Optimal Spatial Allocation of Waste Management Practices to Reduce Phosphorus Pollution in a Watershed[*]

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Selected Paper

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Phosphorus pollution from excessive litter application and municipal discharges causes eutorphication of lakes in the Eucha-Spavinaw watershed in eastern Oklahoma and western Arkansas. Consequent algae blooms impair the taste of drinking water supply drawn from the watershed and reduce the recreational values of the lakes. The paper shows how GIS data based biophysical modeling can be used to derive spatially optimal, least-cost allocation of agricultural management practices to be combined with optimal wastewater treatment activity from the point source in order to achieve socially optimal phosphorus load in the watershed. The optimal level of phosphorus load is determined by equating marginal abatement with marginal damage cost. Transportation activities in the model allow for transportation of litter within and out of the watershed. Results show uniform regulation of litter application is excessively costly relative to measures that encourage adoption of management practices that equate marginal abatement costs across pollution sources. The results also show that change in the land use patterns in a long-run and using alum based litter additives in short-run are economically efficient management options.

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

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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 values of recreation and natural amenities. The Eucha-Spavinaw watershed, 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 is blamed on high phosphorus loading in the watershed attributed to excessive land application of litter produced by intensive poultry industry in the area, and discharges of municipal wastewater from the City of Decatur, AR, emitted from a combined treatment plant for the municipality and a poultry processing facility (Storm *et al*., 2002). Water from eutrophicated lakes is not suitable for drinking due to bad taste caused by chemicals resulting from algae presence (OWRB, 2002). Drinking 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 (TMUA, 2003). There are concerns regarding the recreational values of the area lakes, as well as concerns about the overall ecological impacts of phosphorus pollution in the watershed.

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 enviro-economic processes relevant for the problem of phosphorus pollution in the Eucha-Spavinaw watershed. These advances could be used in designing environmentally and economically effective policies.

The main problem treated in the paper is to use these new developments to assign management practices to particular areas within the watershed that will effectively control the pollution at least cost. The objective of the study is to present a method for deriving least cost watershed management solutions by choosing a combination of management practices for agricultural non-point sources and the municipal point source of phosphorus loading in a watershed.

The study uses a two-step procedure for determination of the optimal set of phosphorus abatement practices. First the Soil Water Assessment Tool (SWAT) is used as a Geographical Information Systems (GIS) data biophysical simulation model for the Eucha-Spavinaw watershed, (Storm *et al*., 2002). The SWAT output data on crop yield, grazed biomass and phosphorus runoff are used in a spatial mathematical programming model to determine optimal allocation of management practices to the point and non-point sources of phosphorus loading within the watershed and to derive the marginal phosphorus abatement costs. Environmental damage costs are calculated as a sum of cost for additional drinking water treatment for the City of Tulsa and the costs of recreational losses of the area lakes.

Conceptual Framework

The conceptual framework is based on minimization of total pollution abatement costs and total environmental damage costs (Freeman, Haveman and Kneese, 1973). The optimal social allocation can be expressed with the following optimization problem

$$\max_{p} W(p) = M^* + E^* - \left(A(p) + D(p)\right), \tag{1}$$

where $W(p)$ is a pollutant dependent welfare function, M^* is the maximum amount of market goods produced in a economy without any abatement, E^* is the maximum potential value of environmental services obtained from a pristine environment, $A(p)$ is the abatement cost function and $D(p)$ is the environmental damage cost function. Since M^* and E^* can be treated as endowments that are fixed in the short and medium-run, the total social well being can be maximized by minimizing the sum of pollution abatement costs and environmental damages costs, or by equating marginal abatement and damage costs. For this approach to be operational in the case of phosphorus pollution in the Eucha–Spawinav watershed, empirical estimation of both abatement and environmental damage costs is needed.

Abatement costs

Total abatement costs are the sum of point and non-point source abatement costs. Abatement costs for a municipal wastewater treatment represent the costs of employing a particular abatement technology to provide a specific quantity of phosphorus reduction. Abatement costs for non-point sources are approximated by the changes in the net income from agricultural enterprises under alternative poultry litter management techniques.

Environmental damage costs

Two main types of environmental damages caused by phosphorus pollution in the watershed are identified as the impairment of the quality of drinking water for city of Tulsa (OWRB, 2002) and the losses of recreational values of the area lakes, reflected in drastic reduction in the number of annual visits (OCC, 1997, OTRD, 2003)).

