



**AgEcon** SEARCH  
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search  
<http://ageconsearch.umn.edu>  
[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Selected Paper

2003 Annual Meeting of the Southern Agricultural Economics Association

**Least-Cost Watershed Management Solutions: Using GIS Data in Economic Modeling of a Watershed\***

**Tihomir Ancev<sup>1</sup>, Arthur L. Stoecker<sup>1</sup> and Daniel E. Storm<sup>2</sup>**

Phosphorus pollution from excessive litter application causes eutrophication of lakes in the Eucha-Spavinaw watershed in eastern Oklahoma and western Arkansas. Consequent algal blooms impair the taste of municipal water supply drawn from the watershed. The paper shows how GIS data based biophysical modeling can be used to derive spatially optimal, least-cost allocation of management practices to reduce phosphorus runoff in the watershed. Transportation activities were added to the model so that transport of litter within and out of the watershed was possible. Results from the mathematical program suggest that uniform regulation of litter application is excessively costly regulatory measure and hence a regulation that assigns management practices according to the specific spatial characteristics is preferred. The results also show that alum based litter additives may be economically efficient management option.

*Key words:* watershed, GIS, poultry litter, phosphorus.

*Copyright 2003 by authors. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.*

---

\* Paper of the Department of Agricultural Economics, Oklahoma State University no. AEP-0304

<sup>1</sup> Graduate Assistant and Associate Professor, respectively, Department of Agricultural Economics, Oklahoma State University

<sup>2</sup> Professor, Department of Biosystems Engineering, Oklahoma State University

## **Introduction**

Serious environmental concerns regarding water pollution, odors, and soil pollution are associated with concentrated animal production in high capacity facilities. In particular, phosphorus pollution of surface water bodies contributes to the eutrophication of lakes and rivers, which impairs drinking water supply and reduces the recreational values of natural amenities. The Eucha-Spavinaw watershed, which is shared by the states of Oklahoma and Arkansas, has been troubled for a number of years and has been a source of considerable controversy between the two states. Eutrophication of lakes Eucha and Spavinaw has been blamed on high phosphorus loading in the watershed attributed to excessive land application of litter produced by intensive poultry industry in the area (Storm *et al.*, 2001). Water from eutrophicated lakes is not suitable for drinking due to bad taste caused by algal blooms. Municipal water treatment facilities are able to treat the water to achieve established drinking water standards, but find it difficult and extremely expensive to treat the water to remove the bad taste.

Recent advances in biophysical modeling due to the advent of the GIS data use (Gurnell and Montgomery, 2000), (Arnold *et al.*, 1998), as well as dramatic improvements in computing capabilities, create an opportunity for more precise modeling of the environmental processes relevant for the problem of phosphorus pollution caused by poultry litter in the Eucha-Spavinaw watershed. These advances could be used in designing environmentally and economically effective policies. The main problem that is treated in the paper is how to use these new developments to assign management practices to

particular areas within the watershed that will effectively control the pollution but at the same time will be least costly to the society.

The objective of the study is to present a method for deriving least cost watershed management solutions by choosing a combination of waste management practices for agricultural sources of phosphorus loading. The paper determines an optimal spatial allocation of waste management practices in the Eucha-Spavinaw watershed.

The study uses a two-step procedure for determination of the optimal set of waste management practices. Soil Water Assessment Tool (SWAT) is used as a Geographical Information Systems (GIS) data biophysical simulation model for the Eucha-Spavinaw watershed. The output data on crop yield, grazed biomass and phosphorus runoff from the SWAT model is used in a spatial mathematical programming model to determine the optimal allocation of management practices within the watershed.

### **Conceptual Framework**

The initial conceptual framework of the paper is based on the notion of minimizing the sum of pollution abatement costs and environmental damages costs (Freeman, Haveman and Kneese, 1973). Within this framework the social well being is maximized by equating the marginal abatement costs to the marginal environmental damage costs. This approach requires estimation of both abatement and environmental damage costs. The main component of the environmental damages costs for the Eucha-Spavinaw watershed is the added cost to the city of Tulsa municipal water supply. The costs of municipal

water treatment for the city of Tulsa can be estimated using the data provided by the Tulsa water treatment facilities. Unfortunately, these data are currently not considered public information due to a litigation process that city of Tulsa has undertaken against several poultry integrators and the municipality of Decatur, AR. Therefore the data is not available for an analysis and presentation.

