An Ecologically Based Approach to Identifying Restoration Priorities in an Acid-Impacted Watershed

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Abstract

The extent of impairment to some Appalachian watersheds from acid precipitation is so extreme that watershed scale analytical tools are needed to help guide cost-effective management decisions. The objective of this study was to develop a measure of the functional value of streams as potential areas for juvenile Brook trout recruitment. This measure, which we term "weighted potential recruitment area" (WPRA), is a function of the expected Brook trout spawning intensity and juvenile survivorship. Estimates of WPRA for each stream segment were then used to identify restoration priorities and optimal restoration programs in the upper Shavers Fork watershed in West Virginia, U.S.A. Using this approach, we determined that the watershed has lost nearly 80% of its historic juvenile recruitment potential as a result of acid precipitation. We also determined that of the 145 stream segments in the watershed, eight critical stream segments account for nearly 20% of the loss. The costs and ecological benefits of a series of five alternative restoration programs were then assessed using an ArcGIS model (Environmental Systems Research Institute, Redlands, CA, U.S.A.). This approach identified two "optimal" alternatives: (1) a low-cost, moderate-benefit approach that would use existing rail access to treat acidification in three critical headwater locations and (2) a high-cost, high-benefit approach that would use aerial limestone application to treat numerous acidic tributaries near their source. The measure of stream ecological value that we developed was effective in identifying critical restoration priorities and optimal restoration strategies in this watershed. A similar procedure could be used to guide watershed restoration decisions throughout the Appalachian region.

Key words: **acid precipitation, Appalachian streams, Brook trout, cost–benefit analysis, restoration priorities.**

Introduction

Acid precipitation is ubiquitous in the eastern United States, and it has had devastating effects on many aquatic ecosystems (Wigington et al. 1996). This is especially true in the high-elevation watersheds of the central Appalachian Mountains. In fact, it is estimated that more than 25% of Brook trout (*Salvelinus fontinalis*) streams in West Virginia have been impaired by acid precipitation. High loadings of acidity from precipitation reduce buffering capacity in surrounding soils, leach nutrients from watersheds (Lajewski et al. 2003), and lead to decreased pH and increased concentrations of dissolved aluminum in surface waters (Wigington & Dewalle 1996; Fitzhugh et al. 1999). Abrupt changes in surface water chemistry typically have severe impacts on aquatic communities. Diverse, highly productive benthic invertebrate communities are converted to communities comprised of only a few acidophilic taxa (Kobuszewski & Perry 1993; Rosemond et al. 1993). In addition, entire fish communities can be lost from acidified streams. Numerous studies have shown that acute depressions in stream pH and increased levels of inorganic, monomeric aluminum cause severe reductions in fish survivorship and growth, especially in early life stages (Menendez 1976; Sharpe et al. 1987; Fiss & Carline 1993; Baker et al. 1996; Van Sickle et al. 1996; Heard et al. 1997).

The only long-term solution to the acidification problem is through reduction of nitrate and sulfate emissions from vehicles and coal-fired power plants. However, in an effort to quickly recover lost ecosystem values, state and federal agencies spend considerable sums of money each year treating acidified streams with limestone (Zurbuch 1984). Although there are numerous methods for treating acidic systems, the most common approach is to add large quantities of limestone sand directly to impacted streams. This approach has proven successful, especially in poorly buffered watersheds of the central Appalachians (Ivahnenko et al. 1988; Downey et al. 1994; Clayton & Menendez 1996; Menendez et al. 1996; Clayton et al. 1998; Hudy et al. 2000). Various studies have determined that regular limestone additions to acidified streams can dramatically improve water quality and result in the recovery of diverse invertebrate and fish communities. In addition to being highly effective, this approach is relatively inexpensive as long as there is existing road access within affected watersheds.

Currently, two important logistical problems limit our ability to effectively manage and recover acid-impacted

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watersheds. First, the vast number of acid-impacted streams in the central Appalachian Mountains makes it impossible to recover even a modest proportion of those systems that have been lost, and treating thousands of streams would be far too costly for any state or federal agency to afford. Second, access to streams can be extremely difficult or prohibited in many of the high-elevation watersheds that experience the greatest rates of acid loading. Consequently, there is a need to develop approaches that can be used to identify restoration priorities and optimal restoration programs in acid-impacted watersheds. The objectives of this study were to (1) develop an index of juvenile Brook trout recruitment potential that can be used to quantify the relative ecological condition of stream segments in the upper Shavers Fork watershed in West Virginia; (2) use the index to identify restoration priorities within the watershed; and (3) use the index to identify restoration strategies that maximize ecological benefits (i.e., increased Brook trout recruitment), while maintaining costs at sustainable levels.

Study Area

The upper Shavers Fork is a 155-km^2 watershed (Monongahela River basin) located on the Appalachian Plateau of east-central West Virginia (lat 38°39′00″, long 80°06′00″). The Shavers Fork originates at nearly 1,350-m elevation and drops to 1,100-m elevation at the lower end of the study area near Cheat Bridge, West Virginia. The watershed comprises a network of small, well-shaded, high-gradient tributaries that drain into a wide, low-gradient main stem (Petty et al. 2001). Historical accounts indicate that the Shavers Fork supported one of the most productive Brook trout fisheries in the central and southern Appalachian Mountains. The current fishery, however, is significantly reduced from historic levels. Numerous factors, including fishing pressure, sedimentation, and loss of riparian vegetation, probably have contributed to the fishery's decline (Petty et al. 2001). However, recent studies indicate that Brook trout populations in the watershed are currently limited by juvenile recruitment, which is itself strongly influenced by water chemistry and acidification (Petty et al. 2005).

Methods

Index of Ecological Condition

The conceptual basis of our approach to optimizing recovery in the Shavers Fork watershed extends from the restoration time line approach described by the National Research Council on Aquatic Ecosystem Restoration (NRC 1992). Briefly, the approach recognizes that, as a result of human-related disturbances, many watersheds possess current ecological conditions that are significantly lower than their historical ideal. Over time, various restoration and management actions can result in ecological improvements that push watersheds closer and closer to their idealized condition. Optimal restoration programs are programs that maximize both the rate and extent of ecological recovery at a watershed scale (NRC 1992).

