Impact Targets versus Discharge Standards in Agricultural Pollution Management

John B. Braden, Robert S. Larson, and Edwin E. Herricks

When attempting to protect fish in streams, sediment or erosion targets are inefficient. Use of a habitat suitability target reveals lower cost abatement measures because it accounts for pesticides as well as soil particles. In Lake Michigan case studies, the lower cost measures involve more crop diversity, less use of no-till, and changes on more acres than the solutions based on sediment discharges or erosion rates.

Key words: environmental policy, fish, nonpoint pollution, optimization, targets.

Protecting water quality has been avowed as a major objective of soil conservation programs (U.S. Department of Agriculture). Yet, controlling soil movement continues to be stressed in practice; an example is the Conservation Reserve Program's emphasis on highly erodible lands. The effectiveness of protecting water quality by stabilizing soil is an open question.

This paper quantifies the economic losses from the use of soil movement rather than water quality criteria for the attainment of an important water quality goal—protection of habitat for high-valued fish species. The estimates are based on a case study of Lake Michigan tributaries. The case study also indicates the differences in farming practices when habitat is protected by controlling soil movement alone versus managing both soil and pesticide pollution.

The analysis extends the methods used previously by Braden et al., Crowder and Young, Heimlich and Ogg, Milon, Park and Sawyer, and Park and Shabman. The common theme of those studies is the linking of land management economics to off-site consequences. The usual aim has been to compare various policies for meeting specified levels of pollutant loads.

The present study goes beyond previous work by considering predicted impacts on fish habitat. The costs and management implications of actual environmental damages, as well as of emissions and pollutant loads, then can be assessed. These three performance measures conform to the policy targets defined by Nichols—emissions, exposure, and damages; however, his "damage" category implies economic evaluation of the impacts, while no such evaluation is attempted here. Insight into the inefficiencies introduced by inexact targets is important in evaluating whether to incur the additional costs of measuring and monitoring actual damages.

Economic Model

The economic model portrays a fully informed watershed planner. The planner's objective is to achieve environmental goals at least cost. Difficulties of attaching values to environmental impacts frequently lead to the use of such second-best cost-effectiveness criteria (Baumol and Oates).

The decision context involves stochastic risks of environmental impacts. The environmental consequences of interest depend in part on the severity and timing of weather events in relation to crop cover and chemical use. All of these factors can vary over a planning horizon. Under

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such circumstances, the planner's decision framework follows in spirit the models of Beavis and Walker and Lichtenberg and Zilberman. Let $C(x)$ be a primal cost function defined over choice variables in the vector x, $q(x, \varepsilon)$ be an environmental quality production function, ε be a stochastic disturbance term, Q be a target level of minimum environmental quality, and A be a measure of reliability (the probability of achieving Q). The cost-effectiveness decision is

$$(1) \quad J = \text{Min } C(x), \text{ s.t. } \Pr[q(x, \varepsilon) \leq Q] \geq A.$$

This framework anticipates that higher quality can be achieved only by sacrificing cost or reliability or both. Greater reliability presents similar tradeoffs.

The environmental quality and reliability targets in (1) may be difficult to measure and monitor. Contributing factors, such as emissions or pollutant loads reaching the stream, may provide alternative policy targets. Suppose that the function $q(\bullet)$ can be rewritten as

$$(2) \qquad q = \hat{q}(x, h(\hat{x}), \varepsilon), \hat{x} \subset x, x \not\subset \hat{x},$$

where $h(\bullet)$ is an intermediate environmental quality indicator, such as emissions or pollutant loads. The planner then may consider the alternative policy:

$$(3) \quad J = \min C(x), \text{ s.t. } \Pr[h(\hat{x}) \leq H] \leq B,$$

where the intermediate objectives H and B are based on knowledge about the stochastic relationship between $h(\bullet)$ and final objectives Q and A.

For achieving Q and A, the management choices based on (3) will never be less costly than selections based on (1). Fewer choice variables (instruments) are relevant to the performance measures, and those measures are inexact proxies for the final objectives. The extent of the inefficiency and the nature of the management miscalculations are empirical questions.

Model Implementation

The empirical model has been described in detail by Braden, Herricks, and Larson; and Larson, Herricks, and Braden. It consists of a version of the Sediment Economics (SEDEC) model (Braden et al.; Bouzaher, Braden, and Johnson; Johnson et al.) that is extended to include (*a*) seasonality of sediment loads; (*b*) pesticide losses, toxicity, and concentrations; and (*c*) effects of sediment and pesticides on the habitat requirements of selected fish species.

