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REGULATING NUTRIENT DISCHARGE FROM POULTRY LITTER INTO SURFACE WATERS: TOTAL MAXIMUM DAILY LOAD RULES AND ECONOMIC INCENTIVES

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ABSTRACT

The first 25 years of the Water Quality Act was characterized by major emphasis on regulating point sources with technology-based standards, but today many water quality problems still remain. The recent renewal of emphasis on water quality has been articulated in the form of proposed total maximum daily load (TMDL) rules. A TMDL identifies the amount of a pollutant that is allowed in a water body, allocates allowable pollutant loadings among sources, and provides a foundation for achieving water quality levels. The most important characteristic of TMDL rules is the impact on nonpoint source pollution. Poultry production has become an important component of the economic base in many watersheds, and the growing concern with the need to dispose of poultry litter that is loaded with nutrients has intensified the discussions surrounding the development of TMDL rules. Once a TMDL rule for nutrients such as phosphorus has been promulgated, it can be implemented by using an "optimal tax," which is levied on poultry litter that is applied to crops and pastures. But to do so is viewed as problematic. This can be done using a "standards and charges" approach, which involves two steps. First, standards or targets for phosphorus in the watershed are set on the basis of the TMDL rule. Second, a set of taxes (charges) is designed and put into place to achieve the stated target for phosphorus. This article explores the application of a standards and charges policy framework for a TMDL rule regulating phosphorus from poultry litter in surface water under stochastic conditions using simulation and mathematical programming techniques. That is, a protocol is established that uses simulation and mathematical programming techniques to compute the tax for a standards and charges framework for implementing a TMDL rule for phosphorus from poultry litter in a stochastic environment. This protocol allows the tax rate to be determined on the basis of information on crop demands for nutrients as well as the amount of nutrients contained in the poultry litter. The tax rate determined from this protocol also reflects the stochastic nature of the fate and transport of the nutrients as well as an appropriately defined margin of safety. As shown, the Kuhn-Tucker conditions are used as the basis to develop the appropriate taxes.

INTRODUCTION

In recent years, poultry production has become an important component of the economic base for many regions around the United States [1, 2]. A corresponding by-product of poultry production is the generation of poultry litter. Poultry litter contains a number of nutrients [1], which suggests a potential source of crop nutrients as well as a substitute for commercially produced fertilizers. Land-based application of poultry litter on crops and pasture lands may seem like a logical method for disposing of poultry litter, but increased applications have led to concerns about the environmental impacts of increased nitrate, phosphorus, and bacteria levels in water supplies [3].

Over the course of the first 25 years of the Water Quality Act, the primary focus was on regulation of point sources with technology-based standards. However, a wide range of water quality problems remain, as noted by Boyd [4]. The recent renewed emphasis on water quality is captured in proposed total maximum daily load (TMDL) rules [4, 5]. A TMDL identifies the amount of a pollutant that is allowed in a water body, allocates allowable pollutant loadings among sources, and provides a foundation for achieving water quality levels. Boyd has characterized the TMDL program as an ambient regulation where regulation and reporting are more concerned with the *in situ* quality of water bodies [4]. The most important characteristic of TMDL rules is the impact on nonpoint source regulation [4].

The purpose of this article is to explore the prospects of using an economic incentive system to manage water quality in a watershed in the case where TMDL rules have been established. Poultry production is assumed to be the primary agricultural activity, and land application is the only option for disposing of litter. The economic model structure includes stochastic specifications that represent key features of a TMDL rule for water quality. The economic incentive system is based on the Baumol aud Oates standards and charges system [6].

MODEL

The modeling framework used in this incorporates poultry production and cropping decisions as well as decisions pertaining to land-based application of litter. It is assumed that profit maximization is the decision criterion.

The model structure used in this research captures a number of important features of broiler production, litter generation and disposal, and cropping activities. The broilers are produced under some type of contract arrangement between a poultry company (integrator) and a grower. The integrator provides the birds and feed and supervises the growth of birds through a "service person." (Note that the integrator retains ownership of the birds.) The grower provides housing, equipment, and labor. In addition, the grower is also responsible for waste management. In many cases the contracts between integrators and growers call for compensation or a price to be paid per unit of weight. The contract may also include incentives to encourage efficient production. (A thorough discussion of these contracts can be found in Knoeber and Thurman [7].

