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Integrating Stakeholder Values with Multiple Attributes to Quantify Watershed Performance

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Integrating stakeholder values with multiple attributes to quantify watershed performance

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[Integrating stakeholder values into the process of quantifying impairment of ecosystem functions is an important aspect of watershed assessment and planning. This study develops a classification and prioritization model to assess potential impairment in watersheds. A systematic evaluation of a broad set of abiotic, biotic, and human indicators of watershed structure and function was used to identify the level of degradation at a subbasin scale. Agencies and communities can use the method to effectively target and allocate resources to areas of greatest restoration need. The watershed performance measure (WPM) developed in this study is composed of three major components: (1) hydrologic processes (water quantity and quality), (2) biodiversity at a species scale (core and priority habitat for rare and endangered species and species richness) and landscape scale (impacts of fragmentation), and (3) urban impacts as assessed in the built environment (effective impervious area) and population effects (densities and density of toxic waste sites). Simulation modeling using the Soil and Water Assessment Tool (SWAT), monitoring information, and spatial analysis with GIS were used to assess each criterion in developing this model. Weights for attributes of potential impairment were determined through the use of the attribute prioritization procedure with a panel of expert stakeholders. This procedure uses preselected attributes and corresponding stakeholder values and is data intensive. The model was applied to all subbasins of the Chicopee River Watershed of western Massachusetts, an area with a mixture of rural, heavily forested lands, suburban, and urbanized areas. Highly impaired subbasins in one community were identified using this methodology and evaluated for principal forms of degradation and potential restoration policies and BMPs. This attribute-based prioritization method could be used in identifying baselines, prioritization policies, and adaptive community planning.


1. Introduction

Degradation to the abiotic, biotic and human components of landscapes is an important problem threatening watershed systems. For example, more than 40% of assessed waters in the U.S. fail to meet state water quality standards [U.S. Environmental Protection Agency (USEPA), 2003b]. Approximately 75% of the population (218 million people) lives within 10 miles of impaired waters [USEPA, 2003b], and 126 ecosystems are acknowledged as critically endangered, endangered or threatened [USEPA, 2003a]. Urban areas are expanding at twice the rate of population growth [U.S. Department of Housing and Urban Development, 2000], creating impervious cover, fragmentation, increased stormflow, and nonpoint source pollution. There is a need to develop ecosystem-based performance metrics to quantify the extent of degradation and to incorporate stakeholder values to prioritize restoration in watersheds. Large-scale strategies and long-term efforts are needed to place specific restoration goals within the context of landscape patterns and processes [Frissell, 1997]. A comprehensive assessment at a watershed scale is required to develop appropriate restoration policies. Such an evaluation necessitates an assessment of multiple attributes of degradation which represent watershed patterns and processes. Restoration policies need to focus on the reestablishment of watershed structure and function [Cairns, 1988; National Research Council (NRC), 1992], and they require the prioritization of restoration needs [Clements et al., 1996; Lamy et al., 2002]. Assessment of the nature and degree of impairment to the structure and function of watershed ecosystems can be used to determine restoration needs and to develop appropriate multiattribute policy design.

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common reference of performance for communities and government agencies. The results of such a methodology can be used to inform policies, planning and decision making at a variety of scales and include public participation.

[1] There are limited studies in the literature on such watershed-based, multiattribute, performance measures. The USEPA [2002] developed the Index of Watershed Indicators (IWI) and uses 15 attributes to evaluate watershed condition and vulnerability. Other researchers have also focused watershed assessment on threats to water quality for humans and aquatic life [Snyder et al., 2003; Richardson and Gatti, 1999; Moyle and Randall, 1998]. The research that develops classification and prioritization methods is driven by specific management objectives such as decreasing sediment loading to streams, maintaining or improving water quality [Frissell et al., 1993; Richardson and Gatti, 1999; Lent et al., 1998; Randhir et al., 2001; Llewellyn et al., 1996] and responding to stakeholder rankings of issues [e.g., Clements et al., 1996; Lamy et al., 2002; Krusipalo and Kangas, 1994; Huang et al., 2002; Qureshi and Harrison, 2001]. These methods are developed from the specific watershed problem or management objective. Since multiple attributes interact in a watershed system, and given the need to evaluate watershed progress, performance measures could help in prioritization for restoration and policy design. For these objectives, there is a need to evaluate watershed performance as a whole through the combined assessment of multiple attributes that are based on abiotic, biotic, and human components. This study fills this gap in the literature by using a broad array of physical, biological and cultural conditions representative of watershed structure and function. Development and use of a method to create preference weights of watershed stakeholders and its incorporation into the performance metric are also unique to this study. The methodology classifies watersheds for restoration by both quantifying attributes of potential watershed impairment and incorporating a quantitative process for assessing human priorities. Relative weights are used in developing a composite measure of performance based on stakeholder values. The attributes identified are associated with restoration benefits. The relative weights assigned by the stakeholders are for the specific attributes used in this study. The methodology opens new opportunities for decision makers to achieve multiple goals in integrated watershed management.

[5] The general objective of this study is to develop a multiattribute performance measure for watershed restoration and evaluate prioritization and conservation strategies. Specific objectives of this study are (1) to quantify potential impairment with respect to selected abiotic, biotic, and human factors using spatial analysis and simulation modeling, (2) to determine the relative importance of each attribute using a multiattribute ranking process and derive corresponding composite measures, and (3) to evaluate potential impairment at a community scale and identify possible restoration policies to improve watershed conditions.

2. Methods

[6] A watershed performance measure \( M' \) is specified as

\[
M' = m(x'_i, \omega_i | z')
\]

where, \( s \) represents the subbasin, \( i \) represents the attribute \((i \in I)\) in set \( I = \{a, b, h\} \), with abiotic \((a)\), biotic \((b)\), and human \((h)\) attributes. The function \( m(.) \) represents attribute-performance relationship, \( x'_i \) is level of attribute \( i \) in subbasin \( s \), \( \omega_i \) is relative weight of attribute \( i \), and \( z' \) represents other variables in subbasin \( s \). A linear form of the performance measure can be formulated as an index and represented as in (2).

\[
M' = \sum_i \omega_i x'_i
\]

[7] Under a linear formulation, the performance measure is in the form of an index [Chu et al., 2003; Karr, 1991]. Thus each subbasin is given a measure of performance based on the specified attributes and weights.

[8] To apply this concept to the study area, a conceptual framework (Figure 1) is used to specify watershed attributes that are important in the watershed, to measure and rank the kind and degree of impairment of subbasins, and to create a watershed performance measure (WPM). Three major components identified for the watershed model are abiotic (a), biotic (b), and human (h).