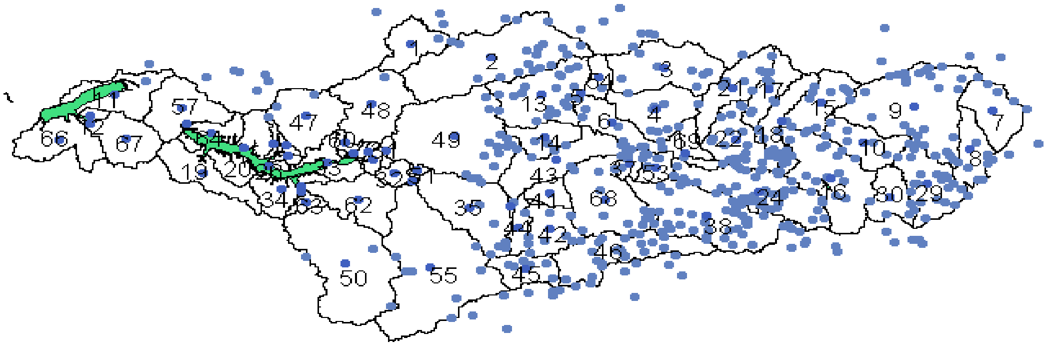
Methods and Procedures

Step 1: Management Practices, Abatement and Damage Costs

The calibrated SWAT model for the Eucha-Spavinaw watershed (Storm et. al., 2001) was used to conduct biophysical simulation for the alternative BMPs. The BMPs were implemented on

695 agricultural hydraulic response units (HRU) from 69 sub-basins in the Eucha-Spavianaw watershed. An HRU represents a combination of a major soil type and land use within a sub-basin. The watershed with broiler houses is shown in Figure 1. The total land area and agricultural land use area are summarized in Tables 1 and 2.

Figure 1. GIS Image of the Eucha- Spavinaw Watershed



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

Table 1. SWAT Model of the Eucha-Spavinaw Watershed

Total Area	1006 km^2	Sub basins	69
Forested Area	547 km^2	HRUs	1052 (695 agricultural)
Agricultural Land	458 km^2	Est. no. of broiler houses	957
Urban Area	2 km^2	Est. quantity of litter produced	85000 tons
Water Area	36 km^2	Est. quantity of P applied	1275 tons
		Est. quantity of P loading	48 tons (35 t. agriculture, 11 t. point-source, 2 tons background)

Table 2. Agricultural Land Uses in the Eucha Spavinaw Watershed

Land Use	Acronym	Area (ha.)	Comment
Grassland used for hay product.	HAY	13402	
Grassland used for pasture (not maintained)	OPAS	6542	
Grassland used for pasture (well maintained)	WPAS	23250	
Row crop	WWHT	2625	Receives inorganic fertilizer (35.2 kg/ha. Nitrogen) always

Best Management Practices (BMPs)

The BMPs correspond to eight levels of poultry litter application to the four agricultural land uses in the watershed for which the litter was or was not treated with aluminum sulfate (alum) (Moore *et al.*, 1999). The alum product is added to the litter in the poultry house in ratio 1:10, alum to litter. Alum ties up phosphorus, thereby significantly reducing the potential for phosphorus runoff once the litter is applied to the agricultural land. Experimental results showed that the addition of alum to broiler litter reduced the soluble phosphorus runoff attributed to litter application by 75% [3]. If the farmers are required to reduce or halt the application of poultry litter on their land, they may either choose to replace the nutrients, nitrogen in particular, by purchasing and applying commercial fertilizer, or they may choose not to replace nitrogen with commercial fertilizer. The economic model presented in this study allows for the decision regarding the substitution of nitrogen from commercial fertilizer at the lower litter application rates. Table 3 presents the alternative litter application rates by agricultural land uses in the watershed and the quantities of nitrogen applied under the two alternative strategies regarding nitrogen replacement with commercial fertilizer.

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[3] 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.

