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Multiattribute optimization of restoration options: Designing incentives for watershed management

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[1] Watershed restoration requires careful assessment of impairment in ecosystem attributes to design appropriate conservation policies. This study applies a multiattribute optimization framework for evaluating relative gains in restoration based on potential improvements in economic and environmental attributes related to water quality, habitat, and urbanization. Policy mechanisms through direct compensation of restoration activities are evaluated based on single-attribute and multiattribute optimization and watershed response to varying levels of restoration incentives. Results indicate that tradeoffs in economic and environmental objectives are critical to identifying optimal restoration strategies at a watershed scale. The multiattribute optimization method developed in this study balances levels of multiple attributes and reflects tradeoffs in preferences for each attribute. Through an evaluation of a variety of attributes for relative gains and costs, opportunities exist for strategic selection of restoration activities in subwatersheds. The multiattribute method is found to be superior to the single-objective method in incorporation of tradeoffs, balancing economic and environmental impacts, and development of participatory solutions. Multiattribute assessment and policies are important for cost-effective and consensus-based watershed restoration practices.

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1. Introduction

[2] Watershed ecosystems display varying degrees of impairment due to increasing demands for food, fiber, shelter, and ecological services. This requires a multiattribute optimization approach to addressing these impairments, which is the main focus of this study. We define impairment as the deterioration of watershed health as expressed in changes in function and structure of the system. For example, land use exerts a major influence on the quality and quantity of runoff [Malina, 1996; McCutcheon *et al.*, 1993; Calder, 1993]. Urbanization increases urban runoff volume and rate, accelerating instream erosion and channel degradation [MacRae, 1997; Booth, 1990; Neller, 1988]. Watersheds are systems that vary in the physical, climatic, biological, and socioeconomic attributes. These features are useful indicators of the state of the ecosystems and reflect the extent of impairment. By attribute we refer to a specific component of the watershed system. The extent of impairment in multiple attributes is important information that can be used to prioritize watershed areas for restoration activities [Jensen *et al.*, 2001; Schueler and Holland, 2000; Brooks *et al.*, 1997; U.S. Environmental Protection Agency (USEPA), 1995]. While the principle of using the watershed as the basis for analyzing ecosystem impairment enjoys support [National Research Council, 1999], there is a need for a multiattribute, optimization framework for prioritizing restoration alternatives [USEPA,

2002; U.S. Department of Agriculture, 2000; Prato, 1999; Black, 1997; Williams *et al.*, 1997; Ziemer, 1997; Montgomery *et al.*, 1995]. The effectiveness of restoration activities can be maximized with a watershed-scale assessment of subwatersheds to target those with highest marginal restoration benefits [Hyman and Leibowitz, 2000]. Given a variety of attributes to consider, this framework requires an assessment of the extent and nature of impairment in major and indicative attributes to evaluate economic and ecological impacts of restoration policies. A common approach used in managing watersheds is the single-objective method (for example, water quality or habitat protection), often based on a priority basis. This often can result in unforeseen implications on other attributes of the system [Randhir and Lee, 1993, 1997; Qiu, 2005] and can also result in suboptimal solutions [Randhir *et al.*, 2000]. A multiattribute approach is needed to manage watersheds in a balanced way, by considering impacts of multiple attributes in decision making [Prato, 1999]. The purpose of this paper is to apply a multiattribute optimization framework that combines economic and environmental objectives for watershed restoration and to evaluate alternative policies to restore watershed ecosystems.

[3] Modeling restoration strategies needs to account for the extent of impairment and the benefits and costs of restoration activities. We propose that a multiattribute optimization approach is appropriate for developing a more comprehensive method for watershed restoration and decision making. A multiattribute approach is used in several areas of natural resource management that include ecosystem management [Prato, 1999], habitat management [Store and Kangas, 2001], environmental decisions [Kiker *et al.*, 2005], fisheries [Mardle and Pascoe, 1999], forestry [Kangas *et al.*,

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2002], and landscape management [Prato, 2000; Randhir et al., 2000]. While the importance of a multiattribute approach to watershed restoration is increasingly being recognized, there are still very limited studies [Lamy et al., 2002; Prato, 1999; Lent et al., 1998; Llewellyn et al., 1996; Frissell et al., 1993] that account for impairment using the combined assessment and optimization of multiple attributes. There is also a need to study implications of multiattribute methods for watershed restoration policy. This study is unique in using a multiattribute optimization that uses sub-basin attributes, restoration cost structure, and relative valuation of attributes at a watershed scale. The use of ecosystem management principles for restoration and evaluation of single and multiobjective methods are also limited in water resources literature. The use of nonlinear tradeoffs in economic and ecological attributes will improve management decisions and policy support in watershed restoration. Specific objectives of this study include (1) developing a multi-attribute policy framework for restoration; (2) evaluating the nature of tradeoffs under optimal, single-attribute, and multiattribute-based restoration policies; and (3) assessing incentive-based restoration policies based on single-attribute and multiattribute utility framework.