[9] Abiotic attributes of water quantity and quality, such as amounts of runoff, the presence of wetlands, concentration of dissolved oxygen, and nutrient enrichment of water bodies are important indicators of stress to the physical system that will impact biological and human systems [Richardson and Gatti, 1999; Heathcote, 1998; Black, 1997]. Within each subbasin the abiotic component was assessed by evaluating two subcategories, water quantity and water quality. Specific characteristics of water quantity impairment included runoff and wetland density. Potential water quality impairment was evaluated using measures of sediment yield, loading of nitrate and phosphorus, and dissolved oxygen (DO) concentrations.

[10] Impacts to the biotic component can be quantified by assessing the amount and quality of habitat for at-risk species, the amount of biodiversity and the relative integrity or fragmentation of habitat areas [USEPA, 1995; Forman, 1995]. The potential impairment of the biotic component was measured by evaluating subbasin land use and several measures of biodiversity. These included percent core/priority habitat, areas which are known to harbor or have the potential to hold rare or endangered plants and animals, measures of species richness as the potential numbers of species of herptiles, birds and mammals and forest fragmentation. Data from the Massachusetts Natural Heritage and Endangered Species Program were used to measure core/priority habitat. Information from Gap Analysis was used to evaluate species richness, and fragmentation was measured as implemented in FRAGSTATS [McGarigal and Marks, 1995], a widely used software program for measuring landscape fragmentation. These tools were deemed most useful for assessing impairment at the subbasin scale.

[11] The human component was evaluated in categories of the built environment and urbanization impacts. Human stressors to the watershed system can be represented by measures of effective impervious area (the portion of the total impervious area that is directly connected to a drainage system [Randhir, 2003]), population and the presence of toxic
Percent effective impervious area (EIA) was a measure of the extent of the built environment. The intensity of urbanization impacts was evaluated by population density and the density of state-listed, 21E toxic waste sites which includes federally listed Comprehensive Environmental Response Compensation and Liability Act (CERCLA) or Superfund sites.

The attributes selected are representative of watershed patterns and processes and are identified in the literature as commonly used indicators of impairment to watershed systems [Shriver, 2005].

Using GIS and simulation modeling, areas for potential restoration were classified through a watershed analysis that placed site-specific impairment in the context of the relative health or degradation of the watershed as a whole. Spatial distribution of conditions in the study watershed is based upon the 14 attributes with every subbasin being assigned a scaled value from 1 to 5 to indicate the relative condition of potential impairment for that indicator. A value of 1 indicates the highest quality (least potential impairment) and 5 a condition of lowest quality (most potential impairment) for that measure. The cumulative impairment value or WPM represents for each subbasin the weighted sum of each scaled value (for fourteen attributes). An Attribute Prioritization Procedure (APP) was developed based on appropriate modification of the Analytic Hierarchy Process [Saaty, 1999] and Delphi Process [Linstone and Turoff, 1975] and was used to derive weights for the watershed attributes in order to analyze policy implications. Thus for each subbasin, the performance is measured as in (3).

\[
M^s = WPM^s = \sum_{i=1}^{14} w_i x_i^s
\]  

where \(WPM^s\) is the performance measure of subbasin \(s\), \(w_i\) is the weight for attribute \(i\) and \(x_i^s\) represents the scaled attribute values of attribute \(i\). \(w_i\) are relative weights associated with corresponding \(x_i^s\) and reflect the restoration value of that particular attribute.

The use of the WPM opens opportunities for analysis and comparison of subbasins. Each subbasin can be ranked according to its performance and thus provides a means of prioritizing areas for restoration as well as indicating the kind and extent of potential impairment. The overall performance of subbasin quality can show “hot spots,” i.e., subbasins that are especially impaired and conversely, those that are relatively unimpaired and therefore may require special protection measures. Highly impaired subbasins can be targeted for further study of the particular sites and causes of impairment and for restoration measures.

The method of classifying, quantifying and prioritizing watershed degradation by the WPM can be used as a decision support system. The performance measures need to be evaluated along with the cost of restoration and the cost of alternatives. Therefore the preference ranking would be used as an objective in decision making subject to cost constraints. The WPM can be used by agencies and communities to target funds for restoration and to evaluate watershed policies such as those for reducing effective impervious area through the use of urban forestry, the protection of endangered or threatened species and policies to reduce runoff and landscape fragmentation, for example. The WPM also provides a baseline of watershed conditions against which to measure the effects of land use changes over time.

2.1. Study Area

The WPM process was applied to the Chicopee River Watershed of western Massachusetts and its 209

![Figure 1. Conceptual model.](image-url)
subbasins (Figure 2). The watershed covers 187,066 hectares (1,871 km$^2$) and is composed of a mixture of rural, heavily forested lands, agricultural, suburban and urbanized areas. The watershed is drained by four major rivers, the Swift, Ware, Quaboag and Chicopee (main stem). The Chicopee River contributes an average annual flow of 913 million gallons per day (MGD) to the Connecticut River [Massachusetts Department of Environmental Protection (MADEP), 2001]. The Quabbin Reservoir covers approximately 10,300 ha of the northwest portion of the watershed. Approximately 155 MGD of water from the Quabbin are transferred out of the Chicopee watershed to supply drinking water to the Boston area (Massachusetts Water Resources Authority, Quabbin Reservoir and Ware River, http://www.mwra.com/04water/html/hist5.htm). The watershed is composed of all or part of 39 towns with a population of approximately 190,600 (2000 Census). The topography consists of rolling hills, alluvial plains and is dotted with numerous lakes and ponds. The land rises to a height of 457m above sea level in the northeastern part of the watershed and drops to 12m in the southwest corner of the watershed on the Connecticut River floodplain [MADEP, 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 [MADEP, 2001].

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 was 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 mainly 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]. Forest accounts for 69.5% of the watershed area. The combination of forest, crop, pasture, open lands, water and woody perennials comprise 86.8% of the landscape.

2.2. Attribute Quantification
2.2.1. Abiotic Components
2.2.1.1. Water Resources

Six water quantity and quality attributes of impairment were assessed for the subbasins of the Chicopee watershed: runoff, wetland density, sediment yield, loading of nitrate and phosphorus and levels of dissolved oxygen. All of the attributes were measured using the Soil and Water Assessment Tool (SWAT) except for dissolved oxygen and wetland density which are described separately.
The SWAT model, developed by Arnold and Allen [1992], is a daily, continuous time step model which can simulate conditions of large watersheds over long periods of time. It has been found useful for evaluating the impacts of land use and management practices on water, sediment, nutrients and agricultural chemical loads in basins with complex soils, topography and development patterns [USEPA, 1999; Neitsch et al., 2001; Santhi et al., 2001]. The model is physically based and requires specific information about a watershed’s weather, soil properties, topography, vegetation, land use and land management practices. SWAT models the hydrologic cycle based on the water balance equation and the routing of water through a subbasin stream and reservoir network. The model applies equations from the literature to evaluate nonpoint source pollution. The modified universal soil loss equation (MUSLE) [Williams, 1975] is used to estimate erosion and sediment yield, and the modified curve number method (CN) [Soil Conservation Service, 1972] is used to estimate runoff. SWAT models nutrients using volume and concentration [Neitsch et al., 2001].

