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A Multiple Objective Decision Analysis of Stakeholder Values

to Identify Watershed Improvement Needs

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Abstract

The paper describes the use of multiple objective decision analysis to qualitatively and quantitatively assess the quality of an endangered watershed and guide future efforts to improve the quality of the watershed. The Upham Brook watershed is an urban watershed that lies at the interface of declining inner city Richmond, Virginia and growth-oriented Henrico County. A section of stream within the watershed has been identified as so dangerously polluted that it threatens the health of the residents who live within the watershed boundaries. With funding provided by the National Science Foundation, the Upham Brook watershed project committee was formed to address the quality of the Upham Brook watershed; it consisted of experts from multiple disciplines: stream ecology, environmental policy, water policy, ground and surface water hydrology and quality, aquatic biology, political science, sociology, citizen participation, community interaction, psychology, and decision and risk analysis. Each members' values and goals were brought together using a watershed management framework to meet the overall objective of the committee: to maximize the quality of the Upham Brook watershed. The resulting model was used to identify the largest value gaps and to identify future programs needed to improve the quality of the watershed.

Keywords: Multidisciplinary, environmental, watershed management, watershed quality, multiple objective decision analysis, Value-Focused Thinking.

1. Introduction

This paper demonstrates a multiple objective decision analysis approach to watershed improvement. We develop a value model to qualitatively and quantitatively define the values of stakeholders and assess the quality of an urban watershed. A watershed is defined as the area where precipitation drains to a common waterway, such as a stream, lake, estuary, wetland, or even the ocean. At a more complex level, a watershed is viewed as a "series of ecosystems linked spatially and temporally by the natural downward flow of water" (Qiu et al. 1998). Watershed management aims to maintain, protect and restore the physical, chemical and biological integrity of the aquatic ecosystem, protect human health and provide sustainable economic growth (Adler 1996, Davis 1998). Many water quality and ecosystem problems are best understood and solved at a watershed level (Environmental Protection Agency 1995, National Research Council 1999). We studied the Upham Brook watershed in Richmond, Virginia. This watershed lies partly in the City of Richmond, a declining urban area, and partly in Henrico County, an expanding suburb. Government of the watershed is dispersed across various local, state and national agencies. Thus, the watershed has multiple stakeholders, including the wildlife and the human residents of the watershed, community organizations, industry, and government.

The multiple objective decision analysis approach allowed the consideration of multiple stakeholders' views. The Upham Brook Watershed project committee was organized with experts from various research backgrounds (Table 1). The project was funded by the National Science Foundation. The purpose of the grant was to perform a multidisciplinary assessment of the problems with the watershed, in order to determine the current health of the watershed along with the needs for improvement. The committee members included university researchers, local environmentalists and specialists from various government agencies, many of whom live within the watershed.

Name	Expertise
Diane Dunaway	Community involvement, bayscaping

Dr. Don Forsyth	Social psychology, attitudes and social cognition
Dr. Margot Garcia	Environmental policy, water policy, citizen participation
Dr. Gregory Garman	Aquatic ecology, fisheries, streams and wetlands, stream ecology
Dr. Mort Gulak	Architecture, urban design, urban revitalization
Dr. Neil Henry	Sociology, statistics
Paddy Katzen	Community Interaction
Dr. Jo Mitchell	Amphibian ecology, streams and wetlands
Dr. John Moeser	Urban politics, policy making and implementation
Dr. Bob Rugg	Geographical Information Systems
Dr. Len Smock	Stream ecology, aquatic biota, water pollution
Gary Speiran	Ground and surface water hydrology, water quality

Table 1. The members of the Upham Brook Watershed Project Committee.

Parnell et al. (1998) define three standards for developing multiple objective value models: platinum, gold and silver standard. A platinum standard process uses interviews with senior stakeholders and decision makers to determine the objectives. A gold standard process determines the objectives from policy or strategic planning documents approved by the decision makers. The silver standard uses interviews with subject matter experts and stakeholder representatives. This project used the silver standard method. As the project committee did not consist of government decision makers with available budgets, the desired end result of the decision process was an identification of leverage points and strategies that could initiate awareness of problems and future action by watershed decision makers. The goal was not to perform a cost-benefit analysis or determine the best portfolio of improvement projects.

Using multiple objective decision-making tools to assist watershed managers is not a new idea. In October of 1997, the Environmental Protection Agency (EPA) developed the first Index of Watershed Indicators. The Index was intended to establish recognized criteria to measure the "health" of watersheds across the nation. However, the indicators were neither mutually exclusive

nor were they combined using any kind of preference function. At about the same time, the Anacostia Watershed Restoration Committee developed a set of ecological indicators for an urban watershed in Maryland (Warner 1996). Their development process closely followed a multiple objective decision analysis process, including developing a value hierarchy and evaluation measures. However, they did not develop a value or utility function. Multiple objective decision analysis has been shown to be a useful technique in the selection of the best management systems for farm properties in an agricultural watershed (Prato 1999; Prato & Hajkowicz 1999). These studies examined several different weighting and ranking methods for multiple objectives and applied them to the selection of fifteen hypothetical farming systems.

One member of the Upham Brook project committee, the fourth author of this paper and principal investigator for the NSF grant that funded this work, believed that multiple objective decision analysis would be a suitable tool for watershed assessment. She recruited the other three authors to convince the rest of the project committee and to facilitate the model building process. Each committee members' values and objectives were integrated using a multiple objective decision analysis framework (Keeney and Raiffa 1993). In order to identify the most serious problems facing the Watershed, we utilized value-focused thinking (Keeney 1992) to compare Upham Brook to hypothetical perfect and completely imperfect watersheds. Our model provides a baseline measure of how well the watershed is currently doing and identifies opportunities for improvement (value gaps).

This approach successfully identified the major problems with the watershed. The model provided an integrated watershed assessment tool for the project committee. Subsequent to our study, pilot improvement projects have been conducted in small, selected areas of the watershed, with the goal of increasing local citizens' awareness of problems. This was followed by education on ways to improve the watershed, focusing on the objectives with the largest value gaps. The qualitative and quantitative assessment of the watershed through a multiple objective value model was also used in this education process and should lead in the long-term to a strong improvement in the health of this impaired watershed.

A summary of the paper is as follows. Section 2 introduces the watershed being studied. The value model is described in Section 3 and the analysis results are discussed in Section 4. In Section 5, we analyze the sensitivity of the model to the assessed weights. Lessons learned for future watershed management projects are provided in Section 6, along with conclusions and areas for future research.