2. Methodology

2.1. Model

[4] We use a conceptual model in developing the optimization framework. A watershed manager is assumed to restore the watershed ecosystem through conservation investments in subwatersheds that have the highest degree of impairment. The manager uses potential economic and ecological gains from potential improvements in multiple attributes to optimize restoration options. Given the high cost of measuring all attributes, the manager focuses on major and representative attributes to assess the nature of impairment in each subwatershed. The manager attempts to maximize the utility of restoration benefits by targeting subwatersheds with the highest marginal gains that result from reducing the impairment in multiple attributes. Thus the objective function is to maximize a combined utility function resulting from improvements in several watershed attributes (multiattribute), represented in (1),

$$\text{Max}_{x_s} U(\cdot) = U(u^1(r_s^1), \dots, u^A(r_s^A), \omega^1, \dots, \omega^A), \quad (1)$$

where a is attribute with $a \in \{1, \dots, A\}$, $U(\cdot)$ is the multi-attribute utility function [Keeney and Raiffa, 1993; Keeney, 1973], u^a is utility function over attribute a , r_s^a is the level of restoration in attribute a in subwatershed s , and ω^a is relative preference weight to attribute a . Each weight ω^a satisfies $\omega^a \in [0, 1]$ and $\sum_a \omega^a = 1$. The objective function is thus a weighted sum of utilities (additive utility function) resulting from restoration gains from multiple attributes in subwatersheds. The restoration (r_s^a) is defined by potential gains from restoring impairment in attribute a , represented in (2),

$$r_s^a = f^a(D_s^a(x_s)), \quad (2)$$

where $D_s^a(\cdot)$ is impairment in attribute a in subwatershed s and x_s is the magnitude of restoration activity (amount

restored) in subwatershed s . The resource constraint facing the manager is represented by (3),

$$\sum_s \sum_a C_s^a(x_s) \leq B, \quad (3)$$

where C_s^a is the restoration cost in subwatershed s and B is the total budget available for restoration. The decision problem can be represented as maximizing (1), and subject to constraints represented by equations (2) and (3), nonnegativity ($x_s \geq 0$), and land availability ($x_s \leq \bar{X}_s$), where $\bar{X}_s$ is area available in subbasin s . Land availability constraint is not presented here for simplicity in presentation. Substituting (2) into (1), the objective function can be rewritten as (4):

$$\text{Max}_{x_s} U(\cdot) = U(u^1(f^1(D_s^1(x_s))), \dots, u^A(f^A(D_s^A(x_s))), \omega^1, \dots, \omega^A). \quad (4)$$

The problem ((4) subject to (3)) can be written as a Lagrangean ℓ as in (5):

$$\begin{aligned} \ell = & U(u^1(f^1(D_s^1(x_s))), \dots, u^A(f^A(D_s^A(x_s))), \omega^1, \dots, \omega^A) \\ & + \lambda_1 \left(B - \sum_s \sum_a C_s^a(x_s) \right). \end{aligned} \quad (5)$$

Differentiating equation (5) with respect to x_s , the first-order condition to maximize restoration gains is given by (6):

$$\begin{aligned} \frac{\partial \ell}{\partial x_s} = & \sum_s \sum_a \frac{\partial U}{\partial u^a} \frac{\partial u^a}{\partial f^a} \frac{\partial f^a}{\partial D_s^a} \frac{\partial D_s^a}{\partial x_s} \\ & - \lambda_1 \sum_s \sum_a \frac{\partial C_s^a}{\partial x_s} = 0. \end{aligned} \quad (6)$$

Here $\partial U / \partial u^a$ is the marginal change in multiattribute utility for changes in the utility of attribute a , $\partial u^a / \partial f^a$ is the marginal change in utility of attribute a for changes in restoration of a , $\partial f^a / \partial D_s^a$ represents the marginal changes in restoration levels for change in impairment, and $\partial D_s^a / \partial x_s$ is the marginal reduction in impairment for changes in restoration activity. The first-order condition in (6) can be rearranged to evaluate optimal conditions in (7):

$$\sum_s \sum_a \frac{\partial U}{\partial u^a} \frac{\partial u^a}{\partial f^a} \frac{\partial f^a}{\partial D_s^a} \frac{\partial D_s^a}{\partial x_s} = \lambda_1 \sum_s \sum_a \frac{\partial C_s^a}{\partial x_s}. \quad (7)$$

Equation (7) represents the standard result that marginal gains from restoration must equate with marginal costs of the restoration activity. The marginal gains are represented by the utility of improvement in impairment in various attributes in all subwatersheds. The other first-order condition is

$$\frac{\partial \ell}{\partial \lambda_1} = B - \sum_a \sum_s C_s^a(x_s) = 0,$$

which represents a positive shadow value of the resource constraint. Application of the optimal conditions in equation (7) to watershed restoration requires extensive spatial and response

Figure 1. Data flows for restoration assessment.

information of several attributes at the subwatershed scale. This includes information on potential restoration gain, cost of restoration, and their tradeoffs among attributes in each subbasin. We focus on multiattribute optimization and assume that spatial interactions have dynamic influence on attribute levels that are in equilibrium. Such dynamic information is relevant in spatial optimization [Randhir *et al.*, 2000]. To represent gains from restoration in watershed attributes, we identify three indicators to represent the state of each component of the watershed ecosystem: abiotic (water quality), biotic (habitat), and socioeconomic (urbanization).

[5] The decision variable in the model x_s is magnitude of change through management practices in the subwatershed. Changes in decision variable have an influence on all components of the watershed ecosystem. The watershed system is composed of interactions between individual components [Shriver and Randhir, 2006]. Restoration decisions involve changes to land practices that mitigate impairment in each subwatershed. Given the complex interaction in watershed systems, restoration practices that are aimed at improving water quality can improve aquatic habitat and to some extent improve riparian habitat for terrestrial species. Land practices that aim at improving water quality can mitigate to some extent the effects of urbanization. Similarly, habitat restoration can improve water quality through creation of pervious cover and reduce impacts of urbanization. Restoration to urban land can improve water quality and improve habitat potential in a watershed. Thus optimal restoration decisions depend on system-wide and simultaneous impacts on all components of the watershed ecosystem.