Briefly, pollutant transport submodels for sediment and pesticides relate farming practices to pollutant delivery to waterbodies. SEDEC places these relationships in a spatial optimization framework, permitting the planner to identify the optimal type and location of interventions to achieve particular goals.

The pollutant loads are translated into habitat quality and reliability through habitat suitability models (U.S. Fish and Wildlife Service). These models are calibrated for individual species, of which more than forty have been characterized. Habitat suitability indices (HSI) are unitless numbers ranging from zero (poor) to one (excellent). They capture the combined effects of relevant habitat parameters, such as temperature, substrate conditions, and concentrations of contaminants.

Timing is extremely important in determining the effects on fish of soil and farm chemicals washed into streams by storm events. Monte Carlo simulations based on historical weather records, planting dates, and chemical application practices are used to capture these stochastic factors. The simulation outputs are probability distributions of pollutant discharges and habitat impacts. The probability distributions identify the likelihood (reliability) of achieving any specific suitability index level with a particular watershed management scenario.

The mathematical expression for the implemented model is a modified and elaborated version of problem (1) above. In addition to the earlier notation, let counting index j, $j = 1, \ldots, J$, refer to subwatersheds and index i, $i = 1, \ldots, I^j$, denote all possible combinations of management practices on the land units within a particular subwatershed. Each i will be called a management path. Variable $x_{ij} \in [0, 1]$ is binary and represents a management path in subwatershed j. Because only one such path can be chosen in each subwatershed, $\Sigma_i x_{ij} = 1$ for all j. PC_{ij} is the probability of pesticide concentrations exceeding a particular suitability level Q^*; PS_{ijg} is the probability of sediment suitability exceeding Q^* in season g; and A is the target level of reliability. Variable a_j is area of subwatershed j and f_{ij} is the predicted median runoff from management path i of subwatershed j. The decision problem is:

$$(4a) \qquad \text{Min } C(x) = \sum_{j=1}^{J} \sum_{i=1}^{I^j} c_{ij} x_{ij}$$

s.t.

$$\text{(4b)} \qquad \frac{\sum_{j=1}^{J}\sum_{i=1}^{I^j} PC_{ij} f_{ij} x_{ij}}{\sum_{j=1}^{J}\sum_{i=1}^{I^j} f_{ij} x_{ij}} \geq A$$

$$\text{(4c)} \qquad \frac{\sum_{j=1}^{J}\sum_{i=1}^{I^j} \mathrm{PS}_{ijg} a_{ij} x_{ij}}{\sum_{j=1}^{J}\sum_{i=1}^{I^j} a_{ij} x_{ij}} \geq A \quad g = 1, \ldots, G$$

$$\text{(4d)} \qquad \sum_{i=1}^{I^j} x_{ij} = 1 \quad j = 1, \ldots J$$

$$\text{(4e)} \qquad x_{ij} = [0, 1].$$

Constraints (4b) and (4c) are weighted-average probabilities of exceeding the target suitability level for pesticides and sediment, respectively. Variables a_j and f_{ij} are weighting terms used to reflect the relative contribution of each subwatershed.

A solution to this problem reveals the management choices that will achieve specified habitat quality and reliability levels at least cost. Varying the constraints will show the trade-offs between cost, quality, and reliability. More important, the model can be modified to constrain emissions or pollutant loads. The resulting solutions can be run through the habitat simulations to reveal how close they come to protecting quality and reliability. Doing so reveals the efficiency losses due to the use of intermediate targets.

Different targets should be good substitutes for policy purposes if they are closely correlated (Nichols). In that case, management prescriptions optimal for one indicator should be nearly optimal (although possibly second-best) for the other indicator.

In the case of agricultural pollution and fish habitat, timing can cause critical differences between emissions, releases, and habitat suitability. The timing effects come through decay in pesticide toxicity and the seasonal patterns of rainfall, erosivity, crop conditions, and fish spawning requirements.

Another source of divergence between targets is oversimplification. Environmental damages are frequently the outcome of complex processes involving many factors. Targets based on a subset of the processes may miss some important contributing factors. For example, erosion rates and sediment loads may not effectively represent the fates of soluble pesticides.

The size of the losses due to the use of proxy targets is an empirical matter. Insights are developed in a case study of sport fish protection in tributaries to Lake Michigan.

