An Optimal Control Approach to Water Quality Trading: Cost/Effective Point/Nonpoint Management in a Watershed Framework

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This study reflects a growing interest in water quality trading involving both point and nonpoint sources in a watershed framework. An empirical spatial-temporal optimal control model is presented and solved to assess the scope and implications of point/nonpoint trading. Results indicate significant economic gains to broader based interpretations of trading rules.

Key words: water quality trading, spatial-temporal optimization, watershed management.

Introduction

U.S. water quality control policies continue to rely heavily on point source pollution control relative to nonpoint source control. Since production managers have little, if any, incentive to consider the costs nonpoint source pollution imposes on others and are usually not subject to direct regulation, nonpoint source pollution externalities continue at inefficiently high levels. This both limits water quality improvement in areas impacted by nonpoint sources and makes improvements more costly. Nonpoint/point trading programs have been suggested and, in a few cases, implemented, as a more efficient approach to reducing pollution. However, the economic implications of alternative program designs involving nonpoint sources remain incomplete. This study addresses the design and implementation of water quality trading programs.

Point and nonpoint sources may be defined by location, time period, and pollutant type and quantity. Benefits of pollution abatement also differ over time and space. This paper considers a basic spatial-temporal optimal control model to determine optimal allocation of pollution treatment investment in impaired streams in a watershed framework. The problem is specified as the maximization of ecological services subject to dynamic constraints including an inter-temporal investment constraint and spatial water quality constraints. This model builds upon an underlying water quality model where pollution loads are driven by both sources and control strategies. It reflects both the spatial aspects of water quality values and treatment and the way the system will react over time to both management options and natural forces.

The empirical application is to the acid mine drainage (AMD) problem in the Cheat River watershed in West Virginia. The resulting temporal and spatial investment strategies are manipulated to assess and evaluate alternative trading scenarios. Specifically, we analyze scenarios in which nonpoint sources dominate loadings in the watershed. The trading scenarios can involve a variety of point and nonpoint sources as well as both same pollutant and cross-pollutant trading.

The rest of the paper is organized into four parts. The next section presents a brief background for the problem. An outline of the spatial-temporal dynamic optimization model that maximizes the present ecological value of the water resources follows. The AMD treatment problem in the Cheat River watershed are discussed in the context of the model. The next section discusses the possibility and potential impacts of water quality trading among sources in the Cheat River watershed but focuses on the Muddy Creek subwatershed; the conclusions follow.

Background

More than half of the 2,000 assessed watersheds in the United States remain impaired due to pollution from point and, especially, nonpoint sources including runoff from urban and suburban areas, agricultural and timber lands, mining sites, and others (National Wildlife Federation, 1999). The U.S. Environmental Protection Agency (USEPA) is developing an overall water-quality based approach (i.e., watershed management) instead of the previous technology-based point-by-point control to improve water quality. This is a consensus-based approach designed to gain support from all stakeholders within hydrological-defined geographic areas and implicitly considers spatial interrelationships among natural ecosystems, anthropogenic forces, and the underlying physical system (Fletcher, et al., 2001). While this approach allows for pollution control by least-cost methods, information on the spatial and temporal dynamics provides additional information to inform decisions by stakeholder groups and management agencies.

This study use the Cheat River which flows north through West Virginia to the Monongahela River just over the Pennsylvania border. The majority of the 1,435 square miles drainage area is located in northeastern West Virginia (Hansen, 2002; Hansen et al., 2004; U.S. Environmental Protection Agency, 2000). AMD, which forms when water, oxygen, and a small amount of bacteria come into contact with pyrite in coal and the surrounding strata, is the primary water quality problem in the Cheat River watershed. AMD is acidic water with high concentrations of dissolved metals such as iron, aluminum, and manganese which pollutes streams, harms aquatic life including insects and fish, reduces recreational activities, and reduces stream aesthetics. As nonpoint, non-permitted sources, abandoned mine lands (lands impacted by surface and deep mining operations completed prior to the 1977 Surface Mining Control and Reclamation Act regulations (SMCRA)) contribute significant amounts of AMD to the Cheat River and its tributaries. Bond forfeiture sites (mines abandoned since SMCRA but without a legally responsible party) are also significant contributors of AMD.

Active mining operations covered by current NPDES permits are considered point sources and contribute AMD as well. Part of the main stem of the Cheat River and 54 other stream segments in the watershed impaired by AMD were included in West Virginia’s 1998 303(d) list under the Aquatic Life and the Human Health use designation categories (U.S. Environmental Protection Agency, 2000). See figure 1.