[6] We focus on water quality ($a = 1$), habitat ($a = 2$), and urbanization ($a = 3$) as specific metrics to represent major classes of restoration. The empirical model that describes the data flows is presented in Figure 1. The impairment in water quality is represented by total suspended sediment (TSS) load in the runoff water. The percent of core and priority habitat is used as an indicator of the extent of habitat function of the watershed. The urban impairment in the watershed is quantified using effective impervious area (EIA), which is the proportion of the landscape composed of built components, representing the extent of urbanization in a watershed. These metrics are identified based on their potential as indicators of impairment of the system. One can extend system-wide impacts of restoration decision on biotic, abiotic, and socioeconomic components of the ecosystem to these indicator

attributes. Changes in land management practices that are aimed at restoring one attribute can change the levels of other attributes. Sediment reductions can improve habitat in a subwatershed and mitigate urbanization influence in a watershed. Similarly, percent core habitat can reduce sediment loading and reduce effects of impervious cover in a watershed system. Restoration of impervious cover in a watershed reduces sediment loading and can minimize habitat impacts. For capturing these interactions in the optimization model, we use response relationship derived from system-wide assessment from simulation modeling and geographic information system (GIS) analysis in the region [Randhir, 2003; Shriver, 2005; Shriver and Randhir, 2006].

[7] The objective function $U(\cdot)$ in the empirical model is specified as an additive multiattribute utility function [Fishburn, 1972; Keeney and Raiffa, 1993; Keeney, 1973], as in (8):

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} \sum_{a=1}^3 \omega^a u^a(r_s^a). \quad (8)$$

The utility function is based on the standard utility theory [Bell *et al.*, 1988]. The negative exponential form [Browne, 1995; Hurley *et al.*, 2004] is used in this study to represent individual utility functions (u^a) of attributes. The restoration potential (r_s^a) is calculated for the three attributes as reduction in the extent of impairment in attribute a in subbasin s . The values are normalized to allow consistency in ranking among attributes and to represent an ordinal degree of impairment in each attribute. The relative weights (ω^a) are based on a stakeholder group valuation exercise in the watershed [Shriver and Randhir, 2006; Shriver, 2005], which employs a pair-wise comparison by representative watershed stakeholders using the analytical hierarchy process [Randhir *et al.*, 2001; Saaty, 1999]. The stakeholder group represented major interest groups (farmers, foresters, watershed managers, ecologists, regional planners, voluntary group, and water suppliers) in the watershed and deliberated on a valuation matrix that ranks each objective against every other objective on a scale of importance. The amount of land in each subwatershed is derived from GIS assessment and specified in the optimization model.

[8] The cost of restoring water quality (C_s^1) is represented as a linear function of per hectare cost to mitigate sediment

contamination. The cost of habitat restoration (C_s^2) is based on average land price in each subbasin with the assumption that the cost of core and priority habitat restoration is proportional to the opportunity cost of land in each subbasin. The cost of restoring built land (C_s^3) is assumed to be a function of the cost of practices to mitigate impairment resulting from impervious cover.

2.2. Incentive Policies for Restoration

[9] Optimal conditions for restoration incentives are based on the first-order conditions derived for multiple attributes in equation (7). We define restoration incentive as a compensation for covering cost of implementing a restoration practice. The compensation is through an increase from available baseline funds (B) for the restoration work. A restoration policy can be designed by maximizing restoration gains from investments using various attributes as criteria and varying incentive levels. Thus policy design using the above model (equations (1)–(3)) is to change policy type, say, P ($P \in \{1, 2, 3, 4\}$ as detailed below), and the level of restoration incentives (I^P) to encourage desirable changes in the watershed, x_s . The policy types (as described below) refer to the use of single attribute and multiattribute objectives in optimizing restoration activities in the watershed system. The type and level of restoration policy can affect multiple attributes of the watershed. Restoration incentives are modeled as changes in the restoration budget as compensation for the cost of restoration as in (9):

$$\sum_s \sum_a C_s^a(x_s) \leq B * I^P. \quad (9)$$

[10] A common approach in the development of a restoration policy is to optimize activities based on a single attribute as a criterion. Such use of a single criterion is simpler but may not account for interactive changes in other attributes resulting from policy design. Thus a single-attribute optimization for restoration policy attempts to achieve maximum gains in one attribute by quantifying the levels of change in watershed practices. An alternate approach is to develop restoration policies based on multiple attributes and their relative utilities. This approach balances tradeoffs among attributes and incorporates information on preferences for multiple attributes. Thus a multiattribute optimization for restoration policy aims to maximize utility from restoring multiple attributes, weighted by preferences.

2.2.1. Water Quality–Based Policy (Type 1)

[11] Sediment loading is a key variable influencing water quality. This policy uses the utility of reduction in sediment loading as a primary objective in identifying subwatersheds with maximum restoration gains in sediment reduction. Changes in habitat and urbanization are evaluated under this policy regime. This policy is represented as the optimization of the objective function

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^1(r_s^1)$$

($a = 1$, representing sediment), subject to the sediment reduction cost function and land constraints. To determine responses to varying restoration budgets, B is parameterized (by changing level of $I^{P=1}$ in equation (9)) to derive corre-

sponding changes in other attributes (habitat and urbanization) under this policy.