The USEPA [2001] has incorporated SWAT in its BASINS (Better Assessment Science Integrating point and Nonpoint Sources, version 3.0) program. BASINS operates in conjunction with ArcView 3.2® (ESRI, Redlands, California) and the latter’s Spatial Analyst Tool. Data for BASINS [USEPA, 2001] and SWAT for the Chicopee River watershed (defined as data sets for basin 01080204, the eight-digit HUC) were projected in State Plane, 1983 Massachusetts Mainland (Lambert Conformal Conic). Subbasins for the Chicopee watershed were delineated using digital elevation model (DEM) and stream network information. National Elevation Datasets (NEDs) of 30 m × 30 m grids derived from 1:24,000 scale DEMs from U.S. Geological Survey (USGS) were used. The horizontal data were projected in NAD83; vertical data were NAVD88. The DEM was masked to the Chicopee watershed boundaries. Stream data were superimposed on the DEM by importing a National Hydrography Dataset (NHD) for the Chicopee watershed through use of BASINS NHD Import tool which links to a USGS server for 1:100K stream data.

SWAT also required land use and soil data to determine the area and hydrologic response parameters of each land-soil category simulated within each subbasin. BASINS incorporated land use polygons classified according to the Anderson level 2 codes. BASINS automatically converted the land use polygons into raster form to allow for integration and analysis with the DEM. BASINS data associated with the Chicopee watershed also contained State Soil and Geographic (STATSGO) grid information (from U.S. Department of Agriculture, Natural Resources Conservation Service) which was added to the project and clipped to the watershed boundaries. BASINS integrated the land use and soil layers with the DEM and stream information.

Hydrologic response units (HRUs) were defined for each land use and soil combination in each subbasin. SWAT later calculated the amount of runoff and pollutant loading for each HRU and totaled output by subbasin. Thus water quantity and quality conditions of the subbasins could be compared. Any land use or soil type that covered 5% or more of the subbasin was defined as a HRU. BASINS automatically eliminated minor land uses covering less than 5% of the subbasin and reappropriated land use categories so that 100% of the land area of each subbasin was modeled. Once the HRUs were defined, the SWAT model was activated.

SWAT integrated the information from the HRUs with precipitation and temperature data. To obtain model results that better reflected local conditions weather data for 43 years were downloaded from the National Climate Data Center of the National Oceanic and Atmospheric Administration (NOAA). Records from four stations were incorporated in the model, three of which are in the Chicopee watershed: Barre Falls Dam (Coop ID 190408), Belchertown (Coop ID 190562) and Ware (Coop ID 198793). Worcester Regional Airport (Coop ID 199923) lying east of the watershed was the fourth station. All stations had continuous daily precipitation statistics from 1 January 1960 through 31 December 2002. Only Worcester Regional Airport had complete temperature maximum and minimum information for the 43 year period, which was included in the SWAT model. SWAT simulated solar radiation, wind speed and relative humidity.

The model was applied to simulate 43 years from 1 January 1960 until 31 December 2002 and calculated results for each subbasin on an average annual basis. The model output was calibrated using the Indian Orchard, Massachusetts (site ID 01177000, USGS NWIS) gauge site on the main stem of the Chicopee River. Streamflow at Indian Orchard drains approximately 178,450 ha or 95% of the Chicopee watershed. The Hargreaves formula for potential evapotranspiration [Hargreaves et al., 1985] method produced the best correspondence of calibrated results with Indian Orchard streamflow data, $R^2 = 0.76$. This shows that the model’s predicted values had more than 76% explanatory power. On the basis of earlier SWAT calibration studies of simulated and monitored flow, $R^2$ values $\geq 0.6$ are considered statistically acceptable for further analysis [VanLiew and Garbrecht, 2003; Santhi et al., 2001]. Model results which incorporated the Hargreaves formula were used as the baseline data for this study.

An internal validation was performed on two subbasins to compare modeled results with monitoring data for nitrates and phosphorus from 1990 to 1994, years when monitoring information was available for both water quality indicators. The difference between mean annual simulated and monitored results for nitrates was $<0.008$ mg/L and $<0.02$ mg/L for phosphorus.

The modeled results from the subbasin output file used in this study were surface runoff contribution to streamflow (mm), sediment yield (metric tons per hectare), nitrate in surface runoff (kilograms per hectare) and soluble phosphorus (kilograms per hectare). Data were averaged by subbasin for 43 years to assess annual means. Annual mean is a sufficient indicator of relative loading from each subbasin on a long-term basis. For nonnormal distributions other statistics could be added.

Since other attributes of impairment were assessed using data from the GIS data repository of the Massachusetts Geographic Information System (MassGIS), SWAT modeled data for 276 subbasins were integrated with those from MassGIS which delineates 209 subbasins in the Chicopee watershed. In ArcView SWAT-delineated subbas-
sins were intersected with shape files of 209 subbasins, and area weighted to transform the data for 209 subbasins.

2.2.1.2. Dissolved Oxygen

[29] Dissolved oxygen was assessed using monitoring information from 36 stream reaches gathered in 1998 by the Massachusetts Department of Environmental Protection [MADEP, 2001], the most recent year for which data were available. For each stream reach, the average DO concentration (mg/L) was calculated. These values were assigned to the contributing subbasins associated with each reach and mapped in GIS.

2.2.1.3. Wetland Density

[30] Wetland density was measured using the MA Department of Environmental Protection (DEP) Wetlands layer (obtained from MassGIS) for the Chicopee watershed interpreted from 1:12,000 scale, stereo color-infrared photographs taken in leaf-off. The data were for two wetland classes, marshes and wooded swamps. The latter category included deciduous, coniferous, mixed trees and shrub swamps. This shape file was intersected with a shape file delineating the 209 subbasins and dissolved by subbasin.

2.2.2. Biotic Components

2.2.2.1. Core/Priority Habitat

[31] Core/Priority Habitat represents the union of the Natural Heritage and Endangered Species (NHESP) Bio-MAP Core Habitat layer with the NHESP Priority Sites Rare Species Habitat layer. It depicts the most viable habitats for rare species and natural communities and important habitats for state-listed species. The layers were intersected with the Chicopee subbasins and the percent area of priority and core habitats were calculated for each subbasin.

2.2.2.2. Habitat Suitability Index for Species

[32] The Gap Analysis Program of the USGS (for history and overview, see http://www.gap.uidaho.edu/About/gap_fs2004.pdf) was initiated to evaluate biodiversity “hot spots,” areas of high plant and animal diversity that were not protected in conservation lands. Areas of the U.S. including Southern New England were assessed and mapped for natural plant assemblages and predicted associated species of amphibians, reptiles, birds and mammals. Gap Analysis has been used to evaluate species richness in a variety of landscapes [Larson and Sengupta, 2004; Hunter et al., 2003; Pearlstine et al., 2002].