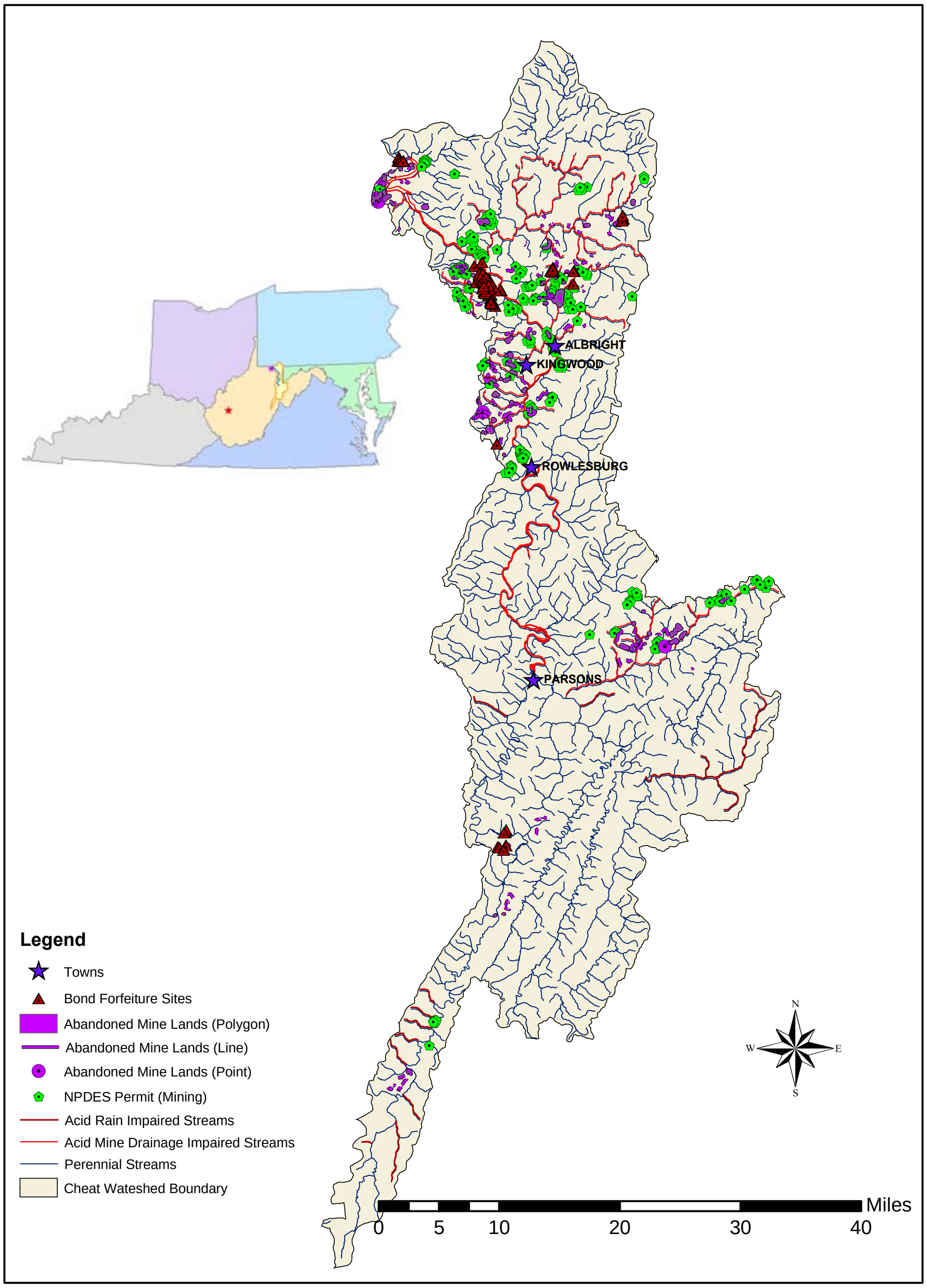

Figure 1 – Cheat River Watershed, West Virginia

In 1996, USEPA issued the Effluent Trading in Watersheds Policy and Draft Framework for Watershed-Based Trading which views pollutant trading as one of the market-based approaches to improve water quality. Trading has been demonstrated in a number of projects including those in Colorado, Wisconsin, Michigan, and Idaho (U.S. Environmental Protection Agency, 2002). In 2000, the USEPA released a draft TMDL for the AMD impacted streams in the Cheat River watershed (U.S. Environmental Protection Agency, 2000). The Cheat was chosen as one of 11 eleven pilot programs for the development of innovative trading programs, in large part because of the effective stakeholder group that has been active in the watershed. The purpose of so called watershed-based trading is to achieve mandated pollution reductions at a low cost while providing economic, environmental, and social benefits when trading allows a pollution source to reduce discharges elsewhere in the watershed in lieu of installing tighter controls for their own discharge. In the Cheat River watershed, trading can potentially involve a variety of point and nonpoint sources such as permitted operational mines, abandoned mine lands, and bond forfeiture sites. The model developed in this paper can be utilized to demonstrate the scope of pollution trading and to evaluate the ecological implications of the AMD component of any proposed trade.

The Spatial-Temporal Optimization Model

An appropriate analytical framework must reflect both the spatial aspects of water quality values and treatment and the way the system will react over time to both management options and natural forces. Most studies of water quality management concentrate on the inter-temporal allocation problem (for example, see Makris, 2001; and Opaluch, 1981), or, more recently, the spatial dynamics (Funk III, 1993; Greiner and Cacho, 2001; and Ali, 2002), but not both. Much of the literature focuses on spatial-temporal dynamics in other fields such as landfills, hedonic prices for environmental goods, dynamic equilibrium in coal market, transportation, climatology, biological population, real estate, and infectious disease, instead of water quality management (Gaudet, Moreaux, and Salant, 1998; Riddel, 2001; Labys, et al., 1989; Zawack and Thompson, 1983; Jagger, Niu, and Elsner, 2002; Renshaw, 1993; Pace, et al., 2000; and Deal, et al., 1999). Studies that involve both time and space dimensions in water allocation include Ejeta (2000) and Brozovic et al. (2002). Studies that combine spatial-temporal issues in an optimization model for water quality management are rare. We present such a model and apply this model to explore the water quality trading issues in this paper.

For expository purposes, we use the following terminology to describe the model. The initial segment of a stream from the source to the first confluence with another stream is called a headwater stream; the point where two or more streams join is called a node, and a stream between two nodes is a downstream segment. A watershed is defined relative to a pour point and includes all areas where, if a raindrop falls, surface runoff will drain through the pour point. Similarly, each stream segment is associated with a catchment area defined by points from which rain runoff directly enters the stream segment. The ecological services provided by each stream segment are taken to be an ecological index of performance weighted by the water surface area.

The spatial-temporal dynamic optimization model for the present value of ecological services of the water resources of a watershed can now be presented. Given the total funds available for treatment and other exogenously determined factors in the study area, the problem is specified as the maximization of ecological services subject to a series of dynamic constraints – an inter-temporal investment constraint and spatial water quality constraints – and other constraints imposed by other physical and behavioral aspects of the problem. Temporal dynamic elements are introduced in the modeling process through the timing of investments in site specific treatment systems. The level of treatment that a specific system produces in any period

(t) can be considered a function of the cumulative investment in the system. Spatial dynamics are introduced by the spatial distribution of investments in treatment within the watershed and interactions with exogenous pollutant inputs that determine water quality at all points.