2.2.2. Habitat-Based Policy (Type 2)

[12] Under this policy framework, habitat protection is used as the primary criterion in prioritizing and optimizing watersheds. The objective function under this policy maximizes the total restoration gains from habitat protection and is represented as

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^3(r_s^3)$$

($a2$, representing habitat), subject to the habitat restoration cost function and land constraints. To derive responses to varying restoration budgets, B is parameterized (by changing level of $I^{P=2}$ in equation (9)) to determine corresponding changes in other attributes (imperviousness and sediment) under this single-attribute policy.

2.2.3. Urban-Based Policy (Type 3)

[13] This policy aims to reduce the effects of the built environment (impervious cover) through single-attribute optimization. This objective represents the degree of urbanization in a watershed. Under this policy, subwatersheds are evaluated using an optimization objective that is represented as

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^2(r_s^2)$$

($a3$, representing imperviousness), subject to the imperviousness restoration cost function and land constraints. To determine responses to varying restoration budgets, B is parameterized (by changing level of $I^{P=3}$ in equation (9)) to derive corresponding changes in other attributes (habitat and sediment) under this single-attribute policy.

2.2.4. Multiattribute-Based Policy (Type 4)

[14] Watershed restoration creates system-wide impacts of particular restoration practices. An evaluation of changes in multiple attributes can incorporate tradeoffs among the attributes. In addition, relative preferences for attributes are important in deriving an optimal policy. The multiattribute-based policy uses utility in restoration of multiple attributes as a primary objective in identifying subwatersheds with maximum restoration gains in all attributes. Changes in sediment, habitat, and urbanization are considered under this policy regime. This policy is represented as optimization of the objective function

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} \sum_{a=1}^3 \omega^a u^a(r_s^a),$$

subject to the restoration cost function and land constraints. To derive responses to varying restoration budgets, B is parameterized (by changing level of $I^{P=4}$ in equation (9)) to determine corresponding changes in all attributes under this policy.

2.3. Study Area

[15] The Chicopee River Watershed (Figure 2) is located in central Massachusetts and covers 1,871 km² (187,066 ha). It is composed of a mixture of rural, heavily forested lands and

Figure 2. Land use/land cover of the Chicopee River watershed.

agricultural, suburban, and urbanized areas. Four major rivers drain the watershed: the Swift, Ware, Quaboag, and Chicopee (main stem). The Chicopee River contributes an average annual flow of $913 \times 10^6 \text{ gal. d}^{-1}$ ($1 \text{ gal.} = 0.003785 \text{ m}^3$) to the Connecticut River [Massachusetts Department of Environmental Protection (MassDEP), 2001]. The watershed is composed of all or part of 39 towns with a population of approximately 190,600 (2000 census) (see the Chicopee River Watershed home page, http://www.mass.gov/?pageID=eoeewaterterminal&L=4&L0=Home&L1=Air%2C+Water+%26+Climate+Change&L2=Preserving+Water+Resources&L3=Massachusetts+Watersheds&sid=Eoea&b=terminalcontent&f=eea_water_chicopee&csid=Eoea). The topography consists of rolling hills and alluvial plains and is dotted with numerous lakes and ponds. The land rises to a height of 457 m above sea level in the northern part of the watershed and drops to 12 m in the southwest corner of the watershed on the Connecticut River floodplain [MassDEP, 2001]. The basin is heavily forested with some areas of agriculture and open lands. The most heavily urbanized regions are in the south and southwest portions of the watershed in the towns of Chicopee, Springfield, Ludlow, and Palmer. Nonpoint source pollution associated with storm runoff, septic systems, dumps, and agriculture contributes to water quality problems [MassDEP, 2001].

[16] The surficial geology of the Chicopee River drainage basin consists primarily of glacial till or bedrock. Sand and gravel are located in or near the riparian zones of the Quaboag, Ware, and Chicopee Rivers. Precipitation varies in the watershed. In a sample of six communities scattered throughout the basin (Chicopee, Ware, Barre, New Salem, Paxton, and Hubbardston), average annual precipitation is 118 cm. The Chicopee River watershed supports a wide range of plant and animal communities. The watershed lies

predominantly within the Lower Worcester Plateau/eastern Connecticut upland ecoregion. The area is characterized by relatively homogeneous vegetation, soils, climate, geology, and human use patterns. The soils of the watershed developed primarily on glacial till in the uplands and on stratified sand, gravel, and silt deposits in the valleys [Swain and Kearsley, 2001]. Forest communities are widely distributed throughout the watershed and are dominated by white pine, hemlock, and oak [Swain and Kearsley, 2001]. Forested area accounts for 69.5% of the watershed area. The combination of forest, crop, pasture, open lands, water, and woody perennials composes 86.8% of the landscape.

[17] The bulk of the medium- to high-density residential areas are concentrated in the cities of Springfield, Chicopee, Ludlow, and Palmer, located in the southwest corner of the basin. Residential land use is 7.92% of the total watershed area, while commercial, industrial, and transportation uses take up just 1.43% of land area. Commercial and industrial activities are also centered in the southwest corner of the watershed.

