Examining Point-Nonpoint Trading Ratios for Acid Mine Drainage Remediation with a Spatial-Temporal Optimization Model

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Abstract This study addresses a growing concern with the identification of point/nonpoint trading ratios in water quality trading programs. An empirical spatial-temporal optimal control model is solved and manipulated to examine the scope of trading ratios in Muddy Creek basin in West Virginia. The results of trading ratios greater than one assumed needed to compensate for risk and uncertainty are described

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Key words: point-nonpoint water quality trading, trading ratio, acid mine drainage, spatial-temporal optimization

Introduction

A trading ratio greater than on is commonly required for water quality trading that involves nonpoint sources to compensate for the difficulty of determining nonpoint loadings, the stochastic characteristics of nonpoint loadings, and the uncertainty inherent in nonpoint source pollution control strategies. Compensation for risk and uncertainty is one of the primary justifications that a trading ratio greater than one is commonly considered (point source emissions more commonly are traded on a one-for-one basis although emissions may be imperfect substitutes in some instances, for example, see Tietenberg, 1995). However, the appropriate value of a trading ratio remains unclear because of qualitative differences between point and nonpoint sources.

A trading ratio defines “how many nonpoint permits substitute for one emissions permit for trades between source categories” (Shortle and Horan, 2001, p. 275). 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). The USEPA 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, Letson, and Crutchfield (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. At a competitive equilibrium, the trading ratio is equated to the ratio of marginal abatement cost of a point source to marginal abatement cost of a nonpoint source when nonpoint loadings are deterministic and enforcement is costless. In general, the trading ratio should equal the relative environmental impacts of the loadings from the two sources (Baumol and Oates, 1988). When loadings are uncertain and enforcement is costly, the trading ratio should reflect all social costs other than abatement costs. However, Stephenson et al. (1998) argue that the physical properties of nonpoint source emission may not offer as significant a barrier to trading as often is presumed. Horan et al. (2004) found that the trading ratios for emission-for-expected loadings programs are much smaller than those found in existing markets. Besides the above literature on trading ratios, Tietenberg (1995) and Shortle and Horan (2001) discussed uniform trading ratios. A uniform trading ratio could provide a net economic gain if it reduces transactions costs. However, uniform trading ratios do not give firms incentives to exploit differences in their relative marginal environmental impacts that vary depending on the location of sources. Most existing trading programs operate with a single trading ratio although the trading ratio is spatially differentiated for a few programs.

This study addresses a growing concern with the analytical underpinnings of point/nonpoint trading ratios in water quality trading programs. An empirical spatial-temporal optimal control model is solved and manipulated to examine the scope of acid mine drainage (AMD) trading ratios in Muddy Creek basin in West Virginia.

The rest of the paper is organized into four parts. The next section presents briefly the empirical spatial-temporal dynamic optimization model that maximizes the present ecological value of the water resources of the Muddy Creek basin. The following section investigates the possibilities of AMD acidity trading in the basin. The next section discusses the trading ratios. Finally, we summarize and draw conclusions.

The Empirical Spatial-Temporal Optimization Model

This paper considers a basic spatial-temporal optimal control model assuming that the goal of the decision maker is to maximize ecological services from the watershed over a 10-year planning horizon given a predetermined budget each year to treat AMD problems in the Muddy Creek basin in West Virginia.

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 Muddy Creek basin. AMD is acidic water with high concentrations of dissolved metals such as iron, aluminum, and manganese that pollutes streams and harms aquatic life. As nonpoint and non-permitted sources, abandoned mine lands contribute significant amounts of AMD to the basin. Bond forfeiture sites are also significant contributors of AMD. Active mining operations covered by current National Pollutant Discharge Elimination System (NPDES) permits are considered point sources and contribute little AMD.

The level of pollution is assumed to be known but declining slightly over time as the AMD sources evolve. Resources are assumed to be spent on remediation projects that produce long term but declining treatment results. The primary goal of the model is to distribute the available resources over the basin by investing in restoration projects for targeted streams each year that will maximize the ecological return on this investment. The model reflects both the spatial reality of variations in flow, in pollution, in treatment, and in the ecological benefits produced and the intertemporal constraints of limited resources and the inability to move remediation programs once the initial investment is made.