Table 3. Litter Application Rates , with and without Nitrogen Replacement and with and without Alum Addition for the Land Uses in the Watershed. (All values in kilograms per hectare)

Land Uses											
HAY			OPAS			WPAS			WWHT		
Litter rate	N w. replac	Nw/o replac	Litter rate	N w. replac	Nw/o replac	Litter rate	N w. replac	Nw/o replac	Litter rate	N w. replac	Nw/o replac
6000	300	300	3230	161.5	161.5	6000	300	300	1950	132.7	132.7
4800	240	240	2585	130	130	4800	240	240	1560	113	113
4000	200	200	2154	107.7	107.7	4000	200	200	1300	100	100
3400	200	170	1830	107.7	91.5	3400	200	170	1105	100	90.5
3000	200	150	1615	107.7	81	3000	200	150	975	100	84
2000	200	100	1077	107.7	54	2000	200	100	650	100	68
1000	200	50	538	107.7	27	1000	200	50	325	100	51
0	200	0	0	107.7	0	0	200	0	0	100	35.2

Stated litter application rates comprise both alum treated and not treated litter. Overall, there are twenty-four different activities (BMPs) (11 distinct alum treated litter activities + 13 non-alum treated litter activities (zero litter rate does not have the alum option)).

Changing the land use patterns in the watershed was tested as another management possibility. It was found with the preliminary results that overgrazed pasture (OPAS) and row crop (WWHT) land uses contribute excessively to the phosphorus load in the watershed. Hence, a conversion of the OPAS land use to WPAS (maintained pasture) land use and conversion of WWHT land use to HAY land use was conducted.

The SWAT biophysical model was run for each of the noted litter application rates and for the two nitrogen replacement strategies. There were total of thirteen SWAT runs. Yield, produced biomass, grazed biomass and phosphorus runoff was read from the SWAT output files for each of the 695 agricultural HRUs in the watershed. These results were used as inputs to the calculations for agricultural income and to the mathematical programming models.

The net 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 data used in the computations is provided in Table AP1 in the

Appendix. Abatement costs for the non-point sources are approximated by the reduction in agricultural income under alternative litter management practices.

Wastewater Treatment Cost

The costs of abatement at the point source were estimated using engineering data. In order to model the cost of phosphorus abatement in the wastewater effluent from the City of Decatur, a specific design for the secondary wastewater treatment had to be projected. A system of secondary chemical treatment using aluminum sulfate was chosen due to its relative simplicity and cost effectiveness for comparably small treatment plants (Metcalf & Eddy, 2003). The system is consisted of the following stages: chemical addition component, settling chamber for flocs, gravity thickening tank for the sludge, additional liquid/solid separation sequence for the sludge, transporting and landfilling the wastewater treatment residuals. The design and the cost of the components vary with the dosage of the chemical added. The phosphorus concentration of the effluent also varies with the dosage of the chemical. Phosphorus abatement costs are determined in this fashion and are displayed in Table AP2 in the Appendix.

Drinking Water Treatment Costs

The costs of additional drinking water treatment to the City of Tulsa consist of costs for additional use of powdered activated carbon in water treatment and costs of pumping from alternative water reservoirs. The powdered activated carbon (PAC) is effective in removing odor and taste of drinking water caused by the chemicals Geosmin and MIB (methyl iso-borneol) that are produced with the algae die-off (OWRB, 2002), but is quite costly (the price of PAC is \$0.2/kg.). The City of Tulsa also tried to divert its water supply from Lake Spavinaw to water supply from Lake Hudson. This provides drastic reduction in chemical treatment costs (very little or no PAC used) but inflicts high pumping costs ($61.44 per million gallons). The data on water treatment costs were obtained from the City of Tulsa.

Observed average annual costs for PAC use and pumping costs from Lake Hudson were regressed on the observed phosphorus load form point and non-point sources in the watershed. The estimated equation (t-values in parenthesis)

$$CT_t = \underset{(-5.36)}{-226394} + \underset{(10.08)}{11.14}\, Z_t\,, \tag{2}$$

where CT_t denotes the costs to the City of Tulsa in year t, and Z_t is the observed phosphorus load in year t, had an R^2 of 0.971. The estimated equation indicates strong positive linear relationship between the phosphorus load in the watershed and the costs of additional drinking water treatment. This is expected since the high phosphorus load results in intensive algae growth, which in turn results in production of Geosmin and MIB. It should be noted that we worked with average annual data and that distribution of costs and phosphorus loading within a year reflects the lagged effects of phosphorus loading on the Geosmin and MIB production.