The profitability levels are based on a constrained optimization model structure. Let I (I = 1, ..., I) denote the ith farm in the watershed and j (j = 1, ..., J) the type of crop produced by the ith farm. Let k (k = 1, ..., K) denote the type of soil the jth crop is produced on for the ith farm. It is assumed that the only nutrients from poultry litter that are of concern are phosphorus and nitrogen. The index n is used to denote nutrients when n = 1 denotes phosphorus and n = 2 denotes nitrogen. In addition, the following notations are used.

P_j = price of crop j;
L_{ijk} = acres of land type k to product crop j by farm i;
Ω_{ijk} = productivity for crop j per acres of land type k for farm i;
c_{ijk} = variable cost per acre of crop j on land type k for farm i;
η_i = amount of poultry litter generated per unit of live poultry weight for farm i;
e_{ijk} = cost of spreading a unit of poultry litter on crop j on land type k for farm i;
θ_{ijkn} = amount of nutrient n in a unit of litter from poultry on farm i spread on crop j produced on land type k, farm i;
Γ_{ink} = response matrix coeffcient for nutrient n in land type k, for farm i that is in runoff;
r_i = profit margin for unit of poultry produced on farm i;
m_{ijk} = profit margin for crop j produced on land type k on farm i ($m_{ijk} = P_i\Omega_{ijk} - c_{ijk}$);
a_{ijkn} = amount of nutrient n used to produce crop on land type k for farm i;
V_i = live weight of poultry produced on farm i;
F_i = amount of feedstuff used for poultry production on farm i;
ϕ_{ijkn} = proportion of nutrient n not used by crop j produced on land type k that becomes available for runoff on farm i;

α_{ijkn} = proportion of applied nutrient n used on crop j, land type k, that is available for use by crop j on farm i;
M_{ijk} = amount of poultry litter applied to crop j produced on land type k for farm k;
$(1-\beta_n)$= exceedance probability for nutrient n in the watershed or basin;
b_i = opportunity cost factor for farm i in use of feedstuff;
L_{ijk} = amount of land of type k on farm i used to produce crop i;
$\overline{L_{ik}}$ = maximum amount of land type k on farm i available for crop production; and
$\overline{G}_n$ = target level of nutrient n in river basin.

Economic profits from broiler production, cropping activities, and litter disposal are determined by the following constrained optimization model.

$$\text{Max} \sum_{i=1}^{I} (r_i - b_i F_i) g_i (F_i) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} m_{ijk} L_{ijk} - \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} e_{ijk} M_{ijk} \qquad (1)$$

subject to

$$\sum_{j=1}^{J} L_{ijk} \le \overline{L}_{ik} \qquad (\Delta_{ik}) \quad (2)$$
$$(i = 1, ..., I)$$
$$(k = 1, ..., K)$$

$$\eta_i g_i(F_i) - \sum_{j=1}^{J} \sum_{k=1}^{K} M_{ijk} = 0 \qquad (\pi_i) \quad (3)$$
$$(i = 1, ..., I)$$

$$a_{ijkn} L_{ijk} = \alpha_{ijkn} \theta_{ijkn} M_{ijk} \qquad (\lambda_{ijkn}) \quad (4)$$
$$(i = 1, ..., I)$$
$$(j = 1, ..., J)$$
$$(k = 1, ..., K)$$
$$(n = 1, 2)$$

$$\Pr \left\{ \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \Gamma_{ink} \phi_{ijkn} (1-\alpha_{ijkn}) \theta_{ijkn} M_{ijk} \le \overline{G}_n \right\} \ge (1-\beta_n) \qquad (n = 1, 2) \quad (5)$$

The variables in parentheses with each constraint are Lagrangean multipliers.