[33] Gap Analysis grid files (30 m × 30 m cells) for potential numbers of species of amphibians, reptiles, birds and mammals for southern New England were projected into State Plane, 1983 Massachusetts Mainland to conform to the projection of MassGIS and masked to the Chicopee subbasins. The grid files for amphibians and reptiles were combined using Map Calculate to create a new grid theme for herptiles. All grid themes were then converted to shape files and intersected with the Chicopee subbasins. Each of the three intersected themes was dissolved by subbasin and average potential number of species of herptiles, birds and mammals was calculated by subbasin.

2.2.2.3. Forest Fragmentation

[34] Since forest is the dominant (69.5%) land cover in the Chicopee watershed, its degree of fragmentation is an indicator of overall landscape fragmentation and habitat viability for forest-dwelling or forest-dependent species in the watershed. Commonly used measures of landscape fragmentation include average patch size, patch density and percent of landscape [McGarigal and Marks, 1995; Apan et al., 2000; Mid-Atlantic Regional Earth Science Applications Center, 2003; Sanchez-Azofeifa et al., 2001].

[35] The Land Use data layer of 21 land use classifications from MassGIS (produced from a 1:25,000 scale aerial photography and updated in 1999) was imported into ArcView and intersected with the Chicopee subbasins. For each subbasin the mean forest patch size (in hectares), forest patch density per subbasin (number of patches per hectare × 100) and percent of subbasin forest cover were calculated.

[36] Attribute tables were sorted sequentially by each fragmentation attribute and assigned scale values from 1 to 5 to divide subbasins into quintiles. Larger mean patch values and percent of forest cover were given lower scale values, indicating less potential impairment; smaller patches received higher values since they represented greater impairment. Conversely, smaller patch density values indicated less impairment and received lower scale values, while greater patch density values resulted in higher numbers indicative of greater potential impairment. Each scale value for every fragmentation measure was multiplied by 0.33 and summed for each subbasin to create an index of forest fragmentation that represented each fragmentation measure with equal weight.

2.2.3. Human Components

2.2.3.1. Effective Impervious Area

[37] The MassGIS Land Use map of 21 land use types was intersected with the Chicopee subbasins and analyzed for impervious surface area using the impervious surface coefficients from the MassGIS Data Viewer Watershed Analyst Tools. These coefficients were adjusted to reflect effective imperviousness based on estimates developed by Aqua Terra Consultants (of Mountain View, California) and MassGIS [2000]. EIA is usually less than total impervious area because not all precipitation falling on impervious surfaces becomes runoff. Some will infiltrate into soil through grassy areas and be intercepted by vegetation. The EIA coefficient was multiplied by the area of each land use within a subbasin to determine the area of impervious surface. The percent EIA was calculated by subbasin. EIA is used as a measure of the broad impacts of the built environment in watersheds.

2.2.3.2. Population Density

[38] The MassGIS Census 2000 TIGER Towns data layer was intersected with the Chicopee subbasin layer. Population density was calculated by dividing total town population by town area in hectares. For each subbasin the population densities per hectare of its associated towns were multiplied by the subbasin area to calculate the average population density per hectare for each subbasin. Population density is a good initial approximation and does not reveal whether populations are dispersed or clustered.

2.2.3.3. Density of Toxic Waste Sites

[39] The DEP (DEP) Classified Oil or Hazardous Material Sites data layer from MassGIS contains approximate locations of oil or hazardous material disposal sites that have been reported and classified under Massachusetts General Law Chapter 21E and the Massachusetts Contingency Plan. Site information was updated as of May 2004. The data layer was clipped and intersected with the Chicopee subbasins and indicated 116 sites including 3 CERCLA sites in 36 subbasins. 173 subbasins had no 21E sites.
number of sites per hectare was calculated for each subbasin to determine the density of toxic waste sites.

[40] The number of toxic waste sites gives a first approximation of potential impairment from toxic waste in a subbasin. The type and level of toxic loading varies among sites, and a complete site-by-site evaluation is beyond the scope of this study.

[41] Other metrics could be used to measure impacts to the human component such as the number of cars or percent area of paved roads. These measures could be included if not correlated with population density and/or EIA, respectively.

2.2.4. Prioritization of Attributes: Attribute Prioritization Procedure

[42] This method combines the AHP [Saaty, 1999] and Delphi process [Linstone and Turoff, 1975] and was conducted using a panel of 10 stakeholders. In advance of the meeting they were given information about the study, its methods and the APP. Representatives were from the University of Massachusetts (UMass) Department of Plant and Soil Sciences, UMass Department of Natural Resources Conservation, UMass The Environmental Institute, Massachusetts Cooperative Fish and Wildlife Research Unit, the USDA Natural Resources Conservation Service, MA Department of Conservation and Recreation, Division of Water Supply Protection, the Pioneer Valley Regional Planning Commission and the MA Watershed Coalition, a nonprofit organization. Panelists represented expertise in agriculture, citizen outreach, wildlife conservation, forestry, water quality, regional development and watershed science.

[43] The aims and methods of the research were reviewed, and the study’s conceptual model was explained. Panelists agreed that the selected attributes were appropriate for evaluating impairment in the study area. Panelists were given a matrix in which they were asked to compare each of the impairment attributes with the others and rank the paired comparisons. Participants were asked a set of questions about each indicator of potential impairment to provide consistent objectives for applying a numerical rank. In evaluating the relative importance of runoff, they were asked: Is reducing runoff more important than increasing wetland area? Each question was repeated in relation to all the other attributes. Panelists were told not to consider cost in making attribute comparisons, only the relative importance of attributes in relation to the health of the watershed as a whole. Panelists completed individual matrices before undertaking group consensus.

[44] They then discussed their individual rankings in order to reach agreement on a single, consensus value for each of 66 paired comparisons. The paired comparison of all attributes allowed panelists a clearer perception of what was being ranked compared to the use of an intermediate hierarchy, e.g., abiotic, biotic and human. The facilitator picked paired attributes for discussion in a randomized fashion. This differed from previous methods [Randhir et al., 2001] in conducting pairwise comparisons whereby the facilitator began in the upper left-hand corner of the matrix and proceeded sequentially along the rows and columns. The randomized method of choosing pairs allowed for more debate about paired attributes from disparate portions of the matrix. Since lengthier discussion tends to take place among the first paired attributes and, due to time constraints, less debate takes place among pairs discussed later in the session; a randomized method of selecting pairs allows some lengthy discussion about all parts of the matrix.