Recreational Visits to the Lakes

The costs of recreational losses at the area lakes were estimated using the theoretical concept of travel cost. Data on visitations to the Eucha and Spavinaw state parks were obtained from the Oklahoma Tourism and Recreation Department (OTRD, 2003). Visitors were divided in iso-travel cost zones according to survey results published in a report by the Oklahoma Conservation Commission (OCC, 1997). Four travel zones were identified: Zone 1 – Tulsa Metropolitan Area, Zone 2 - Siloam Springs and Fayetteville, AR, Zone 3- visitors from Oklahoma other than Tulsa, and Zone 4 – Local area. Travel cost from each zone was calculated using road distances and average gasoline consumption and prices. The value of time spend on recreation (McConnel, 1992) was incorporated in the travel cost estimates using income data (USDC, 2000) to estimate the hourly earnings. The costs of leisure time used to travel to and from the recreation site and the time spent at the recreation site were valued at one third of the estimated average hourly earnings for each iso-travel zone.

Demand equation for recreation in a price flexibility form was estimated according to the following model

$$TC_l = \sum_{k=1}^{12} d_1{}^k D^k + d_2 Q_l, \tag{3}$$

where TC_l denotes the travel cost to the recreational site from the l^{th} zone, $d_1{}^k$ denotes maximum willingness-to-pay at a given level of phosphorus concentration, D^k is a dummy variable for each level of phosphorus concentration (twelve levels, k), and Q_l is the observed number of visits from the zone l. The results from the estimation are presented in Table AP3 in the Appendix. The estimated maximum willingness–to–pay parameters were regressed on the observed phosphorus concentration to yield the following estimated equation (t-values in parenthesis)

$$d_1{}^k = \underset{(4.93)}{72.7} - \underset{(-2.1)}{788.5}\, PC^k, \tag{4}$$

where PC is the observed phosphorus concentration in the lakes. Data published in OWRB, 2002, pp-120-121 were used to convert the phosphorus concentration to phosphorus loading. Consequently, distinct intercepts for each level of phosphorus loading were calculated. The calculation of the consumer surplus and the change in the consumer surplus at the various levels of phosphorus load were conducted using the standard procedures. The results are provided in Table AP4 in the Appendix.

The sum of costs to the City of Tulsa and the cost of recreational losses provides an estimate of the total environmental damage costs. In order to obtain the solution for the socially optimal level of phosphorus abatement one needs to equate estimated marginal damage cost to the estimated marginal abatement cost. The marginal abatement costs are obtained as shadow prices on phosphorus constraint in a linear programming framework. The marginal damage costs are obtained by first expressing the total damage costs as a function of phosphorus load and by differentiating the function with respect to it. The estimated total damage cost function is (t-values in parenthesis)

$$DC = \underset{(10.25)}{585446.9} - \underset{(-15.45)}{59.93\, Zmax} + \underset{(25.18)}{0.0015\, Zmax^2}, \qquad (5)$$

where DC is the total damage cost and Z_{max} is the level of phosphorus loading. Marginal costs are readily calculated by differentiating Eq. (5) with respect to the phosphorus load.

Step 2: Construction of a Spatial Linear Programming Model

The second step builds a set of spatial mathematical programming models, where a production activity for each simulated BMP is constructed for each HRU and for each level of point source abatement in the model. Total abatement cost curve for the Eucha-Spavinaw watershed was traced by maximizing net agricultural income, choosing the most profitable BMP in each HRU while minimizing the sum of wastewater treatment costs and sub-basin transportation costs for poultry litter subject to a limit on total phosphorus loading from the entire watershed.

The linearized mathematical programming model is specified as, (6.1) $$\max_{X_{ij},Y_q} \sum_{i=1}^{N}\sum_{j=1}^{695} \Pi_{ij} * X_{ij} - PSC_q(Z_q) * Y_q - \sum_{s=1}^{695}\sum_{r=1}^{695}\sum_{t=1}^{2} Tt_{sr}c_{sr} - \sum_{b=1}^{B}\sum_{t=1}^{2} Tt_b ct_b$$

subject to

(6.2) $\sum_{i} X_{ij} = 1$ and $X_{jj} \geq 0$ (Select the most profitable BMP in each HRU)

(6.3) $\sum_{q} Y_q = 1$ and $Y_q \geq 0$ (Select a level of phosphorus abatement at the point source)

(6.4) $T_s = T_{ts} + T_{ts},\ s = r = 1 \text{ to } 69,\ t = 1,2$ (t =1 for litter without alum, 2 for alum)