Successful application of this concept requires meaningful measures of ecological condition (NRC 1992). For the upper Shavers Fork, we propose an index of juvenile Brook trout recruitment potential. Brook trout recruitment potential was chosen as a functional measure of ecological condition in this system for several reasons. First, the effects of acid precipitation on Brook trout recruitment are well established throughout the central Appalachian region and specifically within the upper Shavers Fork (Clayton et al. 1998; Bopp 2002; Lamothe 2002; Petty et al. 2005). Second, Brook trout are an important recreational game fish and, like most trout species, are good indicators of water quality and overall ecological condition in Appalachian watersheds (Hudy et al. 2000). Third, and perhaps most importantly, because Brook trout spawning is focused within small basin area, headwater streams, Brook trout recruitment potential may provide an "umbrella" management target that can effectively restore fish, invertebrate, and amphibian communities along stream continua.

We refer to the index as "weighted potential recruitment area" (WPRA), and the index was calculated as:

$$\begin{aligned}\text{WPRA} = {} & (\text{Expected Spawning Intensity}) \\ & \times(\text{Expected Juvenile Survivorship}) \\ & \times(\text{Reach Length})\end{aligned}$$

Expected spawning intensity is a relative value ranging from a low of 0 to a high of 1.0 and is a measure of the expected level of spawning activity by Brook trout in a stream reach given the basin area of the watershed draining to the reach (Fig. 1a). We used data from a previous study that examined factors influencing Brook trout spawning intensity in the upper Shavers Fork watershed to predict expected spawning intensity (Petty et al. 2005) (Fig. 1a). In this study, which measured a variety of physicochemical attributes such as substrate composition, cover, riparian and bank condition, temperature, and flow, we found that nearly 80% of variation in Brook trout spawning could be explained by basin area alone (Petty et al. 2005). Specifically, we found that spawning intensity was highest in streams draining less than 1 km^2 and decreased rapidly with increasing basin area (Fig. 1a). Other factors, such as gradient and in-stream cover, explained only minor amounts (<5% combined) of variation in Brook trout spawning in this system and consequently, were left out of these calculations.

Juvenile survivorship also is a relative value ranging from a low of 0 to high of 1.0 and is a measure of the expected level of juvenile survivorship in a stream reach given the [Ca^{2+}]-to-[H^{+}] ratio (henceforth, Ca:H ratio) of the stream (Fig. 1b). Ca:H ratios are important because

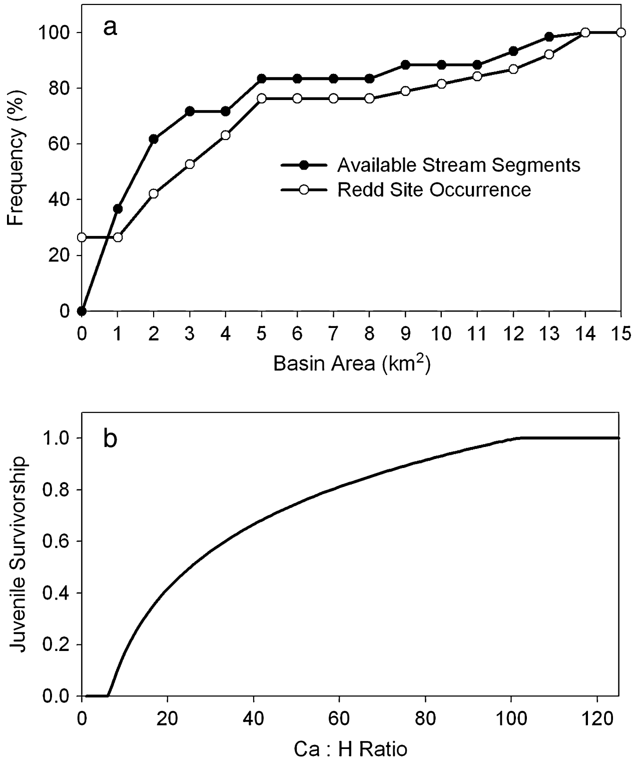

Figure 1. Relationship between basin area and Brook trout spawning intensity (a) and Ca:H ratio (mg/L) and Brook trout juvenile survivorship (b). These relationships were used to quantify the relative quality of all stream segments in the upper Shavers Fork basin as potential habitats for juvenile recruitment by Brook trout.

higher concentrations of dissolved calcium can reduce the toxicity of dissolved aluminum to young trout (Clayton et al. 1998). Data from streams throughout West Virginia, and specifically within the Shavers Fork watershed, indicate that Brook trout recruitment is negligible in streams with Ca:H ratios less than 6 (Lamothe 2002). Juvenile survivorship increases rapidly with increased Ca:H ratios (>6) and is maximized at Ca:H ratios near 100 (Lamothe 2002; West Virginia Division of Natural Resources, unpublished data) (Fig. 1b). As with spawning intensity, additional factors are known to influence juvenile Brook trout survivorship, such as temperature and flow conditions. However, the broad evidence suggests that alkalinity and stream buffering capacity are the dominant factors influencing successful juvenile recruitment in the Shavers Fork watershed (Petty et al. in press).

Multiplying expected spawning intensity by juvenile recruitment produces a relative measure of the value of a given stream reach as habitat for juvenile Brook trout recruitment (range, 0–1.0). A measure of zero indicates that the reach does not function at all, whereas a measure of 1.0 indicates that the reach is among the most important areas for juvenile recruitment in the watershed. This relative WPRA is then multiplied by the length of the stream reach (km) to provide a measure of the functional length of the reach.