2. The Upham Brook Watershed

In this section we describe the physical, biological, political, and socioeconomic characteristics of the watershed. The tributaries and lakes that belong to the Upham Brook Watershed lie in urbanized areas of Henrico County and the City of Richmond in central Virginia. The watershed spans 23,914 acres and includes 54 linear stream miles. The stream miles are mainly comprised of small tributaries that often flow unnoticed through heavily developed neighborhoods. The Upham Brook's waters flow into the Chickahominy River which then connects with the James River, a major tributary to the Chesapeake Bay. Even though the Upham Brook is considered to be an urban watershed, varieties of wildlife reside within the watershed. A range of fish and amphibian species can be found within regions of the watershed. Most of the fourteen different fish species that inhabit streams of the watershed are small fish: for example the Blue Gill, Blue Spotted sunfish, Mud Minnow, and Pumpkinseed. Bull Frogs, Green Frogs, American Toads, Spotted Salamanders, Dusky Salamanders, and the Red Spotted Newt can be found in various sections of the watershed.

A large number of governmental institutions and community organizations contain portions of Upham Brook Watershed within their geographic areas of interest. Ninety-six percent of the watershed is located in Henrico County, with the remaining four percent within Richmond City boundaries. Parts of three City Council Districts and two Magisterial Districts of the county reside within the watershed. The watershed contains portions of two congressional districts, three Virginia Senate districts, and three Virginia House of delegates. The county portion of the watershed includes sixteen neighborhood civic associations, while the city section includes nineteen civic associations. According to the 1990 census, approximately 83,250 people live

within the Upham Brook watershed. The communities within the watershed have a very diverse socioeconomic configuration, ranging from the wealthy to the extremely poor. The city sector of the watershed was mainly developed in the 1950s with ongoing development still occurring within many of the county sections. There are also a number of older homes built within very crucial areas of the watershed. Housing and industry can often be found directly adjacent to the banks of the Upham Brook and its streams.

The state of Virginia has placed the Upham Brook Watershed on their list of impaired waters. The large scale of development that has occurred within the watershed has placed a great strain on its water quality. Storm water flows directly into the Upham Brook's tributaries from streets and parking lots. Biological surveys of the watershed indicate troubled waters, including high fecal coliform and low dissolved oxygen levels throughout the watershed. A section of stream connecting Bryant Park to the confluence with the Chickahominy River has been classified by the state as impaired due to high fecal coliform levels. Many of the watershed's tributaries do not meet water quality standards for fishable and swimmable waters. Benthic macro invertebrate studies have shown that the stream is biologically damaged. Captured fish at twelve of fourteen sites within the Upham brook exhibited physical anomalies. Thus the Upham Brook watershed has hydrological problems, as well as being a damaged aquatic ecosystem.

3. Development of the Upham Brook Watershed Value Model

In this section, we briefly describe the structure and development of the multiple objective value model, beginning with the value hierarchy describing the committee's objectives for the watershed. Evaluation measures are then developed to measure the degree of attainment of the objectives; an additive value function is assumed and single-dimensional value functions and weights determined. Merrick and Garcia (2004) provide a more complete tutorial on multiple objective value models for watershed improvement intended for non-decision analysts.

3.1 Construction of the Value Hierarchy

The first two authors facilitated the development the value hierarchy with the project committee. First, a brainstorming session was held to identify the overall objective of the project. Each

participant was asked to identify the main objective of the project. The committee then discussed each suggestion. The project committee chose "Maximize the Quality of the Upham Brook Watershed" as the overall objective.

A "Silver Standard" technique (Parnell et al.1998) was used to involve the numerous participants from the Project Committee and inductively develop the value hierarchy. The group was asked to identify ten to fifteen action verbs and modifiers that define the quality of the watershed. These action verbs were written on post-it notes and displayed for viewing by the group. Similar verbs were placed together to form affinity groups. An objective was identified that best described each affinity group. The objectives were then logically organized in an objectives hierarchy. An affinity diagram has two major benefits for value model development (Parnell, 2004). First, affinity groups are mutually exclusive and collectively exhaustive. Second, affinity diagramming usually identifies new objectives tailored to the overall objective. As we reviewed the value model, we noted that some of the objectives in the value hierarchy were means objectives that lead to the fulfillment of other fundamental objectives (Keeney 1992). Thus objectives such as *increase local citizen participation* were removed from the value hierarchy, but retained for use in identifying decision alternatives later in the process. After revision of the initial hierarchy, the final value hierarchy was formed (Figure 1). The value hierarchy may be viewed as the group's collective definition of Upham Brook watershed quality, including both the riparian zone (RZ), the banks of the streams, and the impact of land use across the wider watershed area.
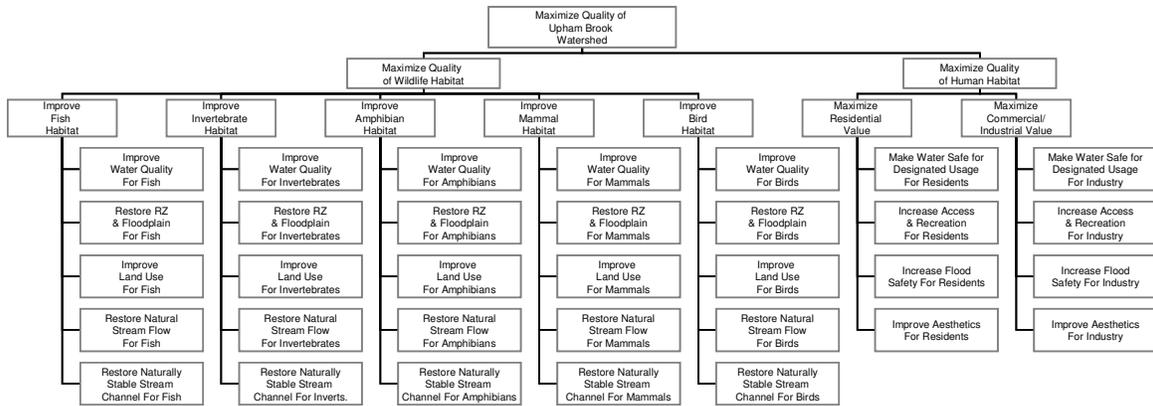
Figure 1. Upham Brook Value Hierarchy