The object function equation (1) is defined as economic profits from broiler production, land use for crop production, and litter application to crops by all firms in the watershed. The first set of terms in equation (1) represents returns from broiler production. The expression $(r_i - b_iF_i)$ shows the "net return" per unit of live weight of broiler production by the ith firm. The term b_iF_i is an opportunity cost imposed on each farm i to encourage efficient use of the feed-stock provided by the integrator in feeding broilers. The weight gain for broiler production is represented by a biological or growth response function where weight gain is stated as a function of feed intake [8]. The biological response function for the ith farm is represented by $g_i(F_i)$ where it is assumed that $g_i^{'}(F_i) > 0$ and $g_i^{''}(F_i) < 0$.

The second set of terms in equation (1) represents the returns from cropping activities. Note that the decision variable in this case is a land activity. The last set of terms in equation (1) represents the cost of applying litter to the various crops produced by the farms in the watershed.

The constraint set for the optimization model is given by equations (2) through (5). Constraint (2) represents restrictions on land availability for each farm i in the watershed. The variable L_{ijk} denotes the amount of land type k used to produce crop j on farm i. Constraint (3) is a balance equation reflecting the generation and disposal of poultry litter. The first term on the left side of constraint (3) defines the amount of litter generated from broiler production on the ith farm.

Equations (4) and (5) show a set of relationships that pertain to the supply and demand of the nutrients phosphorus aud nitrogen applied to the crops on each farm as well as the amount of phosphorus lost to runoff. In particular, equation (4) shows the equality of the supply of nutrients and the corresponding demand for each crop produced by each farm i in the watershed. Equation (4) shows that the source of nutrients is derived from poultry litter.

The nutrient formulations use a structural process design and nutrient balance approach that is similar to the formulation used by Schwabe [9] and Xu et al. [10]. Crop production activities and land-based disposal of litter is represented by a set of discrete production activities with unit activity vectors. It is assumed that part of the nutrients applied to the kth soil with crop j are taken up by the crops while the remaining portion is lost to runoff. The amount of the nutrient lost to runoff is assumed to be proportional to the amount of nutrient not taken up by crops. Constraint (5) is concerned with tracking nutrients from cropping activities that find their way into runoff.

The remainder of the discussions in this section will concentrate on constraint (5). In order to simplify the terms in constraint (5), define the following:

$$d_{ijkn} = \phi_{ijkn} (1 - \alpha_{ijkn}) \theta_{ikjn}. \tag{6}$$

Constraint (5) can be rewritten as follows:

$$\Pr\left\{ \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \Gamma_{ink} d_{ijkn} M_{ijk} \leq \overline{G}_n \right\} \geq (1-\beta_n). \tag{7}$$

$$n = 1, 2$$

It is assumed throughout this discussion that the environmentally limiting nutrient is phosphorus. That is $n = 1$ in constraint (7). The next step is to provide a more workable expression for the constraint (7). The development of this expression will be focused on the problem of implementing a policy that is based on a Total Maximum Daily Load (TMDL) program.

Novotny argues that any model structure used to discuss a TMDL-based policy must be structured around the intertemporal maintenance of water quality standards under a range of conditions with a stated "margin of safety" [5]. It is also important to consider the fact that stream conditions in a watershed are continually changing. Novotny further argues that the typical approach in modeling this sort of problem uses a single observation or average of a few samples and then a sensitivity analysis of factors subject to change is performed [5]. The preferred modeling approach should take into account the statistical properties of various factors in the model [5].

The elements of the formulation used in this article draw from the work of Willett et al. [11]. Suppose that TMDL policies are used to set $\overline{G}_1$ in constraint (7) (see [5]) and the concern is about the stochastic nature of both $\overline{G}_1$ and the Γ_{ink}. Treating $\overline{G}_1$ as a stochastic target as well as assuming that Γ_{i1k} is a stochastic parameter introduces a mechanism for representing the statistical properties of the various factors of concern for the TMDL-based policy.