[45] Panelists were given an additional week to consider changes to the group consensus values, thus incorporating elements of the Delphi process. Each proposed change was debated by the group via email to reach agreement. These group consensus values became the basis for the analysis and calculation of weights or priorities. While the APP was focused on a single face-to-face session, its preparation and completion with panelists spanned a period of approximately seven weeks.

[46] Group consensus values were analyzed to determine priority weights for the indicators of potential impairment. The consistency index (CI) was calculated using $CI = \frac{\lambda_{max} - n}{n - 1}$, where $\lambda_{max}$ is the average of vectors obtained from row total vectors divided by the corresponding priority vector, and $n$ is the number of elements in the matrix. This formula was used to calculate the consistency ratio [Saaty, 1999]. The initial consistency ratio was 11.5%, greater than the maximum of 10% suggested by Saaty [1999]. Inconsistency arises because individuals are making decisions in a complex environment and cannot make perfectly rational judgments, particularly when weighing the relative importance of dozens of paired attributes. This tendency mirrors the intricacy of environmental decision making, and this ratio quantifies such inconsistencies.

[47] Group consensus values were therefore examined for transitivity {If A $\geq$ B and B $\geq$ C, then A $\geq$ C}. Group consensus values for each attribute of impairment were compared with the other values and examined for intransitivity. Three key inconsistencies were identified and were corrected using overall ranking paths of all attributes and a consistency ratio of 5.4% was obtained. Priority weights for each indicator were calculated.

2.2.5. Watershed Performance Measure

[48] The cumulative potential impairment value or WPM was calculated for each subbasin according to Equation 3 and represents for each subbasin the sum of each scaled value (for 14 attributes) multiplied by its weight determined by stakeholders’ prioritization using the APP method. A map was created in which subbasins were divided into 10 groups of relative impairment so that the relative impairment of subbasins for the suite of abiotic, biotic and human components could be compared and analyzed. The 20 most impaired subbasins were identified and the map of cumulative watershed impairment was intersected with the map of community boundaries (towns). This allowed the most degraded subbasins to be located by town and further analyzed for the principal sources of potential impairment.

[49] The integrated method used is data intensive and could be limited in areas where GIS data are not readily available. The set of attributes defined can vary from watershed to watershed. The methodology is dependent on blending technical expertise and stakeholder expertise in assessing watershed performance.

3. Results and Discussion

[50] Results of measures of the abiotic, biotic, and human watershed components are summarized below (Tables 1, 2, and 3) for the subbasins in the Chicopee watershed. The values indicated are subbasin mean, coefficient of variation.
Table 1. Water Quantity and Quality Attributes in the Study Watershed

<table>
<thead>
<tr>
<th>Impairment</th>
<th>Mean per Subbasin</th>
<th>Coefficient of Variation</th>
<th>Subbasin Maximum</th>
<th>Subbasin Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff, mm</td>
<td>337.22</td>
<td>0.17</td>
<td>466.87</td>
<td>193.62</td>
</tr>
<tr>
<td>Sediment, t/ha</td>
<td>0.81</td>
<td>1.35</td>
<td>7.33</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrate, kg/ha</td>
<td>1.31</td>
<td>0.21</td>
<td>1.92</td>
<td>0.70</td>
</tr>
<tr>
<td>Phosphorus, kg/ha</td>
<td>0.07</td>
<td>0.71</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td>Dissolved oxygen, mg/L</td>
<td>8.71</td>
<td>0.13</td>
<td>11.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Wetland density, %</td>
<td>9.2</td>
<td>0.66</td>
<td>35.8</td>
<td>0.00</td>
</tr>
</tbody>
</table>

3.1. Water Quantity and Quality Indicators

[51] The 43-year average values for each indicator of impairment were calculated based upon the simulation modeling and maps were produced to show the conditions of relative potential impairment for runoff, sediment yield, nitrate, phosphorus, dissolved oxygen and wetland density in the Chicopee River Watershed. Averaging water quality impairments for 43 years creates the potential for discounting later impairments. However, this method produces a good indicator of long-term subbasin impairment which allows for relative comparisons of subbasin degradation.

[52] The average runoff in the study area was 337.22 mm. Sediment loading averaged 0.81 metric tons/ha. Nitrogen loading was 1.31 kg/ha, phosphorus loading was 0.07 kg/ha, and dissolved oxygen levels averaged 8.71 mg/L (Table 1). Terms for runoff, nitrogen, phosphorus and sediment are the standard SWAT output for water quantity and quality variables.

[53] Runoff is highest in the north central and eastern portions of the watershed, where greater variation in topographic relief was observed. Runoff hydrology is complex and differs in natural and urban systems. This complexity is not addressed in this study.

[54] Sediment loads are highest in the subbasins downstream of subbasins with higher runoff and are concentrated in the central and south central portions of the watershed. Spatially, subbasin impairment from nitrites is very similar to that for runoff and is focused in the north central and eastern portions of the watershed. Watershed phosphorus impairment is centered in southern parts of the watershed which are more urbanized. Lowest levels of dissolved oxygen and hence greatest potential impairment are also focused in the southern, urbanized portion of the watershed.

Table 2. Habitat and Biodiversity Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Mean per Subbasin</th>
<th>Coefficient of Variation</th>
<th>Subbasin Maximum</th>
<th>Subbasin Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent core/priority habitat</td>
<td>22.89</td>
<td>1.37</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Herptiles</td>
<td>19.85</td>
<td>0.11</td>
<td>26.1</td>
<td>11.9</td>
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<tr>
<td>Birds</td>
<td>53.49</td>
<td>0.10</td>
<td>64.6</td>
<td>31.5</td>
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<tr>
<td>Mammals</td>
<td>33.11</td>
<td>0.11</td>
<td>38.3</td>
<td>19.0</td>
</tr>
<tr>
<td>Forest fragmentation index</td>
<td>2.96</td>
<td>0.43</td>
<td>4.95</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 3. Summary of Human Attributes

<table>
<thead>
<tr>
<th>Impairment</th>
<th>Mean per Subbasin</th>
<th>Coefficient of Variation</th>
<th>Subbasin Maximum</th>
<th>Subbasin Minimum</th>
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</thead>
<tbody>
<tr>
<td>EIA, %</td>
<td>1.17</td>
<td>2.62</td>
<td>27.76</td>
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<tr>
<td>Population density</td>
<td>1.01</td>
<td>1.48</td>
<td>13.26</td>
<td>0.06</td>
</tr>
<tr>
<td>Toxic waste sites</td>
<td>0.0023</td>
<td>1.26</td>
<td>0.01575</td>
<td>0.0044</td>
</tr>
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</table>

[55] Coefficients of variation (CV) for indicators of water quantity and quality show little or moderate variation from the subbasin average: runoff (CV = 0.17), sediment (CV = 1.35), nitrate (CV = 0.21), phosphorus (CV = 0.71) and dissolved oxygen (CV = 0.13).