Examining Figure 1 reveals that the hierarchy divides the quality of the Upham Brook into two fundamental objectives: improving the quality of the wildlife habitat and improving the quality of the human habitat. The wildlife habitat is then broken down into five classes of wildlife species that reside within the Upham Brook watershed's boundaries. The same five objectives are listed below each wildlife class. The experts in the Project Committee believed that the five objectives would have a different importance for each class of wildlife and you would like to achieve them for different reasons for each class of wildlife, thus they are separated in the value hierarchy. The human habitat objective is divided into improving watershed quality for residential stakeholders and improving watershed quality for commercial/industrial stakeholders, each with the same four objectives. Again, the experts believed the four objectives have different importance and implications for the residential and commercial/industrial objectives. It is interesting to note that we could have equivalently grouped the objectives as Improve Water Quality, Restore RZ and Flooplain, etc.. and then had a lower level objective for each class of wildlife below each. Our choice of the form in Figure 1 was due to the experts in the Project Committee; we had species experts who could discuss the importance of water quality and land use for their wildlife specialization, rather than hydrology and water quality experts who considered the implications for each type of wildlife.

3.2 Selection of Evaluation Measures

The project committee members collectively selected the measures that would be used to monitor and report on the attainment of watershed objectives. These are listed in Table 2. Detailed definitions are provided in the Appendix. Note that two of the five repeated objectives for wildlife have different evaluation measures for amphibians than for the other wildlife classes. Thus there are now eleven actual evaluation measures in the value model. Where possible, the group was asked to identify environmental indicators that were comparable to national indicators. Only if an established measure did not exist was a new measure developed. The committee wanted evaluation measures that would be understood by other watershed management teams. Thus, simple evaluation measures were sometimes chosen rather than more complex evaluation measures only used by specialists or researchers in a given field.

The next phase of the process was the creation of the value function. The widely used additive value function was selected to combine the evaluation measures using single dimensional value functions and weights (Kirkwood 1997). If we have n evaluation measures, the additive value function can be written as:

$$v(x_1,\ldots,x_n) = w_1 v(x_1) + \ldots + w_n v(x_n),$$

where $v(x_1,\ldots,x_n)$ is a value or preference function that allows us to rank alternatives, the $v(x_i)$ are single-dimensional value functions that convert each evaluation measure x_i to a

Objectives	Evaluation Measures
Improve Water Quality	% Acidity readings below 4.5 pH (Amphibians) % Dissolved Oxygen readings below 5 ppm (All Others)
Restore Riparian Zone & Floodplain	% of riparian zone with undeveloped or natural vegetation
Improve Land Use	% of Upham Brook with undeveloped or natural vegetation
Restore Natural Stream Flow	% Impervious surface in watershed
Restore Natural Stream Channel	% of non-redirected channel (Amphibians) EPA Rapid Bio-assessment Metric (All Others)
Make Water Safe for Designated Usage	% fecal coliform measurements in violation
Increase Access & Recreation	% of stream length accessible to public
Increase Flood Safety	% of riparian zone and floodplain with construction
Improve Aesthetics	% of stream length with trash present

common value scale and the w_i reflect the weight (or relative importance) of each evaluation measure to overall preference (Keeney and Raiffa, 1993).

Table 2. The Evaluation Measures.

This form assumes that the evaluation measures are mutually preferentially independent. Preferential independence requires that preferences concerning each subset of the evaluation measures should be not depend on the levels of the other evaluation measures (Keeney and Raiffa, 1993). The value hierarchy repeats the same evaluation measures, which would appear to invalidate such independence. However, while the evaluation measures are statistically dependent, each repetition is for a different class of wildlife and thus the objectives are indeed different. The lowest level objectives were determined to be mutually preferential independent; the preferences for any subset are not affected by the levels of any other (mutually exclusive) subset. One question in terms of preferential independence is the relationship between dissolved oxygen levels, the acidity and the safety for skin contact. These measurements are causally or statistically dependent. However, they are preferentially independent as the desire for improvements in each are for different reasons. Dissolved oxygen is healthy for all animals living in or drinking the water; low acidity allows healthy spawning of amphibian eggs; safe skin contact is for humans as the animals are accustomed to fecal coliform in the water. Thus the additive value model is a suitable representation of preferences. Furthermore, the additive value model is generally accepted as robust to minor deviations from this assumption (Belton 1984 and Edwards 1978).

3.3 Development of the Single-Dimensional Value Functions

In the additive value function, single-dimensional value functions formalize the subjective preferences for the attainment of different levels of an evaluation measure. Where the evaluation measures are repeated multiple times, the same function was used in each occurrence. The validity of this assumption was verified with experts for each evaluation measure.

First, all members of the Project Committee were briefed on the meaning and purpose of value functions. Members of the committee were asked to identify any existing studies that would aid in the development of the value functions. The range of values considered for each attribute was the range of possible values rather than the range of plausible values. We intentionally used a wide range of measures so we could assess Upham Brook on a range from a completely imperfect watershed to a perfect watershed. Interviews were conducted with specific subject experts from the Project Committee to elicit the shape of the value functions using the value increment procedure, described by Kirkwood (1997, pages 62 to 64).

The value increment procedure involves assessing the relative value increments for increases in value between segments on the scale of the evaluation measure. For instance, the value increments for the percentage of stream channel in its natural state between 0% and 50% and between 50% and 100% are equal, as each additional piece of stream channel in its natural state is a better environment for wildlife. Such assessments imply that the single-dimensional value functions are linearly increasing or decreasing (Figure 2), with equal value increments for each unit increase in the evaluation measure. These applied to many of the evaluation measures that assessed percentages. The percentage of dissolved oxygen readings below 5 parts per million, pH measurements below 4.5 pH, riparian zone with natural vegetation, watershed with natural vegetation, the stream channel in its natural state, the 100-year floodplain with construction, and stream length with trash were all linear. For these evaluation measures, interviews disclosed that each unit increase in the evaluation measure corresponded to the same increase in value.
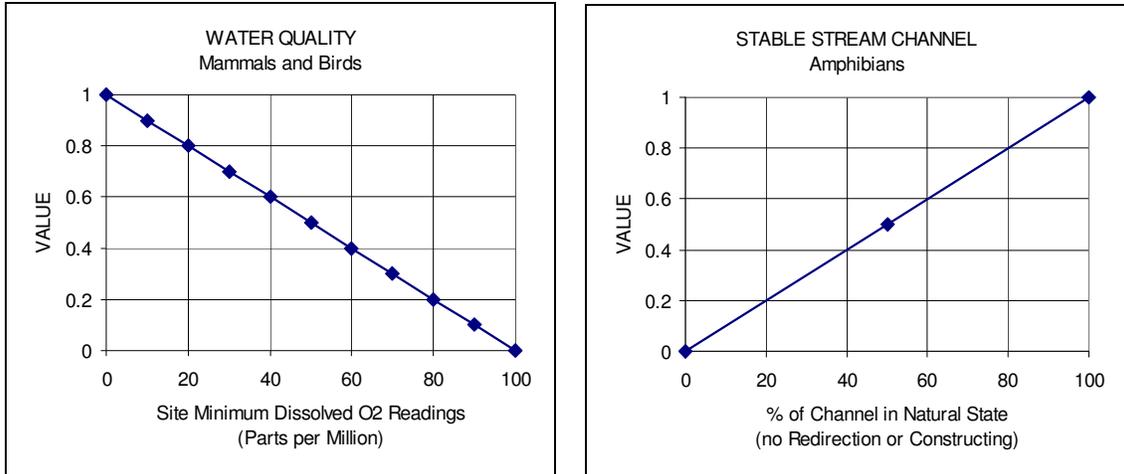
Figure 2. Examples of Linear Increasing and Decreasing Value Functions.