2.4. Data and Methods

[18] Most of the spatial information is derived using GIS processing of data sets from MassGIS [MassGIS, 1999] and BASINS [USEPA, 2001]. A total of 209 subbasins are delineated in the watershed using elevation and stream layers. The loading rates for suspended sediment are calculated using the watershed management model [Camp, Dresser, and McKee, Inc., 1992] and validated using monitored information from the Massachusetts Department of Environmental Protection. These coefficients have been used and tested in several watersheds of the state and also used in the Watershed Analyst tool of the data viewer [MassGIS, 1999]. The method uses event mean concentration for the contam-

inant (TSS) multiplied by the volume of runoff water for each land class. The level of sediment loading in each subwatershed is used as levels of attribute ($a = 1$) in optimization. For calculating the habitat attribute, core and priority habitat is mapped using GIS layers through the union of the Natural Heritage and Endangered Species (NHESP) BioMap Core Habitat layer with the NHESP Priority Sites Rare Species Habitat layer. The map depicts the most viable habitats for rare species and natural communities and important habitats for state-listed and rare species. The layers are intersected with the subwatersheds, and the area of priority and core habitats are calculated for each subbasin. The percent of the area of core and priority habitat to the area of the subwatershed is calculated and used as levels of attribute ($a = 2$) for optimization. The impervious surface area coefficients from the MASSGIS Data Viewer Watershed Analyst Tools for 21 land use types are adjusted to reflect effective imperviousness based upon estimates derived from studies in the area by Aqua Terra Consultants (Mountain View, California). The effective impervious area (EIA) coefficient is multiplied by the area of each land use within a subbasin to determine the area of impervious surface. The sum of impervious surface areas within a subbasin is divided by the total area of the subbasin and expressed as percent of EIA. The percent of EIA in each subwatershed is used as levels of attribute ($a = 3$) in the optimization model.

[19] The cost of restoration for sediment (C_s^1) is assessed using estimates for a low-cost best management practice (BMP) (seeding) to mitigate sediment contamination. Estimates are obtained from the Massachusetts state office of the U.S. Department of Agriculture's Natural Resources Conservation Service for the watershed region. The cost of habitat restoration (C_s^2) is derived from the listed prices for land in all 39 communities in the watershed. They are compiled using the range of land prices for each community within the subwatershed to calculate the mean values. The values are discounted at 3% to determine the final sale price. The value of 3% is chosen after consultation with a local realtor specializing in land transactions in the watershed, who estimated this value using recent transactions in the region. Since the prices are for each community, they are area weighted to derive land values for each subwatershed. For this, community (town) layers are overlaid with subwatershed layers to clip polygons of communities (towns) in each subwatershed. The area of each polygon within a subwatershed is used to calculate percent coverage of each town in the subwatershed. The percent cover is used as a weight in calculating subwatershed land value. The minimum cost of restoring built land is based on a cost equation developed by American Society of Civil Engineers (ASCE), which estimates cost of best management practice as a function of impervious cover [ASCE, 2001]. The model was run to evaluate the nonbinding level of budget. This nonbinding budget level is used as a baseline to develop incentive levels for the model. The optimization equations are modeled using GAMS software [Brooke *et al.*, 1998] and solved as a NLP (nonlinear model) using CONOPT solver. The policy runs are scripted using a looping function that reoptimizes for each successive change in incentive levels. Outcomes of each loop are stored in a multidimensional matrix within the optimization problem. The type of objective and constraints are specified as separate models (types 1 through 4). Model outputs

are compiled within a continuous sequence of runs to allow comparison among models and policy runs. A sensitivity analysis is performed on the value of ω^a for 10% changes in the values from the baseline.

3. Results and Discussion

[20] The results of the analysis are presented in four sections. Section 3.1 presents the results of spatial analysis of the three attributes in the study watershed. In section 3.2 the baseline results of various policy optimizations are presented, which is followed by results of policy runs. Section 3.4 presents practical implications of the results.

3.1. Nature of Impairment

[21] The spatial distribution of impairment in water resources, habitat, and urbanization in subwatersheds is presented in Figure 3. Water quality ($a = 1$) impairment through sediment loading is high in subwatersheds at the lower half of the watershed. This is because of higher disturbance from land usage in these subwatersheds. The subwatersheds with higher sediment loading are along the Quabog branch of the river and along the main stem of the Chicopee River. The study area had a mean of 468 kg/ha of annual sediment loading.

[22] The next attribute is the amount of core and priority habitat ($a = 2$) as a percent of the subwatershed area. The core habitat is an indicator of vulnerability of wildlife and is used to represent watershed habitat function. This attribute had a mean of 6.42% and had high variability among subwatersheds. The habitat availability is concentrated in the central zone of the watershed along the Ware River branch and Chicopee River main stem. Critical habitat also exists in urbanized areas close to the outlet of the watershed.

[23] The last attribute ($a = 3$) reflects the level of impairment resulting from urbanization in the watershed. This attribute indicates the extent of built components in the watershed. The effective imperviousness is concentrated in the lower half of the watershed with higher impairment toward the watershed outlet. This location coincides with the urban areas of Chicopee and Springfield. The suburbanizing watersheds are concentrated on the southern side of the Chicopee Watershed as is evident from the spatial distribution in Figure 3. A low level of imperviousness is distributed in northern and eastern portions of the watershed.

[24] A cross comparison of the spatial distribution of attributes shows a closer correspondence between sediment loading and the percent of EIA in the watershed. Randhir [2003] obtained similar results in the Blackstone River watershed of Massachusetts. The habitat availability is evenly distributed throughout the watershed with varying degrees of available core and priority area. While a visual assessment of the pattern in watershed impairment is useful, further analysis using a watershed-scale optimization model can provide insights into interaction and policy options.