If the data on the environmental damage costs were available they could be used to determine the level of socially optimal phosphorus loading in the watershed. This level is obtained where the sum of abatement and damage costs is minimized, or equivalently where the marginal abatement costs in all HRUs are equalized among them and at the same time are equal to the marginal environmental damage costs.

Having the estimates for the abatement cost, the overall objective is to maximize producers' income from agricultural activities at the watershed level subject to a limit for total phosphorus pollution in the watershed. The total pollution limit is parametrically varied to derive the marginal abatement cost curve. To model the watershed, assume that it is composed of  $n$  unique land areas each denoted by index  $i$ . Let the quantity of agricultural production from the  $i$ 'th land area be denoted by  $Y_i = f_i(X_i)$ , where  $X_i$  is the vector of input quantities used in area  $i$ , and  $Y_i$  is a vector of agricultural outputs produced in that land area. This study is particularly interested in poultry litter and alum, which are elements of the vector  $X$  in the area  $i$ . Let  $Z_i$  be the amount of agricultural pollutant that leaves area  $i$  when  $X_i$  units of input are used,  $Z_i = g_i(X_i)$ . In this study,  $Z_i$  denotes the quantity of total phosphorus loading from the  $i$ 'th land area. The total

allowed quantity of pollution at the watershed outlet is denoted by  $Z_{max}$ . It is assumed that the region of the watershed is sufficiently small so that all commodity ( $\mathbf{Py}$ ) and input ( $\mathbf{Px}$ ) prices are fixed in the short-run. The profit to the agricultural producers operating in the  $i$ 'th land area is <sup>3</sup>

$$(1) \quad \Pi_i = \mathbf{Py} \cdot f_i(\mathbf{X}_i) - \mathbf{Px}_i \cdot \mathbf{X}_i.$$

Total net benefits from agricultural production for the whole watershed is represented by the sum of the profits over all  $n$  land areas,  $\sum_{i=1}^n \Pi_i$ .

The constrained profit maximization problem is to maximize total profits from agricultural activities in the watershed, subject to a limit on total phosphorus pollution. This problem can be expressed in the form of the Lagrangian function as

$$(2) \quad \max_{\mathbf{X}_i, Z_i, \lambda_i, \Psi} L = \sum_{i=1}^n \Pi_i + \sum_{i=1}^n \lambda_i [g_i(\mathbf{X}_i) - Z_i] + \Psi \left( Z_{max} - \sum_{i=1}^n Z_i \right),$$

where the Lagrangian variables  $\lambda_i$  and  $\psi$  represent the changes in the value of the objective function that would result from an increase in the value of the allowed phosphorus pollution constraint.  $\psi$  represents the amount of profit gained (lost) if the quantity of allowable phosphorus pollution from the entire watershed is increased (decreased). The term  $\lambda_i$  represents the change in profits from the land area  $i$  as a result of a change in the quantity of phosphorus pollution from the  $i$ 'th land area due to the quantity of poultry litter applied.

The first order conditions of the Lagrangian function (Eq.2) with respect to the control variables  $\mathbf{X}_i$ ,  $Z_i$ ,  $\lambda_i$  and  $\psi$  are respectively given by

---

<sup>3</sup> Only the agricultural outputs from crop production and grazing are considered in the study. The poultry production in the watershed is held constant at current levels.

$$(2.1) \quad L_{X_i} = P y' f_i'(X_i) - P x_i + \lambda_i (g_i'(X_i)) = 0, \quad \forall i,$$

$$(2.2) \quad L_{\lambda_i} = \lambda_i - \psi = 0, \quad \forall i,$$

$$(2.3) \quad L_{\lambda_i} = g_i(X_i) - Z_i = 0, \quad \forall i,$$

$$(2.4) \quad L_{\psi} = Z_{max} - \sum_{i=1}^n Z_i, \quad \forall i,$$

where the subscripts on the left-hand side denote the partial derivative of the Lagrangian function taken with respect to a variable and the terms  $f'$  and  $g'$  on the right hand side denote first derivatives.