For other evaluation measures, piecewise linear value functions were developed by first identifying the least and most desirable level of the evaluation measure. The value increment procedure was then followed to determine the forms of the value functions for percentage of fecal coliform measurement in violation of EPA standards (Figure 3 left), percentage of stream length accessible to the public (Figure 3 right) and the average EPA Rapid Bio-assessment metric score and percentage of impervious surface (Figure 4).
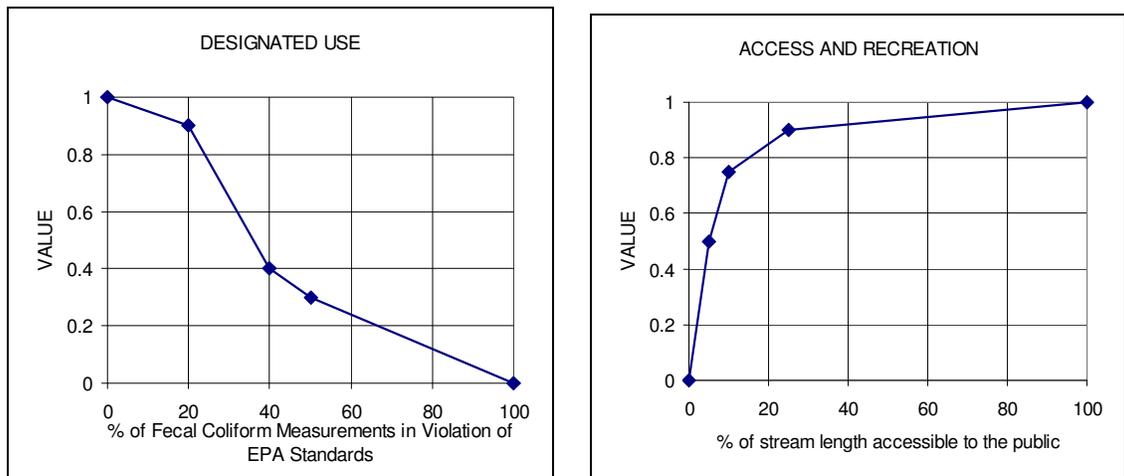

Figure 3. Value Functions Developed by the Identification of Value Increments
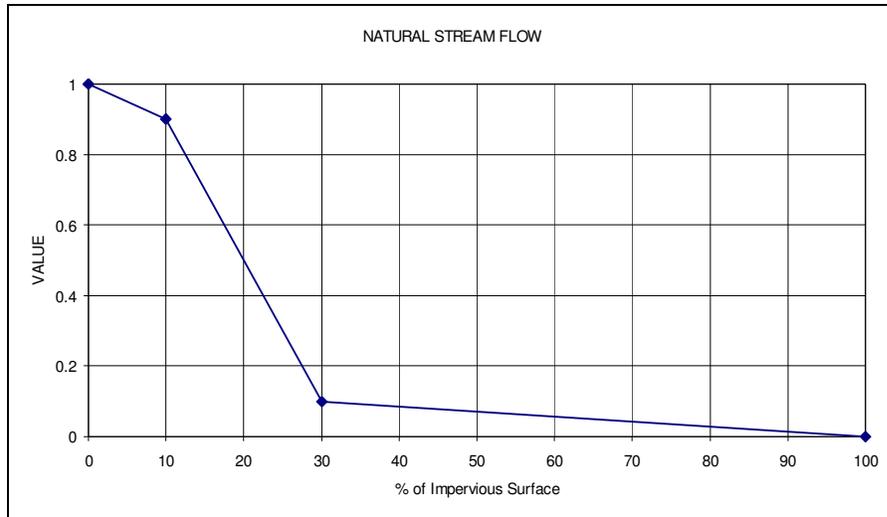
Figure 4. Value Function for the Percentage of Impervious Surface.

Impervious surfaces are materials that prevent the infiltration of water into soil. A previous analysis established thresholds of impervious surface to categorize stream health: less than 10% impervious surface characterized as "protected", 10%-30% as "impacted", and over 30% "degraded" (Arnold & Gibbons 1996).

3.4 Developing the Weights

In the additive value model, each evaluation measure within the hierarchy must be weighed based on relative importance and variation. We assessed the weights using swing weighting procedures (Kirkwood, 1997, pages 68 to 70; Clemen and Reilly, 2001, pages 615 to 618). Determining weights with the swing weight procedure involves considering swings in each objective from the worst score of its evaluation measure to the best score. The swings are then ranked in importance and the assessor determines the relative increase in value for each of the swings compared to either the smallest or largest swing. The weights are then found by normalizing the assessments so they sum to one. The value hierarchy appears in Figure 5 with the weights shown below each objective.