Assume that Γ_{i1k}. and $\overline{G}_1$ are normally distributed with means $\hat{\Gamma}_{i1k}$ and $\hat{G}_1$. The respective variances are denoted by σ^2_{i1k} and ε^2_1. Assume that all of Γ_{i1k} and $\overline{G}_1$ are statistically independent of each other. The constraint (7) is now restated as follows.

$$\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\hat{\Gamma}_{i1k}d_{ijk1}M_{ijk}+\varphi_{\beta 1}\left[\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\sigma^2_{i1k}M^2_{ijk}+\varepsilon^2_1\right]^{0.5}\leq\hat{G}_1 \quad (8)$$

Constraint (8) lends itself to some interesting interpretations concerning uncertainty and the margin of safety, which are key elements of TMDL rules. First, define the following.

$$h_1=\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\Gamma_{i1k}d_{ijk1}M_{ijk}-\hat{G}_1 \quad (9)$$

assume that h_1 is normally distributed variable with mean

$$\mu(h_1)=\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\hat{\Gamma}_{i1k}d_{ijk1}M_{ijk}-\hat{G}_1 \quad (10)$$

and variance

$$\mathrm{var}(h_1) = \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \sigma_{i1k}^2 d_{ijk1} M_i^2 + \varepsilon_1^2 . \tag{11}$$

It can be concluded that the value $\mu(h_1)$ is related to decisions derived from the optimization model while φ_β is a critical value of the standard normal distribution exceeded only with probability $(1 - \beta_1)$. This formulation raises two important points. First, regulatory decisions are based on two important parameters: the maximum allowable amount of phosphorus $\overline{G}_1$ as determined by TMDL considerations and the margin of safety $(1 - \beta_1)$, which is part of the TMDL rule to be articulated. Second, the constraint formulation includes a weighted value of uncertainty that is consistent with the regulator's margin of safety in the articulation of the TMDL rule. The weighted uncertainty is given by:

$$\varphi_\beta [\mathrm{var}(h_1)]^{0.5} = \varphi_\beta \left[\varepsilon_1^2 + \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \sigma_{1ik}^2 M_{ijk}^2 \right]^{0.5} . \tag{12}$$

Equation (12) shows the regulator's aversion to uncertainty and is similar to the notion of risk aversion [12]. The expression in brackets on the right side of equation (12) shows the uncertainty inherent in estimating the response matrix coefficients and also explicitly represents the margin of safety. As the margin of safety is increased, the larger is the value of $\varphi_{\beta 1}$, implying that a higher weight is being placed on uncertainty by the regulator.

MODEL IMPLICATIONS

Derivation of the optimality conditions and a corresponding set of decision rules are deduced from the Kuhn-Tucker conditions, which are in turn derived from the appropriately defined Lagrangean function for the constrained optimization model defined in the previous section. The Lagrangean function and the corresponding Kuhn-Tucker conditions are shown in Appendix A. The decision variables are F_i, L_{ijk}, and M_{ijk}.

The focus of the policy question in this article is concerned with the disposition of poultry litter. Poultry litter that is disposed of by land application has economic value as a source of nutrients for crops, but also entails an environmental cost. Consider first the economic returns for the nutrients in poultry litter applied to crop *j* produced on land type *k* for the *i*th farm.

$$m_{ijk} - \Delta_{ik} = \sum_{n=1}^{2} \lambda_{ijkn} a_{ijkn} \tag{13}$$

with $L_{ijk} > 0$ for all *i, j,* and *k.* The right side of equation (13) shows the marginal imputed value of the nutrients phosphorus and nitrogen while the left side of equation (13) shows the "net" marginal return for a unit of litter applied. Note that Δ_{ik} is the shadow price on the land constraint for land used to produce crop *j* by farm *i* is zero if this constraint is nonbonding.

