured sediment accumulation and predictive equations (Cordova and Gonzalez, 1997). These relationships are functions of several measurable, independent variables such as drainage area, annual runoff, watershed shape, relief length ratio, average slope, particle size of the surface soil and others.

Only part of sediment eroded from upland areas of watershed is carried out of the watershed. Sediment delivery ratio is defined as the ratio of sediment delivered at a given location in the stream system to the gross erosion from the drainage area above that location. The delivery of the sheet erosion quantities to streams defines the sediment yield of a catchment. Higher the channel density, the shorter the distances the erosion products are moved. Slope also affects movement. Sediment particles are supported and distributed in the flow through turbulence. Superimposed on this action is the condition that sediment particles are continuously settling toward the channel bed. As velocities decrease, such as at the entrance to a reservoir, more sediment is deposited.

Economics of reservoir sedimentation and soil conservation has been addressed in the literature by a few studies. For example, Gunatilake and Gopalakrishnan (1999) have discussed the sedimentation cost of Mahaweli reservoir in Sri Lanka, but with little emphasis on conservation practices upstream. Southgate and Macke (1989) investigate the reduced hydroelectric benefits due to soil erosion, but do not account for the cost of controlling erosion. De Janvry and Sadoulet (1995) evaluated the effect of Plan Sierra management techniques on Bao reservoir in Dominican Republic with an aim to reduce intense soil erosion in the watershed. Adoption of the plan increased the life of the reservoir by 23 years.

There are also case studies in the literature which suggest that watershed management might be difficult to justify based only on downstream benefits. Evidence examined by Doolette and Magrath (1990) from Asian regions suggest limited potential for watershed management in specific areas. In Bangladesh, where floods are a recurring phenomenon, the authors found no statistical evidence of reduction in floods due to such practices.

None of the above papers accounts for the possibility of sediment removal at the reservoir level. This subject is addressed in Palmieri, et al. (2001), but their analysis does not allow for watershed management. Our paper adds to the literature by presenting a unified framework of engineering and benefit cost analysis in which the economic impact of changes in catchment level policies may be analyzed.

III. General Model

This section describes the flow of the model. For the purpose of simplification the schematic given (Figure 1) is divided into two modules, watershed and reservoir. The description of each module and the processes associated with it are explained below. Each module consists of sub sections, which are very detailed. These are not included here, but can be produced on request. Readers may refer to the appendix for the actual STELLA □ (High Performance Systems) diagram of the modules.