WPRA Calculations for the Upper Shavers Fork

We used the Hydrology Modeling Sample Extension 1.1 of ArcGIS v8.3 (Environmental Systems Research Institute, Redlands, CA, U.S.A.) to determine the basin area (km^2) and length (km) for all stream segments in the watershed. This procedure used a 30-m filled digital elevation model to produce flow direction and flow-accumulation grids within the upper Shavers Fork watershed. The upstream extent of flow accumulation was set at 0.25 km^2. Streams draining areas less than 0.25 km^2 were not mapped, because extremely small streams identified by Geographic Information Systems (GIS) often do not exist (J. T. Petty 2003, West Virginia University, personal observation). Basin area was derived from the flow-accumulation grid at the most downstream grid cell of each stream segment. The flow-accumulation grid delineating stream channels was then converted from raster into vector format, creating a stream network shapefile, which was then used to calculate stream segment length.

Field measures of dissolved calcium concentration (mg/L) and pH were obtained in 94 stream segments in early summer 2002 and 2003. Water samples were taken near the mouth of each stream and/or above current limestone treatment sites, and pH was measured with an Oakton 110 pH meter with an automatic temperature compensation electrode (Oakton Instruments, Vernon Hills, IL, U.S.A.). Dissolved calcium concentrations (±0.08 mg/L) were determined in the lab following the Hach Buret Titration Method 8222. Data from these samples were then used to calculate Ca:H ratios for each stream segment. We sampled water chemistry in 62% (94 of 154) of the available stream segments, which represent 82% (120 of 146 km) of the available stream length in the watershed. Unless otherwise noted, stream segments of unknown water quality were not included in our analyses.

Water sampling was not conducted during stormflow events even though water quality in acid-impacted streams often is at its worst during high-flow events (Wigington 1996). Nevertheless, we avoided stormflows for three reasons. First, it is impossible to sample water chemistry simultaneously at a watershed scale, and simultaneous samples would be needed to quantify spatial variation in water quality during stormflow events. Second, recent studies in this watershed indicate that the period of baseflow conditions in early summer is an effective time to characterize the chemical condition of acid precipitation–impacted streams (Petty & Barker 2004). Third, Ca:H ratio during early summer baseflow conditions is a strong indicator of water quality across a range of flow conditions. If Ca:H ratio is low during baseflow conditions, then water quality is likely to be very poor during acidic episodes.

Finally, measures of basin area and Ca:H ratios were used to calculate expected spawning intensity and juvenile survivorship, respectively, for each stream segment. These values were then used along with measures of segment length to calculate a WPRA for each segment and summed across all segments to give a basinwide measure of WPRA. The WPRA can be viewed as a measure of the current juvenile Brook trout recruitment potential for the watershed. For comparison, we also calculated the ideal WPRA for the watershed by simply assigning a Ca:H ratio greater than 100 to each segment. This calculation provides a measure of the expected value of the watershed for Brook trout recruitment in the absence of acid sources.

Identifying Restoration Priorities

We calculated the intensity and extent of ecological loss associated with each stream segment in the watershed. Loss intensity was calculated as the percentage of difference between the current WPRA and the ideal WPRA:

$$\text{Loss Intensity} = [(\text{Ideal WPRA} - \text{Current WPRA})/\text{Ideal WPRA}] \times 100.$$

Loss extent was calculated as the absolute difference between the current and ideal WPRA:

$$\text{Loss Extent} = (\text{Ideal WPRA} - \text{Current WPRA})$$

High-priority restoration sites are those stream segments for which both the intensity and extent of ecological losses are high.

Costs and Benefits of Alternative Restoration Programs

We used the ecological index developed above to assess a series of alternative restoration programs and determine which program would maximize the extent of recovery in the watershed. To do this, we modeled segment-specific and basinwide changes in ecological condition expected to result from five alternative limestone mitigation programs (Table 1). These programs range from simple and cheap (e.g., Alternatives 1 and 2) to complex and increasingly more expensive (Alternatives 4 and 5). We selected these programs because they cover a full range of costs and expected ecological benefits. Throughout our analyses, Alternative 1, which represents the current management program, is used as the baseline for comparison.

We calculated the cost of each alternative by first calculating the initial capital costs needed to initiate the program. Costs associated with road construction and maintenance were estimated by personnel at the Monongahela National Forest in Elkins, West Virginia (T. Cain 2004, Monongahela National Forest, personal communication). Helicopter rental costs were estimated by personnel at the West Virginia Division of Natural Resources (S. Brown 2004, WV Division of Natural Resources, personal communication). We then used the methods of Clayton et al. (1998) to calculate the total cost of limestone needed to effectively treat acid load in targeted reaches. The annual limestone cost was then added to annual maintenance and equipment costs expected under each alternative. We then projected the total cost of each alternative annually over a period of 20 years. We did not incorporate cost inflation into our calculations because it should affect each alternative equally. We also did not depreciate the value of initial capital investments because annual maintenance costs (e.g., road maintenance) are included in our calculations.

Table 1. Description of alternative restoration programs considered for recovering juvenile Brook trout recruitment potential in the upper Shavers Fork watershed.

Alternative	*Description*
1	Current management, which includes limestone treatment at the lower reaches of First Fork, Lambert Run, Fish Hatchery Run, Black Run, Buck Run, and the main stem of Shavers Fork above Lambert Run and above Slide Run. Treatment targets recovery of the Shavers Fork main stem only and uses existing road crossings for stream access. WPRA gain from this alternative is minimal because treatment does not target small tributaries. The costs and benefits of Alternatives 2 and 5 are set relative to this alternative.
2	Existing rail access. Two commercial railroads operate within the watershed. One crosses the upstream limits of Oats Run, Second Fork, and an unnamed tributary of Shavers Fork. The other crosses a headwater tributary of Powerhouse Run. This alternative would use the crossings to apply limestone to priority reaches and would require no initial capital investment. This alternative affects 41 km and 25 stream segments.
3	Existing rail + abandoned road upgrade. An extensive abandoned road network exists in the watershed as a result of past logging and mineral extraction. Fifty-nine access points that will require minimal road construction and upgrading have been identified as potential limestone treatment sites. Only roads that provide access to high-priority watersheds have been targeted. This alternative will require an initial capital investment for road improvements followed by annual maintenance costs. This alternative affects 82 km and 62 stream segments.
4	Existing rail + abandoned roads + new road construction. This alternative would add newly constructed roads to high-priority stream reaches that currently have no road access. Initial capital costs for new road construction are high. This alternative affects 98 km and 79 stream segments.
5	Helicopter access. This is a high-cost, high-benefit management alternative that would use helicopters to target high-priority but isolated headwater tributaries in the watershed. This alternative would have no initial capital investment because road construction and upgrades are unnecessary. However, it has a high annual operation cost. This alternative affects 109 km and 84 stream segments in the watershed.