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 is the index of stream segments; 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 Muddy Creek Basin, i = 1, 2, …, 23 (the number of stream segments is in NHD 1:100,000-scale coverage); t = 0, 1, …, 10 (planning horizon is in years). And a value of 6% is used for the time preference r for the Muddy Creek basin.

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 Muddy Creek basin, this step function is written 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.

Specifically, based on analysis of available data, we estimate a ten-step ecological condition function:

$$
\begin{array}{lll}
EC_{i,t}(a_{i,t}) = 27.3 & if & a_{i,t} < -68.62 \\
EC_{i,t}(a_{i,t}) = 63.6 & if & -68.62 \le a_{i,t} < -33.58 \\
EC_{i,t}(a_{i,t}) = 81.8 & if & -33.58 \le a_{i,t} < -11.87 \\
EC_{i,t}(a_{i,t}) = 100 & if & -11.87 \le a_{i,t} < 0 \\
EC_{i,t}(a_{i,t}) = 81.8 & if & 0 \le a_{i,t} < 5.58 \\
EC_{i,t}(a_{i,t}) = 72.7 & if & 5.58 \le a_{i,t} < 75.29 \\
EC_{i,t}(a_{i,t}) = 54.5 & if & 75.29 \le a_{i,t} < 321.55 \\
EC_{i,t}(a_{i,t}) = 36.4 & if & 321.55 \le a_{i,t} < 613.11 \\
EC_{i,t}(a_{i,t}) = 27.3 & if & 613.11 \le a_{i,t} < 1222.27 \\
EC_{i,t}(a_{i,t}) = 0 & if & 1222.27 \le a_{i,t}
\end{array}
$$

Constraints

Numerous factors are included via sets of 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) $CC_{i,t}$. In this paper, AMD is assumed treated by open limestone channels that are one of passive AMD treatment systems. u_i is 0.006 for these systems in the Muddy Creek basin.

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 Muddy Creek basin, δ is assumed to be 0.02, representing the diminishing rate of alkalinity generation.

Spatial equations of motion are:

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

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 $y_{i,t} = a_{i,t} w f_{i,t}$ within each segment during each time period. For AMD, $y_{i,t}$ is the annual acid load in segment i at time t; $x_{i,t}$ is the exogenously determined pollution load generated within the drainage area of segment i during period t.

In the Muddy Creek basin, 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:

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

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 Muddy Creek basin, $C_t^{\max}$ is selected as $50,000.

Finally, the initial loadings are given by:

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

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

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 (Zhao and Fletcher, 2003).

The Possibilities of AMD Trading in the Muddy Creek Basin

The resulting optimal temporal and spatial investment strategies of the above model are derived from solutions to a mixed integer programming problem obtained using the GAMS/CPLEX mixed integer programming package. The optimal results are then manipulated to evaluate trading possibilities.

Figure 1 shows the Muddy Creek basin with NPDES permitted mines, bond forfeiture sites, and abandoned mine lands. This basin is located in the northeast of West Virginia. Among 23 stream segments in this basin, 12 segments are impaired by AMD. Figure 1 also provides a stream network with segments numbering to provide direct context for the discussion of potential AMD trades within the Muddy Creek basin.

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).

Costs of AMD treatment technologies are very different for point and nonpoint sources. Assume that pollution from a point source is treated by active systems while pollution from a nonpoint source is reduced by passive systems. Costs of passive systems are primarily represented as fixed costs with negligible variable costs. Both the fixed and variable costs of active systems are much higher. Where technically feasible, passive systems are much more cost effective. For example, for the active AMD technology hydrated lime, when flow is 250 gpm, acidity concentration is 500 mg/l, and plant capacity is 249 mt/yr, fixed cost is then $106,000, and variable cost is $38,890/yr.