We used swing weights with the subject matter experts for each category. Moving up the hierarchy, each of the five wildlife classes is weighted equally at 0.2 to consider each class of wildlife equally important. The weights for the commercial and residential objectives were set at

0.3 and 0.7 respectively, as these are the proportions of land use within the Upham Brook watershed. The committee decided that neither the wildlife nor the human habitat objective was more important. Therefore, they decided to weigh each objective 0.5. We did point out that this meant that swings in all the wildlife attributes were equally as important as swings in all the human habitat attributes. However, the committee felt strongly in favor of such an assignment, a reflection of their strong environmental focus. The project committee did, however, think that government officials might place different weights on these objectives.
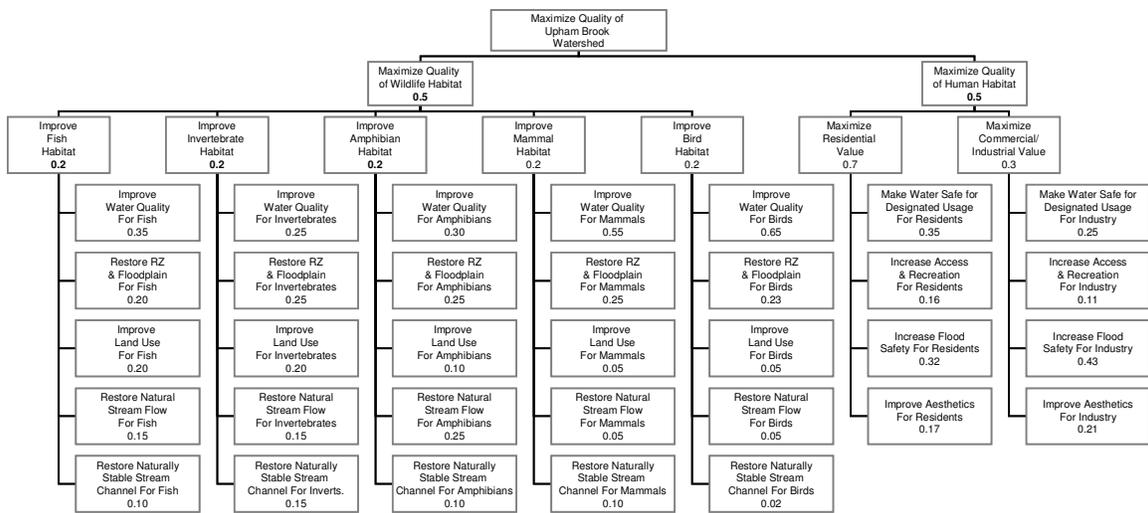

Figure 5. Weights for Upham Brook Value Hierarchy.

4. Demonstration of the Model and Analysis of Results

4.1 Initial Baseline Data and Assessment

Table 3 displays the data collected by the project committee to assess the physical, chemical, biological, and human systems associated with the watershed. Note that in the table we provide the eleven different evaluation measures and the objectives that they are used to evaluate. The collection of this data involved members of the Project Committee taking measurements at multiple sites in the watershed at regular intervals over a six-month period. The measures for land use, riparian zone and flood safety involved extensive use of a geographic information system to

integrate multiple data sources. The measures for stream access and aeshetics required students walking every length of stream in the watershed.

As a reference point, we defined Utopia as a hypothetical perfect watershed that completely fulfills each of the committees' objectives. Utopia's scores are set at a level that maximizes each single attribute value function. Thus, Utopia will receive the maximum value of 1.0 irrespective of the assigned weights. Utopia's value serves as an ideal value in the analysis of the Upham Brook. At the other end of the scale, a hypothetical completely imperfect watershed would achieve a score of 0, with a score that minimizes each single attribute value function. The initial assessment of the Upham Brook was a weighted value of 0.53, which is broken down by the human and wildlife objectives in Figure 6. This score is consistent with the original observation that the Upham Brook watershed is impaired.

Objective	Evaluation Measure	UB's Score	UB's Value
Improve Water Quality (Amphibians)	% of pH measurements below 4.5	0%	1
Improve Water Quality (All Others)	% of DO measurements below 5 ppm	27%	0.73
Restore RZ & Floodplain	% of RZ with Natural Vegetation	64%	0.64
Improve Land Use	% of Watershed with Natural Vegetation	30%	0.3
Restore Stream Channel (Amphibians)	% of Channel in Natural State (no Redirection or Constructing)	85%	0.85
Restore Stream Channel (All Others)	Average EPA Rapid Bioassessment Metric Score	5	0.08
Restore Natural Stream Flow	% of Impervious Surface	26%	0.26
Make Water Safe for Designated	% of Fecal Coliform Measurements	75%	0.15

Usage	in Violation of EPA Standards		
Increase Access & Recreation	% of stream length accessible to public	9.6%	0.73
Improve Flood Safety	% of 100 year Floodplain with construction	21.4%	0.786
Improve Aesthetics	% of Stream Length with Trash	35%	0.65

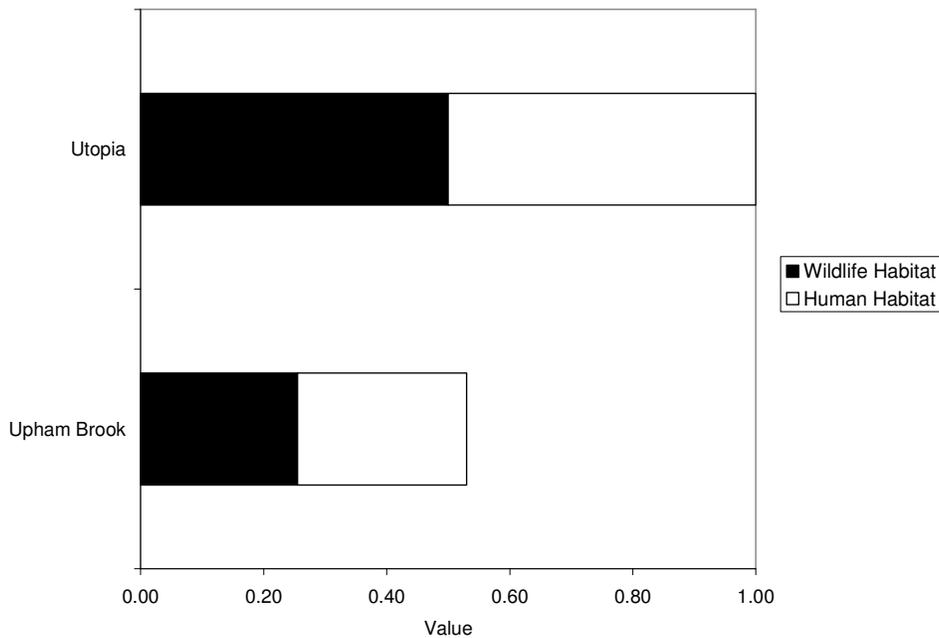**Table 3. Initial Data and Values for Upham Brook (UB).**

Figure 6. A Comparison of the Values Obtained for Upham Brook and Utopia.