We used ArcGIS to simulate changes in water quality expected to result from each of the alternative restoration scenarios. We assumed that effective limestone treatment would increase Ca:H ratios in downstream reaches to 100 or greater, which is an assumption strongly supported by previous research (Clayton et al. 1998). Based on these improvements, we then recalculated WPRA for each stream segment in the watershed and used new and old values to calculate the total WPRA gain under a given restoration alternative. Figure 2 illustrates WPRA maps generated for Alternatives 1, 2, and 5. Ecological gains and costs for each alternative were set relative to the costs and benefits of Alternative 1.

Results

Current Watershed Conditions

Flow-accumulation modeling identified 145 stream segments draining watersheds of at least 0.25 km^2 in size. Of the available stream segments, most (>80%) drain watersheds smaller than 2 km^2 and therefore may provide ideal habitats for Brook trout spawning (Fig. 3a). However, nearly 40% of all streams in the watershed are too acidic for juvenile survivorship (i.e., Ca:H ratio < 6) (Fig. 3b). Consequently, the current availability of potential areas for juvenile recruitment in the upper Shavers Fork watershed is significantly lower than the idealized condition of the watershed (Figs. 3c & 3d). Currently, the average relative WPRA for stream segments in the watershed is 0.18, whereas ideally we projected an average relative WPRA of 0.59. At the watershed scale, we calculated a current WPRA for the entire basin as 16.5 km, whereas we projected a basinwide idealized WPRA of 74.4 km. Consequently, 58 km of WPRA or 78% of the idealized recruitment capacity has potentially been lost from the watershed.

Restoration Priorities

Examining WPRA losses at the stream segment scale allowed us to identify critical restoration priorities in the watershed (Fig. 4; Table 2). Figure 4 is an *x–y* scatter of the relationship between proportional WPRA loss (i.e., loss intensity) in a given stream segment and the absolute WPRA loss in kilometers (i.e., loss extent). Stream reaches in the upper right-hand corner of this plot have experienced intensive and extensive loss of recruitment potential and, therefore, represent restoration priorities. Of all the stream reaches that have experienced functional loss, the eight reaches listed in Table 2 account for 9.8 km or 17% of the total WPRA lost in the watershed. The reaches themselves represent only 5.5% of the entire watershed.

Cost and Benefits of Restoration Alternatives

Expected costs associated with the five proposed restoration alternatives vary widely (Table 3). Alternatives 1 and 2 represent extremely inexpensive restoration options. Alternative 1 costs are limited to the cost of limestone delivery to stream dump sites ($25 per ton of limestone). Alternative 2 incurs the cost of leasing a rail car in addition to limestone costs, but this cost is very low on an

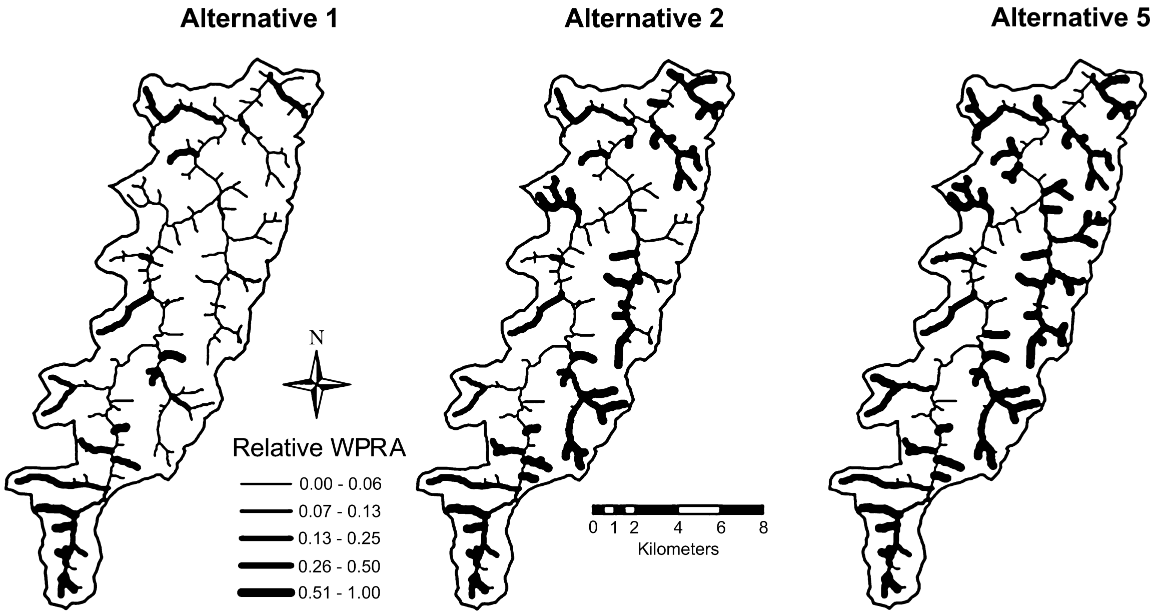

Figure 2. Maps of the upper Shavers Fork watershed, illustrating the current WPRA landscape (Alternative 1) and the WPRA landscape expected under Alternatives 2 and 5. The darkest lines represent stream reaches with the greatest potential for Brook trout reproductive success. Maps such as these were used to calculate WPRA gains resulting from five alternative restoration scenarios.