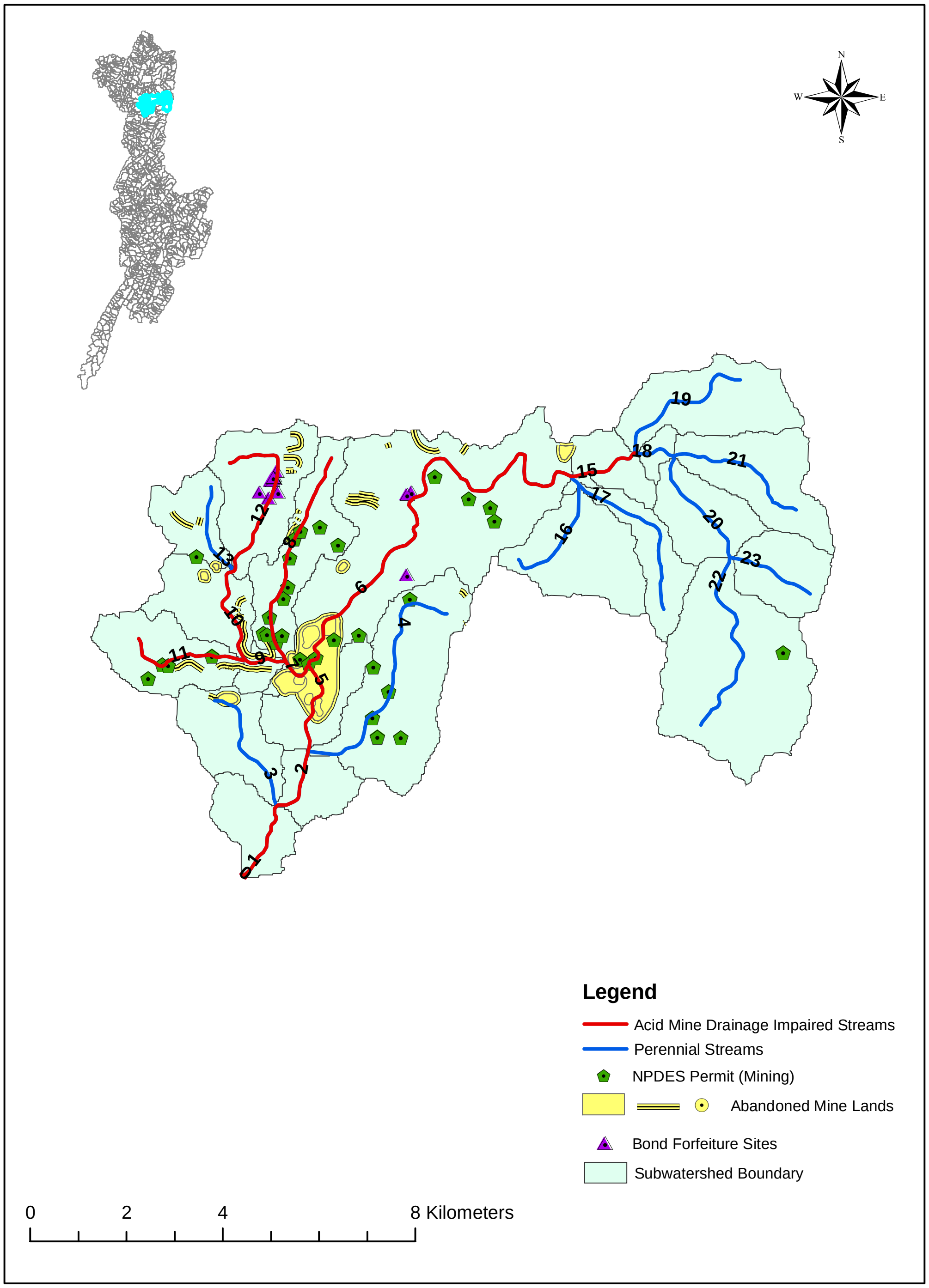

Figure 1 – The Muddy Creek Basin in West Virginia

Three Trading Cases

Three trading cases are presented for the Muddy Creek basin. The proposed sites for credit generation are nonpoint sources discharging AMD to the streams within the basin. The proposed credit buyer is point source A that represents a new coal mine subject to the Total Maximum Daily Load (TMDL). Point source A discharges AMD to segment 7. Three proposed cases are case 1 (the base case), case 2 (does not consider trade but includes the new coal mine – point source A), and case 3 (trades are considered).

Case 1 (base case): this is the original empirical model results for the Muddy Creek basin that demonstrate the distribution of AMD treatment investments over time and space given initial loadings (see Table 1). The optimal results show that investments in AMD treatment should be distributed among severely impaired stream 8 and moderately impaired streams 10, 11, 12, 13, 19, and 21 over the 10-year planning horizon.