Equation 2.2 indicates that  $\lambda_i = \psi$  for each of the  $n$  land areas. This is reasonable in the case where pollution flows are channeled and there are no pollutant transport losses within the reach system of the watershed. The present study uses biophysical simulation that did not use the reach system in the watershed so that the phosphorus pollution leaving one land area exits the watershed unaffected by any transport processes.

Equations (2.1) and (2.2) can be combined to obtain

$$(3) \quad P y' f_i'(X_i) = P x_i - \psi g_i'(X_i), \quad \forall i.$$

The optimal combination of inputs  $X$  to use in the  $i$ 'th land area is the quantity  $X_i$  for which the value of the marginal product is equal to the marginal factor cost plus a penalty cost (or tax) on phosphorus loading that insures the maximum allowed phosphorus pollution is not violated. Since these calculations are expected to be unique for each area  $i$ , the model should allow for the quantity of input  $X_i$  to be unique to each land area. This implies that the optimal litter application rate is non-uniform across individual land areas.

## **Methods and Procedures**

GIS based simulation models are gaining widespread acceptance with researchers and policy analysts in studying point and non-point pollution problems. However, the simulation models such as SWAT are not optimization models. On the other hand, even the simple conceptual model discussed above shows that the optimality conditions must hold for each of possibly thousands of point and non-point sources in a watershed, if it is desired to meet the overall abatement targets at least cost. Therefore, a combination of a biophysical and optimization modeling needed in order to determine least cost combination of abatement practices.

A two-step procedure for environmental and economic modeling of the watershed is developed and used. In the first step, the standard GIS simulation protocol is followed to determine the effects of selected best management practices (BMP) on the watershed level agricultural pollution. For each BMP in each HRU, the simulation provides input-output estimates for crop yields, pasture yields, and estimates of each pollutant leaving the HRU. The second step is to construct a spatial mathematical programming model. A production activity for each simulated BMP is constructed for each HRU in the model. The effect of the individual BMP in the HRUs on the total income is readily calculated using exogenous prices and the simulated yield. Other inputs and outputs including the contribution of the individual BMP to the overall watershed pollution are also readily calculated. The mathematical programming model permits a choice of BMP, which is unique to a particular HRU, while insuring (if feasible) that overall pollution targets are met.



### *Procedure Step 1*

An analysis based on the abatement costs has been done for eleven BMPs for the Eucha-Spavinaw watershed. The BMPs correspond to six levels of poultry litter application: 150%, 100%, 75%, 50%, 25% and 0% of the current litter application rate combined with the use of aluminum sulfate additives to litter for the non-zero application rates (Moore, 1999).

The calibrated SWAT model for the Eucha-Spavinaw watershed (Storm et al., 2001) was used to conduct biophysical simulation for each of the six litter application rates. SWAT uses Geographical Information Systems (GIS) data to create a detailed digital image of the watershed, to simulate climate and to simulate phosphorus loading (Arnold *et al.*, 1998). Within the SWAT framework the watershed is divided in a number of Hydrologic Response Units (HRUs), which represent relatively homogenous units with respect to soil type, land use and climate. The SWAT model was run as a twelve year simulation (1990 - 2001, inclusive) with averages for the last six years used in actual computations (the first six years essentially used as warm-up period). Technical description of the SWAT model for the watershed is given in Table 1.