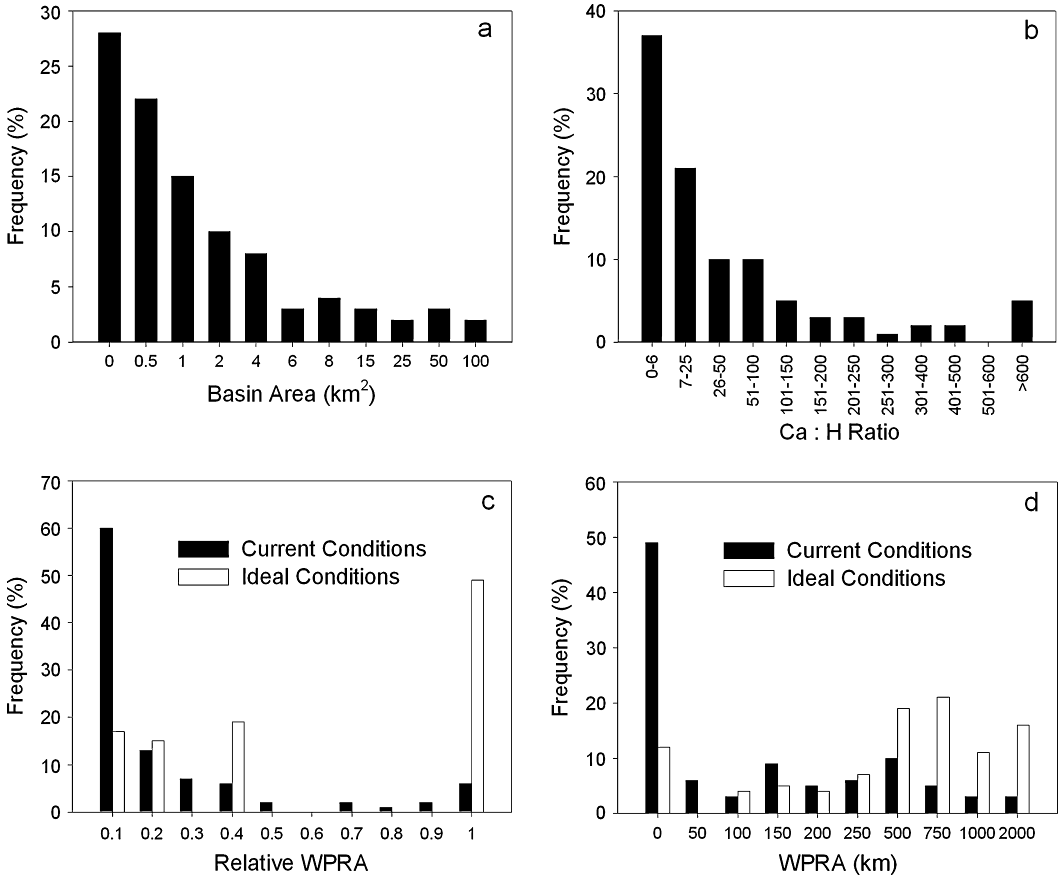

Figure 3. Frequency distributions of stream segments based on basin area (a) and Ca:H ratios (b) Frequency distributions of stream segments with various measures of relative (c) and absolute (d) WPRA are also presented. Distributions for the current watershed condition are presented along with the estimated distribution under ideal water quality conditions.

annual basis (not more than $1,000/year). Consequently, Alternatives 1 and 2 incur almost negligible costs on a per year basis and when accumulated over a period of 20 years (Fig. 5a; Table 3). Road reconstruction, construction, and maintenance represent substantial costs for Alternatives 3 and 4, especially in the first year when capital improvements are needed (Table 3). The Monongahela National Forest estimates the cost of new road construction and abandoned road reconstruction as $74,580/km and $37,290/km, respectively. Consequently, after a period of 20 years the accumulated costs exceed $1 million for Alternative 3 and nearly $3 million for Alternative 4 (Fig. 5a). Finally, using helicopters to access remote headwater streams (Alternative 5) has a significant annual cost associated with leasing aircraft operation time ($1,000/hour for 80 hours/year; Table 3). However, Alternative 5 does not incur an initial capital cost, and consequently the accumulated cost is less than that for Alternative 3 for 15 years and Alternative 4 for the entire 20-year period (Fig. 5a).

Alternative 1 produced the lowest ecological benefit to the watershed. Only 0.8 km (1.2% of the total loss) of WPRA is recovered each year by Alternative 1 (Table 3). Treating at three locations where the existing railroad grade crosses acidic headwater tributaries (Alternative 2) resulted in a modest ecological benefit to the watershed (Table 3). Our model projects that 5.3 km (9.1% of total loss) of WPRA will be restored each year through implementation of Alternative 2, which is a significant improvement over Alternative 1 especially when considered over a 20-year period (Fig. 5b). Given that the implementation cost of Alternative 2 is so low, the cost-to-benefit ratio of Alternative 2 relative to Alternative 1 is substantially lower than 1:1. In fact, we calculated a cost-to-benefit ratio of 0.19 for Alternative 2, which indicates that it is a much more effective restoration approach (Table 3; Fig. 5c). Alternatives 3 and 4, which require either road improvements or new road construction to targeted streams, are expected to produce dramatic improvements to WPRA in the watershed (Fig. 5b). Our model projects that Alternative 3 will produce almost 25 km (43% of total loss) of WPRA and Alternative 4 will produce 33.2 km (57% of total loss) of WPRA each year (Table 3). However, because the initial costs of these alternatives are so high, the cost-to-benefit ratios for Alternatives 3 and 4 are three and seven times higher, respectively, than that for Alternative 1 (Table 3; Fig. 5c). Over time the discrepancy between these alternatives is reduced, because the annual