The Kuhn-Tucker condition for M_{ijk} is given by equation (A.4). Assume that for some *i, j, k,* $M_{ijk} > 0$. Use equation (13) along with equation (A.4) to state the marginal decision rule for M_{ijk} as follows.

$$\pi_i + \sum_{n=1}^{2} \lambda_{ijkn} \alpha_{ijkn} \theta_{ijkn} = e_{ijk} + \rho_1 \left\{ \hat{\Gamma}_{i1k} d_{ijk1} + \varphi_{\beta 1} \left[\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \sigma_{i1k}^2 M_{ijk}^2 \right]^{-0.5} M_{ijk}\, \sigma_{ijk}^2 \right\} \tag{14}$$

Note that π_i can be written as follows.

$$\pi i = \frac{(r_i - b_i F_i) g_i'(F_i) - b_i g_i(F_i)}{\eta_i g_i'(F_i)} \tag{15}$$

Equation (15) is the net marginal return for litter related to the production of the live weight of poultry. Equation (15) is used to rewrite the marginal decision rule for litter application as follows.

$$\begin{aligned} &\frac{(r_i - b_i F_i) g_i'(F_i) - b_i g_i(F_i)}{\eta_i g_i'(F_i)} + \sum_{n=1}^{2} \lambda_{ijkn} \alpha_{ijkn} \theta_{ijkn} = e_{ijk} + \rho_1 \\ &\left\{ \hat{\Gamma}_{i1k} d_{ijk1} + \varphi_{\beta 1} \left[\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \sigma_{i1k}^2 M_{ijk}^2 \right]^{-0.5} M_{ijk}\, \sigma_{ijk}^2 \right\}. \end{aligned} \tag{16}$$

The left side of equation (16) represents the marginal return from poultry litter in terms of the live weight of poultry produced along with the return from the crop to which the litter is applied. This interpretation is consistent with a joint production perspective.

The right side of equation (16) shows the marginal opportunity cost of poultry litter application. The term e_{ijk} is the marginal opportunity cost of applying a unit of litter to crop *i* on soil type *k* for farm *i.* The second expression in brackets is concerned with the watershed-based restriction imposed on phosphorus using a TMDL rule.

The target level of phosphorus is stochastic in nature amd captures the elements of uncertainty that are relevant to the TMDL target. Uncertainty is addressed by specifying a margin of safety or probability level of exceeding the TMDL established limit for phosphorus.

Ideally, the elements discussed in the above paragraph should be included in the measure of opportunity cost. The second component on the right side of equation (16) represents the marginal opportunity cost of the TMDL-based limit on phosphorus for the watershed as well as the uncertainty inherent in estimates of the values of the response matrix coefficients.

Now consider the various components of the above expression. The variable ρ_1 is the shadow price for the TMDL-based target value of phosphorus as well as the uncertainty of this target value. If the target level of phosphorus is reduced by one unit, given a particular level of uncertainty as represented by the variance ε_1^2 of $\overline{G}_1$, the level of farm profits is reduced by $\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \hat{\Gamma}_{i1k}\rho_1$ across the watershed. If, on the other hand, there is an increase in ε_1, the marginal opportunity cost of the error in the TMDL-based target is measured by $\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \hat{\Gamma}_{i1k} d_{ijk1}\rho_1$.

The marginal opportunity cost of the uncertainty inherent in the estimates of the response matrix coefficients is represented by the second expression on the right side of equation (16). This uncertainty is represented by the term σ_{i1k}^2. It should be apparent that as the size of this uncertainty increases, so does the marginal opportunity cost. The marginal opportunity cost of uncertainty about the estimates of the response matrix coefficients also includes a weighting $\varphi_{\beta 1}$, which reflects the pre-specified margin of safety. If the regulator increases the margin of safety, then $\varphi_{\beta 1}$ is increased by the appropriate amount with a corresponding increase in the marginal opportunity cost of the phosphorus constraint for each farm. The overall expression shows directly how such decisions on the margin of safety for the TMDL-based rule are brought to bear on the marginal opportunity cost of land-based poultry litter application throughout the watershed.

Recall that stream conditions in a watershed are stochastic in nature (instream flows and pollution level in stream vary with time and season) as are the ways in which phosphorus is transported to a stream in runoff. The stochastic nature of conditions in the stream are reflected in estimates of $\overline{G}_1$, while uncertainties of the phosphoros runoff are reflected in estimates of $\hat{\Gamma}_{i1k}$. The magnitude of ε_1 and σ_{i1k} reflect the degree of uncertainty in estimates of these linkages. Suppose the estimates of $\hat{\Gamma}_{i1k}$ are improved and are manifested in the lower values of σ_{i1k}. This implies that the marginal opportunity cost of uncertainty has been reduced and it is now possible to increase the land-based application of litter throughout the watershed.