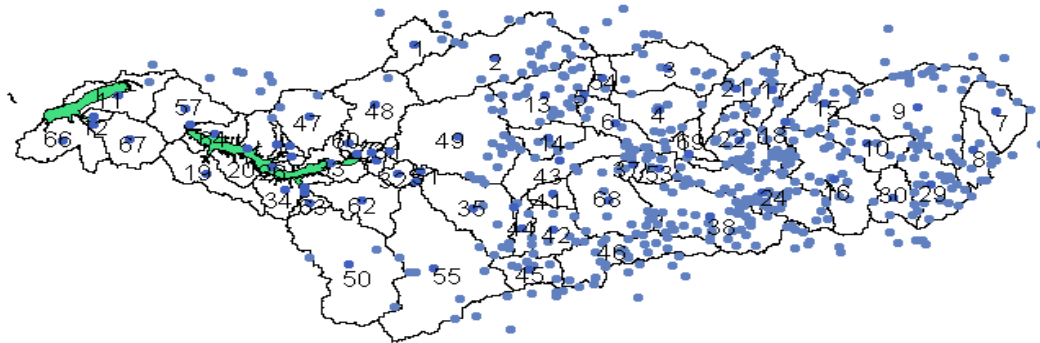
Table 1. SWAT Model of the Eucha-Spavinaw Basin

Total Area	1670 km <sup>2</sup>	Sub basins	69
Forested Area	918 km <sup>2</sup>	HRUs	1052 (694 agricultural)
Agricultural Land*	704 km <sup>2</sup>	Est. no. of broiler houses	957
Urban Area	2 km <sup>2</sup>	Est. quantity of litter produced	85000 tons
Water Area	36 km <sup>2</sup>	Est. quantity of P applied	4000 tons
		Est. quantity of P runoff	31 ton

\* Agricultural land comprises of Pasture (Overgrazed and Well maintained), Grassland for hay, and row crop (wheat pasture/green beans rotation).

The Eucha - Spavinaw Basin is graphically represented in Figure 1.

Figure 1. GIS Image of the Eucha- Spavinaw Basin .



Legend: • Broiler Houses ; Numerals - Sub Basins ; Shaded areas - Lakes Eucha and Spavinaw.

### *Procedure Step 2*

The income from agricultural activities was estimated by enumeration using data from the SWAT model (yield and biomass data), Oklahoma State University Enterprise Budgets and various published (USDA, 2002) and unpublished (personal communications) sources. An overview of some data used in the computations is provided in Table 2.

Table 2. Prices, Costs and Conversion Factors Used in Estimating Income from Agricultural Activities in the Eucha –Spavinaw Watershed.

Prices:		Cost :	
Hay	\$60/ton	Litter appl.	\$4/ton
Beef	\$1300/ton	Urea appl.	\$12/ha.
Green beans	\$120/ton	Urea	\$200/ton
		Alum	\$220/ton
Conversion:			
Mixed pasture/Beef	10 kg / 1 kg		
Wheat pasture/ Beef	7 kg / 1 kg		

The income for four agricultural enterprises: Hayed non-grazed pasture, Well Maintained Pasture, Overgrazed Pasture and Row Crop (Wheat-Green bean rotation), corresponding to SWAT land uses, was estimated for eleven various BMPs using enterprise budgeting. Each BMP is associated with specific phosphorus runoff estimated in SWAT. Estimated income is used in a mathematical programming model, which maximizes the sum of income from the whole watershed subject to phosphorus loading constraints.

The possibility to add aluminum sulfate to the litter was modeled using data published in Moore (1999). The income estimates from the agricultural activities in HRUs where alum was added to the litter have been lowered by a symbolic 1% <sup>4</sup>. The reduction of phosphorus runoff with alum addition is estimated using the experimental data from Moore (1999) from a controlled small-scale watershed. The experiments showed that the addition of alum reduced the phosphorus runoff attributed to litter application by 75% <sup>5</sup>.

This result is represented by

$$(4) \quad 0.75 (P_{current} - P_{zero}) ,$$

where  $P_{current}$  is the phosphorus runoff under current litter application rate and  $P_{zero}$  is the phosphorus runoff under zero application rate.

---

<sup>4</sup> Studies found that use of the alum sulfate increases the income to the producers. However, a confirmation to this finding is not observed in the practice. The reason for this may be asymmetric information and/or income distribution problems. It is conceivable to think that adding alum would inflict some costs, at least to crop producing farmers. Therefore a small, arbitrary reduction of income was assumed.