(6.5) $T_{st} = T_{sst} + T_{rst} - T_{rst}$, $s \neq r$ (All litter applied or shipped out of the watershed)

(6.6) $Z_k + \sum_{i=1}^{N}\sum_{j=1}^{694} Z_{ij} X_{ij} \leq Z_{\max}$, (total phosphorus loading less than $Z_{\max}$)

where;

Π_{ij} is the net income from the i^{th} BMP in j^{th} HRU,
X_{ij} is the adoption of the i^{th} BMP in the j^{th} HRU.
PSC_q is point source abatement cost for the q^{th} level of phosphorus abatement (Y_q).
Ts is the total quantity of litter in produced in s^{th} subbasin.
T_{tsr} is the quantity of litter with treatment t shipped from the s^{th} to the r^{th} sub basin[4].
ct_{sr} is the cost of transporting litter with treatment t from the s^{th} to the r^{th} sub-basin.
T_b is the quantity of litter shipped out of the watershed from point b.
Z_{ij} is the amount of phosphorus runoff in tons from the j^{th} HRU under the i^{th} BMP.
Z_q is the q^{th} level of phosphorus loading from the point source.
Z_{max} is total allowed phosphorus loading, Z_{max} was varied from 18000 to 46000 kilograms.

The above model does not incorporate damage costs because a separate objective was to parametrically trace out total and marginal phosphorus abatement cost curves for the watershed. The marginal abatement cost for phosphorus is obtained from the shadow prices for each of the parametric solutions. The damage cost could be linearized and subtracted from the above objective function so that a single optimal abatement level could be determined. Estimated marginal abatement costs are equated to marginal damage costs and the optimal level of

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[4] The SWAT model divides the watershed in total of sixty nine subbasins.

phosphorus abetment and optimal abatement practice at each non-point and the point source is determined and reported in the following section.

Results

The results obtained from the linear program runs for the BMPs (change in litter application rates, with and without alum amendments, with and without nitrogen replacement by commercial fertilizer) are presented in Table 3.

Table 3. Results from the Linear Program Runs for the BMPs

Phosphorus loading (Z max)	Value of the objective function	Phosphorus shadow price	Total abatement cost for Agricultural Enterprises	Total abatement cost to the point source
kg / year	dollars	dollars	dollars	dollars
46000	5616335	9.1723	0	0
40000	5546346	14.5304	57139	12850
35000	5473694	14.5304	56645	85996
30000	5387629	22.4559	98573	130133
25000	5221834	56.7481	226826	167675
20000	3605787	886.5588	1826188	184360
18000*	1610470	inf	3821505	184360

* Solution not feasible

The results show that the use of BMPs can result in effective reduction of phosphorus load. For example, the phosphorus load could be reduced from current 46 tons/year to 30 tons/year (16 tons reduction) at total cost of about $230,000 distributed to agricultural enterprises ($100,000) and to the point source ($130,000). However, any further reduction comes at excessively high costs, characterized by the dramatically increasing shadow price (marginal abatement cost) at lower levels of phosphorus loading. The burden of this drastic phosphorus load reduction is almost exclusively on the agricultural enterprises, since the maximum reduction at the point source has already been achieved.

A summary of costs to the City of Tulsa and losses of recreational values, as well as the abatement costs for the various levels of phosphorus loading is given in Table 4.

Table 4. A Summary of the Abatement and Damages Costs and their Sum.

P loading	City of Tulsa Costs	Predicted Total Number of Visits to Spavinaw and Eucha State Parks	Consumer Surlplus	Total damage costs	Abatment costs	Sum of abatment and damage costs
kg/year	dollars	count	dollars	dollars	dollars	dollars
18000	0	263256	633222	0	inf	
20000	7693	198325	579518	61397	2010548	2071945
25000	52281	151756	457509	227995	394501	622496
30000	99758	138890	353001	379980	228706	608686
35000	168849	96826	265994	536077	142641	678718
40000	232107	60840	195939	669390	69989	739379
46000	276863	17238	129851	780235	0	780235

The optimal level of abatement is indicated in the rightmost column of Table 4 at the point where the sum of abatement plus damage costs is at minimum. The optimal level could be found at the phosphorus load in between 25 and 30 tons a year. At the exact optimal point the marginal abatement costs will be equal to marginal damage costs. The marginal abatement costs can be approximated by the following function

$$MAC_1 = 466 - 0.025\, Zmax_k + 0.0000003\, Zmax_k^2. \tag{7}$$

Solving simultaneously for the *Zmax* using calculated marginal damage and abatement costs yields a quadratic equation with a root of 26062, which represents the optimal phosphorus loading in kg./year using the described BMPs. The linear program was rerun for this phosphorus constraint yielding a distinct management practice for each spatially distinct agricultural enterprise in the watershed and for the point source. The optimal level of phosphorus abatement at the point source is 9687 kg/ year, which corresponds to the effluent phosphorus concentration of 1.13 mg./litter.