Objective Function

The objective function is to maximize the present value of ecological services (TEI) from all streams in the watershed over the planning horizon:

$$\underset{\{C_{i,t}\}}{Max}(TEI) = \underset{\{C_{i,t}\}}{Max} \sum_{t=0}^{T} \sum_{i=1}^{I} \frac{EI_{i,t}}{(1+r)^t}$$

where:

i = 1, 2, …, I is the index of stream segments;

t = 0, 1, …, T is the index of time periods in years;

r is the rate of time preference for ecological services;

$EI_{i,t}$ is the value of the ecological index for segment i at time t.

For the Cheat River watershed,

i = 1, 2, …, 1793, the number of stream segments in NHD 1:100,000-scale coverage of the Cheat River watershed;

t = 0, 1, …, 10, the planning horizon in years.

The choice of the time preference, r, is controversial. A high r lowers the weight of ecological values received in the future which leads to the argument that discounting discriminates against future generations. Recent studies have utilized a value for r ranging from 3% (real rate of interest) to 7% (Office of Management and Budget (OMB)'s estimate of the opportunity cost of private capital) (Fletcher, et al., 2001). For this example, a value of 6% is used. The ecological index function depends on the pollution load which measures $a_{i,t}$ as net acidity in segment i at time t in mg/l.

Potential ecological condition indices include species diversity, total biological productivity, targeted fish biomass, invertebrate based condition index, and fish based condition index. Ecologists working on the project have recommended the invertebrate based condition index, partially on scientific considerations and in part because this index is currently used in the Cheat by monitoring and regulatory agencies. Commonly used measures relevant to ecological services that could serve as a weight for the primary index include stream miles, stream area, stream order, and the maximal area of the watershed drained by the stream segment. The technical team for the Cheat project chose to use stream surface area, a continuous cardinal measure, to weight the ecological coefficient based on the observation that ecological productivity is roughly proportional to surface area.

The ecological index for segment i at time t, $EI_{i,t}$, is the product of the stream surface area in segment i, SA_i, and the stream's ecological condition in segment i at time t, $EC_{i,t}(a_{i,t})$, which depends on water quality or pollutant concentration, $a_{i,t}$. That is:

$$EI_{i,t} = SA_i EC_{i,t}(a_{i,t})$$

where $a_{i,t} = y_{i,t} / wf_{i,t}$, $y_{i,t}$ is pollution loading in segment i during time t, and $wf_{i,t}$ is water flow. $EC_{i,t}(a_{i,t})$ is modeled as a step function to reflect ecologically based threshold responses of aquatic populations to changes in pollutant concentration. In the Cheat River watershed, $a_{i,t}$ is net acidity concentration which has the following properties:

$$\begin{aligned} a_{i,t} &> 0 \quad if \quad pH < 7 \\ a_{i,t} &= 0 \quad if \quad pH = 7 \\ a_{i,t} &< 0 \quad if \quad pH > 7 \end{aligned}$$

From an ecological perspective, either excess alkalinity or acidity reduces ecological services. This is represented in the ecological condition function as:

$$\begin{array}{lll} EC_{i,t}(a_{i,t}) = e_{-N} & if & a_{i,t} < A_{-(N-1)} \\ & \vdots & \\ EC_{i,t}(a_{i,t}) = e_{-2} & if & A_{-2} \le a_{i,t} < A_{-1} \\ EC_{i,t}(a_{i,t}) = e_{-1} & if & A_{-1} \le a_{i,t} < 0 \\ EC_{i,t}(a_{i,t}) = e_{1} & if & 0 \le a_{i,t} < A_{1} \\ EC_{i,t}(a_{i,t}) = e_{2} & if & A_{1} \le a_{i,t} < A_{2} \\ & \vdots & \\ EC_{i,t}(a_{i,t}) = e_{K} & if & A_{K-1} \le a_{i,t} \end{array}$$

where $e_1, e_2, ..., e_K, e_{-1}, e_{-2}, ..., e_{-N}$ are the ecological values associated with each step and $A_1, A_2, ..., A_{k-1}, A_{-1}, A_{-2}, ..., A_{-(N-1)}$, are net acidity concentrations corresponding to the threshold levels that separate the $K + N$ steps.

Constraints

Numerous factors are included via sets of constraints including the level of treatment as a function of total investment in water quality improvement projects, inter-temporal equations of motion which depend on the level of investment in treatment in each segment, spatial equations of motion which correspond to the imposition of a mass balance water quality model, and exogenously determined investment constraints.

Treatment constraints are:

$$u_{i,t} = u_i CC_{i,t}$$

where:

$u_{i,t}$ is the level of treatment in segment i during period t and is directly proportional to the cumulative investment (costs) $CC_{i,t}$ (i.e., the effective capital investments defined as the effectiveness of all investments through all t years within segment i).

Recently, a variety of passive treatment systems such as open limestone channel and limestone leach beds have been developed to treat AMD with a low cost and little maintenance (Skousen, and Ziemkiewicz, 1996). The traditional approach to AMD relies on active treatment that uses alkaline chemical reagents and a mechanical system to neutralize the acidity. Within the Cheat River watershed, earlier work by the River of Promise (i.e. ROP, which is a shared commitment for the restoration of the Cheat River) focused on passive systems to fix AMD problems in the Big Sandy sub-basin and has proven successful. Application of passive systems to other AMD impaired streams is strongly recommended. In this paper, AMD is assumed treated by passive systems including open limestone channels and limestone leach beds. u_i is 0.006 for these passive systems in the Cheat River watershed.

Intertemporal equations of motion are:

$$CC_{i,t} = \frac{CC_{i,t-1}}{1+\delta} + C_{i,t} = \sum_{\tau=0}^{t-1} \frac{C_{i,t-\tau}}{(1+\delta)^{\tau}}$$

where:

$C_{i,t}$ is investment in watershed remediation/water treatment in segment i during time t, and

δ is the degradation or depreciation rate of investments in passive treatment which reflects the physical depreciation of the quality of the investment over time.

In the Cheat River watershed, δ is assumed to be 0.02. Generally, alkalinity production is maximum at project initiation. Over time, the ability of a passive treatment system to generate alkalinity falls. δ represents the diminishing rate of alkalinity generation.