A SECOND-BEST TAX SOLUTION

A second-best tax scheme based on the standards and charges approach advocated by Baumol and Oates [6] is derived in this section. There are a number of important points to bear in mind in the derivation of this tax. First, with nonpoint sources it is difficult to observe (without excessive cost) the level of nutrients in runoff as it finds its way to a measurement point. Second, phosphorus problems in runoff are closely associated with the way that poultry litter is applied as well as the crops to which it is applied. These two points are concerned with physical circumstances that can be determined by a regulatory agency through mechanisms such as best management practices. There are also important unobservable inputs such as soil and topographic characteristics where litter is applied. The unobservable factors can be approximated to some extent in the model structure used in this study.

The optimal tax rate for the standards and charges approach is applied on the basis of litter applications following arguments provided by Horan and Shortle [13]. The optimization problem in the presence of a tax is as follows.

$$\max \sum_{i=1}^{I}(r_i - b_i F_i) g_i(F_i) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{ijk} L_{ijk} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(e_{ijk} + t_{ijk}) M_{ijk} \tag{17}$$

subject to

$$\sum_{j=1}^{J} L_{ijk} \le \overline{L}_{ik} \qquad (\Delta_{ik}) \tag{18}$$

$$(k = 1, \ldots, K)$$
$$(i = 1, \ldots, I)$$

$$\eta_i g_i(F_i) - \sum_{j=1}^{J}\sum_{k=1}^{K} M_{ijk} = 0 \qquad (\pi_i) \tag{19}$$

$$(\mathrm{i} = 1, \ldots, \mathrm{I})$$

$$a_{ijkn} L_{ijk} = \alpha_{ijkn} \theta_{ijkn} M_{ijk} \qquad (\lambda_{ijk}) \tag{20}$$

$$(i = 1, \ldots, I)$$
$$(j = 1, \ldots, J)$$
$$(k = 1, \ldots, K)$$
$$(n = 1, 2)$$

The last component of the objective function, equation (17) represents the total cost for land-based disposal of poultry litter, including the total amount of tax revenues paid.

The decision variables in this model are F_i, L_{ijk}, and M_{ijk}; and the corresponding decision rules are shown in Appendix B. The optimal application of poultry litter in this model is based on the following marginal decision rule:

$$\frac{(r_i - b_i F_i) g_i'(F_i) - b_i g_i(F_i)}{\eta_i g_i'(F_i)} + \sum_{n=1}^{2} \lambda_{ijkn} \alpha_{ijkn} \theta_{ijkn} = e_{ijk} + t_{ijk} \tag{21}$$

$$(\mathrm{i} = 1, \ldots, \mathrm{I})$$
$$(j = 1, \ldots, J)$$
$$(k = 1, \ldots, K)$$

The left side of equation (21) represents the overall marginal return from poultry litter application, while the terms on the right side of equation (21) represent the marginal opportunity cost of applying poultry litter and includes the second-best tax rate. The regulator's objective is to motivate a level of poultry litter application that is consistent with that implied by the optimization model in the previous section. The tax rate consistent with this objective can be determined by comparing equation (21) with equation (16). The cost minimizing level of poultry litter applications will be chosen if

$$t_{ijk} = \rho_1 \left[\hat{\Gamma}_{i1k} d_{ijk1} + \varphi_{\beta 1} \left[\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \sigma_{i1k}^2 M_{ijk}^2 \right]^{-0.5} M_{ijk} \sigma_{ijk}^2 \right]. \qquad (22)$$

(i = 1, ..., I)
(j = 1, ..., J)
(k = 1, ..., K)

The optimal tax rate as shown by equation (22) includes an accounting of the marginal opportunity cost of the TMDL rule for phosphorus in surface water, including the notions of risk and uncertainty. The marginal opportunity cost of uncertainty, in turn, includes a weighting factor $\varphi_{\beta 1}$ in equation (22), which reflects the margin of safety associated with the TMDL. If regulators should choose to increase the safety level (or margin of safety), then $\varphi_{\beta 1}$ is increased by the appropriate amount with the corresponding increase in the optimal tax rate. Bear in mind that the determination of the tax rate in this framework is based on the objective of motivating farmers to make certain types of decisions in the application of litter.