Case 2 (no trade): in this case, it is assumed that additional acidity of 237.5 metric tons of $CaCO_3$ equivalent acid per year (tpy) discharges to stream segment 7 that is subject to the TMDL. It is also assumed that stream segment 7's assimilative capacity – the amount of a particular pollutant a water body can absorb while still remaining healthy – is entirely used up. The discharger is point source A that represents a new coal mine. We get the number 237.5 as follows: hydrated lime is selected as an active treatment technology. With flow of 250 gpm, acidity concentration of 500 mg/L, and plant capacity of 249 tpy, its fixed cost is $106,000, and variable cost is $38,890/yr. The acid loading is calculated as following:

$$250 \text{ gpm} \times 500 \text{ mg/L} \times 0.0019 = 237.5 \text{ tpy}.$$

where 0.0019 is a conversion factor (Skousen and Ziemkiewicz, 1996).

New permitted coal mines subject to the TMDL will be assigned water quality-based effluent limitations (WQBELs) based on meeting water quality standards at end-of-pipe. To restore the basin and meet its beneficial uses, it is necessary for segment 7 to face the choice between zero discharge permits or trades that would offset the new discharge.

Without a trade, on-site active treatment is required to achieve zero discharge permits. How can we calculate the required on-site cost? Assume that in the 1st year, there are both fixed cost and variable cost as follows: fixed cost is $106,000, and variable cost is $38,890. Total costs in the 1st year are $106,000+ $38,890 = $144,890. From the 2nd year to the 10th year, there is only variable cost of $38,890. Optimal investments in AMD treatment in other stream segments remain unchanged.

Case 3 (trade): With trade that would offset the new discharge from point source A, treatment in segment 7 would cease, and money saved could be used to treat AMD in other segments within the Muddy Creek basin.

The Possibilities of AMD Trading

Trading opportunities in the Muddy Creek basin can be observed by comparing the spatial and temporal distribution of AMD treatment investments for cases 2 and 3 as shown in Tables 2 and 3 separately. Table 2 for case 2 is based on the results of base case (i.e., case 1) shown in Table 1.

From Tables 2 and 3, we see that the distribution of investments in case 3 differs from those in case 2. There are trading possibilities among different sources. Point source A could buy permits from different segments. To be more precise, it is determined that new discharge from point source A should be traded from segment 7 to other segments where the credit generation sites are located. Take the 2nd year as an example: Table 2 shows that, in the 2nd year, without trading (case 2), point source A in segment 7 should have on-site active treatment with the investment of $38,890. In segment 12, an investment of $50,000 should also be given to treatment of AMD by passive systems. Total investment is $88,890. However, with trading (case 3), we see a different allocation of investment. Table 3 shows, in the 2nd year, all of available investment (in passive treatment systems) should be given to segments 8 and 12 with the investment of $86,480 and $2,410 respectively. The sum of $86,480 and $2,410 is $88,890. From case 2 to case 3, investment in segment 7 changes from $38,890 to $0; investment in segment 8 changes from $0 to $86,480; and investment in segment 12 decreases from $50,000 to $2,410 (with the difference of $47,590). The indications are: in the 2nd year, with trading, treatment in segment 7 would cease, and money saved (i.e., $38,890) could be used to treat AMD at the nonpoint sources located in segment 8. The investment decreased in segment 12 (i.e., $47,590) also goes to segment 8, which means, money saved in segment 12 could also be used to treat AMD at the sites located in segment 8. The sum of investment transferred from both segments 7 and 12 to segment 8 is $86,480 (=$38,890+$47,590), which is exactly equal to the investment allocated to segment 8 shown in Table 3. Trading participants here include segments 7, 8 and 12. There are multiple segments involved in this trading process.

Note that, first, from a spatial perspective trades among streams are interspatial trades and permits are interspatial tradable permits; from a temporal perspective, permit banking and borrowing over time are intertemporal trades and permits are regarded as bankable permits. The trades considered in this study are interspatial trades.

Second, there are three categories of geographic restrictions on trades. In the first category, credits must be generated upstream; reduced pollution loads (due to credit generation) impact the same stream where credits are used. The second one is a broader system that allows credits to be generated anywhere in the same basin. The third category is the least restrictive approach that allows credits to be generated anywhere within different basins. The trades presented here fall into the second category, i.e., trades occur in the same basin.