Spatial equations of motion are:

$$y_{i,t} = (\sum_{l\in\{i\}^{upstream}} y_{l,t}) + x_{i,t} - u_{i,t} \text{ for downstream segments}$$

where:

$\{i\}^{upstream}$ represents the set of segments directly upstream of segment i (i.e., those segments that flow directly into segment i);

$y_{i,t}$ is pollution loadings and can be equivalently given as $y_{i,t} = a_{i,t} wf_{i,t}$ within each segment during each time period. For AMD, $y_{i,t}$ is the annual acid load in segment i at time t. The current application uses average water flow in each segment so that $y_{i,t} = a_{i,t} wf_i$;

$x_{i,t}$ is the exogenously determined pollution load generated within the drainage area of segment i during period t.

The above equation represents a mass-balance model of pollution generation and control. For headwater streams (i.e., those streams in the upper end of a watershed that only include direct flow), this reduces to:

$$y_{i,t} = x_{i,t} - u_{i,t} \text{ for headwater stream segments}$$

In the Cheat River watershed, many of the mining sites have a long history (over 50 years), exogenously determined AMD generation for each segment during each period, $x_{i,t}$, is currently slowly decreasing over time. To reflect this, AMD generated by abandoned mines is assumed to decrease over time at the rate α. That is,

$$x_{i,t} = \frac{x_{i,t-1}}{1+\alpha} \text{ with initial conditions } x_{i,0} = \overline{x_{i,0}} \quad \forall\, i$$

A relatively low value for α (0.05) is used.

Investment constraints are:

$$\sum_{i=1}^{I} C_{i,t} \le C_t^{\max},\ C_{i,t} \ge 0 \quad \forall i,t \text{ with initial conditions } C_{i,0} = 0 \ \forall\, i$$

where $C_t^{\max}$ is the maximum level of investment for water quality projects available during time period t. Available remediation funds may be divided among segments but investment in any segment is non-negative. In the Cheat River watershed, $C_t^{\max}$ is selected as \$100,000.

Assuming that the mass balance model is a reasonable approximation to a true water quality model and that sufficient information is available on concentrations and flow to calculate loadings in each segment during the base period, the exogenous loadings can be calculated by:

$$\overline{x_{i,0}} = \overline{y_{i,0}} - \sum_{l \in \{i\}^{upstream}} \overline{y_{l,0}} \text{ for downstream segments, and}$$

$$\overline{x_{i,0}} = \overline{y_{i,0}} \text{ for headwater stream segments}$$

This defines exogenous pollution from the drainage to segment i from respective sub-watersheds at the initial time period. In the Cheat River watershed, given measured pollution loadings in each segment at time period 0, $\overline{y_{i,0}}$, the AMD generation to each segment at time period 0, $\overline{x_{i,0}}$, can be estimated. Then, assuming that the AMD generation declines at the annual rate α, one notes:

$$x_{i,t} = \frac{x_{i,t-1}}{1+\alpha} \text{ with initial conditions } x_{i,0} = \overline{x_{i,0}} \quad \forall \text{ segments } i$$

for any time period, t = 1, 2, …, 10.

There are two vectors of state variables in the model: pollution loadings in each segment during each time period, $y_{i,t}$, and the level of treatment in each segment during each period, $u_{i,t}$. There is a single vector of choice variables during each time period: the additional investment in treatment within each segment, $C_{i,t}$. The level of treatment in each segment is defined by the cumulative treatment from current and past investment and can be considered an intertemporal variable. The pollution loadings in each segment during each period represent spatial variables determined by the level of the intertemporal state and the spatial equations of motion.

Application of the Model – Water Quality Trading in the Cheat River Watershed

Background on Water Quality Trading Concepts

Watershed-based trading is thought to be a cost-effective strategy to achieve water quality improvements in impaired watersheds as required by total maximum daily loads (TMDLs) (Horan, 2001). Under USEPA guidelines, it appears that trading can be considered if the result is a reduction in overall pollution loads without generating water quality violations. Five types of trades are often discussed: point-to-point trading, intra-plant trading, pretreatment trading, point source-to-nonpoint source trading, and nonpoint source-to-nonpoint source trading (National Wildlife Federation, 1999). USEPA allows and supports same-pollutant and, in some cases, cross-pollutant trading.

In the Cheat River watershed, trading can potentially involve a variety of point and nonpoint sources as well as both same pollutant and cross-pollutant trading. Examples include trading between permitted operational mines, between permitted mine operations and abandoned mine sites, and trading between heat discharges from a power plant and AMD reduction from abandoned mines. The main focus of the trading program is to reduce AMD pollutants which include acidity, iron, aluminum, and manganese.

The model developed in this paper can be utilized to demonstrate the scope of AMD trading between and among permitted and abandoned mines. Similarly, the model could be used to evaluate the ecological implications of the AMD component of any proposed trade.

Cheat River Watershed

An overview of the Cheat River watershed is included as Figure 2. It includes a simple representation of both impaired and non-impaired stream segments in the watershed. There are nearly 1800 stream segments in this NHD 1:100,000-scale coverage of the Cheat.

For a more concrete example, Figure 2 shows selected Muddy Creek subwatershed with NPDES (green pentagons) permitted mines, bond forfeiture sites (purple triangles), and abandoned mine lands (irregular yellow shapes). Figure 2 also provides a stream network with segments numbering to provide direct context for the discussion of potential water quality trades within the Muddy Creek subwatershed.

AMD Trading Facts

A prerequisite condition for trading to occur is at least two pollution sources have different treatment costs. In such cases, it is well known and relatively easy to show that efficiency (i.e., the best use of scarce resources) of meeting stated water quality standards is improved by reallocating pollution reduction from sources with high abatement costs to sources with low abatement costs, at least under the assumption of non-stochastic emissions (Shortle, 1990). Our approach uses variations in ecological services resulting from variations in water quality to evaluate such trades. The model presented provides an opportunity to demonstrate the potential ecological and environmental gains from trading since the ecological values differ across space and time.