General Model Description

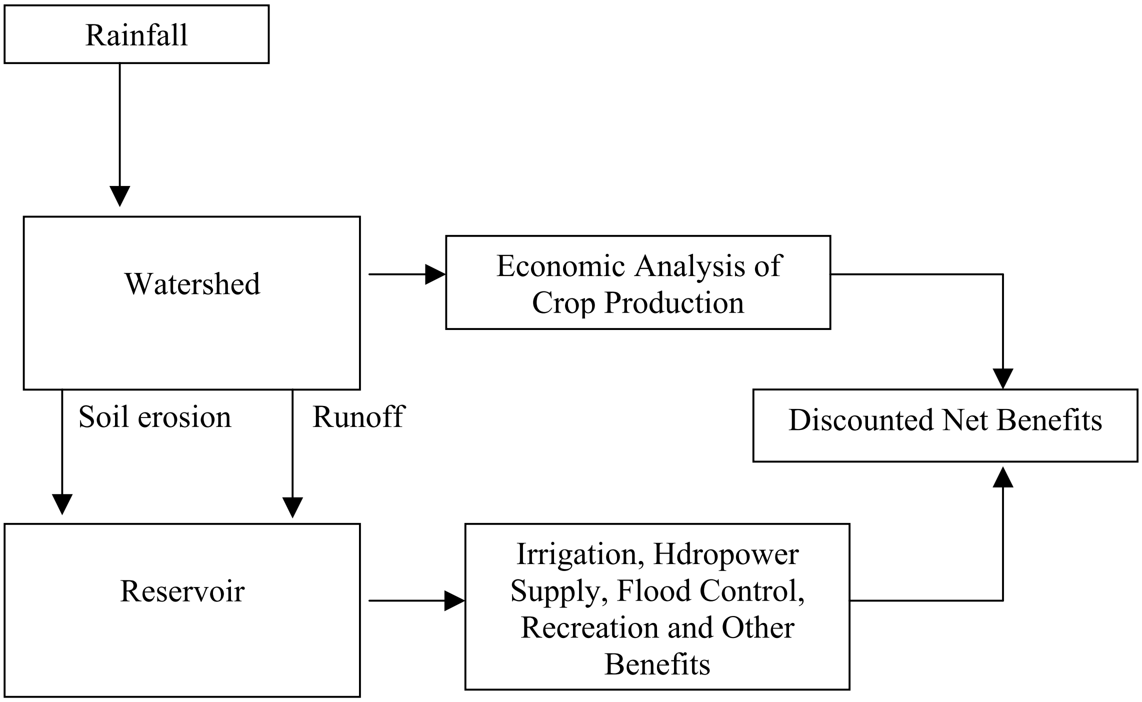

Figure 1. Schematic of General Model

The above figure illustrates the flow of activities in the model. A watershed is considered with a reservoir downstream. Rainfall in the watershed causes runoff and soil erosion. Soil loss due to runoff contributes to siltation in the dam. Benefits of soil conservation to the watershed are mainly from increased long term profits to farmers upstream while downstream benefits accrue due to enhanced reservoir life and may occur in the form of greater flood control, hydropower, irrigation, recreation and other benefits storage.

Soil Erosion from Watershed

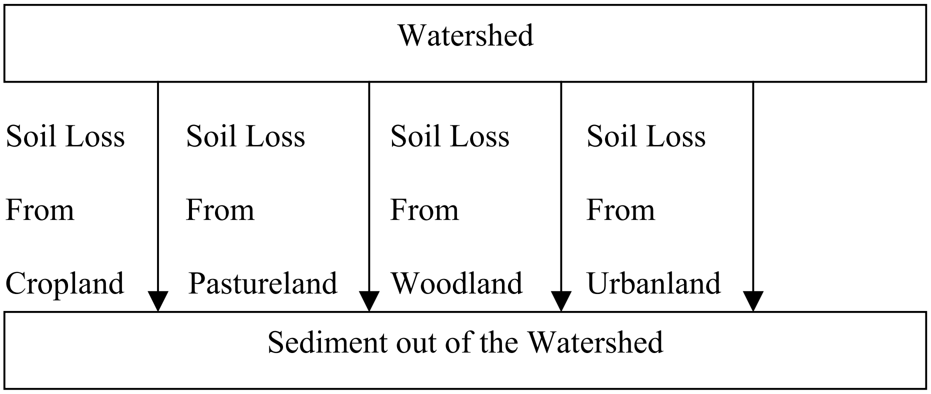

Figure 2. Schematic of Watershed Components Contributing to Sedimentation

Figure 2 illustrates the land use of watershed that contributes to soil loss. These are agriculture/ cropland, pastureland, woodland and urban land. For the purpose of this paper we focus on soil loss from cropland and pastureland. Crop productivity reduces with increase in soil erosion. Benefits to the farmer from sale of these crops are hence reduced. Adopting different conservation practices can improve soil productivity but lead to increase in production cost. These are shown in the flow diagram later in the section.

Flow of Sediment Through Reservoir

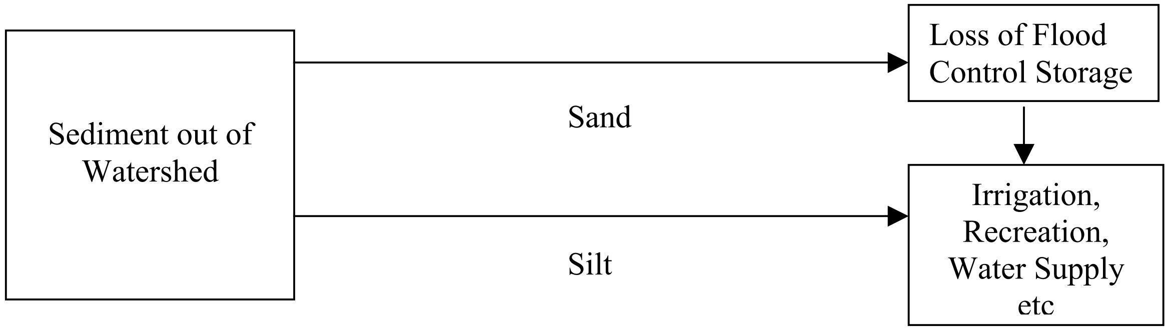

Figure 3. Schematic of Sediments Entering the Reservoir

Reservoir is silted over the years form the upstream sediment. Increased erosion rates reduce the life of the reservoir faster while conservation practices increase its life. Soil loss from watershed is usually made up of sand and silt, which gets distributed in the flood storage and other sections of the dam. Reduction in storage capacity increases the probability of floods downstream of the dam and also reduces other benefits accruing from it.