Third, there are three possible categories of trading regarding pollutant in the basin. Same pollutant trades, cross-pollutant trades within AMD, and cross-pollutant trades outside of AMD. As for the common currency, same-pollutant trades would use tons of metals; cross-pollutant trades within AMD should use acidity; and cross-pollutant trades outside of AMD could use ecological index. Apparently, the trades presented here fall into cross-pollutant trades within AMD. However, since tons of metals can be easily converted to acidity, the trades in this study could also be same-pollutant trades.

Finally, three factors necessary for a trade to occur are credit buyers, credit generators, and sites for credit generation. Credit buyers could be operations targeted by the TMDL, new mines, new coal mining operations subject to anti-degradation rules, and so on. Credit generators could be agencies and organizations, credit users that generate credits for their own use, and other entities that generate credits for sale. Sites where credits can be generated are abandoned mine lands and bond forfeiture sites. Regarding the potential trades in the Muddy Creek basin discussed in this study, the credit buyer is the new coal mining operation located in segment 7; credit generators could be government agencies or nonprofit organization; and abandoned mine lands and bond forfeiture sites can be sites where credits are generated. In other words, government agencies or nonprofit organization can treat AMD on abandoned mine lands and bond forfeiture sites in segment 8 and would deposit credits into the credit bank; and the new coal mine operation would use money saved from cease of treatment by itself (i.e., $38,890) to buy permits from the credit bank. Actually, the trade between segments 7 and 8 is accompanied by the investment reallocation between segments 12 and 8. The investment decrease in segment 12 (i.e., $47,590) goes to segment 8. That is, government agencies or nonprofit organization can use this amount of money to treat AMD on abandoned mine lands or bond forfeiture sites in segment 8. This amount of money comes from the investment saved in segment 12.

Table 1 The Spatial and Temporal Distribution of AMD Treatment Investments (C) in the Muddy Creek Basin (base case) (thousands of dollars)

	Time Period									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream										
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	16.29	0.00	50.00	34.56	0.00	31.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	50.00	0.00	15.44	50.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.00	50.00
12	6.83	50.00	50.00	33.71	0.00	0.00	0.00	0.00	0.00	0.00
13	36.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	3.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	2.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2 The Spatial and Temporal Distribution of AMD Treatment Investments in the Muddy Creek Basin for Case 2 (No Trade) (Thousands of Dollars)

	Time Period									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream										
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	144.89	38.89	38.89	38.89	38.89	38.89	38.89	38.89	38.89	38.89
8	0.00	0.00	0.00	16.29	0.00	50.00	34.56	0.00	31.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	50.00	0.00	15.44	50.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.00	50.00
12	6.83	50.00	50.00	33.71	0.00	0.00	0.00	0.00	0.00	0.00
13	36.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	3.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	2.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Trading Ratios in the Muddy Creek Basin

Generally, trading ratios are required for each trade to compensate for the difficulty of determining nonpoint loadings, the stochastic characteristics of nonpoint loadings, and the uncertainty inherent in nonpoint source pollution control strategies. Compensating risk and uncertainty is one of the primary justifications that a trading ratio greater than one is commonly considered.

Table 3 The Spatial and Temporal Distribution of AMD Treatment Investments in the Muddy Creek Subwatershed for Case 3 (Trade) (Thousands of Dollars)

	Time Period									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream										
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	153.83	86.48	88.89	68.64	88.89	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.26	88.89
10	0.00	0.00	0.00	0.00	0.00	0.00	48.91	64.45	0.00	0.00
11	18.06	0.00	0.00	0.00	0.00	0.00	0.00	24.44	30.63	0.00
12	0.00	2.41	0.00	0.00	0.00	88.89	39.98	0.00	0.00	0.00
13	15.41	0.00	0.00	20.25	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	5.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	2.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Specifically, in the Muddy Creek basin, there are several sources of uncertainty. The smallest sources of uncertainty are those related to individual measurements of chemical composition or water flow, from either a permitted or an orphan site. Extrapolating from instantaneous acid loads to the longer term adds uncertainty to the measurement. Although there is a clear relationship between chemical and ecological condition in a stream, this relationship supports only a general prediction of ecological improvement with improved chemical conditions. Comparison of the predicted ecological effect of one pollutant to the predicted ecological effect of another pollutant is the most uncertain situation (Hansen et al., 2004, p. 60).