4.2 Identification of Value Gaps

A more refined analysis can be used to assess and identify the problem areas of the watershed and provide information to guide development of future programs. Effective watershed management programs should focus on the objectives that can achieve the largest overall increase in value. A useful first step is to identify the largest value gaps, that is, the objectives that

have the most room for improvement. Figure 7 visually displays the value gaps for the human habitat objectives. Figure 8 provides a similar analysis of the Upham Brook's wildlife habitat objective.
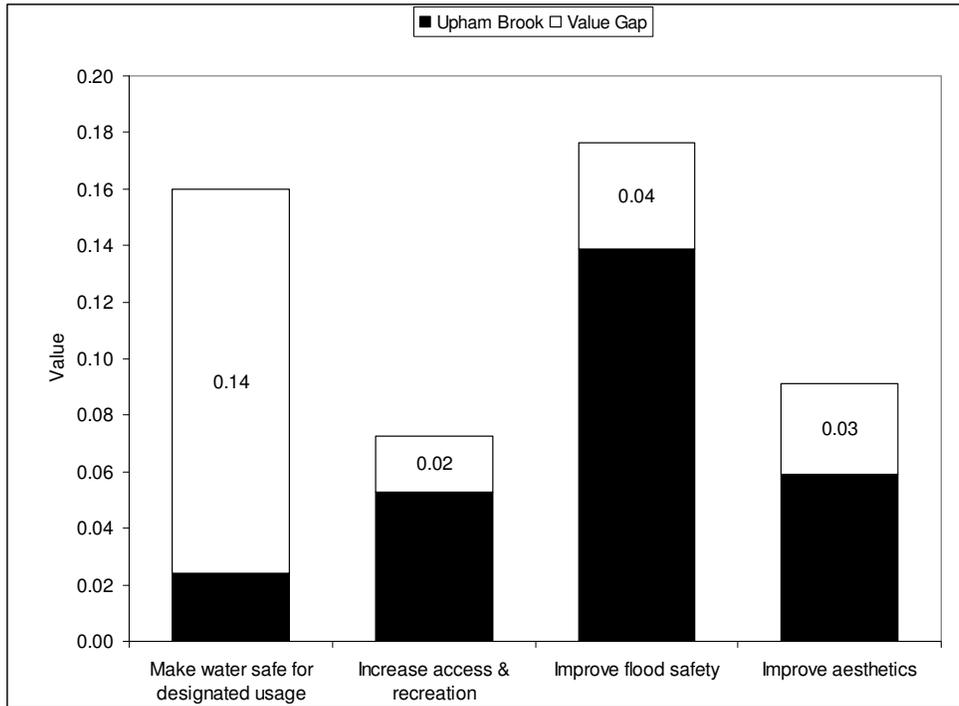

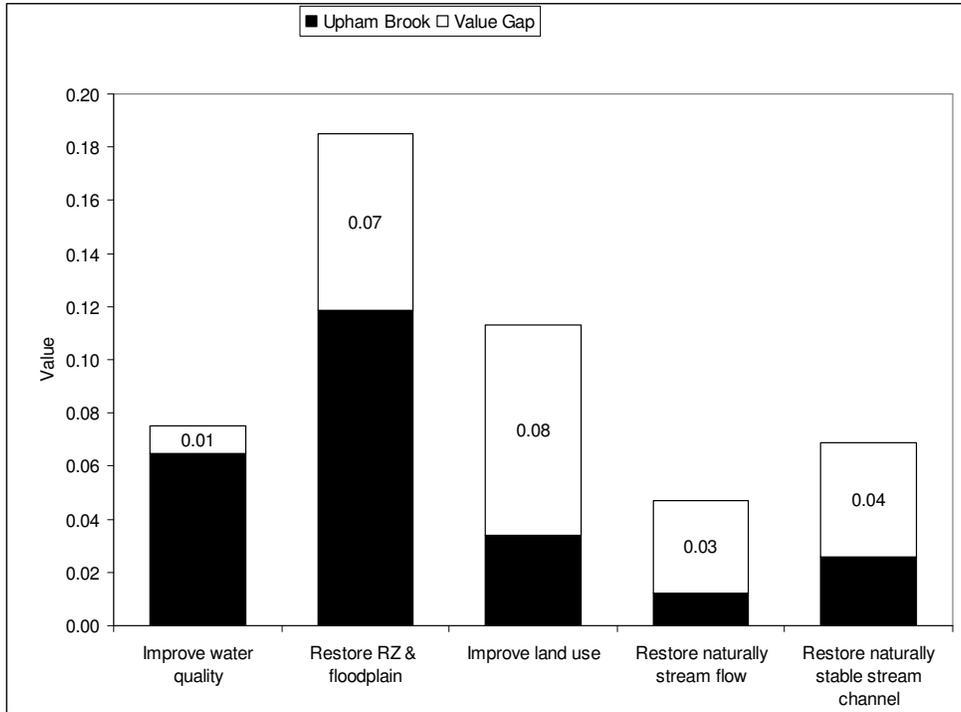**Figure 7. Value Gaps for Human Habitat Objectives.**

Figure 8. Value Gaps for Wildlife Evaluation Considerations

The value gaps for each objective are displayed in descending order in Table 4 for comparison. There are nine in the list as we added the value gaps for each lower level objective across the wildlife classes. The ranking defines which objectives could return the largest increase in value if perfectly achieved, thus implying an order of attack for addressing problems with the watershed. Improvements in each objective are not equally easy or hard. The same investment of money or time may yield different improvements in each objective or even improvements across several objectives. Thus the value gaps are indicative of problem areas in the watershed, but a cost-benefit analysis should be performed using the value model when determining specific improvements to implement.

RANK	OBJECTIVES	VALUE GAP
1	SAFE FOR DESIGNATED USE	0.14
2	LAND USE	0.08
3	RZ & FLOODPLAIN	0.07

4	STABLE STREAM CHANNEL	0.04
5	SAFETY & FLOOD CONVEYANCE	0.04
6	NATURAL STREAM FLOW	0.03
7	IMPROVE AESTHETICS	0.03
8	ACCESS & RECREATION	0.02
9	WATER QUALITY	0.01

Table 4. Ranking of Value Gaps.