Calculation of Discounted Net Benefits from Agriculture and Dam for Economic Analysis

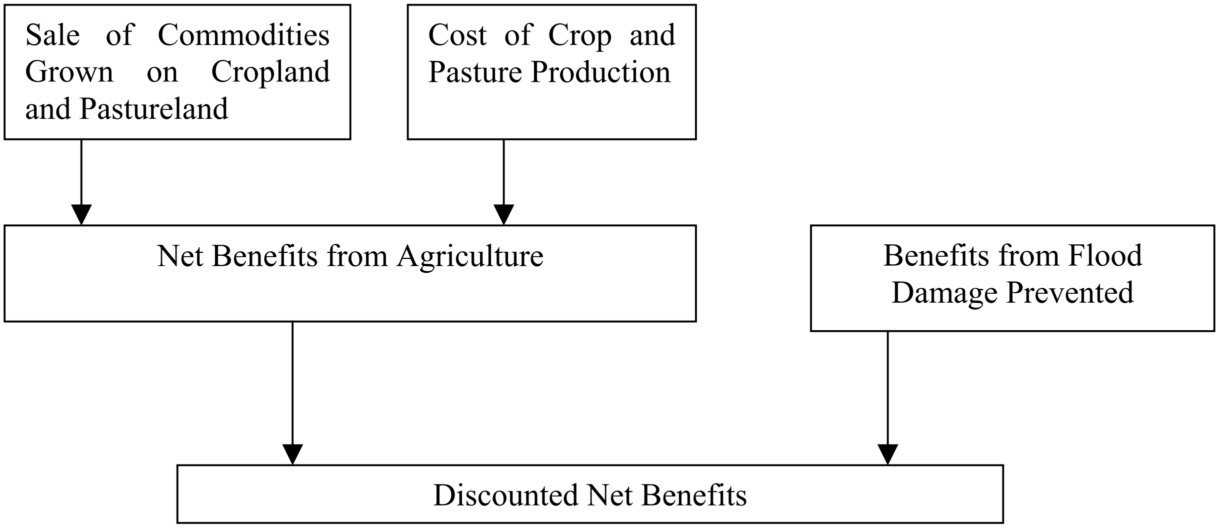

Figure 4. Schematic of Estimation of Discounted Net Benefits

Net benefits from both agriculture and dam are estimated and combined for the exercise of economic analysis.

IV. Application

In order to illustrate the use of our model, we apply it to the case of a watershed entering in a flood control reservoir in northwest Connecticut. The analysis is based partly on data collected from the site, partly on published studies, and to some extent on assumed values. While sensitivity analysis is carried out to test the robustness of some of our assumptions, it should be borne in mind that the main purpose of the exercise is illustrative.

Land in the watershed is used for cropping, pasture, and miscellaneous use. The rest of the area is woodland. Historic land use for the period of study is obtained from various sources such as sedimentation survey report, aerial photographs and GIS data. Total drainage area contributing to sedimentation is 7.92 sq miles which is also the area of the watershed. The soil erosion rate is estimated using USLE (Wischmeier, et al., 1978). The main crop grown in the watershed is corn and pasture. Crop productivity is obtained from soil survey reports. Sale prices for the commodities are obtained from the NASS census while that of pasture is calculated (Edward, 2002). Farm expenditure and installation cost for conservation techniques are obtained from (USDA, 1993).

Watershed problems in the study area include flooding, soil erosion, siltation, flood water and sedimentation damages to infrastructure in residential and business areas. For the purpose of this study we focus on the flood control use of the dam. The engineering data is taken for the sediment survey, hydrology and hydraulics report. Gross storage capacity for flood control is 3570 acre-feet with trap efficiency of 94%. Data on sediment discharge and characteristics can be obtained from (United States. Soil Conservation Service, 1983).

Results of Case Study

While most data values used for calibrating the model are based on documented evidence, some of the parameters values are based on assumptions. These parameters are the discount rate and the soil erosion rate for contour farming, for which the respective assumed values are 6% and 3.4 tons/acre/year.

The model is run from year 1958 – 2000. The dam was completed in 1961. The values for aggregate net present value obtained after running the model are reported below along with the expected life of the dam for three scenarios: (I) No Soil Conservation, (II) Contour Farming, and (III) Strip Cropping. Scenario I corresponds to the historical situation in the study area. Sensitivity analysis is then conducted for changes in various parameters.

Base Case

Tables 1 and 2 display the base case, which is a comparison of the no soil conservation scenario with ones involving conservation practices. Table 1 indicates the key inputs while Table 2 shows the important results. Land distribution is assumed to follow the existing historical pattern for all three scenarios in the base case. This distribution is reproduced in the section II of the appendix along with the distribution of historical soil erosion rates for the study area.