[56] Wetlands occur in all subbasins except one. The density of wetlands ranges from 0.0% to 35.8%. Average wetland density for all subbasins is 9.2%; the coefficient of variation is 0.66. Spatially, highest wetland densities occur in the northeast and southeast portions of the watershed with a small area of low potential impairment in the southwest part of the watershed. These subbasins could be targeted for protection and/or restoration of wetland areas. Subbasins in the northeast and southeast portions are in the headwaters of the Ware and Quaboag Rivers, respectively. Those in the southwest part are near tributaries of the Chicopee River main stem. Measures to protect wetlands in all three areas could have beneficial downstream impacts for water quality and flood water detention.

3.2. Habitat and Biodiversity Indicators

[57] The percent of core/priority habitat was used as an indicator of the vulnerability of wildlife and loss of biodiversity based on habitat characteristics. This attribute had a mean value of 27.8% and showed high variability among subbasins (Table 2). Values varied between 0 and 100%. Habitat availability is concentrated in the northwest portion of the watershed around the Quabbin reservoir and the northeast area. Some critical habitat exists in the lower half of the watershed near urbanized areas and could therefore be targeted for preservation actions.

[58] The average potential number of species for herptiles, birds, and mammals is smallest in the subbasins in the southwest portion of the watershed near the outlet, the most heavily urbanized area of the watershed. The distribution of subbasins with potential species of herptiles shows high variability, particularly for the subbasins that have the highest potential numbers of species of herptiles; i.e., with scale values of 1. Average potential number of herptile species ranged from 11.9 in the more highly impaired subbasins to 26.1 in the least impaired subbasins. Average potential number of herptile species for all subbasins was 19.9. The spatial distribution of the average potential number of species of birds and mammals is focused in the northeastern part of the watershed. Average potential number of species of birds varies from 31.5 in the most impaired subbasins to 64.6 in the areas with greatest potential bird diversity. Average potential number of species of birds for the Chicopee watershed is 53.5. Average potential number of species of mammals ranges from 19.0 to 38.3; the average number of potential species of mammals for all subbasins is 33.1.
Table 4. Group Consensus Weights for Impairment Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Group Consensus Weight</th>
</tr>
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<tbody>
<tr>
<td>Runoff</td>
<td>0.15</td>
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<tr>
<td>Wetland density</td>
<td>0.05</td>
</tr>
<tr>
<td>Sediment yield</td>
<td>0.09</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.045</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.045</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>0.05</td>
</tr>
<tr>
<td>Percent core/priority habitat</td>
<td>0.06</td>
</tr>
<tr>
<td>Potential number of species reptiles</td>
<td>0.04</td>
</tr>
<tr>
<td>Potential number of species birds</td>
<td>0.025</td>
</tr>
<tr>
<td>Potential number of species mammals</td>
<td>0.025</td>
</tr>
<tr>
<td>Forest fragmentation</td>
<td>0.06</td>
</tr>
<tr>
<td>Effective impervious area</td>
<td>0.09</td>
</tr>
<tr>
<td>Population density</td>
<td>0.09</td>
</tr>
<tr>
<td>Number of toxic waste sites</td>
<td>0.19</td>
</tr>
</tbody>
</table>

[59] The combined measures of forest fragmentation (mean forest patch size, forest patch density and percent of subbasin forest cover) show that subbasins with greatest fragmentation occur in the more heavily urbanized southern portion of the watershed. Forest fragmentation is least in the northern one third of the watershed. Mean patch area varies from 4.3 ha to 632.2 ha. Average subbasin mean patch area is 81.90 ha. Patch density values range from 0.13 to 14.12, with an average value for all subbasins of 1.77. The percent of subbasin forest cover varies from 14.4 to 99.7 with an average subbasin forest cover of 73.0% for the Chicopee watershed.

[60] The coefficients of variation indicate highest variability among subbasins for core/priority habitat, where values may range 137% around the mean (CV = 1.37). Forest fragmentation values show the next highest variability with CV = 0.43. Coefficients of variation for average potential numbers of species of reptiles (CV = 0.11), birds (CV = 0.10) and mammals (CV = 0.11) indicate that subbasin values may vary by 10% to 11% from the mean.

3.3. Impacts of the Built Environment and Urbanization

Potential watershed impairment from impacts of EIA is concentrated in the lower half of the watershed with higher impairment toward the watershed outlet. This location coincides with portions of the cities of Chicopee and Springfield. Suburbanizing watersheds are concentrated in the southeastern portions of the Chicopee watershed. A low level of imperviousness is distributed in northern and eastern areas of the watershed. Percent EIA ranged from 0 to 27.76 (Table 3).

The impact of urbanization due to population density indicates that densities are highest in the southern half of the watershed, particularly in the southwest corner near the outlet in the cities of Chicopee and Springfield. Population densities range from 0.06 to 13.26 persons per hectare. Average subbasin population density is 1.01 persons per hectare (Table 3). Areas of high population density and greatest EIA show similar distribution patterns throughout the watershed.

Most of the subbasins (173) in the Chicopee watershed have no state-classified 21E, oil or hazardous materials waste sites. Thirty-six subbasins (17%) contain a total of 116 sites. Potential impairment comes from a variety of industries that use or produce hazardous chemicals as well as from electric power plants, landfills, fuel oil companies, automobile service stations and dry cleaners. While impairment differs among industries, this study focuses on densities. Assessment based on industry is complex and beyond the scope of this study. Most impaired subbasins are concentrated in the southwest corner of the watershed in the urbanized areas. A surprising result is that a string of highly impaired subbasins occurs in the north central area of the Ware River watershed. Among subbasins with toxic waste sites, densities range from 4.4 sites to 157.5 sites per 10,000 hectares.

[64] Fairly high variability exists among the subbasins for EIA (CV = 2.62), population density (CV = 1.48) and toxic waste sites (CV = 1.26) indicating that values vary about the means from 262% (EIA) to 126% (toxic waste sites).

3.4. Attribute Prioritization Procedure

The priority weights derived from the APP (Table 4) were multiplied by the scale values for each of the 14 attributes of potential impairment for each of the 209 subbasins of the Chicopee watershed (see equation (3)). These products were then summed for all attributes by subbasin to produce a composite value of potential impairment for each subbasin or WPM. Thus the relative impairment of subbasins for the suite of abiotic, biotic and human components can be compared and analyzed. Results of the WPM for 14 attributes of potential impairment are presented in Figure 3. Subbasins were divided into 10 groups of relative impairment. Subbasins in the darkest shade are the 20 most impaired subbasins in the Chicopee watershed based on the WPM.