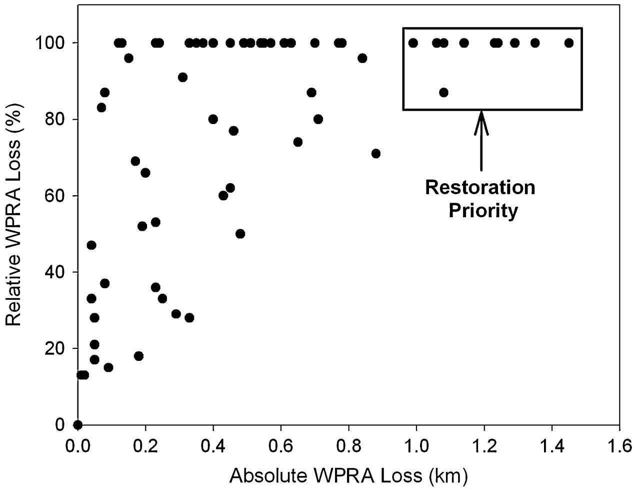

Figure 4. Relationship between relative WPRA loss (i.e., loss intensity) in specific stream segments and the absolute WPRA loss (i.e., loss extent) in those segments. Stream segments in the upper right-hand corner of the graph are restoration priorities because they have suffered intensive and extensive loss of juvenile recruitment potential.

costs of Alternatives 3 and 4 are much lower after the first year (Table 3; Fig. 5c). Finally, use of a helicopter to reach targeted headwater reaches is expected to produce the greatest benefit to the watershed: 38.3 km (66% of total loss) of WPRA each year (Table 3; Fig. 5b). The extensive ecological benefit associated with this approach offsets the relatively high annual costs and produces a cost-to-benefit ratio of 0.25 (Table 3; Fig. 5c).

Discussion

Brook trout populations in the upper Shavers Fork watershed are currently limited by reproductive success, and juvenile recruitment in this watershed is strongly affected by water quality and stream size (Clayton et al. 1998; Lamothe 2002; Petty et al. 2005). We have determined that nearly 80% of the weighted usable recruitment habitat that was historically available to Brook trout in the upper Shavers Fork has been lost as a result of acid precipitation. Clearly, Brook trout populations in this watershed will never be fully recovered unless we implement restoration programs that target recovery in headwater streams, where most Brook trout spawning occurs.

Table 2. Highest priority stream segments for restoration based on estimates of relative and absolute WPRA losses.

Stream Segment	*Absolute WPRA Loss (km)*	*Relative WPRA Loss (%)*
Upper First Fork	1.45	100
Upper Blister Run	1.35	100
Upper Second Fork	1.29	100
Upper Odey Run of Second Fork	1.24	100
Unnamed tributary of First Fork	1.23	100
Unnamed tributary (1) of Shavers Fork	1.14	100
Right Fork of Rocky Run	1.08	87
Unnamed tributary (2) of Shavers Fork	1.06	100

Streams listed represent the largest contributors to ecological loss in the upper Shavers Fork watershed.

Currently, limestone treatment programs in West Virginia are focused on the recovery of larger water bodies that may be important recreational fisheries for stocked trout (Zurbuch 1984; Clayton & Menendez 1996). This is economically justified, because stocking programs are expensive, and many recreational fishermen in this region place a high value on catching large fish in large streams and rivers. Nevertheless, treatment of large basin area water bodies does not address the loss of important aquatic habitats in upstream reaches. In the case of Brook trout populations, these are critical areas for the recovery and maintenance of productive, wild fisheries (Petty et al. 2005). We believe that treating the smallest streams possible will dramatically improve the recovery rate of Brook trout populations in this region. In addition, treatment in upstream reaches will necessarily produce benefits in the larger water bodies downstream.

The approach that we followed in this study allowed us to quantify a functional measure of benefit from various restoration approaches. In this case, we chose juvenile Brook trout recruitment potential as the functional measure. This measure was chosen because Brook trout are such an important native aquatic resource in central Appalachian watersheds. In addition, Brook trout populations in this system are recruitment limited, and the effects of acid precipitation on Brook trout reproduction are well understood. Nevertheless, it is important to realize that our choice of Brook trout recruitment as a functional measure necessarily places a much higher value on small streams than large streams in the watershed. For example, if we had selected Brook trout foraging habitat instead, larger streams would have received more attention, because they tend to provide more profitable foraging habitats than small streams (Bopp 2002). Consequently, the identification of "optimal" restoration strategies is strongly influenced by the ecological measures chosen to quantify functional benefit.

Our approach also allowed us to quantify ecological losses and restoration benefits at the scale of the whole watershed. Current efforts to quantify the benefits of proposed management actions tend to focus at the stream reach or segment scale. However, there is mounting evidence that the watershed is the appropriate scale of management (Fausch et al. 2002). Consequently, watershed scale analytical tools, such as the one we present here, are needed.

Combining measures of restoration costs and benefits provides a way to objectively assess alternative restoration approaches and guide watershed restoration decisions,

Table 3. Summary of the expected WPRA gains, dollar costs, and relative cost-to-benefit ratios for each of five restoration alternatives in the upper Shavers Fork watershed.

Restoration Alternative	*Initial Cost ($)*	*Annual Cost ($)*	*WPRA Gain (km/yr)*	*Relative Ecological Benefit*	*Cost:Benefit (Year 1)*	*Cost:Benefit (Year 10)*	*Cost:Benefit (Year 20)*
1	0	6,875	0.8	low	1:1	1:1	1:1
2	0	8,500	5.3	moderate	1:5	1:5	1:5
3	563,079	47.098	24.7	high	3:1	1:2	1:3
4	1,927,893	64,756	33.2	high	7:1	4:5	3:5
5	0	83,750	38.3	high	1:4	1:4	1:4

Annual costs are a combination of road maintenance, equipment use (i.e., helicopter in Alternative 5), and limestone treatment costs. Benefit is in units of WPRA gain and not dollars. Cost-to-benefit ratios are standardized to the relative cost and benefit associated with restoration alternative 1 (i.e., current management action). Lower ratios are better.

even when ecological benefits are not converted to dollars. For example, our model indicates that current actions (Alternative 1) are suboptimal with regard to recovering Brook trout spawning habitat in the upper Shavers Fork.