Case Study

Active sport fisheries have been successfully developed in Lake Michigan over the past two decades with substantial economic benefits for the near-shore area. Chinook, coho, steelhead, and other salmonids are the most prized varieties.

The salmonid populations have been sustained and enhanced through extensive stocking. Natural spawning has been limited in many tributaries by nonpoint pollution from farmland and by channelization that eliminates habitat while enhancing drainage. These factors not only compel continued stocking, they also reduce the range of seasonal salmon migrations. The migrations are highly valued by individuals and communities near the lake who seek to lengthen and enhance the fish runs.

The model was applied to two agricultural subwatersheds in Berrien County, Michigan, along Lake Michigan's southeastern shore. The Pipestone Creek site drains to the St. Joseph River and on to Lake Michigan. The states of Michigan and Indiana are working together to extend the salmon runs in the St. Joseph River system. The river and its tributaries have been abundantly stocked with juvenile sport fish in recent years. Portions are classified as trout streams. However, the segment of Pipestone Creek chosen for study has been channelized and the silty substrate is poor for spawning and fry development. The 93 hectare (ha) study site contains gently sloping farmland with silty and loamy soils.

The Galien River (east branch) site is part of a smaller river system that also is classified for trout. The habitat conditions are good for salmonids with a meandering channel, cobble and gravel substrate, and pools interspersed with riffle segments. The study site contains 139 hectares of gently sloping farmland with sandy and loamy soils.

Data

Catchments and transects were defined from U.S. Geological Survey topographic maps. Management units were identified from Soil Conservation Service (SCS) soil survey maps, plat maps, and Agricultural Stabilization and Conservation Service aerial photographs. Soils information, including productivity classifications, also came from soil surveys (U.S. Soil Conservation Service). Rainfall distributions were based on a fifty-seven-year record for nearby Eau Claire, Michigan. Basic stream data were compiled through fieldwork.

Coefficients for the Universal Soil Loss Equation (Wischmeier and Smith) and crop budgets, including pesticide application rates and assumptions about the timing of farming operations, were prepared by experts in the Michigan Cooperative Extensive Service and the SCS (J. Black, Dep. Agr. Econ., Michigan State University, personal communication 1988). Corn, grains, and soybeans are the most common farm crops in Berrien County, although orchards, vegetables, and vineyards also are present. The crop-cover (C) factors for the USLE were disaggregated for crop growth phases, and variability was introduced following Thomas, Snider, and Langdale. Twelve possible cropping systems were considered, consisting of combinations of two rotations—wheat-corn (3)-soybeans (WCCCS) and alfalfa (3)-corn (2) (AAACC), three tillage methods—moldboard plowing, till-planting, and no-till, and two mechanical practices—vertical plowing and contour plowing. These options are typical of the area, and the rotations make use of similar pesticides. Three pesticides were selected for study: Atrazine, Furadan, and Bladex. Atrazine and Bladex use does not vary with tillage practices, while Furadan is used in fewer years when tillage is reduced. Assumed crop prices were \$60 per ton for alfalfa hay, \$2.25 per bushel for corn, \$5.40 per bushel for soybeans, and \$2.30 per bushel for wheat.

Chemical toxicity data for salmonids were obtained from Mayer and Ellersieck and incorporated into habitat relationships using the techniques developed by Herricks and Braga. Physical suitability relationships were adapted from existing HSI models (e.g., Raleigh et al.).

Analysis

The SEDEC model was used to determine the economically optimal management practices for meeting sediment targets. The consequences for fish habitat suitability of the practices that optimally control sediment were determined using the extended model (without optimizing for suitability impacts). A similar approach was followed for erosion targets. The analysis also was performed in reverse—the optimal practices were determined with respect to suitability targets and the sedimentation and erosion consequences of those practices were traced. Finally, the subwatershed suitability target was applied to all individual catchments to assess the consequences of imposing uniformity throughout the stream reach.

While any suitability, sedimentation, or erosion levels could be selected for analysis, levels of 0.5, 0.7, and 0.9 were chosen here. These cover average to very good suitability conditions, on the assumption that poor conditions are not relevant environmental targets.

Results

The results are summarized as cost frontiers relating the minimum losses in farming profits associated with attaining particular environmental targets. The cost estimates do not reflect differences in farmer risks that may accompany different management systems; they assume that watershed management can be highly selective; and they assume all farmers would settle for the minimum compensation.