In the relevant literature, a trading ratio greater than 1 is suggested for point/nonpoint trading. Point source emissions are often traded on a one-for-one basis. In the trading scenarios presented above, all trades are point source-to-nonpoint source. The trading ratio is the amount of pollutant removed from the trading site where money is received divided by the amount of pollutant not removed from the stream where money is saved. For brevity and ease of interpretation, this discussion focuses on the trades that would occur in the 1st year (see Table 4).

Table 4 Trading in the 1st Year in the Muddy Creek Basin

	Investment before Trade (dollars) (Table 2)	**Investment after Trade (dollars) (Table 3)**	**Change in Investment (dollars)**	**Investment Moved out (dollars)**	**Investment Received (dollars)**	**AMD Treatment before Trade (tpy) (Table 1)**	**AMD Treatment after Trade (tpy) (Appendix 1)**	**The Amount of AMD not Removed due to Trade**
Stream								
7	144,890	0	↓144,890	144,890 to segment 8	0	237.5	0	237.5
8	0	153,830	↑153,830	0	144,890 from segment 7; 6,830 from segment 12; 2,110 from segment 13	0	923 (=144,890× 0.006+ 6,830× 0.006+ 2,110× 0.006 =869 +41+ 13)	
11	0	18,060	↑18,060	0	18,060 from segment 13	0	108 (=18,060× 0.006)	
12	6,830	0	↓6,830	6,830 to segment 8	0	41 (=6,830× 0.006)	0	41
13	36,900	15,410	↓21,490	2,110 to segment 8; 18,060 to segment 11; 1,320 to segment 19	0	221 (=15,410× 0.006+ 21,490× 0.006 =92+129)	92	129 (=13+108 +8)
19	3,870	5,190	↑1,320	0	1,320 from segment 13	23	31 (=1,320× 0.006+ 3,870× 0.006 =8+23)	

Note: ↓ represents decrease, and ↑ represents increase.

As shown in Table 4, in the 1st year the trading scenarios could be to not treat in segment 7 with $144,890 investment available to treat AMD at the nonpoint sources located in segment 8; the investment reallocated from segment 12 ($6,830) could also be used to treat AMD at the sites in segment 8. In addition, the investment reallocations from segment 13 ($21,490) could be used to treat AMD at the sites in segments 8, 11, and 19 ($2,110 for segment 8, $18,060 for segment 11, and $1,320 for segment 19). After trading, the total amount of AMD removed in segment 8 is 923 tpy, including 869 tpy reduction made using $144,890 transferred from segment 7, 41 tpy reduction made using money of $6,830 from segment 12, and 13 tpy reduction made using money of $2,110 from segment 13. The total amount of AMD removed in segment 11 is 108 tpy made using money of $18,060 transferred from segment 13. The total amount of AMD removed in segment 19 is 31 tpy and 8 (out of 31) tpy removal is achieved using money of $1,320 transferred from segment 13. In addition, the amount of AMD not removed due to trade in segments 7 and 12 are 237.5 and 41 respectively. The amount of AMD not removed due to trade in segment 13 is 129 tpy (13 tpy due to the trade with segment 8, 108 tpy due to the trade with segment 11, and 8 tpy due to the trade with segment 19). Trades occur between segments 7 and 8 accompanied by the investment reallocation between 12 and 8, 13 and 8, 13 and 11, and 13 and 19.

Note that segment 8 is upstream of segment 7. This indicates that the upstream partners are preferred due to the additive effect of the improvements of water quality and ecological condition represented by the objective function. Such a trade would guarantee that reduced pollution loads due to credit generation in segment 8 impact the same stream or downstream where credits are used (i.e., segment 7) instead of other streams. However, this does not preclude other trading possibilities.

For the basic point source-to-nonpoint source trade between segments 7 and 8, the amount of AMD not required to be removed from segment 7 due to the trade is 237.5 tpy while the amount of AMD removed from the trading site in segment 8 using the money saved in segment 7 is 869 tpy. The trading ratio is 3.66 (or 3.66:1) (that is 869 tpy divided by 237.5 tpy). In conclusion, the potential trading ratio for poin/nonpoint trade is greater than 1.

Current regulations give a lower bound for point/nonpoint trading ratio of 1:1. The upper bound for point/nonpoint trading ratio depends on technical aspects of the relative costs of treating the point source or treating nonpoint sources. This limits how much one is willing to pay for credits.