Table 1. Comparison of Parameters Used

	No Soil Conservation	**Contour Farming**	**Strip Cropping**
Land Use acres	Unchanged	Unchanged	Unchanged
SER tons pe racre per year	Appendix II	3.4	3
Discount rate	0.06	0.06	0.06

Table 2. Comparison of Agg.NPV and Siltation Year for Different Scenarios

	Agg. NPV $	**Year of Complete Siltation**
No Soil Conservation	15,266,035	2039
Strip Cropping	14,572,704	2071
Contour Farming	15,287,846	2070

Table 2 shows the aggregate net present value (Agg. NPV) of farming, pasture, and the dam, as well as the year in which the dam would get silted under each scenario. Note that both types of soil conservation practices would be beneficial in terms of prolonging reservoir life, but only contour farming would be preferred to no soil conservation in terms of aggregate net benefits. It turns out that strip cropping is technically more effective in reducing soil erosion, but it is also more expensive.

Sensitivity Analysis

It is interesting to examine the implications of varying some of the parameter values on the relative desirability of the watershed management options under consideration. For example, our assumed value for the soil erosion rate (SER) with contour farming is probably on the conservative side. The effect of increases in this rate on aggregate net present value for contour farming is reported in Table 3.

Table 3. Comparison of Agg.NPV and Siltation Year for Different SER's

SER tons per acre per year	Agg. NPV for Contour Farming $	Year of Complete Siltation
3.4	15,287,846	2070
3.6	15,278,070	2069
3.8	15,268,295	2069
4	15,258,519	2068

Observe that the NPV for contour farming is higher as compared to no conservation case for SER less than or equal to 3.8. A similar exercise with strip cropping shows that the economic disadvantage of this practice increases as its SER increases, but strip cropping is technically more effective in controlling erosion so that it does prolong the life of the reservoir compared to contour farming.

Changes in discount rate are also investigated and the outcomes are presented in Table 4.

Table 4. Comparison of Agg. NPV and Siltation Year of Different Scenarios for Changes in Discount Rate

Discount Rate	**0.04**	**0.06**	**0.08**	**0.1**	**Year of Complete Siltation**
	Agg. NPV $	**Agg. NPV $**	**Agg. NPV $**	**Agg. NPV $**	
No Soil Conservation	19,974,372	15,266,035	11,978,898	9,623,601	2039
Strip Cropping	19,172,034	14,572,704	11,370,434	9,083,323	2071
Contour Farming	20,062,958	15,287,846	11,958,864	9,577,607	2070

Two points are worth noting. First, the aggregate net present value of each management practice decreases as the discount rate increases. This is to be expected. Secondly, observe that the relative advantage of Contour farming decreases as the interest rate increases. Indeed, the No Soil Conservation case produces the highest net present value for a discount rate of 8% (or above). This is also reasonable, given that discounting penalizes net benefits in later years and the fact that conservation practices take some time to show their effects.

Sensitivity analysis with respect to the discount rate was also extended to higher erosion rates for contour farming. Results are given below. Observe that with high enough SER, No Soil Conservation may come out ahead even with the base case discount rate of 6%.

Table 5. Comparison of Agg. NPV and Siltation Year of Contour Farming for Different Discount Rate

Discount Rate	**0.04**	**0.06**	**0.08**	**0.1**	**Year of Complete Siltation**
SER tons per acre per year	**Agg. NPV $**	**Agg. NPV $**	**Agg. NPV $**	**Agg. NPV $**	
3.4	20,062,958	15,287,846	11,958,864	9,577,607	2070
3.6	20,050,233	15,278,070	11,951,161	9,571,395	2069
3.8	20,037,507	15,268,295	11,943,457	9,565,184	2069
4.0	20,024,782	15,258,519	11,935,753	9,558,972	2068

If contour farming or strip cropping is adopted, it would allow farming to be carried out profitably for longer periods and might slow the decline in land devoted to agriculture. To simulate this possible effect, the agricultural land in each year after the peak of the distribution (see section II in appendix) was increased by a given percentage. The results are reported below in Tables 6 and 7. Observe that the advantage of soil conservation increases as does the aggregate net present value, but the life of the dam is not impacted much as the bigger land base tends to increase erosion.