Consider the model presented above modified to reflect the conditions of the Cheat River watershed. Specifically, consider a seven-step ecological condition function for the Cheat River watershed as a function of net acidity represented by (Figure 3 is a graphical representation):

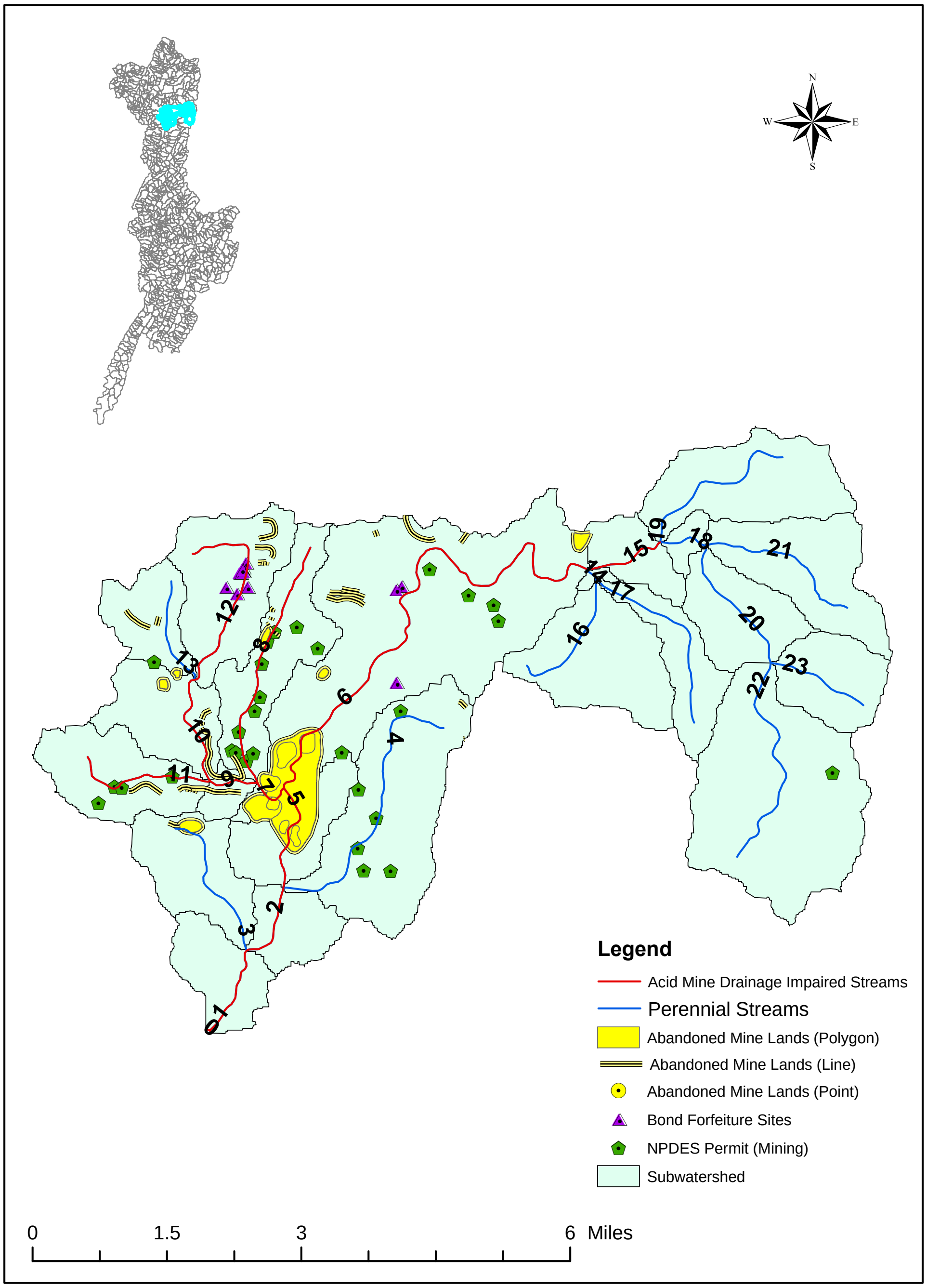

Figure 2 – The Muddy Creek Subwatershed in the Cheat River Watershed

$$\begin{array}{lll} EC_{i,t}(a_{i,t}) = 25 & if & a_{i,t} < -98 \\ EC_{i,t}(a_{i,t}) = 55 & if & -98 \le a_{i,t} < -18 \\ EC_{i,t}(a_{i,t}) = 95 & if & -18 \le a_{i,t} < 0 \\ EC_{i,t}(a_{i,t}) = 95 & if & 0 \le a_{i,t} < 15 \\ EC_{i,t}(a_{i,t}) = 68 & if & 15 \le a_{i,t} < 150 \\ EC_{i,t}(a_{i,t}) = 35 & if & 150 \le a_{i,t} < 1500 \\ EC_{i,t}(a_{i,t}) = 10 & if & 1500 \le a_{i,t} \end{array}$$