Figure 1 shows the cost curves for the two study sites assuming the extreme habitat suitability targets of 0.5 and 0.9 and allowing reliability to vary. The costs are per hectare for comparison, although the costs are borne unevenly across management units as a result of the optimization.

The curves are quite different for the two sites, and this is attributable to the different background conditions. The Galien site is already highly suitable and reliable for salmonids, while Pipestone is not. Thus, the costs are greater for attaining high reliability levels at Pipestone.

The curves for the 0.5 suitability level extend to higher levels of reliability than do the 0.9 curves. This suggests that the best practices for usual weather circumstances (that dominate the suitability determination) are not the same as the best practices for extreme conditions (that dominate reliability). Furthermore, conservative farming practices alone cannot achieve high levels of suitability with high reliability. The dual extremes would require either land use changes more substantial than those considered here or supplementary measures within the stream channels.

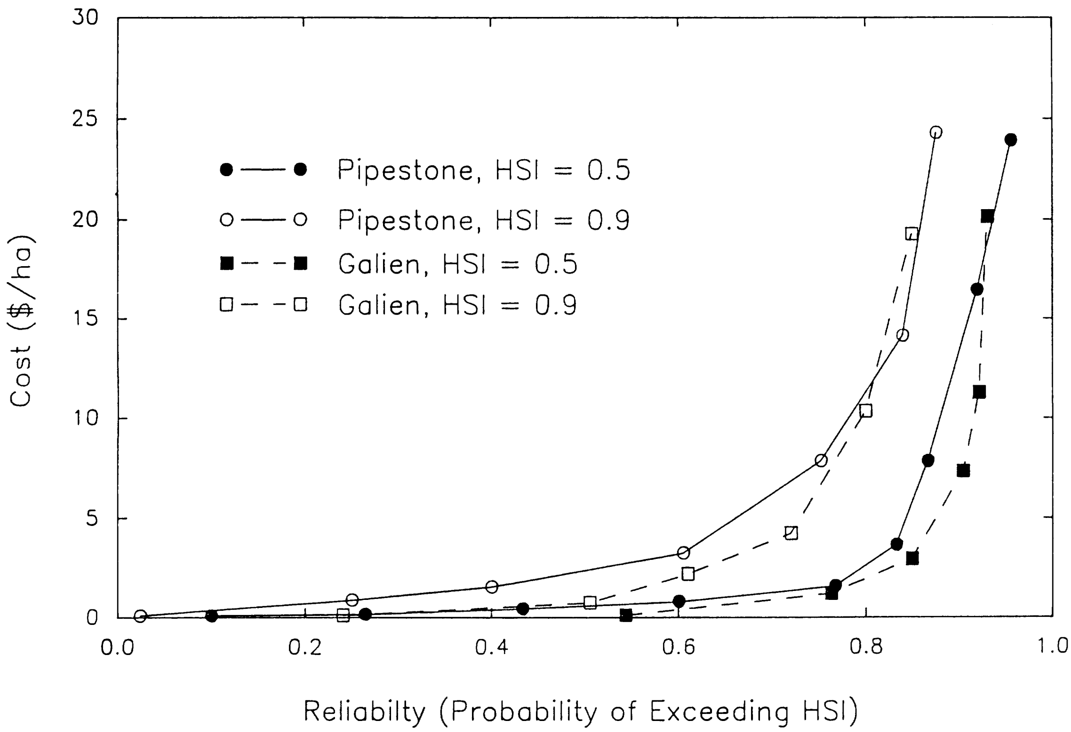

Figure 1. Minimum costs of achieving selected salmonid habitat suitabilities and reliabilities, Pipestone Creek and Galien River sites

The constraint on pesticide suitability is nonbinding at low levels of reliability. The pesticide constraint does not become binding until rather high probabilities of exceeding the target suitability levels are reached, at which point the risk of excessive sediment accumulation is relatively low. (The reliability level at which pesticides become important varies inversely with the suitability level). These findings are consistent with the consensus among fisheries biologists that deteriorated substrate conditions are most responsible for the general degradation of fish populations in midwestern streams (e.g., Smith).

For the comparison of targets, figures 2 through 5 display the cost-suitability frontiers for (*a*) targeting directly on suitability; (*b*) constraining the total sediment load in the watershed; (*c*) constraining the sediment load from each catchment; and (*d*) constraining the soil erosion on each LMU, and the frontier from targeting directly on suitability. The 0.5 and 0.9 levels of suitability illustrate extremes.