The WPM indicates that greatest potential impairment is focused in the southwest and southern portions of the watershed, particularly near the outlet. These are the most highly urbanized areas. There is also significant potential impairment in the east central portion of the watershed in aging industrial communities. Several highly impaired, “hot spot” subbasins are located in the north...
central portion of the watershed in the headwater areas of the Ware River watershed. A band of lesser, but significant potential impairment extends south of these hot spots and may indicate subbasins at particular risk of continued impairment. Least impaired subbasins are in the northwest section of the watershed near the Quabbin Reservoir and in the northeast part of the watershed. Both of these areas have extensive amounts of state-owned land in conservation for water supply protection. A small number of unimpaired subbasins are distributed throughout the south central part of the watershed. They could be targeted for land conservation and protection measures. Cumulative impairment scores range from 1.40 for the least impaired subbasin to 4.44 in the most impaired subbasin.

3.6. Analysis of the 20 Subbasins of Least Performance

The primary contributors to subbasin impairment are remarkably consistent, are focused in the attribute measures from the human component, water quantity and habitat measures and reflect the seven highest priority weights of expert stakeholders in the AHP. Seventeen of the 20 most impaired subbasins had EIA among the primary contributors of potential impairment (priority weight: 0.09); 16 subbasins had impairment from sediment among the highest three or four forms of degradation (priority weight: 0.09); and 5 subbasins had a high amount of impairment from forest fragmentation (priority weight 0.06) and lack of core and priority habitat (priority weight 0.06) (Table 5). Among the primary contributors to subbasin impairment in the 20 most degraded subbasins (Table 5, italic values), damage from toxic waste accounted for an average of 21.3% of subbasin impairment; runoff contributed an average of 16.6% of subbasin degradation; EIA accounted for 11.3%; impacts of population density contributed 10.3%; sediment impairment accounted for 10.0%; forest fragmentation contributed 7.8% and lack of core/priority habitat accounted for an average of 7.7% of subbasin degradation. Therefore, if the 20 most impaired subbasins are targeted for restoration, the greatest potential benefit to the Chicopee watershed as a whole will come from implementing policies and management practices to address potential impairment from toxic waste, runoff, impacts from EIA, population density, sediment, forest fragmentation and loss of habitat. The choice of policies and best management practices (BMPs) would also be affected by their costs and other economic implications.

Figure 3. WPM, composite index of potential impairment, and town boundaries.
An examination of the three or four major contributors to subbasin potential impairment in the 20 most degraded subbasins showed that these forms of impairment account for between 39.8% and 55.4% of subbasin impairment (Table 5). Italic values indicate the three or four largest contributors to subbasin impairment. The largest percent contribution of degradation for each subbasin is in bold. Impairment from toxic waste contributed the most degradation in 13 of the 20 most impaired subbasins and runoff contributed the most in 7 of the most highly impaired subbasins.

### 3.7. Subbasin Performance at a Community Scale

The above analysis can provide a tool for community members and decision makers at local, regional, state and federal levels to understand the kinds and degree of degradation of the whole watershed and its spatial distribution. This analysis of potential subbasin impairment can be used as the basis for a protocol to target subbasins and communities for restoration. The rank ordering by impairment of the 20 most impaired subbasins can be augmented with information about the towns in which they are located (Figure 3).

Communities with subbasins among the 20 most impaired are Barre, Brimfield, Chicopee, East Brookfield, Ludlow, Monson, North Brookfield, Palmer, Spencer, Springfield, Ware, Warren and Wilbraham. Most of these towns are located in the southern and eastern portions of the watershed and are aging industrial communities with toxic waste sites and impairment from runoff.

By contrast, Barre is located in the north central part of the watershed and has two highly impaired “hot spot” subbasins. Subbasins 77 and 79 rank, respectively, as the 4th and 20th most impaired subbasins in the Chicopee watershed (Figure 4). They are located in the upper reaches of the Ware River watershed in relatively steep terrain. Surrounding subbasins to the north, east and west are of low potential impairment, but those southwest and downstream of the hot spot subbasins are of relatively high impairment. Table 6 indicates that 18.3% of subbasin 77’s and 20.5% of subbasin 79’s impairment is from toxic waste sites. Potential impairment from runoff, impacts of effective impervious area, and sediment impairment rank high for both subbasins. Thus restoration for these Barre subbasins should target these forms of impairment in order to improve conditions in the watershed as a whole. Given the location of these subbasins in the upper reaches of the Ware River watershed, it is possible that amelioration of these subbasins’ impairment could have downstream benefits.

Barre land use offers insights to some possible causes of impairment in these two subbasins. Among them are areas of mining operations, particularly in subbasin 77 as well as industrial sites, commercial areas, crop land and medium and high-density residential development. These can be sites of toxic waste contamination, runoff and impacts from EIA. This information can serve as a starting point for ground truthing through on-site visits and can help the community assess its zoning and other policies and BMPs for methods to reduce runoff and impacts of EIA.

The high rank of these subbasins in overall Chicopee watershed impairment and the significant potential impairment from toxic waste sites could leverage Barre’s position for receiving state and federal aid for toxic waste cleanup. The information from this analysis is not intended to prescribe specific actions at particular sites, but rather offers a context for placing the potential impairment of these subbasins in relationship to impairment of the whole watershed.

It is important that restoration decisions take into account the community’s knowledge of its areas and causes of impairment, as well as information from monitoring and other environmental studies. The costs and benefits of

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### Table 5. Major Sources of Potential Impairment in the 20 Least Performing Subbasins

<table>
<thead>
<tr>
<th>Rank</th>
<th>Subbasin Number</th>
<th>Area, Ha</th>
<th>Sum Scale Values</th>
<th>Runoff</th>
<th>Sediment</th>
<th>Habitat</th>
<th>Forest Fragmentation</th>
<th>EIA</th>
<th>Population Density</th>
<th>Toxic Waste</th>
<th>All Major Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>347</td>
<td>2190.207</td>
<td>4.437</td>
<td>10.1</td>
<td>8.1</td>
<td>5.4</td>
<td>6.2</td>
<td>10.1</td>
<td>10.1</td>
<td>21.4</td>
<td>51.7</td>
</tr>
<tr>
<td>2</td>
<td>286</td>
<td>272.833</td>
<td>4.408</td>
<td>17.0</td>
<td>8.2</td>
<td>4.1</td>
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<td>21.6</td>
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<td>3</td>
<td>218</td>
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<td>4.3</td>
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<td>10.8</td>
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<td>18.3</td>
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<td>12.2</td>
<td>4.9</td>
<td>20.5</td>
<td>54.6</td>
</tr>
</tbody>
</table>

---

*aItalic indicates the three or four largest contributors to subbasin impairment. Bold indicates largest percent contribution of degradation for each subbasin.

bDenotes percent subbasin impairment from the attribute.
specific restoration measures would be debated at a later stage but with the added benefit of the assessment of the standing of Barre’s subbasins in the context of the whole watershed. Another benefit is increasing the community’s awareness that it encompasses subbasins which should be managed based on an understanding of watershed patterns and processes, not only on the basis of political boundaries.