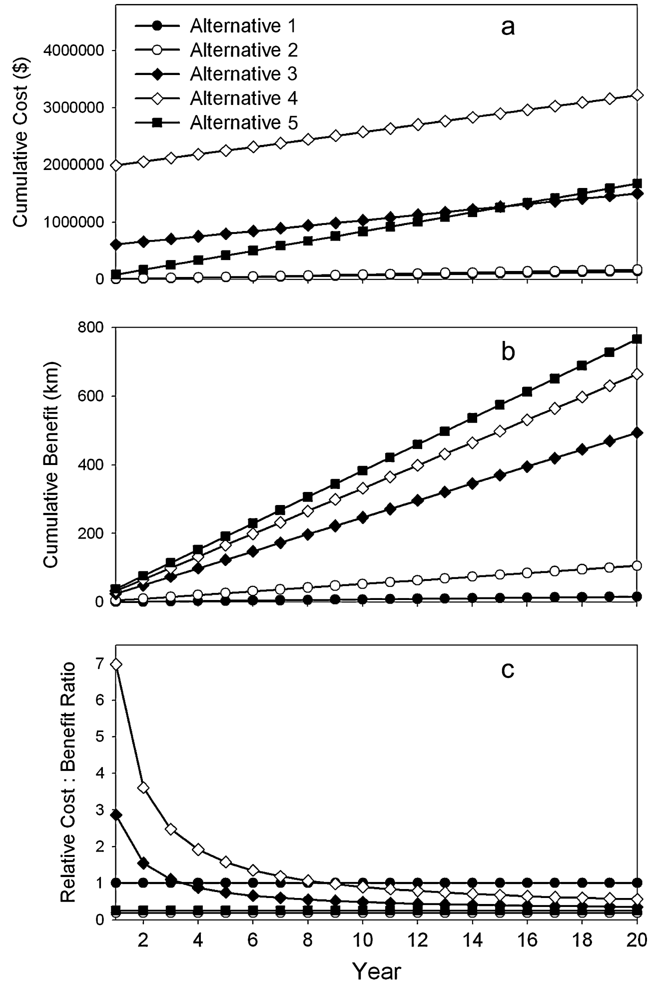

Figure 5. Expected dollar costs (a) and benefits as WPRA gains (b) accumulated over 20 years for each of five alternative management scenarios. Also presented are changes in the relative dollar cost-to-benefit ratio (c) over a 20-year period for each alternative.

Limestone treatment occurs too far down in the watershed to provide meaningful benefit to reproduction. Our model also indicates that road development in the watershed is a suboptimal approach. Despite producing significant improvements to recruitment potential, Alternatives 3 and 4 do not produce enough benefit to justify the extremely high capital and annual costs to implement. In addition, there may be significant social and ecological costs associated with road building (e.g., increased sedimentation, noise, tree removal, increased motorized access) that make Alternatives 3 and 4 even less desirable. In contrast, our model indicates that use of the existing rail access (Alternative 2) or use of helicopters to access headwater streams (Alternative 5) are viable alternatives, but for different reasons. Alternative 2 is an inexpensive way to produce moderate ecological improvements in the watershed. Alternative 5, on the other hand, is an expensive approach that is expected to produce exceptional benefits to Brook trout recruitment potential.

Unfortunately, our approach cannot easily distinguish between Alternatives 2 and 5. In this case, it may be informative to monetize the ecological benefits of restoration. However, current procedures to quantify the economic benefit of fishery recovery are based on the amount of expenditures directly related to fishing per mile of stream. Applying this approach to Alternatives 2 and 5, however, would not help, because economic benefits are directly proportional to the length of stream recovered. Consequently, the relative costs and benefits of each alternative would not change. In order to identify differences between Alternatives 2 and 5, procedures that quantify nonlinear relationships between economic benefit and stream length recovered would be needed. For example, significant economic benefits may not be realized in the absence of broadscale restoration efforts, and such a relationship would place a higher priority on Alternative 5. In contrast, economic benefits from restoration may diminish as more and more streams are restored, which would place a higher priority on Alternative 2.

In the absence of such a procedure, we propose the following restoration program for the upper Shavers Fork watershed. First, Alternative 2 should be immediately implemented in the watershed. This approach has essentially no additional cost and should produce a significant benefit to the watershed. Dosing rates can be set such that both local improvements to Brook trout spawning are made and the viability of stocked fisheries downstream is maintained. At the same time a comprehensive monitoring program should be initiated to obtain a complete picture of the condition landscape and to quantify the ecological benefits of Alternative 2 implementation. Over a period of several years, it may be determined that Brook trout populations have recovered to the extent that additional restoration actions are unnecessary. Alternatively, monitoring may discover that significant recovery is possible only through full implementation of Alternative 5. In that case, obtaining sufficient funding to implement Alternative 5 would become an important priority.

Future Application

The approach that we have followed in this study demonstrates that it is possible to (1) quantify the degree of ecological loss from acid precipitation at a watershed scale; (2) quantify the amount of ecological habitat that may be recovered through alternative restoration programs; and (3) incorporate restoration costs so that optimal restoration approaches can be identified. We believe that a similar approach can be used to identify restoration priorities and optimal restoration programs in acid-impacted watersheds throughout the Appalachian region. However, in order to apply this approach more broadly, the following steps are needed. First, ecological end points for restoration must be identified. Here, we chose Brook trout recruitment. Future applications may target fish species richness or an invertebrate community index. Second, the key physicochemical factors limiting the ecological end points must be known. Only then is it possible to design and assess the efficacy of alternative restoration programs. In our current application, we incorporated known relationships among juvenile recruitment and basin area and water chemistry to develop measures of WPRA for the Shavers Fork watershed. However, ecological conditions in other watersheds may be limited by multiple factors, including sedimentation, temperature, and flow regime. Finally, costs associated with specific restoration alternatives may be watershed specific, especially if limiting factors vary among watersheds. Calculating remediation-specific costs may be necessary to apply our approach regionally.