SUMMARY AND CONCLUSIONS

The first 25 years of the Water Quality Act was characterized by major emphasis on regulating point sources with technology-based standards. However, many water quality problems remain. The recent renewal of emphasis on water quality has been articulated in the form of proposed total maximum daily load (TMDL) rules. A TMDL identifies the amount of a pollutant that is allowed in a water body, allocates allowable pollutant loadings among sources, and provides a foundation for achieving water quality levels. The most important characteristic of TMDL rules is the impact on nonpoint source pollution.

Poultry production has become an important component of the economic base in many watersheds, and the growing concern with the need to dispose of poultry litter that is loaded with nutrients has intensified the discussions surrounding the development of TMDL rules. Once a TMDL rule for nutrients such as phosphorus has been promulgated, it can be implemented by using an "optimal tax," which is levied on poultry litter that is applied to crops and pastures. But to do so is viewed as problematic. This can be done using a "standards amd charges" approach, which involves two steps. First, standards or targets for phosphorus in the watershed are set on the basis of the TMDL rule. Second, a set of taxes (charges) is designed and put into place to achieve the stated target for phosphorus. Thus, the policy problem for setting taxes on litter applied is to identify a tax or set of taxes aimed at reducing the total amount of phosphorus to a pre-specified level as determined by the TMDL rule. The phosphorus that is of concern in this case is a form of nonpoint emissions that is stochastic in nature. Thus, knowledge of relationships governing the fate and transport is imperfect, and observations only yield imperfect forecasts of the nonpoint emissions and their environmental impacts. This has motivated empirical researchers to increasingly turn to simulation and/or mathematical programming techniques for policy-making decisions. This article explored the application of a standards amd charges policy framework for a TMDL rule regulating phosphorus from poultry litter in surface water under stochastic conditions using simulation and mathematical programming techniques. That is, a protocol is established that uses simulation and mathematical programming techniques to compute the tax for a standards and charges framework for implementing a TMDL rule for phosphorus from poultry litter in a stochastic environment. This protocol allowed the tax rate to be determined on the basis of information on crop demands for nutrients as well as the amount of nutrients contained in the poultry litter. The tax rate determined from this protocol also reflects the stochastic nature of the fate and transport of the nutrients as well as an appropriately defined margin of safety. As shown, the Kuhn-Tucker conditions were used as the basis to develop the appropriate taxes.

The most significant advantage of the combined use of simulation/mathematical programming models as proposed here is that they allow the analyst the opportunity to examine counterfactual situations. Thus, various kinds of situations can be represented with the model structure discussed in this article. The chief shortcoming of these types of modeling structures is that they deal with idealized situations. In the final analysis, it is believed that the framework proposed in this article has a great deal of promise as a policy-making tool for implementing TMDL rules designed to regulate phosphorus in surface waters from poultry litter.

APPENDIX A

$$\begin{aligned}\mathcal{L} = &\sum_{i=1}^{I}(r_i - b_iF_i)g_i(F_i) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{ijk}L_{ijk} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} e_{ijk}M_{ijk} - \sum_{i=1}^{I}\sum_{k=1}^{K}\Delta_{ik}\left[\sum_{j=1}^{J}L_{ijk} - \overline{L}_{ik}\right] \\ &- \sum_{i=1}^{I}\pi_i\left[\eta_i g_i(F_i) - \sum_{j=1}^{J}\sum_{k=1}^{K}M_{ijk}\right] - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{2}\lambda_{ijkn}\left[a_{ijkn}L_{ijk} - \alpha_{ijkn}\theta_{ijkn}M_{ijk}\right] \\ &- \rho_1\left[\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\hat{\Gamma}_{i1k}d_{ijk1}M_{ijk} + \varphi_{\beta 1}\left[\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\sigma_{i1k}^2M_{ijk}^2 + \varepsilon_1^2\right]^{0.5} - \hat{G}_1\right]\end{aligned} \tag{A.1}$$