Combination of BMPs and land use changes

The results from the linear program run where the possibility of land use change was combined with the described BMPs are presented in Table 5.

Table 5. Results from the Linear Program Runs for the Combination of the Land Use Change and the BMPs (various litter application rates, with and without alum, with and without nitrogen replacement with commercial nitrogen)

Phosphorus loading (Z max)	Value of the objective function	P shadow price	Total abatement cost for Agricultural Enterprises	Total abatement cost to the point source
kg / year	dollars	dollars	dollars	dollars
46000	5831270	0.5886	0	0
40000	5822066	2.3974	9204	0
35000	5801104	6.4967	30166	0
30000	5757993	11.023	73277	0
25000	5688941	14.5304	101802	40526
20000	5615442	16.2149	111621	104206
18000	5579609	20.3467	130121	121540

The results show that significant reduction of phosphorus load can be achieved at quite low cost. For example, the phosphorus load could be reduced from current 46 tons/year to 30 tons/year at total cost of about $73,200 by agricultural non-point source loadings. Further reductions from both point and non-point sources could reduce total loading to 18 tons per year for an annual abatement cost of approximately $250,000 per year. The results suggest that allowing for land use changes in addition to the alum based BMPs would be a very effective and economically efficient way to reduce phosphorus loading in the watershed. One has to keep in mind however that the changes in land use patterns can only be achieved in the long-run and would require changes in the economic structure of the region's agricultural production.

To obtain an exact point of optimum phosphorus abatement, the marginal abatement costs are equated to the marginal damage costs. Marginal abatement costs for this linear program run can be expressed as a function of the phosphorus load by

$$MAC_2 = 31.657 - 0.0007\ Zmax_k. \tag{8}$$

Solving simultaneously for phosphorus load using marginal abatement and damage costs one obtains a value of 24753, which is the socially optimal level of phosphorus load in kg./year, when combining the BMPs with land use changes. At the optimal solution, phosphorus abatement at the point source is 3012 kg./year corresponding to total annual abatement cost for the point source of approximately $44,000. The total abatement cost from agricultural enterprises is approximately $100,000. This combination of the BMPs and land use changes is able to achieve even the lowest phosphorus loading at relatively low cost (marginal cost of $20.34/ kg. phosphorus) while still maintaining quite high level of agricultural income (agricultural income net of point source abatement cost is $ 5,579,609). Again one should be warned that these results are only achievable in the long run, since they rely on possibility for change in land uses. It is to be expected that in the short run, reduction of phosphorus loading in the watershed can be achieved only at higher costs as noted before in Table 3.

Summary of the results with respect to land use changes and the use of alum are presented in Table 6.

Table 6. Summary of Use of Alum Treated Litter, and Changes in Land Uses at Current and Optimal Level of Phosphorus Loading in the Eucha-Spavinaw Watershed.

	Land Use		Alum Use	
	OPAS	WWHT	Non-treated litter	Treated litter
	hectares		tons	
P loading				
Current (46t.)	6542	2625	85000	0
Optimal (24.7t.)	0	1920	23510	61490
Land Converted	6542	705		

To exemplify the spatial distribution of BMPs across the presented solutions, one agricultural HRU from each original land use is chosen, and the allocation of BPMs are followed across the presented linear program solutions. The results are presented in Table 7.

Table 7. Management Practices in HRUs 17, 64, 471 and 1036, at the Current Level of Phosphorus Loading and at the Optimal Level of Phosphorus Loading.