Table 6. Comparison of Agg. NPV and Siltation Year Strip Cropping for Changes in Land Use

% Change in Land Use	**10**	**20**	**30**	**40**	**50**
Agg. NPV for Strip Cropping $	15,174,932	15,777,160	16,379,389	16,981,617	17,583,845
Year of complete siltation	2071	2070	2070	2069	2069

Table 7. Comparison of Agg. NPV and Siltation Year for Contour Farming for Changes in SER

% Change in Land Use	10	20	30	40	50
SER tons per acre per year	**Agg. NPV for Contour Farming $**	**Agg. NPV for Contour Farming $**	**Agg. NPV for Contour Farming $**	**Agg. NPV for Contour Farming $**	**Agg. NPV for Contour Farming $**
3.4	15,898,488	16,509,131	17,119,773	17,730,415	18,341,058
3.6	15,888,320	16,498,570	17,108,819	17,719,069	18,329,319
3.8	15,878,152	16,488,009	17,097,865	17,707,722	18,317,579
4.0	15,867,983	16,477,448	17,086,912	17,696,376	18,305,840
4.5	15,842,563	16,451,045	17,059,527	17,668,010	18,276,492
5.0	15,817,142	16,424,642	17,032,143	17,639,643	18,247,144

Year of Complete Siltation for Contour Farming					
% Change in Land Use	**10**	**20**	**30**	**40**	**50**
SER tons per acre per year					
3.4	2069	2069	2068	2068	2067
3.6	2069	2068	2068	2067	2067
3.8	2068	2067	2067	2066	2066
4.0	2067	2067	2066	2066	2065
4.5	2065	2064	2064	2063	2063
5.0	2061	2061	2062	2062	2063

Finally, changes in SER for contour farming and strip cropping are investigated for extreme case values. Even though the case study area is know to have an annual SER of 3 tons per acre for strip cropping, it may be of interest to see if the economic performance of strip cropping improves at higher levels of SER for both practices.

Table 8. Comparison of Agg. NPV and Siltation Year for Contour Farming for Changes in SER

SER tons per acre per year	3.4	4.4	5.4	6.4	7.4
Agg. NPV for Contour Farming $	15,287,846	15,238,968	15,190,091	15,141,213	15,092,335
Year of Complete Siltation	2070	2067	2064	2061	2059

Table 9. Comparison of Agg. NPV and Siltation Year for Strip Cropping for Changes in SER

SER tons per acre per year	3	4	5	6	7
Agg. NPV for strip cropping $	14,572,704	14,525,153	14,477,602	14,430,051	14,382,500
Year of Complete Siltation	2071	2068	2065	2062	2059

As the results reported above show, so long as the difference in SER is held constant at 0.4, contour farming is the better option. As compared to the no conservation case, contour farming is viable for erosion rates less than 3.6 tons per acre per year. For rates above this value, farmers are better with no soil conservation.

Prevention vs Clean up

Contour farming increases reservoir life by 30 years (Table 1). Practicing sediment removal from the dam can also extend reservoir life. A total of 1069.2 acre ft of sediment has to be excavated to achieve 30 years extension in reservoir life. The cost incurred for this practice is $17,819,287. Assuming the removal takes place in 1994 (the year of major storm in our simulation) the discounted value of this cost would be 26,099. This is the amount that is saved by the society if conservation is practiced in upstream cropland.

V. Conclusions

A model is developed to carry out economic analysis of soil conservation in a watershed that has a reservoir downstream. The link between soil erosion from agricultural land and reservoir sedimentation is specified in a scientifically rigorous manner. It is known that in many situations soil conservation on agricultural land reduces erosion. If the conservation techniques are effective, they should reduce sedimentation at the reservoir and increase its life. This type of extension of life is also possible through sediment removal from the reservoir. The model allows the net benefits of the latter option to be compared with the former.

Applicability of the model is demonstrated with an illustrative case study. Several scenarios with respect to type of watershed management practices are examined. In the first set of scenarios, we keep land use at its historical values, and then in the second set we allow the land allocated to agriculture to increase relative to its historical pattern. Results show that for the base case values of parameters, contour farming is more beneficial than strip cropping and no conservation. Sensitivity analysis is then performed with respect to discount rate and SER parameters. Results indicate that contour farming is economically more viable unless these parameters are raised to relatively high values. On the whole erosion is controlled more effectively with strip cropping, but economic analysis favor adoption of contour farming.

The model has certain shortcomings. First it does not incorporate any comparison of alternative sediment removal techniques. The model can be easily extended to allow for such comparisons. The second limitation is that although the data used is partly from published documents, reports and is also partly synthetic. The value of the simulation exercise can be enhanced if a more comprehensive and detailed data set is made available.

VI. Appendix

The first section of the appendix contains the STELLA □ (High Performance Systems) diagrams for the modules explained in section III. The formulas associated with the stocks, flows and converters are complex and not included in this section. The second section presents data on historical land use and SER.

Section I

Soil Erosion From Watershed

Figure 1A below illustrates the different components contributing to soil erosion in a watershed. Historic land use for the period of study is obtained from various sources such as sedimentation survey report, aerial photographs and GIS data. The soil erosion rate is estimated using USLE (Wischmeier, et al., 1978). Both land use and soil erosion rates are a function of human activities. In this paper we concentrate on human impacts on crop and pasture land. Precipitation is modulated for 2, 5, 10, 50, 100 and 500-year storm frequencies based on DeGaetano (1996) and a random number generator-recurrence interval scheme by the authors.