The figures show that a sediment target reasonably approximates a habitat suitability target only over a limited range. The approximation grows worse as pesticides play a greater role in suitability determination, i.e., at higher levels of reliability where the pesticide suitability constraint is controlling. Because the critical pesticides are in solution, and because sediment runoff is not necessarily correlated with runoff volume or concentration, "targeting" sediment is a poor way to deal with pesticide effects.

Comparisons of the figures suggests that the range of reasonable approximation shrinks as the suitability target is raised. This shrinkage occurs because the pesticide constraints bind at lower reliability levels when suitability targets are higher.

The sediment and erosion target curves in figures 2 through 5 are not smooth because some strategies (e.g., alfalfa rotations) used to control soil movement also lower pesticides while others (e.g., no-till) can increase pesticide concentrations in runoff. Erosion and sedimentation targets take no account of the pesticide consequences and result in higher costs and greater or lesser reliability depending on the nature of the sediment control regime.

Management Implications

Optimal management scenarios for the HSI target are summarized in table 1, and corresponding results for the alternative targets appear in

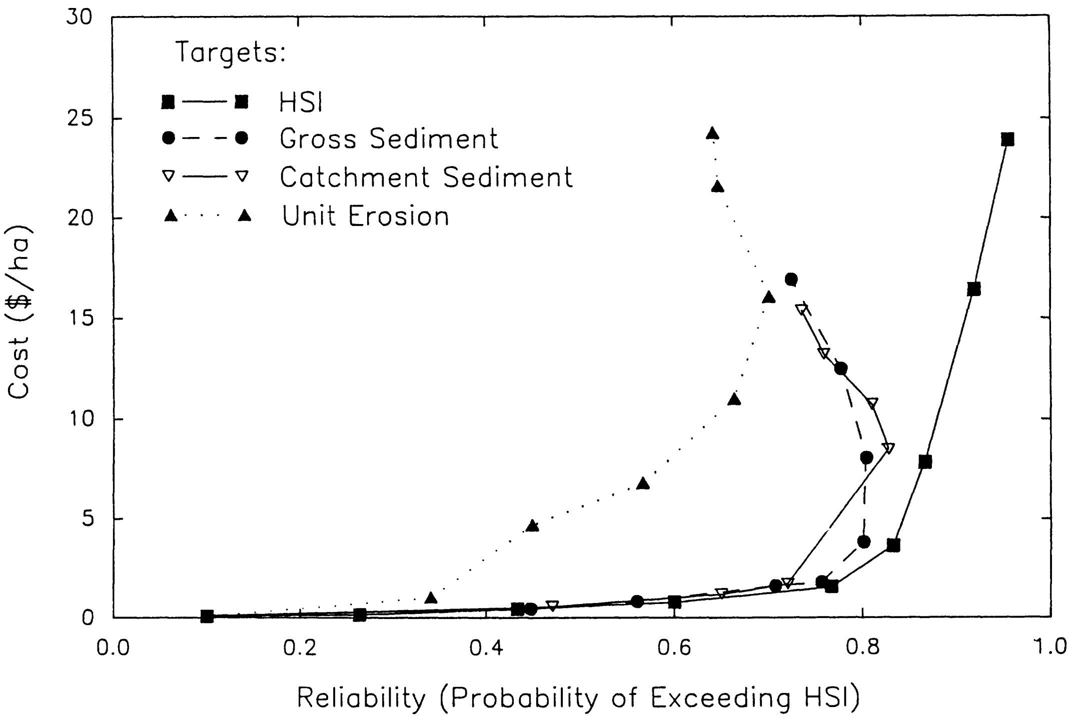

Figure 2. Cost of salmonid reliability with selected discharge targets and impacts, Pipestone Creek, HSI = 0.5