A variety of factors determined trading ratios. First, to encourage trades with less uncertainty, trades in which the credit seller and buyer are in close proximity, and in which the credit seller is upstream, lower trading ratios for such trades are recommended.

Second, the management agency has to adjust trading ratios to favor trades that contribute to strategic watershed restoration goals, such as the improvement or maintenance of water quality in a particular basin. In this manner, reduced ratios could be used as incentives to promote the generation of credits in priority locations.

Finally, trading ratios for same-pollutant trades should be lower than those for cross-pollutant trades. Three separate trading currencies would be used to account for same-pollutant AMD trades: pounds of iron, aluminum, and manganese. There would be little uncertainty in the outcome of a trade if the credit generator and buyer were affecting the same pollutant. In contrast, cross-pollutant trades outside of AMD that use a common currency such as ecological indices would be measured based on their ecological effect, which is one step removed from the actual changes in pollutant loads. The higher trading ratio required for cross-pollutant trades reflects this greater uncertainty (Hansen et al., 2004, p. 60).

Note that, case 3 (with trading) has a greater total ecological index than case 2 (without trading). Trading increases the total ecological index by 6,729,549 (=184,387,769-177,658,220) ecological units, i.e., 4%. That is, ecological service provided by all streams in the Muddy Creek basin are improved by 4% due to the trading initiated by the new coal mine operation, A, in segment 7. More benefits would be achieved if more point sources like A had an incentive to trade. This implies that trading is a cost-effective strategy to achieve water quality improvement.

Conclusions

This paper considers a basic spatial-temporal optimal control model assuming that the goal of the decision maker is to maximize ecological services from the watershed over a 10-year planning horizon given a predetermined budget each year to treat AMD problems in the Muddy Creek basin in West Virginia.

The resulting optimal temporal and spatial investment strategies are derived from solutions to a mixed integer programming problem obtained using the GAMS/CPLEX mixed integer programming package. The optimal results are then manipulated to evaluate trading ratios. A hypothetical acidity trading scenario is proposed in which a point source (a new coal mine operation subject to TMDL rules) uses credits generated through remediation projects at other sites from treatment of nonpoint sources within the same basin over the 10-year planning horizon.

The trading ratio is the ratio of the expected amount of pollutant removed by treating the nonpoint source divided by the amount of additional pollution allowed from the new point source. Our results indcate that point/nonpoint trading ratios in proposed trading scenarios greater than one can be justified. For example, for a point/nonpoint trade between sources in adjacent stream segments, the appropriate trading ratio is 3.66 (or 3.66 to 1).

We note that current regulations give a lower bound for point/nonpoint trading ratio of 1:1. The upper bound for point/nonpoint trading ratio depends on technical aspects of the relative costs of treating the point source or treating nonpoint sources and reflects the limit of how much one is willing to pay for credits.

For trades in which the credit seller and buyer are in close proximity, and in which the credit seller is upstream, lower trading ratios are recommended. Trading ratios should also be adjusted to favor trades that contribute to strategic restoration goals such as the improvement or maintenance of water quality in a particular basin. Trading ratios for same-pollutant trades should be lower than those for cross-pollutant trades.

All potential trades considered in this study are interspatial trades; trades occur in the same basin; trades could be cross-pollutant trades within AMD and same-pollutant trades as well; and the credit buyer is the new coal mining operation; credit generators could be government agencies or nonprofit organization; and abandoned mine lands and bond forfeiture sites can be sites where credits are generated.

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Appendix 1

The Spatial and Temporal Distributions of AMD Treatment (u) in Case 3 (with Trading) in the Muddy Creek Basin (tpy)

	Time Period									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream										
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	923	1,424	1,929	2,303	2,791	2,737	2,683	2,630	2,579	2,528
9	0	0	0	0	0	0	0	0	350	876
10	0	0	0	0	0	0	293	674	661	648
11	108	106	104	102	100	98	96	241	420	412
12	0	14	14	14	14	547	776	761	746	731
13	92	91	89	209	205	201	197	193	189	185
14	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0
19	31	31	30	29	29	28	28	27	27	26
20	0	0	0	0	0	0	0	0	0	0
21	14	14	14	14	13	13	13	13	12	12
22	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0