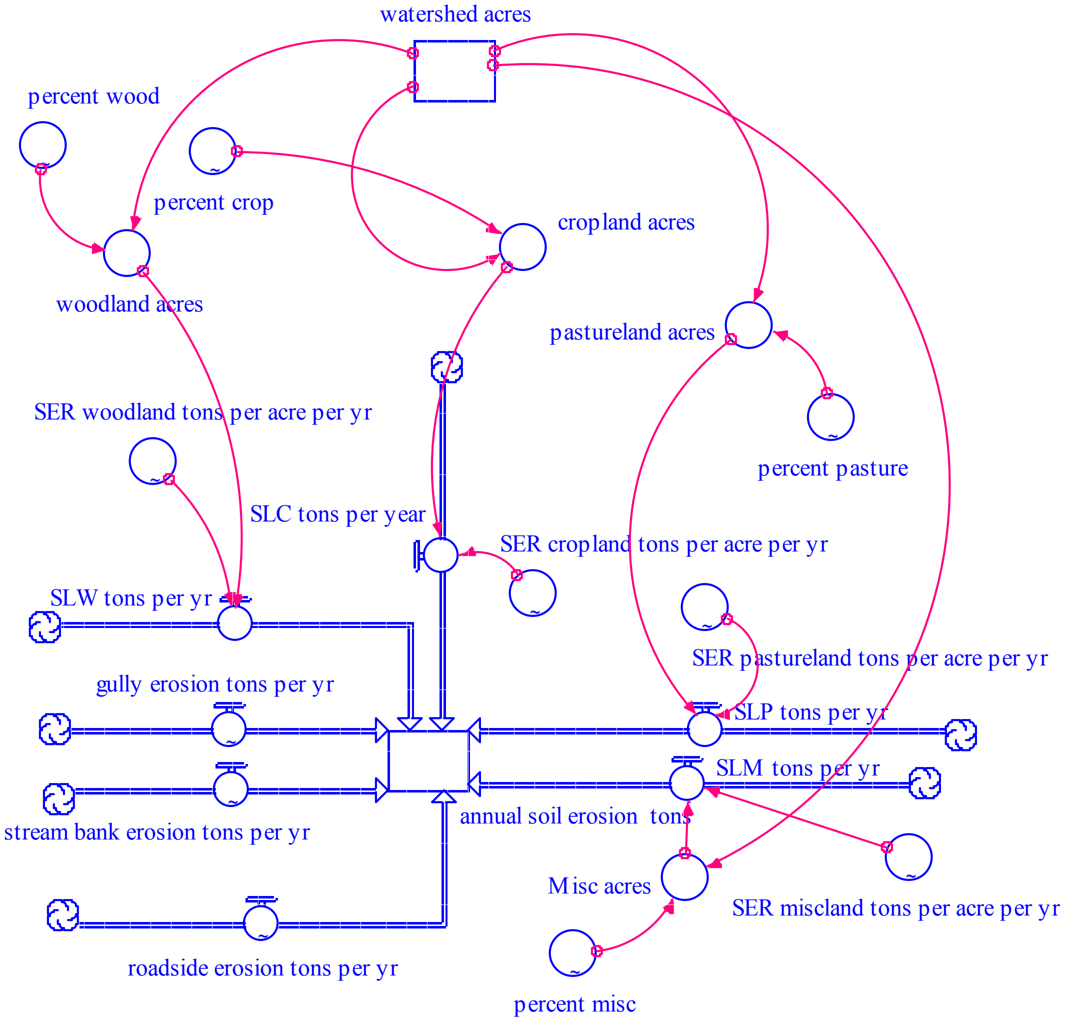

Figure 1A. Stella Model of Erosion

Hydraulics

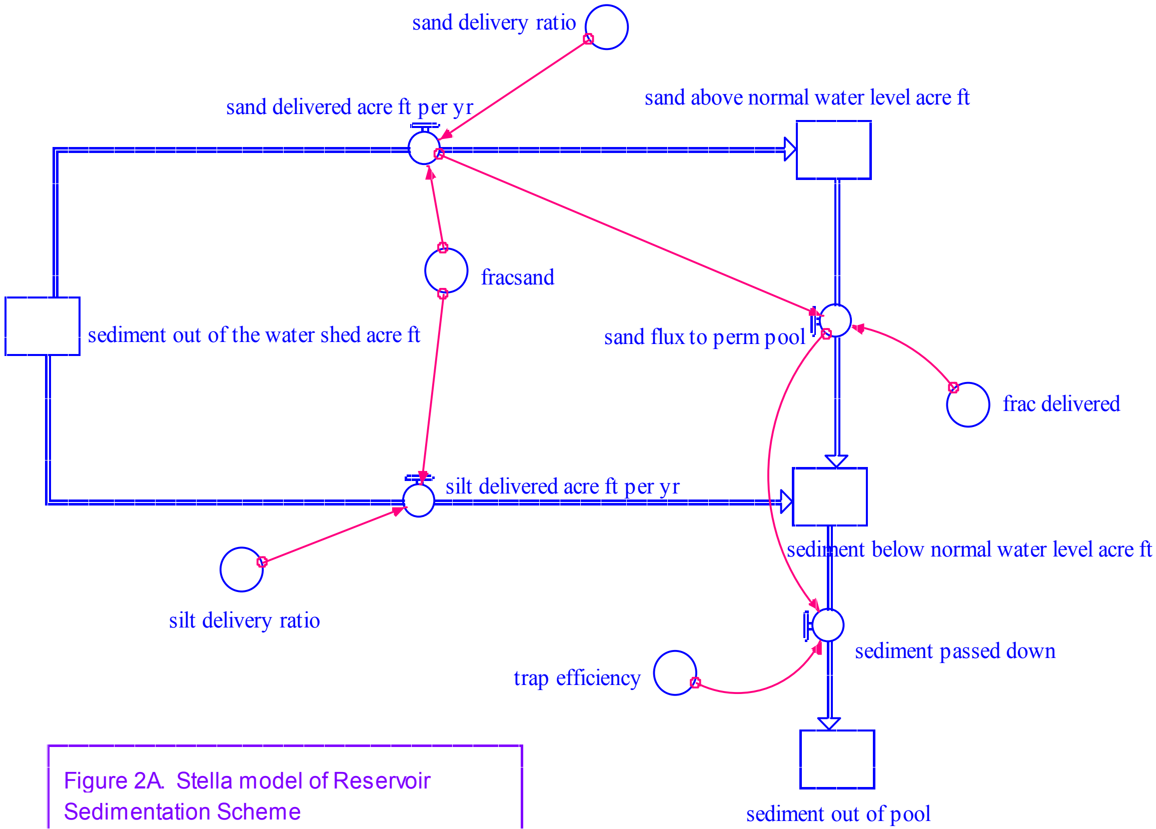

Figure 2A. Stella model of Reservoir Sedimentation Scheme

Soil loss from the watershed gets accumulated in the reservoir downstream as shown in Figure 2A. The incoming sediment is divided into slit and sand. Silt deposits predominantly into permanent pool above normal water level (flood control purpose) while sand below normal water level (recreation and water supply purpose). Runoff from the water shed is a function of rainfall and curve number (United States. Soil Conservation Service., 1983). In a separate model an inflow hydrograph is created using previous storm as the base. Peak inflow Q_{pin} and outflow Q_{pout} are then calculated to obtain the ratio of Q_{pin}: Q_{pout} for various accumulation of sediment in the reservoir by changing the water height. Q_{pout} for the watershed under study can be easily calculated from the above-calibrated ratio. The reservoir is allowed to be silted. The goal of this exercise is to prove the significance of upstream management in reducing sedimentation and avoidance of expensive removal techniques.

Calculation of Net Benefits for Economic Analysis

The aggregate net present value is calculated as shown in Figure 3A below. It consists of two-subsection, agriculture and reservoir.