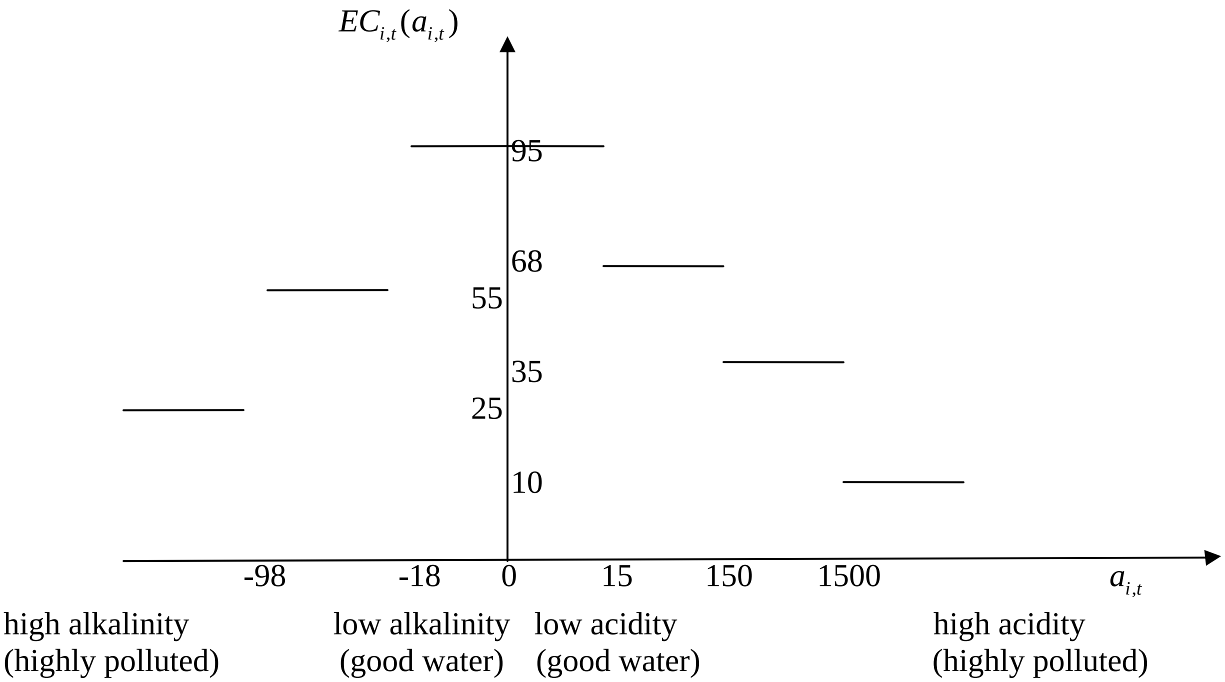

Figure 3 Estimated Step Ecological Condition Index of Stream Segments in the Cheat River Watershed as a Function of Net Acidity

From this specific model for AMD problem in the Cheat River watershed, $EI_{i,t}$ decreases (increases) as $|a_{i,t} - 7|$ increases (decreases), $a_{i,t}$ is directly proportional to $y_{i,t}$ for a given flow rate, and $y_{i,t}$ decreases (increases) as $u_{i,t}$ increases (decreases). Finally, $EI_{i,t}$ (which is a measure of the ecological services in segment i at time t) increases over time as $u_{i,t}$, pollution treatment, increases. That is, in the long run at least, ecological value is partially determined by treatment. The same amount of treatment generates different ecological values among segments depending on the flow and the current level of services provided. Thus there may be ecological benefit for even (without a trading ratio greater than 1) for acidity trading between two stream segments which have different ecological values.

The Scope and Ecological Implications of AMD Point/Nonpoint Trading

The Empirical Model Results

The empirical model is developed in GAMS and solved using the Cplex mixed integer programming (MIP) package based on the assumptions presented in Ali (2002). The GAMS integer solutions show the spatial and temporal distribution of AMD treatment investments, AMD reductions, the spatial and temporal distribution of water quality, and the value of ecological index over 10 years and 23 stream segments in the Muddy Creek subwatershed. Investments over time and space are important information and provide useful insight for stakeholders. The results indicate that most of the available investment should be distributed in heavily impaired stream segments. Figure 4 depicts the investment distribution over time and space.

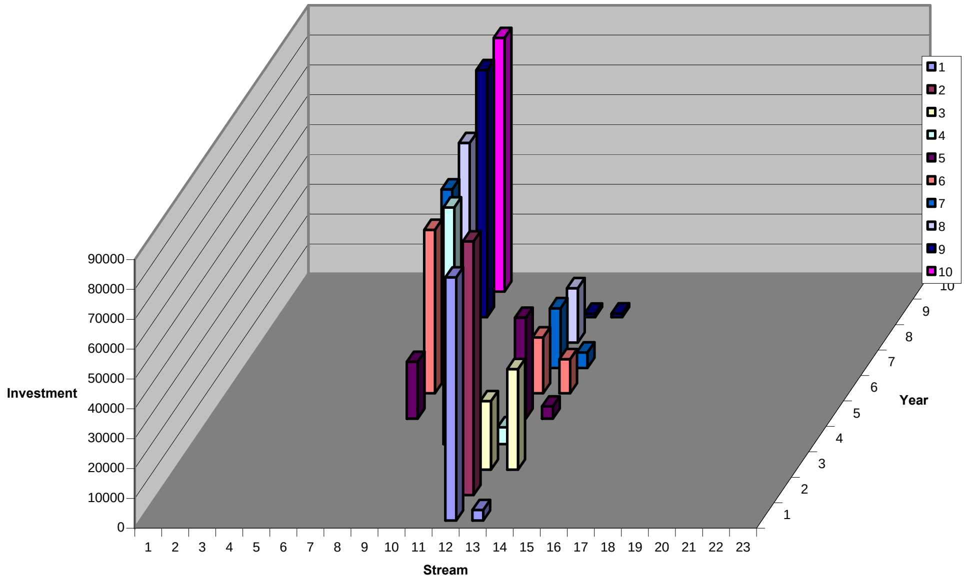

Figure 4 Investment Distribution Over Time and Space

What would a trade look like?

To explain the scope and ecological implications of trading as envisioned for the Cheat River watershed, we discuss several trading scenarios. For sake of discussion, assume that the base case is that, at the beginning of the 11th year, point source A around stream segment 7 would like to increase mining operation resulting in an increase in acidity discharge from 2287 t/yr to 2537 t/yr. Without a trade, the source would be required to meet water quality based standards, a very expensive alternative requiring significant additional treatment costs. However, under a water quality trading program, A could purchase credits elsewhere in the watershed to offset the increased discharge of 250 t/yr. Table 1 includes relevant information on the base case (implications for water quality impacts of additional mining without trading and without additional treatment of the effluent) including average flow, net acidity, acid load, stream surface area, ecological condition, and ecological index for the selected segments (11, 9, 7, 5, 2, and 1). A preliminary analysis of four alternative trading scenarios assuming conservation of all pollutants follows to help understand the trading framework. Note that the analysis presented here is strictly a lower bound. A full analysis including all downstream impacts would be at least as great and, most likely, considerably larger.