<sup>5</sup> There is a current debate among the soil scientists and agricultural engineers, especially in Oklahoma and Arkansas. One camp believes that the phosphorus runoff can be attributed to current litter application, but also to the past litter application reflected in high accumulation of Soil Test Phosphorus. Under this doctrine, there would still be significant phosphorus runoff even if the litter application were completely halted. The other camp believes that the phosphorus runoff can be attributed almost exclusively to current litter application, especially in the absence of soil erosion. In the present study it was assumed that the quantity of runoff attributed to soil test phosphorus is unaffected by the alum application.

Using these data, the optimal levels of abatement practices for the watershed as a whole can be obtained in the framework of a mathematical programming model (Beneke and Winterboer (1973)). The model has the following form:

$$(5.1) \quad \max_{X_{ij}} \sum_{i=1}^N \sum_{j=1}^{694} \Pi_{ij} X_{ij} - \sum_{k,z=1}^{69} T_{kz} c_{kz} d_{kz} - \sum_{b=1}^B T_b c d_b$$

subject to

$$(5.2) \quad \sum_i X_{ij} = 1$$

$$(5.3) \quad X_{ij} \geq 0$$

$$(5.4) \quad T_k = T_{kk} + T_{lk} - T_{kl}, k \neq l$$

$$(5.5) \quad \sum_{i=1}^N \sum_{j=1}^{694} Z_{ij} X_{ij} \leq Z_{\max},$$

where  $\Pi_{ij}$  represents net income under  $i^{th}$  BMP in  $j^{th}$  HRU <sup>6</sup>,  $X_{ij}$  is the BMP indexed across the set of possible practices ( $i=1$  to  $N=11$ ), and across agricultural HRUs ( $j=1$  to 694),  $T_{kl}$  is the quantity of waste (litter) in tons shipped from the  $k^{th}$  to the  $l^{th}$  sub basin within the watershed <sup>7</sup>,  $c$  is a unit cost of transportation per mile, and  $d$  is distance in miles between sub basins  $k$  and  $l$ .  $T_b$  is the quantity of litter shipped out of the basin from different points (indexed from 1 to  $B$ ) at cost  $c$  and for average distance of  $d_b$ . The symbol  $Z$  represents the amount of phosphorus runoff in tons from the  $j^{th}$  HRU under the  $i^{th}$  BMP, while  $Z_{\max}$  is parametrically varied maximum level of phosphorus runoff for the whole watershed. The model was run for the three levels of total phosphorus loading  $Z_{\max}$ . The first level of 30.1 tons/year corresponds to the SWAT estimate of phosphorus runoff under current litter application rate - Scenario 1. The second level of 27.1 tons / year

<sup>6</sup> There are a total of 694 agricultural HRU's in the watershed.

<sup>7</sup> The SWAT model divides the watershed in total of sixty nine subbasins.

corresponds to the SWAT estimate of phosphorus runoff under uniform reduction across all HRUs of 50% from the current litter application rate - Scenario 2. The third level of 23.7 tons/year corresponds to the SWAT estimate of phosphorus runoff under uniform zero litter application across all HRUs - Scenario 3. The mathematical program was solved using standard MPS linear programming format in the C-WHIZ Version 4 Linear Programming Optimizer (Ketrion Management Science).

Since the SWAT model is not able to simulate transportation activities, a GIS based analysis of the road network within the watershed was conducted to estimate the transportation distances. Transportation costs within the watershed were estimated using the distances between sub basins calculated with the Network Analyst Extension for ArcView. The costs for transporting out of the watershed were approximated using the county level phosphorus assimilative capacity for the surrounding counties in the states of Oklahoma, Arkansas, Kansas and Missouri. The costs were computed by estimating the distances to haul the litter before the phosphorus assimilative capacity in a county allows for net import of litter. The estimated average distances were 30 miles to the North of the watershed, 40 miles to the South, 20 miles to the West and 40 miles to the East. The transportation activities were added to the mathematical programming model.

## **Results**

The optimal allocation of management practices is observed in relation to the land use, land class, SWAT sub basin etc. Table 3 summarizes some of the main results.