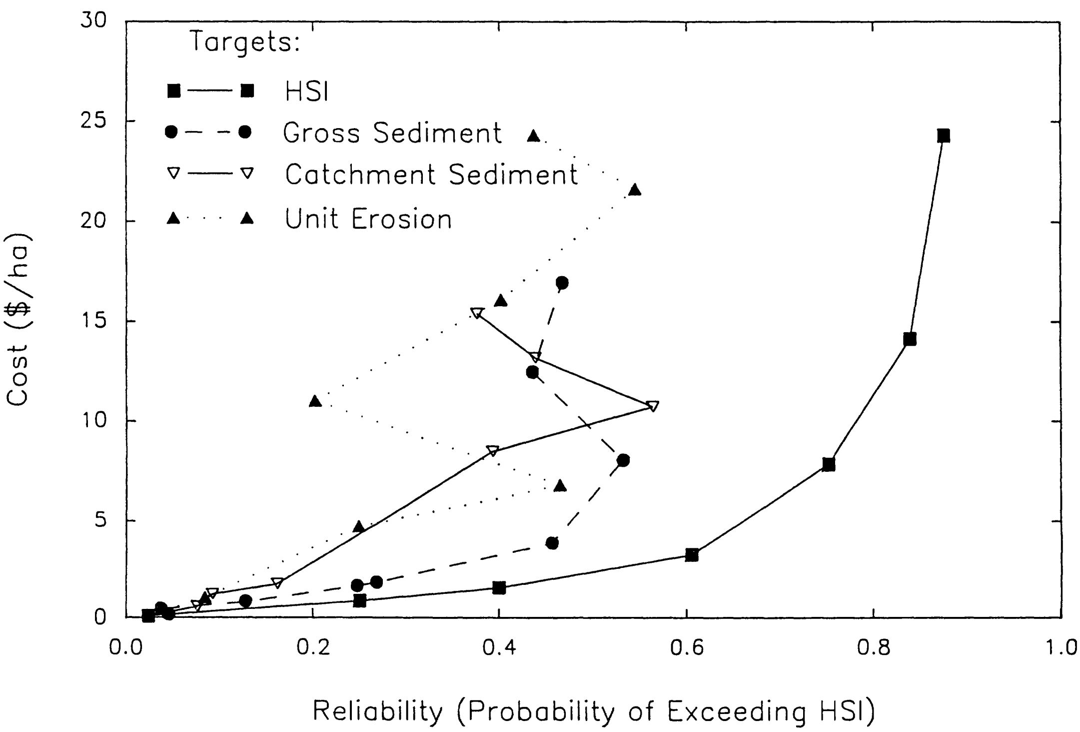

Figure 3. Costs of salmonid reliability with selected discharge targets and impacts, Pipestone Creek, HSI = 0.9.

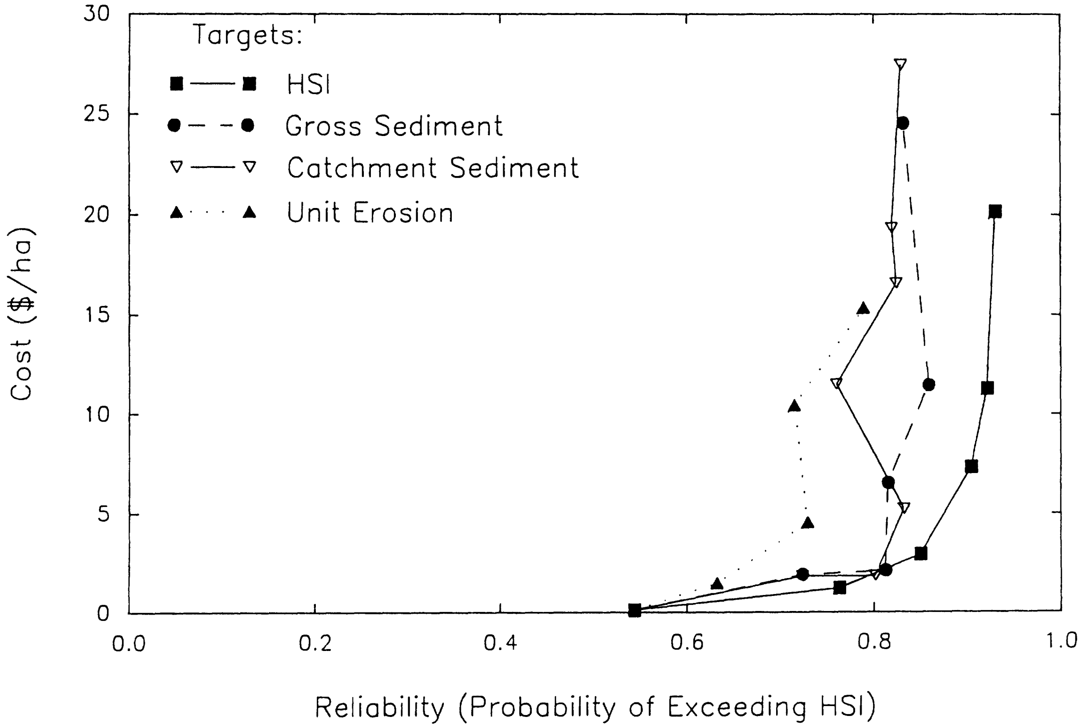

Figure 4. Costs of salmonid reliability with selected discharge targets and impacts, Galien River, HSI = 0.5