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LITERATURE CITED

Baker, J. P., J. Van Sickle, G. J. Gagen, D. R. Dewalle, W. E. Sharpe, R. F. Carline, et al. 1996. Episodic acidification of small streams in the northeastern United States: effects on fish populations. Ecological Applications **6:**422–437.

Bopp, J. 2002. The combined effects of water chemistry, canopy cover, and basin area on benthic macroinvertebrates along a central Appalachian stream continuum. Master's thesis. West Virginia University, Morgantown.

Clayton, J. L., E. S. Dannaway, R. Menendez, H. W. Rauch, J. J. Renton, S. M. Sherlock, and P. E. Zurbuch. 1998. Application of limestone to restore fish communities in acidified streams. North American Journal of Fisheries Management **18:**347–360.

Clayton, J. L., and R. Menendez. 1996. Macroinvertebrate responses to mitigative liming of Dogway Fork, West Virginia. Restoration Ecology **4:**234–246.

Downey, D. M., C. R. French, and M. Odom. 1994. Low cost limestone treatment of acid sensitive trout streams in the Appalachian Mountains of Virginia. Water, Air, and Soil Pollution **77:**1–29.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience **52:**483–498.

Fiss, F. C., and R. F. Carline. 1993. Survival of brook trout embryos in three episodically acidified streams. Transactions of the American Fisheries Society **122:**268–278.

Fitzhugh, R. D., T. Furman, J. R. Webb, B. J. Cosby, and C. T. Driscoll. 1999. Longitudinal and seasonal patterns of stream acidity in a headwater catchment on the Appalachian Plateau, West Virginia, USA. Biogeochemistry **47:**39–62.

Heard, R. M., W. E. Sharpe, R. F. Carline, and W. G. Kimmel. 1997. Episodic acidification and changes in fish diversity in Pennsylvania headwater streams. Transactions of the American Fisheries Society **126:**977–984.

Hudy, M., D. M. Downey, and D. W. Bowman. 2000. Successful restoration of an acidified stream through mitigation with limestone sand. North American Journal of Fisheries Management **20:**453–466.

Ivahnenko, T. I., J. J. Renton, and H. W. Rauch. 1988. Effects of liming on water quality of two streams in West Virginia. Water, Air, and Soil Pollution **41:**331–357.

Kobuszewski, D. M., and S. A. Perry. 1993. Aquatic insect community structure in an acidic and a circumneutral stream in the Appalachian Mountains of West Virginia. Journal of Freshwater Ecology **8:**37–45.

Lajewski, C. K., H. T. Mullins, W. P. Patterson, and C. W. Callinan. 2003. Historic calcite record from the Finger Lakes, New York: impact of acid rain on a buffered terrain. Geological Society of America Bulletin **115:**373–384.

Lamothe, P. J. 2002. Spatial population dynamics of brook trout (*Salvelinus fontinalis*) in a central Appalachian watershed. Master's thesis. West Virginia University, Morgantown.

Menendez, R. 1976. Chronic effects of reduced pH on brook trout (*Salvelinus fontinalis*). Journal of the Fisheries Research Board of Canada **33:**118–123.

Menendez, R., J. L. Clayton, and P. E. Zurbuch. 1996. Chemical and fishery response to mitigative liming of an acidic stream, Dogway Fork, West Virginia. Restoration Ecology **4:**200–233.

NRC (National Research Council). 1992. Restoration of aquatic ecosystems. National Academy Press, Washington, D.C.

Petty, J. T., and J. Barker. 2004. Water quality variability in tributaries of the Cheat River, a mined Appalachian watershed. Proceedings of the American Society of Mining and Reclamation **15:**1–21.

Petty, J. T., J. Freund, P. J. Lamothe, and P. M. Mazik. 2001. Quantifying the microhabitat characteristics of hydraulic channel units in the upper Shavers Fork basin. Proceedings of the Southeastern Association of Fish and Wildlife Agencies **55:**81–94.

Petty, J. T., P. J. Lamothe, and P. M. Mazik. 2005. Spatial and seasonal dynamics of brook trout populations in a central Appalachian watershed. Transactions of the American Fisheries Society (in press).

Rosemond, A. D., S. R. Reice, J. W. Elwood, and P. J. Mulholland. 1993. The effects of stream acidity on benthic invertebrate communities in southeastern United States. Freshwater Biology **27:**193–209.

Sharpe, W. E., V. G. Leibried, W. G. Kimmel, and D. R. Dewalle. 1987. The relationship of water quality and fish occurrence to soils and geology in an area of high hydrogen and sulfate ion deposition. Water Resources Bulletin **23:**37–46.

Van Sickle, J., J. P. Baker, H. A. Simonin, B. P. Baldigo, W. A. Kretser, and W. E. Sharpe. 1996. Episodic acidification of small streams in the northern United States: fish mortality in field bioassays. Ecological Applications **6:**408–421.

Wigington, P. J. Jr, J. P. Baker, D. R. Dewalle, W. A. Kretser, P. S. Murdoch, H. A. Simonin, J. Van Sickle, M. K. McDowell, D. V. Peck, and W. R. Barchet. 1996. Episodic acidification of small streams in the northeastern United States: episodic response project. Ecological Applications **6:**374–388.

Wigington, P. J. Jr, and D. R. DeWalle. 1996. Episodic acidification of small streams in the northeastern United States: ionic controls of episodes. Ecological Applications **6:**389–407.

Zurbuch, P. E. 1984. Neutralization of acidified streams in West Virginia. Fisheries **9:**42–47.