Best Management Practices (litter application rates (kg/ha, w and w/o alum, w and w/o N replacement)					
Alum		Land Use Change		Combination	
P loading		P loading		P loading	
Current 46t.	Optimal 26 t.	Current 46t.	Optimal 23.6 t.	Current 46t.	Optimal 24.75 t.
HRU ID 17, original land use HAY, 52ha., Sub 1 (36.44, -94.67), soil Rezort, aver. Slope 0.066					
4000 w/o alum	4000 w alum	4000 w/o alum	4000 w/o alum	4000 w/o alum	4000 w/o alum
HRU ID 64, original land use OPAS, 44ha., Sub 3 (36.42, -94.57), soil Nixa, aver. Slope 0.072					
3230 w/o alum	3230 w/o alum	0* w/o N replacem.	0* w/o N replacem.	0* w/o N replacem.	0* w/o N replacem.
HRU ID 471, original land use WPAS, 110ha., Sub 21 (36.4, -94.51), soil Captina, aver. Slope 0.041					
2000 w/o, w/o N replac.	2000 w alum, w/o N replac.	1000 w/o alum, w/o N replac.	1000 w/o alum, w/o N replac.	2000 w/o alum, w/o N replac.	2000 w alum, w/o N replac.
HRU ID 1036, original land use WWHT, 20ha., Sub 68 (36.24, -94.61), soil Clarksville, Slope 0.024					
1560 w/o alum	1950 w alum	4000** w/o alum	4000** w alum	1300 w/o alum	1300 w/o alum

* Land use changed from OPAS to WPAS

** Land use changed from WWHT to HAY

Sub 1, denotes sub-basin one. The values in parenthesis are latitude and longitude in decimal degrees at the center of a sub-basin.

Summary and Conclusions

The paper presents a method for deriving socially optimal level of phosphorus loading in the watershed by equating marginal abatement costs to the marginal environmental damage costs. At the optimal point, the sum of total abatement and damage costs is minimized corresponding to the maximum value of the social welfare function. Abatement costs are composed of costs to the point source (wastewater treatment technology) and to the non-point sources (change in net income under alternative litter management practices) of phosphorus loading in the watershed.

Two types of agricultural management changes were considered. These were: 1) changes in litter application rates with and without aluminum sulfate amendments and with and without replacement of nitrogen with commercial fertilizer; and 2) changes in land use from row crops to hay and improvements in pasture management to convert overgrazed pastures to well maintained. These management choices were included in a linear programming model. The programming model was solved by parameterizing the allowable phosphorus loading to trace out a phosphorus abatement cost curve for the Eucha-Spavinaw watershed.

The environmental damage costs were approximated by the costs of additional drinking water treatment to the City of Tulsa and the value of consumers' surplus as a function of the reduced recreational demand for Lakes Eucha and Spavinaw. These costs were estimated using observed data and were combined in order to derive a marginal damage cost curve.

Marginal abatement costs were obtained as shadow prices on phosphorus loading from the linear program runs. They were then equated to the marginal damage costs to obtain a socially optimal level of phosphorus loading in the watershed. Since the non-point sources could be identified at considerable level of spatial detail, the results imply spatially optimal litter management practices for the agricultural enterprises in the watershed.

Several conclusions could be derived from the presented results. First, the optimal level of phosphorus loading in the watershed appears to be between 23,000 to 26,000 kilograms per year. Reduction below these levels would be quite costly in the sense that the costs of further reduction exceed the estimated benefits of damages avoided. Second, land use changes, especially a conversion of overgrazed pasture to well maintained, would be a most efficient long-term solution to the problem of phosphorus pollution in the watershed. However, this would require longer time and changes in the economic structure of the agricultural production in the watershed. Finally, the use of alum is adequate and economically efficient litter management practice, and can be used to reduce phosphorus loading in the watershed in the short-run.

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Table AP1. 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	$230/ton	Urea	$200/ton
		Alum	$220/ton
Conversion:			
Mixed pasture/Beef	10 kg / 1 kg		
Wheat pasture/ Beef	7 kg / 1 kg		

Table AP.2 Costs of various components of the secondary chemical wastewater treatment.