Scenario I: trade between A (point source) in 7 and B (point source) in 11 (1:1)

Assume that source A discharging into stream segment 7 enters into a trade with an existing point source, B, in upstream segment 11. The trading ratio between these two point sources is 1:1. Assume that the accepted trading ratio between A and B is 1:1 (a further discussion on trading ratios follows below). Source A purchases point source controls from B which is located upstream of A. The controls at point source B reduce acidity in stream segments 11, 9, 7, 5, 2, and 1 by 250 t/yr resulting in increase of 0.44 million units in ecological index in stream segment 2. The specifics of the scenario are provided in Table 1.

The benefits of the trade in this scenario are: (a) improved water quality in six stream segments 11, 9, 7, 5, 2, and 1 (points downstream); (b) improved ecological indices in stream segment 2; and (c) efficiency in achieving necessary acidity reduction (National Wildlife Federation, 1999).

Table 1 – Base Case and Trading Scenarios I-IV

Stream Segment/Source	Water Flow wf (cfs)	Net Acidity a (mg/l)	Net Effect of Permit and/or Trade (t/yr)	Acid Loadings y (t/yr)	Surface Area (m^2)	Ecological Condition (EC)	Ecological Index
Base case (t=10)							
11	2.5	124		308	3977	68	270416
9	9.9	278		2741	3620	35	126683
7	13.2	173		2287	2992	35	104720
5	50.0	140		7007	18510	68	1258667
2	50.6	166		8264	13340	35	466889
1	60.5	151		9016	15058	35	527039
Total							2754414
t=11: 7↑250, without treatment or trading, 5, 2, and 1↑250							
11	2.5	125		308	3977	68	270416
9	9.9	282		2741	3620	35	126683
7	13.2	194	**250**	2537	2992	35	104720
5	50.0	147	**250**	7257	18510	68	1258667
2	56.6	152	**250**	8514	13340	35	466889
1	60.5	155	**250**	9266	15058	35	527039
Total							2754414
Scenario I: t=11, trade between 7 (point source) and 11 (point source) (1:1)							
11	2.5	24	**-250**	58	3977	68	270416
9	9.9	256	**-250**	2491	3620	35	126683
7	13.2	175	**-250**	2287	2992	35	104720
5	50.0	142	**-250**	7007	18510	68	1258667
2	56.6	148	**-250**	8264	13340	**68**	**907098**
1	60.5	151	**-250**	9016	15058	35	527039
Total							**3194624**
Scenario II: t=11, trade between 7 (point source) and 11 (nonpoint source) (1:2)							
11	2.5	-78	**-500**	-192	3977	**55**	**218719**

9	9.9	230	**-500**	2241	3620	35	126683
7	13.2	156	**-500**	2037	2992	35	104720
5	50.0	137	**-500**	6757	18510	68	1258667
2	56.6	144	**-500**	8014	13340	**68**	**907098**
1	60.5	147	**-500**	8766	15058	**68**	**1023962**
Total							**3639849**

Scenario III: t=11, trade between 7 (point source) and 11 (nonpoint source) (1:3)

11	2.5	-180	**-750**	-442	3977	**25**	**99418**
9	9.9	205	**-750**	1991	3620	35	126683
7	13.2	137	**-750**	1787	2992	**68**	**203457**
5	50.0	132	**-750**	6507	18510	68	1258667
2	56.6	139	**-750**	7764	13340	**68**	**907098**
1	60.5	143	**-750**	8516	15058	**68**	**1023962**
Total							**3619284**

Scenario IV: t=11, trade between 7 (point source) and 1 (point source) (1:1)

11	2.5	125		308	3977	68	270416
9	9.9	282		2741	3620	35	126683
7	13.2	194		2537	2992	35	104720
5	50.0	147		7257	18510	68	1258667
2	56.6	152		8514	13340	35	466889
1	60.5	151	**-250**	9016	15058	35	527039
Total							2754414

Scenario II: trade between A (point source) in 7 and C (nonpoint source) in 11 (1:2)

Assume in this case that there is another opportunity for a trade in upstream segment 11 so that a trade occurs between point source A in stream segment 7 and nonpoint source C in stream segment 11. Assume further that the trading ratio between A and C is 1:2. Source A purchases nonpoint source controls from C. The figures for scenario II in Table 1 indicates that the controls at nonpoint source C reduce acidity in 9, 7, 5, 2, and 1 by 500 t/yr; there are increases of 0.44 million and 0.50 million units of ecological indices in streams 2 and 1, respectively while there is a decrease of 0.05 million units of ecological index in stream 11 due to over treatment. However, the increases in ecological indices are much greater than the decrease. Thus, the benefit in this scenario is improved water quality in all listed stream segments in table 1 and increased total ecological services.

Scenario III: trade between A (point source) in 7 and D (nonpoint source) in 11 (1:3)

Now assume that a point/nonpoint trade involves point source A in stream segment 7 and nonpoint source D in stream segment 11. The trading ratio between A and D is now assumed to increase to 1:3 to offset the further uncertainty inherent in nonpoint source controls. Source A purchases nonpoint source controls from D which is located in 11. 11 is upstream of A. The controls at point source D reduce acidity in all listed stream segments in table 1, i.e., 11, 9, 7, 5, 2, and 1 by 750 t/yr individually. The ecological indices in streams 7, 2, and 1 increase by 0.1 million, 0.44 million, and 0.5 million units, respectively while stream 11 has a relatively small decrease of 0.17 million units in ecological index. See scenario III in Table 1 for details. The benefits in this case are improved water quality and increased total ecological indices.

Scenario IV: trade between A (point source) in 7 and E (point source) in 1 (1:1)

Assume now that a trade occurs between point source A in stream segment 7 and point source E in stream segment 1, a segment downstream from A. The trading ratio between A and E is assumed to be 1:1. Source A purchases point source controls from E. The controls reduce the acidity of 250 t/yr only in stream 1. No increase of ecological index occurs in any stream. See scenario IV in Table 1. The benefit in this case is improved water quality in stream 1.