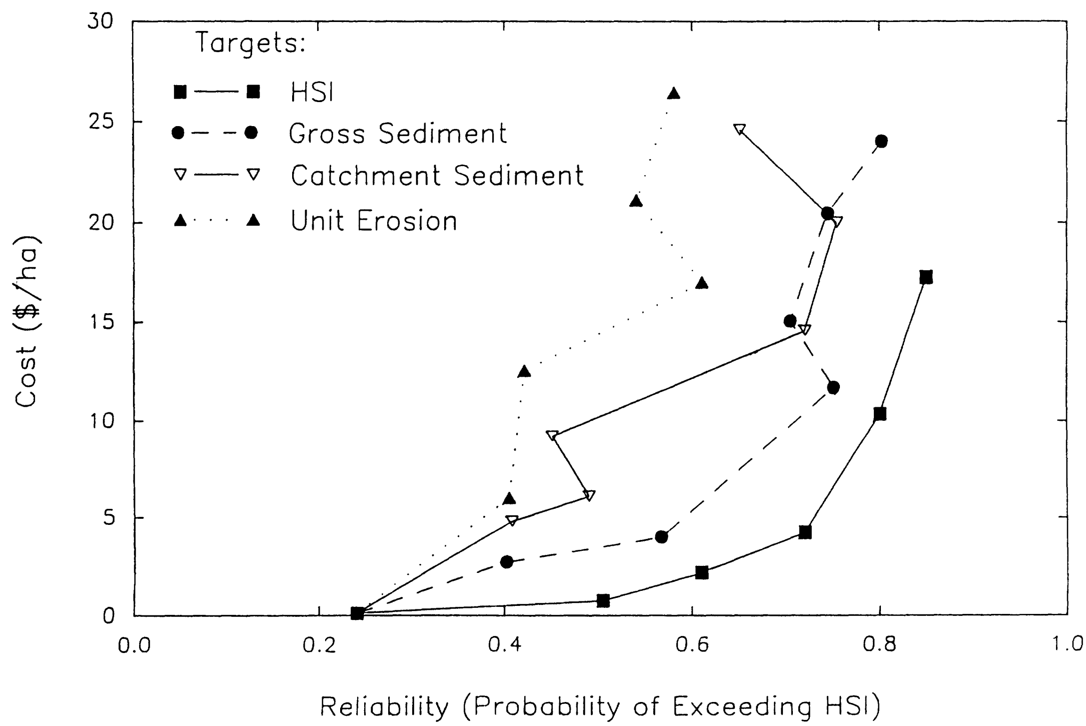

Figure 5. Cost of salmonid reliability with selected discharge targets and impacts, Galien River, HSI = 0.9

Table 1. Optimal Management Summaries for Selected Salmonid Suitability/Reliability Levels, Pipestone Creek and Galien River Sites

Salmonid HSI/Reliability	Management Practices: Rotation	Management Practices: Tillage	Management Practices: Mechanical	Extent of Management Changes		Cost
	(% ha WCCCS)	(% Mold-board)/ (% No-till)	(% Verticle)	(% Area)	(% units)	($/ha)
		Pipestone Creek				
Baseline	100	67/6	93			0.00
0.5/0.40	100	55/17	93	13	5	0.43
0.5/0.80	91	27/28	93	33	11	2.30
0.9/0.40	92	48/28	93	30	26	0.57
0.9/0.80	72	18/31	93	71	80	11.03
		Galien River				
Baseline	100	42/22	87			0.00
0.5/0.40	100	42/22	87	0	0	0.00
0.5/0.80	82	26/26	84	41	17	1.60
0.9/0.40	87	35/24	87	33	18	0.45
0.9/0.80	64	24/17	84	65	73	8.77

table 2. The selection of performance goals for table 2 was limited because some or all of the alternative targets could not achieve reliability of 0.8 at Pipestone with either the 0.5 or the 0.9 HSI, nor at Galien with 0.9 HSI.