3.2. Baseline Optimization Results

[25] The baseline results of optimization for each policy type ($P = 1, 2, 3$), compared to multiattribute ($P = 4$), are presented in Figure 4. Relatively more area is restored under the type 1 policy, followed by policy types 3, 2, and 4, respectively. This can be attributed to lower cost of water quality restoration through sediment BMPs. Water quality restoration is highest under type 1, followed by policy types

Figure 3. Spatial distribution of impaired attributes in the study watershed.

Figure 4. Baseline levels of attributes under various policy types.

4, 2, and 3, respectively. As expected, the single-objective method of maximizing water quality achieved highest gains in water quality, followed by the multiattribute type. Habitat restoration is highest under type 2, followed by policy types 4, 3, and 1, respectively. The single-objective maximization of habitat achieved the highest habitat restoration, followed by the multiattribute type. Urban restoration is highest under type 4, followed by policy types 3, 1, and 2, respectively. Higher urban restoration was achieved under multiattribute policy type, followed by single-objective maximization of urban restoration gains.

[26] It can be observed from baseline results that a water quality-based policy resulted in restoration of the largest area compared with all other policies. This is because of lower restoration costs compared with all other policies with gains in other attributes under this policy. Habitat-based policy resulted in improvements in both sediment pollution and impervious cover. This is because allocation of land for habitat requires land cover with no disturbance; with low impacts therefore from water quality changes and imperviousness. The urban-based policy resulted in lowest allocation in

watershed area and can be attributed to the high cost of restoring impervious cover. This policy had low improvements for habitat restoration and water quality protection. Habitat improvement is assumed to be small, resulting from the practices for reducing impacts of imperviousness. Water quality improvement is through changes in flow regime as effective imperviousness is reduced. The baseline allocation under multiattribute policy resulted in improvements in all attributes as expected from the multiattribute utility objective function.

3.3. Policy Runs

3.3.1. Water Quality-Based Policy (Type 1)

[27] This policy focuses on using a single attribute, water quality, as a criterion for optimization of

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^1(r_s^1)$$

and is evaluated for incentive responses. The results of various incentive levels aimed at water quality (sediment) restoration are presented in Figure 5. The curve represents the

Figure 5. Water quality-based ($a = 1$) restoration policy.

Table 1. Characteristic Curves of Attribute Response to Various Policies

Attribute	Characteristic Curve	R^2
Sediment-based policy		
Habitat protection	$R = 3.075 \times B + 12.82$	0.67
Sediment reduction	$R = 0.17 \times B^2 - 1.60 \times B + 7.32$	0.47
Habitat-based policy		
Sediment reduction	$R = -0.09 \times B^2 + 6.44 \times B - 13.60$	0.91
Habitat protection	$R = 0.37 \times B^2 - 5.53 \times B + 16.68$	0.77
Imperviousness-based policy		
Sediment reduction	$R = 0.005 \times B^2 + 0.52 \times B + 1.14$	0.99
Habitat protection	$R = -0.006 \times B^2 + 1.60 \times B + 1.39$	0.99
Imperviousness reduction	$R = -0.014 \times B^2 + 2.16 \times B + 8.08$	0.95
Multiattribute policy		
Sediment reduction	$R = 0.18 \times B^2 + 0.29 \times B + 3.15$	0.98
Habitat protection	$R = 0.17 \times B^2 + 0.50 \times B + 2.70$	0.98
Imperviousness reduction	$R = 0.18 \times B^2 + 0.27 \times B + 3.18$	0.98

percent change in water quality restoration for each percent change in restoration incentive based on water quality objectives. It is observed that higher increases in incentives had a nonlinear response, compared with smaller increases. The reduction in sediment loading showed a quadratic curve with smaller rates of reduction associated with initial increases in the restoration budget (B) through increasing incentive $I^{P=1}$. The incentive response equation (Table 1) of the sediment policy runs had an R^2 of 0.47, indicating that 47% of the water quality response derives from incentive levels. Each percent increase in water quality incentive increased the restoration in water quality by $0.17 \times B - 1.6$ units. The impact of water quality incentives on habitat protection is linear with marginal increases of 3.08% increase for each addition of water quality incentive. The response equation can be used in the design of incentives for water quality-based incentives. Optimal restoration efforts could be designed using a reward structure based on the $r = 0.17 \times b - 1.6$ rule, where r is the desired restoration effort (to restore water quality) and b is the optimal incentive level. Such linear rules can be effective in encouraging optimal efforts [Holmstrom and Milgrom, 1987; Randhir and Lee, 1996]. While water quality-based incentives can create minor improvements in habitat, improvements in water quality are

relevant to aquatic ecosystems and to smaller improvements in terrestrial ecosystems through natural components of BMPs.

3.3.2. Habitat-Based Policy (Type 2)

[28] The type 2 policy focuses on habitat protection as a single criterion for optimizing watershed restoration using

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^3(r_s^3).$$

Response to incentives that encourage habitat restoration is studied by assessing effects on the watershed ecosystem components. The results of the habitat-based restoration policy are presented in Figure 6. As expected from the high cost of restoring habitat, the rate of increase in habitat protection is smaller at low levels of restoration investments. Beyond 10% of the baseline restoration budget, water quality increased sharply from the baseline. This is because water quality benefits from protected habitat land. The marginal increases for each attribute under this policy had a varying response to restoration incentives. The gradual increase in potential gains from habitat protection did not coincide well with the two other attributes. While the habitat increased

Figure 6. Habitat-based ($a = 2$) restoration policy.