Summary of Scenarios I-IV

In summary, the above four trading scenarios have different benefits due to several factors. Refer to Table 2 for details.

(1) Threshold: The step function relationship between acidity (water quality measure) and the ecological index leads to significant threshold effects around the break points. All scenarios obtain improved water quality and increased ecological indices. Scenario II reflects the biggest improvement in ecological index, when increases of ecological indices in stream segments 2 and 1 are much greater that the decrease since ecological indices in 2 and 1 reach higher levels of

ecological services. Scenario III ranks second since three segments reach higher thresholds of ecological services but one segment has a decrease in ecological services. Scenarios I reflect the same increase in ecological indices caused by the increase in the index for 1 and rank third. A net increase in ecological index won't be achieved until water quality reaches a sufficiently higher level to reach the next threshold of ecological services. Scenario IV has no increase in index.

(2) Upstream and downstream: Scenarios I and IV have the same trading ratios (1:1). B and E are both point sources but scenario I results in a greater increase in ecological services. In this case scenario I would be a higher choice for a trade on two grounds: B is upstream of A so that all streams are improved and it has the greatest improvement in ecological services. The additive effect of improvements in multiple stream segments favors upstream trading.

(3) Trading ratio: In scenarios I, II and III, decreases in acid loadings in every segment are 250t/yr, 500t/yr, and 750 t/yr respectively due to different trading ratios (1:1, 1:2, and 1:3). When a point/point trading is switched to a point/nonpoint trading, trading ratio is also from 1:1 to 1:2, thus total ecological index increases due to a greater decline in acid loadings. However, as trading ratio continues to increase (from 1:2 to 1:3), total ecological index does not continue to increase but decrease due to over treatment in some stream segment.

A Review of Trading Program Concepts and Application to the Cheat River Watershed

Several key concepts for successful trading programs can be identified from a review of literature on marketable permits that has been developed over the past 30 years. Three key issues arise when considering trades between point and nonpoint sources: (1) the difficulty of determining nonpoint loadings, (2) the stochastic characteristics of nonpoint loadings caused by weather related and other factors difficult to assess, and (3) the uncertainty inherent in nonpoint source pollution control strategies (Malik, Letson, and Crutchfield, 1993; and Shortle and Dunn, 1986). The primary strategy proposed for compensating for these factors in any trading program is to impose a trading ratio greater than 1, i.e., for a point source to successfully trade for reductions from a nonpoint source, the expected reduction in nonpoint source loadings must be greater than the expected increase in point source loadings by the ratio specified. A 3:1 ratio means that three units of pollutant reduction from a nonpoint source are needed to offset one unit of pollutant increase from a point source (National Wildlife Federation, 1999). EPA requires that this trading ratio be adequate; a range of 2:1 to 4:1 is considered sufficient in most circumstances. The smaller the trading ratio, the less point source traders must spend to purchase nonpoint source control (Horan, 2001). Malik et al. (1993) found the optimal trading ratio depends on the relative costs of enforcing point versus nonpoint pollutant reductions and on the uncertainty associated with nonpoint pollution loadings. However, Stephenson et al. (1998) argue that “the physical properties of nonpoint source discharge may not offer as significant a barrier to trading as often is presumed”.

Enforcement issues pose an additional problem for point-nonpoint trading. Established models and professional judgment are often used to evaluate nonpoint reductions. Adequate monitoring to assess nonpoint contributions are related both to the very meaning of nonpoint source (there is no discharge point to monitor – thus upstream and downstream monitoring is required to measure nonpoint contributions) and the stochastic nature of many nonpoint issues. Statistical distributions of nonpoint loads tend to be highly skewed and exhibit fat tails. That is, long term, situation (often storm event driven) specific sampling is required to adequately assess the full impact of nonpoint sources. These factors tend to increase the cost of nonpoint enforcement significantly.

Other important concepts that must be considered by any successful trading program include transaction costs, number and relative discharge of potential trading participants, abatement costs, loading limits, and market structures (Hoag and Hughes-Popp, 1997; and Woodward, and Kaiser, 2002).

Conclusions

Our research shows that point/nonpoint trading is most feasible when both point and nonpoint sources contribute significantly to total pollutant loads. Our results indicate that allowing water quality trading over space could increase the ecological value of water resources for a given investment in remediation. We note that the efficiency of a potential trading program in the Cheat watershed is increased significantly if nonpoint sources are allowed to trade with point sources.

We note that the size of a water quality trading unit must be chosen with care. There are potential trading partners in some segment but not others. In terms of policy implementation, this implies that the designation of a water quality trading unit based on economic and hydrologic parameters may not necessarily follow watershed geographical boundaries. The step function approach to water quality threshold relationships between acidity (a water quality measure) and the ecological index (a proxy for environmental benefits) leads to significant threshold effects around the break points. A net increase in the ecological index is not considered achieved until water quality reaches a sufficiently higher level to pass the next threshold of ecological services. The additive effect of improvements in multiple stream segments favors upstream trading but does not necessarily preclude the possibility that other alternatives are in some cases more beneficial. Finally, changes in trading ratios obviously lead to changes in water quality improvements in the stream segments affected. However, the bigger trading ratio does not necessarily lead the greater ecological improvement. The cost-effective ratios for each scenario can vary considerably depending on watershed characteristics.

A preliminary analysis of several alternative trading scenarios assuming conservation of all pollutants follows to help understand the trading framework. Note that the analysis presented is strictly a lower bound. A full analysis including all downstream impacts would be at least as great and, most likely, considerably larger.

The spatial-temporal dynamic model presented in this paper appears to have significant potential for providing a rational base to assess the economic implications of point/nonpoint water quality trading and alternative watershed management strategies. The empirical application of the model has been delayed due to increased development time for the base water quality models and the collection of data to better represent the relationship between AMD pollutants and ecological services. The model could be applied to various watershed management problems although only AMD treatment in the Cheat River watershed is discussed.

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