The largest value gap is the safety of the water for its state designated usage, namely wading and swimming for the Upham Brook watershed. While the water does not need to be improved to drinkable quality to meet this objective, the fecal coliform levels are too high to be safe for skin contact in some areas of the watershed. The next two largest value gaps are mainly a consequence of the urban location of the watershed. The land use across the watershed is well developed and this will probably not be changed, but the land to either side of each stream and tributary, the riparian zone, can be improved by returning it to its natural state. The stream channel and flow (value gap ranks 4 and 6) also need to be returned to their natural states in some sections of the watershed. Improving flood safety in the watershed (rank 5) will probably require time. The buildings constructed in the 100 year floodplain have been grandfathered from new laws banning such construction, but renovation and improvement of these buildings is not allowed. The next highest ranked value gaps are improving the aesthetics of the streams by removing trash and increasing public access to them. The lowest ranked value gap is improving water quality. This objective was the combination of water quality objectives for all types of wildlife, measured by acidity levels for amphibians and dissolved oxygen for other wildlife. The majority of these measurements were acceptable with only the occasional poor readings after storm surges through the watershed.

4.3 Identifying Value Improvement Projects

With the value gaps of the Upham Brook Watershed identified, the next step in the project was to identify how to improve the watershed quality by targeting the largest value gaps. As mentioned previously, the project committee did not have an improvement budget allowing a straightforward cost-benefit analysis using the value model. Rather the committee wished to identify focus areas. Historically, there have been multiple strategies for watershed management. Many environmental groups concentrate on lobbying state and local government, with varying results. Another approach is to appeal to nationwide environmental organizations to fund professional improvement projects. The project team developed a means objective network (Figure 9) that represented their thinking and determined a possible critical leverage point.
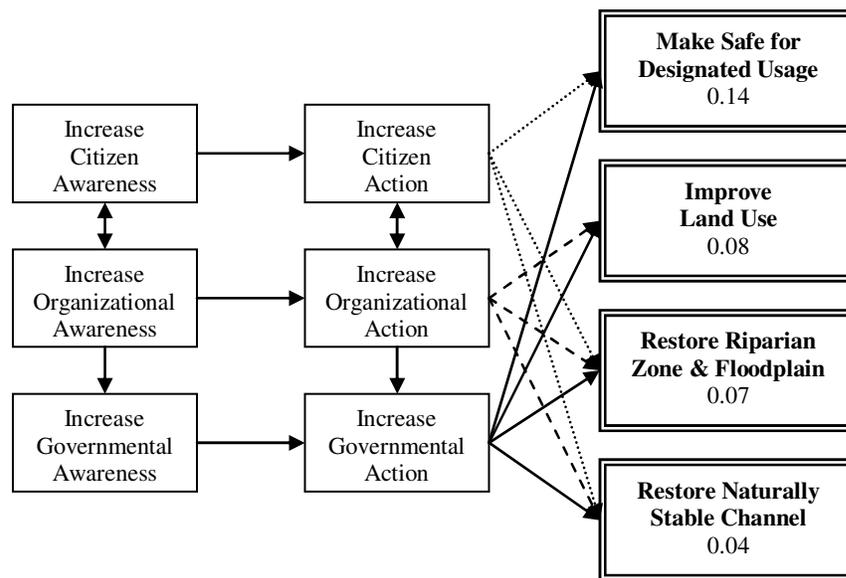

Figure 9. Means Objective Network.

Recall that during the development of the value hierarchy, the committee initially felt that improving community participation was important to the health of an urban watershed. It was not included in the hierarchy, since it is a means to achieve the fundamental objectives, rather than an objective. At the point of considering initiating improvements, we returned to this means objective. The psychologist on the committee noted that action must be preceded by awareness of a problem. The committee believed that increasing awareness of the watershed's problems

would be the critical leverage to initiate improvements. The committee began to decompose community awareness into three categories: the individual citizens, the organizations they belong to, and their representatives in government. This structure was used in the means objective network depicted in Figure 9. The right hand side of the network consists of the objectives with the four largest value gaps. The network displays the committee's belief about the relationship between awareness of the problems across different levels of organization in society, the participation of these levels, and the four largest value gaps.

Surveys of local citizens and organizations were performed by the psychologist on the Project Committee to assess the attitudes of citizens to the watershed indicated that at the time of our study, awareness of the Upham Brook watershed problems was very limited. Similar surveys of elected officials revealed that awareness was restricted to relatively few public representatives. Although the standard approach is to go straight to government officials to bring about watershed improvement, the project committee determined that citizen and organizational awareness could be a better leverage point. The reasoning was that citizen awareness leads to their participation. It also leads to the awareness and participation of their local organizations. The awareness of many citizens and organizations within elected officials' jurisdictions will further promote their awareness and participation. Thus, the main thrust of the Upham Brook project's improvement phase was targeted at the grass roots level. Programs selected by the committee have focused on increasing citizens' and local organizations' awareness. The main problems highlighted through these programs are the high fecal coliform levels, the redirection of stream channels and unnatural vegetation or construction in the riparian zone. It is too early to claim that the committee's hypothesis represented by Figure 9 is valid, but the thought process may be interesting to consider for other groups interested in watershed improvement.

5. Weights Sensitivity Analysis

As discussed in Section 3.4, the project committee chose the first tier weights based on some fairly arbitrary assumptions. The weights assigned to the wildlife versus human habitat objectives were assumed to be equal, although the committee recognized that political and governmental

decision-makers might weight these objectives differently. The residential and commercial/industrial weights were chosen to be 0.7 and 0.3 respectively, based on current land uses within the watershed. Again, decision-makers might choose different weights.