Figure 7. Urban-based ($a = 3$) restoration policy.

steadily beyond the 50% level of incentive, the urban restoration did not show significant improvements. This is because the habitat criteria in the optimization had less urban improvement potential. Water quality improved for each increase in habitat investments. The marginal increases led to a rapid increase in the two attributes (habitat and water quality) beyond 80% level of restoration investment.

[29] The incentive response functions for habitat policy are listed in Table 1. The nonlinear response models of each attribute are highly significant in explaining the variability in attributes. The R^2 values are 0.91 for sediment response and 0.77 for habitat response. The slope of each response curve indicates potential improvements resulting from one additional percent of watershed area identified for restoration through the habitat-based policy. The habitat restoration increased nonlinearly with sediment and habitat responses. The water quality increased in a quadratic form with the habitat-based incentives, accounting for $6.44 - 0.18 \times B$ tons of sediment reduced for each percent increase in habitat-based incentives. Habitat benefits increased at a rate of $5.53 + 0.74 \times B$ units for each percent increase in habitat-based incentive. This indicates that habitat-based incentives can be designed as linear efforts toward watershed restoration. Habitat-based policy could produce complementary restoration of water quality.

3.3.3. Urban-Based Policy (Type 3)

[30] This policy focuses on impervious cover as a single objective of optimization of land area for watershed restoration through

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} u^2(r_s^2).$$

Results of the urban-based restoration policy are presented in Figure 7, representing relative changes in the three watershed attributes under varying urban incentive levels. As expected, restoration through reduction in impervious cover improved steadily for each increase in urban-based incentives. Water quality and habitat attributes show varying responses to urban incentives. Water quality improved gradually up to 20% for

each increase in urban incentives. With further increases in incentives, the marginal increase in water quality is higher. The response of habitat to urban incentives shows a constant rise for each increase in urban incentives. This is due to the creation of new habitat resulting from restoration of urban areas.

[31] The incentive-response functions for urban-based restoration policy are listed in Table 1. The sediment, habitat, and urban response functions fitted with the specified functional form with a high explanatory power (R^2 values are 0.99, 0.99, and 0.95, respectively). All functions followed a quadratic form, with nonlinear marginal increases in response to incentives. The sediment reduction is at $0.01 \times B + 0.52$ tons per hectare for each increment in urban incentive. Habitat potential increased at $0.012 \times B + 1.6$ hectares for each percent rise in urban incentive. The urban area restored grew nonlinearly by $2.16 - 0.028 \times B$ ha for each percent increase in urban incentive.

[32] These results show that a quadratic incentive rule that has higher marginal compensation for initial restoration in urban areas can be used for urban-based restoration policy. In general, urban restoration policy produced a good response on water quality, habitat, and urban attributes of a watershed. This policy gives greater priority to highly disturbed areas (usually urban areas) of the watershed and could perform well in urbanized subbasins.

3.3.4. Multiattribute-Based Policy

[33] This policy uses multiple criteria in optimizing watershed restoration based on a multiattribute utility model for watershed restoration:

$$\text{Max}_{x_s} U(\cdot) = \sum_{s=1}^{209} \sum_{a=1}^3 \omega^a u^a(r_s^a).$$

The results of the multiattribute-based restoration policy are presented in Figure 8. The response functions showed balanced responses in all three attributes for changes in incentive levels under the type 4 policy. In general, all attributes showed improvement for all marginal increases in incentives. The restoration potential of each attribute of the watershed grew at

Figure 8. Multiattribute-based ($a = 4$) restoration policy.

an increasing rate, and the rate of increase is similar in direction and magnitude.

[34] Incentive response functions of various watershed attributes under the multiattribute policy are presented in Table 1. All attributes followed a quadratic form with 98% explanatory power (R^2). The sediment reduction increased at $0.29 + 0.36 \times B$ tons for each incentive level based on type 4 policy. Habitat potential increased by $0.34 \times B + 0.5$ units for each increase in multiattribute-based incentive policy. The urban impacts from impervious cover reduced by $0.36 \times B + 0.27$ units for each increase in multiattribute-based policy. The response relationship is useful in designing nonlinear incentive structures to achieve desired restoration levels in a watershed. Given a balanced increase in all attributes, the multiattribute policy could be a preferred approach to watershed restoration compared with single-attribute policies. Use of single-attribute methods can bias restoration toward specific attributes (attribute bias) and sometime to specific subbasins (spatial bias) in the watershed. In addition, the multiattribute approach reflects preferred tradeoffs among attributes by stakeholders through multiattribute weighting of the optimization [Shriver and Randhir, 2006]. These relative attribute preferences are not incorporated in single-attribute policies. The model is sensitive to attribute weights (ω^a) as observed in the sensitivity analysis (Table 2). The maximum sensitivity is observed for changes in $a = 2$ (habitat preference), followed by $a = 1$ (water quality) and $a = 3$ (urbanization), respectively.

3.4. Practical Implications

[35] Watershed restoration involves improving both the structure and function of the system from an impaired state [Randhir, 2007]. A typical restoration objective is to reduce impairment and move the system toward a desired level of quality. The desired level can be the historic watershed condition or a benchmark subwatershed that has the best conditions. While restoration toward these goals is an objective of most watershed planners, the costs of restoration could be prohibitive, especially in urbanized systems. The results of the study indicate that it is possible to make gradual improvements by encouraging restoration efforts through incentives. Incentive rules can be implemented at a community level and at varying scales by focusing on subwatersheds that have highest restoration potential as identified in this study.