In the baseline case, without habitat constraints, the WCCCS rotation and a combination of tillage practices are implemented at both sites. As indicated in table 1, tightening the habitat constraint initially (the 0.5/.40 case) prompts greater use of no-till WCCCS. Requiring reliability of .80 causes a shift away from no-till WCCCS and toward the AACCA rotation. The greater availability and concentration of pesti-

Table 2. Comparison of Watershed Management for Selected Alternative Pollution Abatement Targets and Impacts, Pipestone Creek and Galien River Sites

Impact HSI/Reliability	Target	Management Practices: Rotation	Management Practices: Tillage	Management Practices: Mechanical	Extent of Management Changes		Cost
		(% ha WCCCS)	(% Mold-board)/ (% No-till)	(% Verticle)	(% Area)	(% units)	($/ha)
			Pipestone Creek				
0.5/0.40	Gross Sed.	100	55/17	93	5	2	0.43
	Catch Sed.	100	53/19	93	7	3	0.50
	Unit Erosion	100	51/26	93	13	8	4.39
0.9/0.40	Gross Sed.	92	51/26	93	21	15	2.51
	Catch Sed.	93	53/31	93	24	19	7.87
	Unit Erosion	96	49/44	93	36	25	5.47
			Galien River				
0.5/0.80	Gross Sed.	100	42/20	87	2	1	1.73
	Catch Sed.	100	40/20	87	5	2	1.84
	Unit Erosion	100	35/28	87	12	21	2.63
0.9/0.40	Gross Sed.	89	44/32	87	27	8	2.72
	Catch Sed	90	41/33	87	31	12	4.81
	Unit Erosion	94	33/41	87	37	33	6.02

cides with no-till accounts for this shift. Tightening the constraints also requires that changes be made in more management units and more acres.

For each site, the mechanical practices change little or not at all with different constraints because contour and vertical plowing perform very similarly on the long gentle slopes of the sites.

In comparing tables 1 and 2, the erosion and sediment targets generally lead to more acreage in the WCCCS rotation and more no-till. (An exception to the no-till result appears in the Galien 0.5/.80 case, but more use of conservation tillage with the HSI/Reliability target accounts for this apparent anomaly.) These results are as expected and are more pronounced, respectively, for gross sediment, catchment sediment, and erosion, that is, as the target becomes further removed from fish habitat.

An unexpected result, at least for the sediment targets, is that less area and fewer management units are involved in the solutions, albeit at higher overall costs. An interesting implication is that if administrative costs increase with the area and number of farms involved in abatement actions, the ostensible efficiency gains of using suitability/reliability targets could be offset.

Conclusions

This study suggests that protecting fish habitat can be quite distinct from reducing agricultural erosion or sediment discharges. Policies that address sediment or erosion effectively are less effective in protecting habitat, especially at high suitability and reliability levels. This is because soluble pesticides dominate extreme suitability and reliability conditions, and the correlation to sediment loads is not high. This result is not surprising because fish respond to multiple qualities of the stream channel. Single-dimensional policies will be effective only if the dimension chosen is highly correlated with overall suitability.

A specific policy concern involves no-till farming. No-till has been widely encouraged. At least in the cases studied here, this approach appears sound with respect to erosion and sedimentation. But the consequences for fish, and perhaps other wildlife, may be perverse; no-till sometimes involves greater use of pesticides, which are not as fully incorporated, while it also reduces runoff volume. Nonincorporation means that less water will move more chemicals. The results point toward the desirability of no-till systems that better control pesticide releases.

Another policy issue involves the apparent desirability of heterogenous cropping systems in a watershed. When suitability and reliability goals are high, changes in tillage and mechanical practices are inadequate. Crop changes are needed (unless stream channel measures are undertaken), and the changes entail more diversity. More diversity reduces the probability of any one chemical exerting influence in a particular weather event. Agricultural policies favoring the cultivation of fewer crops may hamper efforts to attain high quality stream fisheries in some areas.

The results suggest that less area and fewer farms are affected by targeting on sediment than on suitability. Thus, the apparent disadvantages of sediment targets may be less pronounced when administrative costs are considered.

Finally, the differences between targets in the costs of attaining particular quality/reliability goals are the potential gains from intensive water quality monitoring and measurement to fine tune abatement efforts. Intensive programs will undoubtedly be quite costly. There is apparently little to gain when quality/reliability goals are modest or when existing conditions are generally good. The emissions or exposure targets perform reasonably well. For fish habitat purposes, the gains from intensive programs probably warrant the costs only where they stand a good chance of greatly improving habitat for high-value species.

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