P load in the watershed kg/year	Alum AlSO4 used (50% product) mg/l	P concentration in efluent mg/l	Alum annual cost	Annualized cost of alum addition	Annualized cost of settling basin	Annulized cost of gravity thickening	Annualized separation costs	Annualized transportation costs and Landfilling costs	Total annual cost	P removed (abatted) Kg./year
11686.02	0	6.63	0	0	0	0	0	0	0	0
10365.67	10	5.88	$2,329	$9,267	$13,111	$14,345	$2,339	$1,629	$43,020	1,320
9176.83	20	5.21	$4,659	$10,188	$13,111	$19,232	$3,119	$3,257	$53,565	2,509
8109.66	30	4.60	$6,988	$10,948	$13,111	$22,716	$3,898	$4,886	$62,546	3,576
7155.00	40	4.06	$9,318	$11,751	$13,111	$26,200	$4,677	$6,515	$71,571	4,531
6304.28	50	3.58	$11,647	$12,564	$13,111	$29,684	$5,456	$8,143	$80,606	5,382
5549.53	60	3.15	$13,977	$13,335	$13,111	$33,168	$6,236	$9,772	$89,598	6,136
4883.29	70	2.77	$16,306	$14,362	$13,111	$36,652	$7,015	$11,400	$98,846	6,803
4298.63	80	2.44	$18,635	$15,304	$13,111	$40,136	$7,794	$13,029	$108,009	7,387
3789.06	90	2.15	$20,965	$16,054	$13,111	$43,620	$8,573	$14,658	$116,980	7,897
3348.56	100	1.90	$23,294	$16,814	$13,111	$47,104	$9,353	$16,286	$125,962	8,337
2971.52	110	1.69	$25,624	$16,935	$13,111	$50,588	$10,132	$17,915	$134,304	8,715
2652.70	120	1.50	$27,953	$17,057	$13,111	$54,072	$10,911	$19,544	$142,647	9,033
2387.24	130	1.35	$30,283	$17,178	$13,111	$57,556	$11,690	$21,172	$150,990	9,299
2170.63	140	1.23	$32,612	$17,299	$13,111	$61,040	$12,470	$22,801	$159,332	9,515
1998.64	150	1.13	$34,941	$17,421	$13,111	$64,524	$13,249	$24,430	$167,675	9,687
1867.38	160	1.06	$37,271	$17,542	$13,111	$68,008	$14,028	$26,058	$176,018	9,819
1773.22	170	1.01	$39,600	$17,663	$13,111	$71,492	$14,807	$27,687	$184,360	9,913

Table AP3. Results from estimation of the demand equation for recreation in a price flexibility form (Eq.3)

		Region 1		Region 2		Region 3		Region 4	
Pload (kg/ha)	Estimated intercept (Max WTP)	CS	ΔCS	CS	ΔCS	CS	ΔCS	CS	ΔCS
18000	55.01798	33250.66	33250.66	109208.8	104510.8	127617.7	118533.6	363145.3	247076
20000	53.96961	26777.6	26777.6	97193.35	92495.41	114600.6	105516.6	340946.7	224877.4
25000	51.34868	13657.7	13657.7	70217.58	65519.63	85120.78	76036.74	288512.9	172443.5
30000	48.72775	4913.122	4913.122	47617.14	42919.19	60016.26	50932.22	240454.3	124385
35000	46.10682	543.8776	543.8776	29392.03	24694.08	39287.08	30203.04	196771.2	80701.83
40000	43.48589	0	0	15542.25	10844.3	22933.23	13849.19	157463.3	41393.98
46000	40.34078	0	0	4697.947	0	9084.038	0	116069.3	0

Table AP 4. Estimated Maximum WTP, Consumer Surplus (CS) and Change in Consumer Surplus from Each Iso- Travel Cost Region

Effect	Pconc level	Estimate	Error	DF	t Value	Pr > |t|
Q		-0.00157	0.000079	35	-19.85	<.0001
d_1^{1}	0.037675	43.1634	1.4812	35	29.14	<.0001
d_1^{2}	0.038232	42.4313	1.4706	35	28.85	<.0001
d_1^{3}	0.038719	41.8975	1.4634	35	28.63	<.0001
d_1^{4}	0.039133	41.8838	1.4633	35	28.62	<.0001
d_1^{5}	0.039477	42.4304	1.4706	35	28.85	<.0001
d_1^{6}	0.039749	41.347	1.4565	35	28.39	<.0001
d_1^{7}	0.039887	39.0826	1.4333	35	27.27	<.0001
d_1^{8}	0.03995	42.3921	1.4701	35	28.84	<.0001
d_1^{9}	0.040042	39.6035	1.4379	35	27.54	<.0001
d_1^{10}	0.04008	41.7904	1.4621	35	28.58	<.0001
d_1^{11}	0.040126	41.7886	1.462	35	28.58	<.0001
d_1^{12}	0.040139	41.4425	1.4577	35	28.43	<.0001