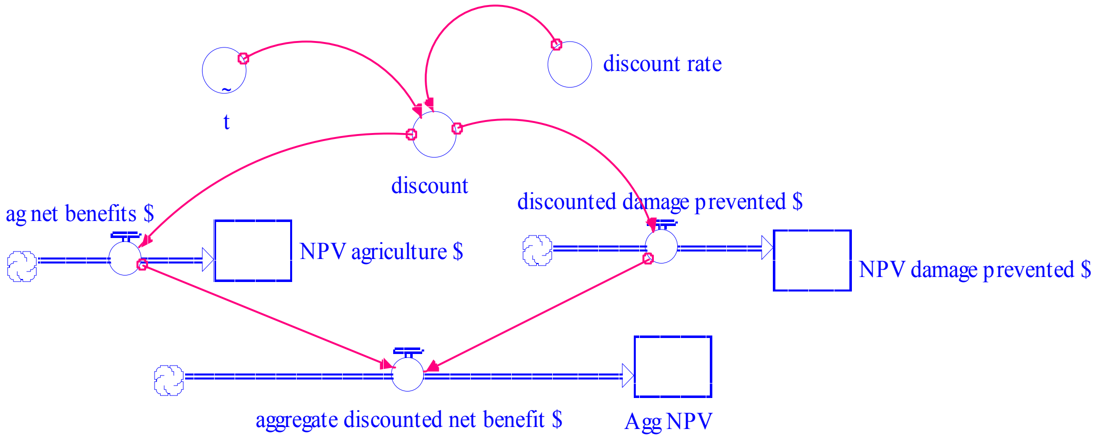

Figure 3A. Stella Model of Agg. NPV

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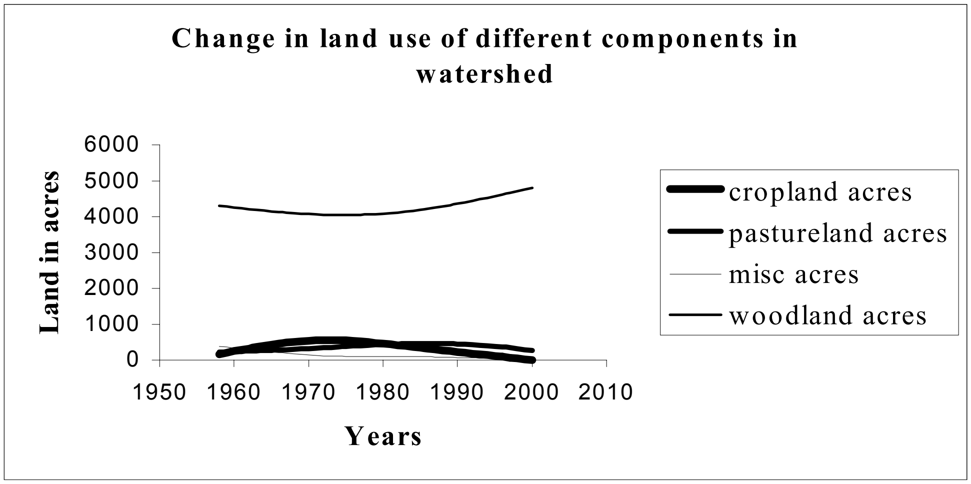
Agriculture: In this section we deal with the production of corn and pasture. Benefits accrue from sale of these commodities. The sale prices obtained from the (NASS) census while that of pasture is calculated (Edward, 2002). Cost of production is divided into farm expenditures and fix cost. Fix costs includes installation cost of conservation techniques and is obtained from (United States. Division of Soil Survey., 1993). The net benefits are calculated and discounted to get net present value for agriculture section

Reservoir: Flood control dam is built to prevent flooding of land down stream during a storm. Benefits are estimated in terms of damage prevented form reduction in floods. These are discounted to get net present value.

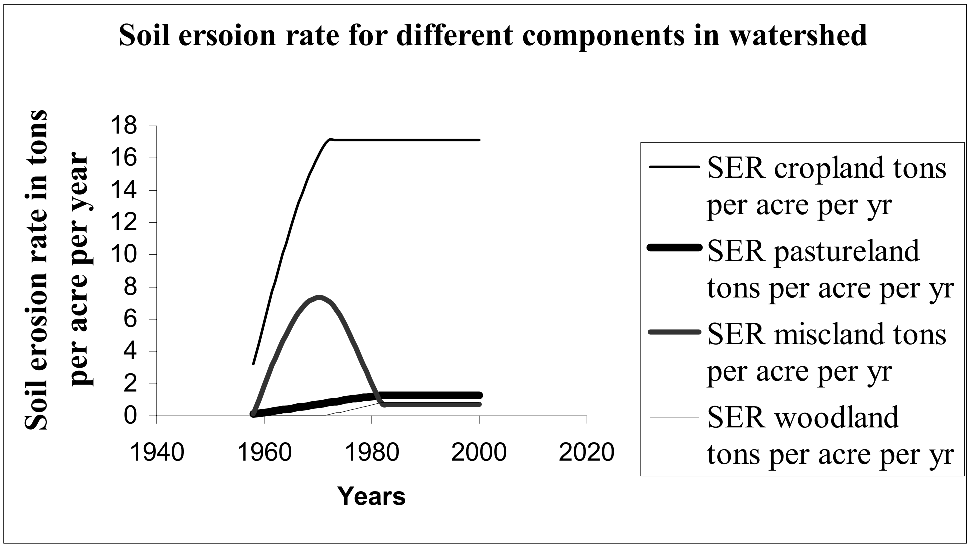
Aggregate net present value is obtained by adding the values from above sections

Section II

Change in land use (Graph 1) and soil erosion rate (Graph 2) for the watershed under study are reported below.



Graph 1. Change in Watershed Land Use



Graph 2. Change in SER for Land Use in Watershed

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