3.8. Community-Based Subbasin Restoration Strategies

[76] Restoration strategies for subbasins 77 and 79 in Barre can be further analyzed to determine appropriate policies and BMPs to restore toxic waste sites and mitigate impairment from runoff, EIA and sediment. See Shriver [2005] and MADEP [1993] for a discussion of practices.

3.9. Community Collaboration for Watershed Restoration

[77] Where subbasins cross community boundaries, it will be necessary for towns to work together to plan and implement restoration strategies. As well, upstream and downstream communities in the greater watershed will benefit from collaboration on subbasin restoration. Such cooperation could range from voluntary measures to legal mandates. Voluntary measures could be based on efforts to educate community members, especially local select boards, planning boards and conservation commissions about the importance of working with communities to restore shared subbasins. Voluntary instruments could include nonbinding memoranda of understanding between communities to engage in specified restoration practices [Heathcote, 1998]. Voluntary efforts to encourage collaboration among com-

Table 6. Attribute Mapping of Performance in Barre Subbasins 77 and 79

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>77</th>
<th>79</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, Ha</td>
<td>569.3</td>
<td>772.0</td>
</tr>
<tr>
<td>Runoff, %</td>
<td>18.0</td>
<td>12.2</td>
</tr>
<tr>
<td>Wetland density, %</td>
<td>3.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Sediment, %</td>
<td>8.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Nitrate, %</td>
<td>5.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Phosphorus, %</td>
<td>5.4</td>
<td>4.9</td>
</tr>
<tr>
<td>DO, %</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td>C/P habitat, %</td>
<td>4.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Herptiles, %</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Birds, %</td>
<td>2.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Mammals, %</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Forest fragmentation, %</td>
<td>6.2</td>
<td>6.9</td>
</tr>
<tr>
<td>EIA, %</td>
<td>10.8</td>
<td>12.2</td>
</tr>
<tr>
<td>Population density, %</td>
<td>4.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Toxic waste, %</td>
<td>18.3</td>
<td>20.5</td>
</tr>
</tbody>
</table>

*Values associated with impairment attributes denote percent subbasin impairment. Bold values indicate highest percentages of impairment.
communities may take more time to build, but could be very effective if, by educating the public, they develop grassroots support for shared restoration measures.

[78] Government can use tools to mandate or provide incentives for community collaboration [Stokey and Zeckhauser, 1978]. The state could pass legislation to require communities to collaborate for watershed restoration or provide incentives for community cooperation. For example, Massachusetts could make Community Preservation Funds, which may go to towns for the purchase of open space, contingent upon cooperation with other communities for watershed planning and restoration.

3.10. Practical Implications

[79] This study develops a methodology that integrates many modeling and analytical procedures in the development of the performance metrics. While a combinatorial method is inevitable given the complex nature of the assessment, it is worth noting the potential pitfalls in terms of uncertainty and errors. As in any modeling, simulation can involve errors from parameter measurement and the specification of process equations for watershed systems. The calibration and validation of the simulation model can reduce the deviation between simulated and observed values and thereby minimize errors. The availability and spatial extent of multiatribute data continue to be a challenge in development of watershed simulation models. Uncertainty associated with data availability could be reduced by careful application of the process models.

[80] Another area of potential error is in the prioritization of multiple attributes. Improper representation of the stakeholders could result in biased weights. It is important to include major players and provide adequate opportunity for information exchange. The potential for bias exists from dominant players in the group. Such bias needs to be balanced through facilitation. It is critical to test prioritization outcomes for violations of preference ordering using preference mapping and consistency tests.

[81] The identification of relevant, major watershed attributes can be a source of error if improperly done. A careful selection and quantification of major attributes of impairment should be based on watershed history, literature, and previous research in the watershed. The weights assigned to these attributes should be determined by representative stakeholders who are familiar with the watershed. The weights are specific to the set of attributes that are considered in the preference ordering. The addition of new attributes would thus require a reevaluation of the preference weights. The preference assessment can be easily reevaluated at local community and subscale watersheds as a conditional assessment.

[82] Integrated modeling involves many analytical procedures and improper integration could result in biased or erroneous results. The procedures and integrated methods need to be based on a common platform such as GIS (as used in this study) or an optimization framework. Errors in one procedure can be transmitted into the integrated model and care must be taken to recognize and minimize such error propagation.

[83] The methodology is data intensive and requires technical expertise in quantifying attributes. Stakeholder expertise is also central to developing the performance metrics. Application of this methodology in other watersheds requires appropriate identification of relevant attributes and priority weights. As in the case of any methodology minimization of errors is critical to this method. Uncertainty, errors and bias could arise in information, measurement, and model output, if these are not correctly evaluated. These caveats are typical in any experimental methods and should be considered with this analysis.

[84] In spite of the extensive data collection and modeling complexity, gains achieved by using integrated methods to analyze complex processes in watershed systems can far outweigh potential uncertainty and errors in modeling. Simplified models are often ineffective in reflecting the watershed system as a whole and can result in inaccurate and unreliable results. Integrated methods are superior if properly applied and constantly updated.

4. Conclusion

[85] The purpose of this study has been to develop and apply a performance based approach to classify and prioritize subbasins for restoration based upon a broad array of indicators of impairment related to the physical, biological and human components of a watershed. The quantification of multiple attributes of potential impairment has been linked with a prioritization process to incorporate stakeholder values. This effort is important because watershed restoration requires an assessment to quantify the extent of impairment of ecosystem processes and a comprehensive approach to analyze, prioritize and allocate resources to areas of greatest impairment. By assessing the condition of the abiotic, biotic and human systems within the watershed, the relative health and degradation of the components of those systems can be ascertained, sources of potential impairment identified and policies and strategies formulated for restoring and sustaining watershed health. This assessment method can help inform policies, planning and decision making at a variety of scales (local, regional, state, and federal) by providing important information about baseline conditions in the watershed and relative potential impairment at a subbasin scale. The use of spatial modeling in this methodology allows ungauged watersheds or those with insufficient monitoring data to be assessed and compared. The methodology is also useful in identifying upstream “hot spots” where timely remediation could have downstream benefits and in distinguishing subbasins of very low potential impairment where conservation and protection measures may be important. It can also provide information that is useful in developing incentives and mechanisms to facilitate cooperative action among upstream and downstream communities to reduce impairment of shared subbasins. The method is transferable to other watersheds and is also flexible, allowing for the use of other indicators of impairment and a prioritization process that can incorporate values of a variety of stakeholders. While the methodology is complex, its results can be readily understood by the public.

[86] This methodology provides a performance metric which enables communities to plot the relative impairment of their subbasins in relationship to the watershed as a whole and to adopt restoration policies and BMPs with short-term strategies that serve long-term restoration goals for ecosystem sustainability.
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