Table 3. Results Overview from a Linear Program under the Three Scenarios for Phosphorus Emitted in the Eucha-Spavinaw basin.

	Scenario 1 (30.1t P)		Scenario 2 (27.1t P)		Scenario 3 (23.7t P)	
Value of the objective function:	mill.dollars		mill.dollars		mill.dollars	
Linear program	10.087		10.062		8.138	
Uniform reduction = SWAT simulation	9.85		7.79		6.078	
	Hydrologic response units (HRUs) in the solution basis					
Optimal litter application rate, with or w/o alum :	Count	Average current applicati on rate	Count	Average current application rate	Count	Average current application rate
		t/ha		t/ha		t/ha
No litter*	39	3.01	38	3.23	295	1.66
25% of current	10	5.32	8	5.05	3	3.32
25% of curr. + alum	0	0	2	6.38	1	0.29
50% of current	2	5.97	1	4.75	28	0.62
50% of curr. + alum	0	0	1	7.17	0	0
75% of current	0	0	0	0	3	1.74
75% of curr. + alum	0	0	1	0.46	3	4.34
Current	290	1.30	175	1.27	37	0.21
Current + alum	15	0.33	143	1.15	72	2.81
150% of current	333	1.15	249	0.94	115	0.17
150% of curr. + alum	5	0.46	76	1.65	137	1.24
Total transport activity (thousand ton miles)	275		121		600	
Transported out of the basin (tons)	0		0		40925	

\* 22 out of the reported number of HRUs did not receive litter in the Swat simulation

The results presented in Table 3 show that the optimal solution to the mathematical program differs greatly from what would have been implied by any policy of uniform reduction of litter application rate. Allowing for transportation improves one of the shortcomings of the SWAT model and makes the optimal solution more realistic. The results also show that the desired target of phosphorus emissions can be achieved at much lower cost by optimal spatial allocation of management practices as opposed to uniform reductions. For example, in order to reduce the phosphorus load from 30.1 to 27.1 tons per year the uniform reduction policy will require all producers to cut in half their application of litter. This policy would result in abatement cost close to \$2 million or in

average abatement costs of \$686,000 per ton of phosphorus. The same effect with respect to phosphorus load can be achieved by the optimal spatial allocation solution at an average cost of \$8,350 per ton of phosphorus abated.

The use of aluminum sulfate, the changes in the optimal litter application rate as well as the intensity of transportation activities have a clear pattern in the solution. As the phosphorus constraint becomes more stringent, there is more use of alum, more HRUs with no litter application and more transportation in the optimal solution. At the most restrictive phosphorus constraint, a significant amount of litter has to be exported out of the basin, which significantly adds to the abatement costs. The shadow price per ton of phosphorus under the Scenario 1 is \$1,670, under Scenario 2 is \$19,290 and under Scenario 3 is \$1,396,570, which indicates that moderate reduction of phosphorus pollution could be achieved at relatively low cost, while the costs are much higher if the target for reduction of phosphorus pollution is high.

The distribution of abatement by land use and land class is given in Table 4. Optimal average litter application rates in tons per hectare by land use and land classes are given in Table 5. The breakdown of agricultural land use by land classes is given in the Appendix Table A1. The land classes are arbitrarily defined using the measures of slope to categorize the HRUs. The values used in categorization are corresponding to the values usually used in a phosphorus index calculations (USDA, 2001).<sup>8</sup>

---

<sup>8</sup> Class 1 with a slope less than 0.01, class 2 with a slope between 0.01 and 0.03, class 3 with a slope between 0.03-0.05, class 4 with a slope 0.05-0.08, and class 5 with a slope greater than 0.08.

Table 4. Distribution of Abatement by Land Use and Land Classes as a Percentage Change of the Number of HRUs Where the Litter Application Rate is Changed.