[36] A common approach taken by land managers is to use a single objective as a main criterion in evaluating restoration options. The results show that such an approach could lead to suboptimal decisions and might overlook sensitive areas of the watershed. If carefully planned, watershed restoration could be achieved using multiple-attribute methods that maximize total gains from several attributes in watershed restoration with least cost. A multiattribute policy is information intensive and can be implemented by watershed managers and communities to achieve balanced restoration in watershed systems. In addition, the multiattribute method is critical for “bottom up” and participatory solutions where criteria are decided by stakeholders rather than centralized

Table 2. Sensitivity Analysis of Attribute Weights

Change in ω^i From Baseline	Water Quality (% Change From Baseline Levels)	Habitat (% Change From Baseline Levels)	Impervious Cover (% Change From Baseline Levels)
$\omega^1 + 10\%$	0.18	-0.49	0.27
$\omega^1 - 10\%$	-0.19	0.52	-0.21
$\omega^2 + 10\%$	-0.37	1.05	-0.43
$\omega^2 - 10\%$	0.41	-1.15	0.53
$\omega^3 + 10\%$	0.20	-0.57	0.27
$\omega^3 - 10\%$	-0.22	0.60	-0.27

regulators as in cases of single objective method. Critical elements are gathering, maintaining, and updating spatial information using GIS. Economic information on restoration costs in watersheds is often limited, and an integrated and updated database is necessary to develop multiattribute approaches.

[37] Incentives for watershed restoration can be designed to achieve gains in multiple attributes with better knowledge of their tradeoffs and response behavior. In some cases where limited spatial data are available, extent of impervious cover could be derived from land use data and used as a single criterion. Past studies show that imperviousness is correlated to sediment loading [Randhir, 2003], and such information can be used in developing a single criteria-based policy to achieve gains in more than one attribute. A watershed manager can use readily available attribute information as a prioritization criterion and achieve restoration gains in other attributes.

4. Conclusions

[38] With increasing rates of depletion in watershed systems, restoration is becoming an important part of conservation planning and policy [Randhir, 2007]. Impairments often affect multiple attributes of a watershed, which makes assessment and decision making more complex and information intensive. With increasing interest in prioritizing restoration efforts and in the maintenance of the physical, chemical, and biological integrity of watershed systems, the evaluation based on multiple attributes and the design of appropriate policies are becoming critical to natural resources management. A watershed scale, multiattribute approach [Randhir et al., 2000; Prato, 1999] is important for comprehensive assessment of impairment and development of optimal restoration policies. By developing optimal conditions for restoration at a subwatershed scale, four specific policies are evaluated for the Chicopee River Watershed in central Massachusetts.

[39] Our results indicate that the nature of impairment varied spatially among the subbasins in the study watershed. Higher sediment loading is observed in the main stem and suburbanizing parts of the watershed. Habitat availability is high in central parts of the watershed. Critical habitat areas exist within urbanized areas of the watersheds. A strong relationship between urbanization and sediment loading is also observed. The cost of restoration related to each attribute varied spatially and is a critical factor in restoration decisions.

[40] Results show that a water quality-based restoration policy could restore a greater watershed area, but produced only limited improvement in other attributes. A habitat-based policy resulted in improvement in all other attributes, but involved a high cost of restoration because of land retirement to create habitat function. An urban-based policy improved water quality to some extent, but improvements to habitat are relatively less. Watershed restoration under the water quality-based policy increased with incentive levels. Thus a simplified rule of incentive-reward could be used to restore the watershed under this policy. Changes in incentive levels under a habitat-based policy had nonlinear effects on other attributes (sediment and imperviousness) and in the effect on habitat restoration. Thus a linear rule based on habitat could be used under this policy to encourage restoration efforts. Urban-based incentives had a quadratic effect on restoration levels in

all attributes. Thus a rule that associates efforts at initial urbanization (low levels of imperviousness) with higher incentives compared with higher urbanized subbasins could be used to restore the watershed.

[41] A multiattribute-based incentive policy balances restoration in all attributes of a watershed. In addition to balanced allocation, the preferences specified are reflected in optimal outcomes. A multiattribute-based policy uses spatial and tradeoff information and can lead to better restoration efforts than approaches that consider a single attribute in optimization. While the cost of collecting spatial information and complicated procedures are constraints in applying multiattribute methods, the outcome has several advantages over single attribute methods: balanced restoration of a watershed, less impairment to nontargeted attributes, and the incorporation of relative preferences for attributes. Our results indicate that policies based on a single attribute have variable implications for other attributes. Given the deviation in outcomes of the single-attribute approach, it becomes inevitable to use the multiattribute approach in achieving optimal decisions related to restoration of watersheds. This is especially important to achieve balanced changes in attribute levels of the watershed ecosystem.

[42] Careful evaluation of relative tradeoffs among attributes and strategic spatial targeting provide opportunities to reduce the costs of restoration. Conservation easements can be used as policy mechanisms to restore watersheds. Such mechanisms could be designed to enroll areas based on relative gains and costs. In addition, best management practices could be targeted in areas with higher potential gains from restoration using their characteristic curves. Multiattribute optimization allows one to gain insights and information into the complexity of the problem.

[43] Watershed restoration policy needs to account for various changes in attributes associated with each level of policy. Results show that watershed indicators could play a vital role by representing major objectives in watershed restoration. Multiattribute evaluation is a critical element of watershed restoration that could avoid inefficient and sub-optimal practices in a watershed.

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