$$\frac{\partial\mathcal{L}}{\partial F_i} = -b_ig_i(F_i) + (r_i - b_iF_i)g_i'(F_i) - \pi_i\eta_i g_i'(F_i) \le 0 \tag{A2a}$$

$$\frac{\partial\mathcal{L}}{\partial F_i}\cdot F_i = 0 \tag{A.2b}$$

$$(i = 1, \ldots, I)$$

$$\frac{\partial\mathcal{L}}{\partial L_{ijk}} = m_{ijk} - \Delta_{ik} - \sum_{n=1}^{2}\lambda_{ijkn}a_{ijkn} \le 0 \tag{A.3a}$$

$$\frac{\partial\mathcal{L}}{\partial L_{ijk}}\cdot L_{ijk} = 0 \tag{A.3b}$$

$$(i = 1, \ldots, I)$$

$$(j = 1, \ldots, J)$$

$$(k = 1, \ldots, K)$$

$$\begin{aligned}\frac{\partial\mathcal{L}}{\partial M_{ijk}} = &-e_{ijk} + \pi_i + \sum_{n=1}^{2}\lambda_{ijkn}\alpha_{ijk}\theta_{ijkn} \\ &-\rho_1\left\{\hat{\Gamma}_{i1k}d_{ijk1} + \varphi_{\beta 1}\left[\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\sigma_{i1k}^2M_{ijk}^2\right]^{-0.5}M_{ijk}\sigma_{ijk}^2\right\} \le 0\end{aligned} \tag{A.4a}$$

$$\frac{\partial\mathcal{L}}{\partial M_{ijk}}\cdot M_{ijk} = 0 \tag{A.4b}$$

$$(i = 1, \ldots, I)$$

$$(j = 1, \ldots, J)$$

$$(k = 1, \ldots, K)$$

APPENDIX B

$$\mathscr{L} = \sum_{i=1}^{I}(r_i - b_i F_i) g_i(F_i) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{ijk} L_{ijk} - \sum_{i=1}^{I}\sum_{k=1}^{K}\Delta_{ik}\left[\sum_{j=1}^{J} L_{ijk} - \overline{L}_{ik}\right] \tag{B.1}$$
$$- \sum_{i=1}^{I}\pi_i\left[\eta_i g_i(F_i) - \sum_{j=1}^{J}\sum_{k=1}^{K} M_{ijk}\right] - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{2}\lambda_{ijkn}\left[a_{ijkn}L_{ijk} - \alpha_{ijkn}\theta_{ijkn}M_{ijk}\right]$$

$$\frac{\partial\mathscr{L}}{\partial F_i} = -b_i g_i(F_i) + (r_i - b_i F_i) g_i'(F_i) - \pi_i \eta_i g_i'(F_i) \le 0$$

$$\frac{\partial\mathscr{L}}{\partial F_i} \bullet F_i = 0$$

$$(i = 1, \ldots, I)$$

$$\frac{\partial\mathscr{L}}{\partial L_{ijk}} = m_{ijk} - \Delta_{ik} - \sum_{n=1}^{2}\lambda_{ijkn} a_{ijkn} \le 0 \tag{B.2a}$$

$$\frac{\partial\mathscr{L}}{\partial L_{ijk}} \bullet L_{ijk} = 0 \tag{B.2b}$$

$$(i = 1, \ldots, I)$$
$$(j = 1, \ldots, J)$$
$$(k = 1, \ldots, K)$$

$$\frac{\partial\mathscr{L}}{\partial M_{ijk}} = -\left(e_{ijk} + t_{ijk}\right) + \pi_i + \sum_{n=1}^{2}\lambda_{ijkn}\alpha_{ijk}\theta_{ijkn} \le 0 \tag{B.3a}$$

$$\frac{\partial\mathscr{L}}{\partial M_{ijk}} > M_{ijk} = 0 \tag{B.3b}$$

$$(i = 1, \ldots, I)$$
$$(j = 1, \ldots, J)$$
$$(k = 1, \ldots, K)$$

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