	Total no. of HRUs	Change of practice in HRU Scenario 1 to 2 (% of total HRUs)	Change of practice in HRU Scenario 1 to 3 (% of total HRUs)	Change of practice in HRU Scenario 2 to 3 (% of total HRUs)
Average abat. cost (\$ thous./ton of P)		8.3	304.5	565.8
<b>Agricultural use</b>				
Hay	199	14.7	76.37	74.87
Overgrazed Pasture	162	63.58	82.71	80.86
Well Maintained Past.	208	9.13	75	74.03
Row Crop	125	59.2	87.2	86.4
<b>Land Classes</b>				
1( slope < 1%)	2	0	100	100
2(1% < slope < 3%)	116	40.51	93.1	91.37
3(3% < slope < 5%)	150	43.33	81.33	80.66
4(5% < slope < 8%)	301	30.23	79.73	78.73
5(slope > 8%)	125	16.8	63.20	60.80

Table 5. Average Optimal Litter Application Rate (tons ha<sup>-1</sup>) for the Eucha-Spavinaw Basin by Land Uses and Land Classes. \*

Agricultural Use	Land class (slope)				
	1(0-1%)	2(1-3%)	3(3-5%)	4(5-8%)	5(>8%)
Scenario 1					
Hay		0.82	0.71	0.79	0.74
Overgrazed Pasture		0.62	0.56	0.56	0.54
Well Maintained Past		0.75	0.64	0.51	0.51
Row Crop	0.69	0.70	0.72	0.70	0.69
Scenario 2					
Hay		0.83	0.76	0.79	0.74
Overgrazed Pasture		0.64	0.57	0.56	0.58
Well Maintained Past		0.75	0.64	0.51	0.51
Row Crop	0.69	0.67	0.70	0.65	0.68
Scenario 3					
Hay		0.63	0.67	0.63	0.69
Overgrazed Pasture		0.00	0.18	0.17	0.39
Well Maintained Past		0.46	0.44	0.44	0.61
Row Crop	0.27	0.18	0.19	0.19	0.14

\* Application rates are for litter that may or may not have been treated with alum.



Results presented in Table 4 show the distribution of optimal management practices over land uses. The results show that there was little change in litter application practices for the agricultural uses “Hay” and “ Well maintained pasture”, which is represented by a low percentage change from Scenario 1 to Scenario 2. By changing the waste management practices in "Hay" and "Well maintained pasture" HRUs there is relatively little to be gained in preventing phosphorus loading and relatively more to lose in terms of income reduction. This means that the agricultural uses "Overgrazed pasture" and "Row crop" should be targeted more aggressively with a policy towards reducing phosphorus loading in the basin. Results in Table 5 show the changes in optimal litter application rates by agricultural use and land class as the constraint on the phosphorus loading in the watershed becomes more stringent.

The results with respect to land classes are somewhat surprising. The results show that the most changes should take place in the flatter HRUs, which is contrary to what may be an impression at a first glance. We usually think that the abatement should first occur on fields with higher slope, because the runoff and erosion potential is higher. However, it is also important to recognize the role of the land use. In this particular case the "row crop" land use produces by far the most runoff compared to the other land uses. This land use also tends to be more present in the low slope HRUs, which matches the reality well. Most farmers would plant wheat, green beans etc. on flatter, less sloped fields, while leaving the slopes for the pasture. This is reflected in the results on the land classes presented in Tables 4 and 5. The row crop is predominant in the land classes 1, 2 and 3 while it is almost not present in land classes 4 and 5. Since the changes in litter

management practice (application rate combined with alum) are highly required on the row crop, the changes in practices by land class reflect the same requirement. Thus, contrary to the expectations, the most changes are required for flatter HRUs, while for more steeper sloped HRUs where pasture is a dominant land use, less changes are required.

## **Conclusion**

The paper presents a procedure to devise optimal BMPs with respect to litter application rate and alum use in order to reduce environmental problems attributed to excessive phosphorus load in the watershed. The method uses SWAT model as a biophysical simulator. SWAT uses GIS data to simulate the biomass, yield and phosphorus runoff from the HRUs in the watershed. The HRUs are homogenous units with respect to economic activity, soil properties and topography.

A mathematical programming model was run for three scenarios determined by the allowed phosphorus runoff. The results from the runs suggests the following conclusions:

1. Regulating the application rate of litter in the watershed by requiring all producers to uniformly reduce their litter application rate is economically ineffective. The same results with respect to phosphorus abatement may be achieved by allocating litter management practices according to the specific spatial characteristics of the individual HRUs in the watershed at much lower cost.

2. The use of aluminum sulfate is economically effective in reducing the phosphorus runoff. As the constraint on phosphorus becomes more stringent, the use of alum becomes more prevalent. Although not reported in the paper, we have findings showing that having alum as a management option significantly increases the value of the objective function.

3. Incorporating transportation in the model ameliorates the shortcomings of the SWAT model in this part of the simulation. Transportation activities are significant, even under least stringent phosphorus constraint, which reflects the observed behavior in the watershed that can not be simulated by SWAT. Exporting litter out of the watershed is necessary if the target for phosphorus abatement is set higher. This affects the abatement cost quite significantly.

4. The "row-crop" and "overgrazed" pasture land uses should be considered first in any regulatory attempt. Their relative contribution to the phosphorus runoff is much higher than their relative contribution to the total income, so restriction on litter use and/or mandating a use of alum should begin with these land uses. Land uses "hayed pasture" and "well maintained pasture" are much less susceptible to phosphorus runoff and very little changes are needed.

5. Since the "row crop" land use dominates the land classes with lower slopes, the most changes are needed in these "flatter" HRUs. This is contrary to the intuition, but is a result of the effect that a certain land use dominates the land class.

The procedure presented in this paper has clear policy implications. The advances in GIS and in computational resources make it easier and less expensive to apply this procedure to real life situations. For example, the procedure can be used in the permitting process for the poultry industry in the watershed, where the poultry producers could be prescribed a least socially costly management practice according to the particular spatial characteristics of the fields used for litter application.

## Appendix

Table A1. Breakdown of Agricultural Land use by Land Class.

	Land Classes					Total HRU's
	1(0-1%)	2(1-3%)	3(3-5%)	4(5-8%)	5(>8%)	
Agricultural use	Count					
Hay	0	24	35	99	41	199
Overgr. Pasture	0	20	36	78	28	162
Well Maintained Past.	0	25	36	101	46	208
Row crop	2	47	43	23	10	125
Total HRU's	2	116	150	301	125	694

## References:

Arnold, G.J., R. Srinivasan, R.S. Muttiah, and J.R. Williams. " Large Area Hydrologic Modeling and Assessment Part I: Model Development." J. of Amer. Wat. Res. Ass., 34(1):73-89, 1998.

Beneke, R.R. and R. Winterboer. " Linear Programing Applications to Agriculture.", Iowa State University Press, Ames, Iowa, 1973.

Enterprise Budgets, Oklahoma State University, Accessible at: <http://agecon.okstate.edu/budgets/index.html>

Freeman, A. M., R.M. Haveman and A.V. Kneese. " The Economics of Environmental Policy.", Willey Pub., New York, N.Y., 1973

Gurnell, A. M. and D.R.Montgomery." Hydrological applications of GIS.", John Wiley Chichester, New York, 2000.

Hollenback, J. Personal Communications. 2002.

Moore., P.A., T.C. Daniel and D.R. Edwards. " Reducing Phosphorus Runoff and Improving Poultry Production with Alum.", Poultry Science 78: 692-698, 1999.

Srinivasan, R., T.S. Ramanayaranan, G.J. Arnold and S.T. Bednarz. " Large Area Hydrologic Modeling and Assessment Part II: Model Application." J. of Amer. Wat. Res. Ass., 34(1):91-101, 1998.

Storm, D.E., M.J. White, M.D. Smolen and H. Zhang. " Modeling Phosphorus Loading for the Lake Eucha Basin.", Final Report. Dept. of Biosystem Eng. Oklahoma State Univ., Stillwater, OK, 2001.

U.S. Department of Agriculture, Natural Resources Conservation Service. "Agronomy Technical Note, AL – 72.", Auburn, AL, 2001.

U.S. Department of Agriculture, National Agricultural Statistics Service. "Agricultural Prices.", Washington D.C., March, 2002