Sensitivity analyses were performed to test how much the value gaps changed with variations in these weights. Figure 10 shows how the top four value gaps change as the wildlife habitat weight increases and the human habitat weight decreases. The current (equal) weight assignment is shown as a vertical dashed line. The largest value gap with the original weights was for the objective *Make safe for designated usage*, part of the overall *Improve Human Habitat* objective. The next three highest value gaps were under the wildlife objective. As the weight for the wildlife habitat objectives increases, the size of the value gap for the *Make safe for designated usage* sub-objective decreases, until it ceases to be the largest at about 0.62. However, the committee believed that it was more likely that political and governmental decision-makers would decrease the weight assigned to wildlife habitat objectives in favor of the human habitat objectives. Thus the value gap analysis appears robust to possible changes in the top-level weights.
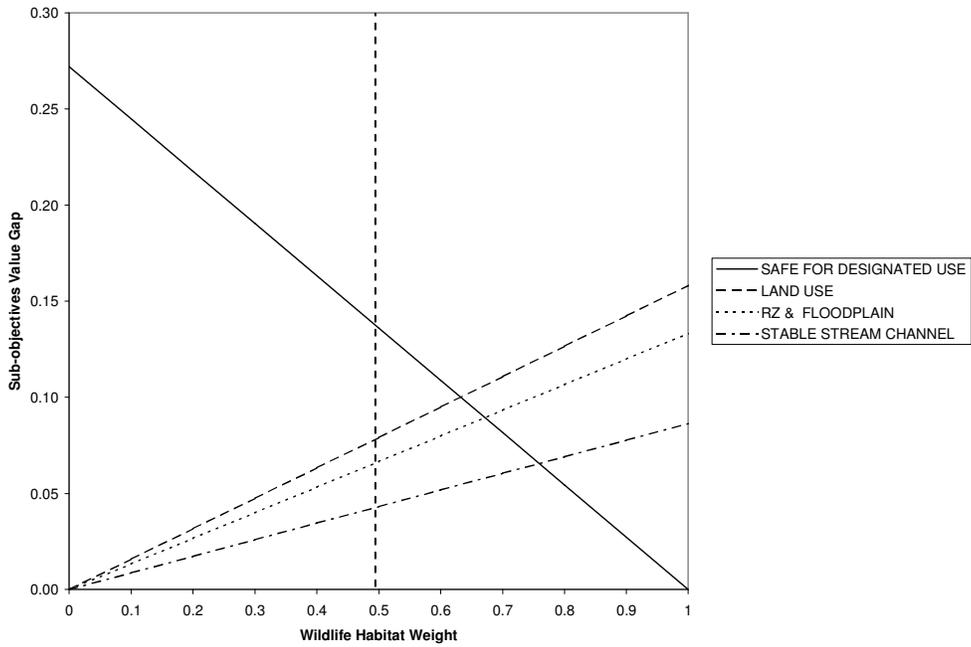
Figure 10. Sensitivity of the 4 Top Value Gaps to the Wildlife and Human Habitat Weights.
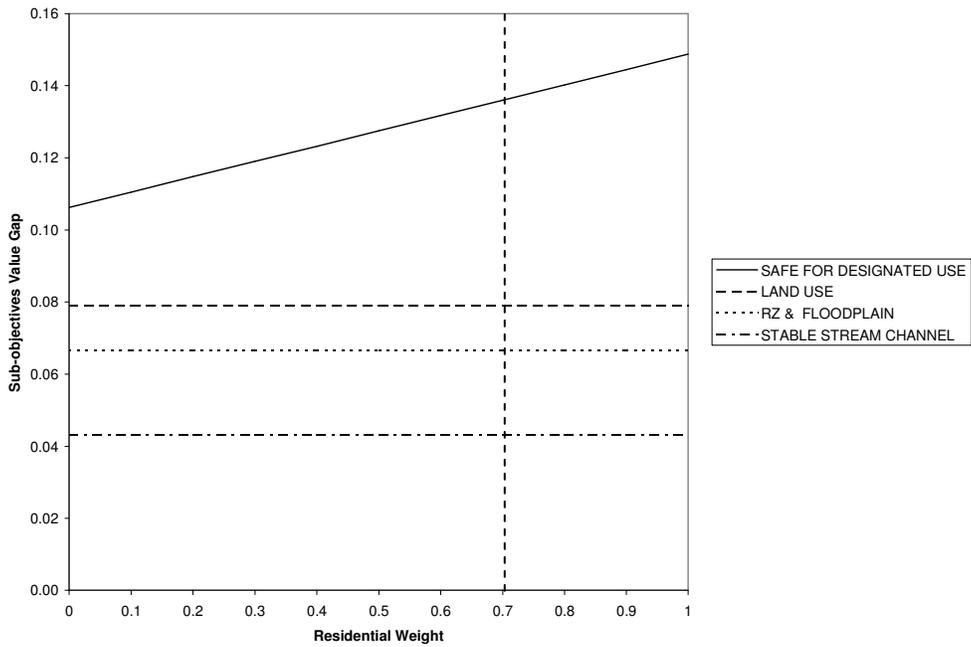

Figure 11. Sensitivity of the 4 Top Value Gaps to the Residential & Commercial/Industrial

Weights.

Figure 11 shows a similar analysis for the weight of the residential and commercial/

industrial sub-objectives for the human habitat objectives. Again, the current weight is shown as a

vertical dashed line. These weights do not affect the second through fourth highest value gaps, as these are wildlife objectives. Increasing the weight for residential objectives further increases the value gap for the *Make safe for designated usage* objective. However, a decrease in the residential weight in favor of the commercial/industrial weight does not decrease the gap enough to change the ordering. The value gaps appear to be robust over large variations in the assumed weights.

6. Lessons Learned

Over the years, the failure of previous environmental strategies has heightened the importance of three principles in environmental resource management, each of which is embodied in the model described here. One is the integration of environmental and socioeconomic objectives into the decision making process. This has been addressed by the interdisciplinary approach to development of the value model. The second principle is the incorporation of community participation into the improvement process. The means objective network identified citizen and organizational awareness and participation as the critical leverage point to improve the quality of the watershed. This provides the foundation for the selection of effective integrated watershed management strategies and programs through multiple objective decision analysis. The third principle, and the one that we will seek to follow more closely in a future project, is to include actual decision makers and other stakeholders in the model development process to facilitate the transition from analysis to resource allocation decision-making. While the experts used to construct this model were invaluable, even broader stakeholder involvement could have led to an even more effective model.

The results of this project are currently being used to guide Upham Brook restoration efforts. The creation of the value model took approximately 6 months, primarily due to delays imposed by the need to schedule committee meeting times. The calculations were performed using Microsoft Excel so that the model could easily distributed to decision makers and other interested parties. We used the model comparison of the *status quo* to a perfect watershed in order to identify the most important opportunities for improvement. However, the same model

could also be used to compare multiple watersheds to identify those most in need of improvement. This would be particularly useful for government agencies with many watersheds in their jurisdiction. Our team is currently educating citizens and officials in the watershed about the greatest problems and implementing the programs identified as most valuable to the Upham Brook watershed.

Acknowledgments

Appendix: Discussion of the Evaluation Measures

Dissolved oxygen is the concentration of free, not chemically combined, oxygen dissolved in water. Dissolved oxygen in water typically ranges from 0-18 parts per million (ppm). Dissolved oxygen must be present for the survival of many aquatic plants, fish and animals. Most natural water systems require 5-6 ppm to support a diverse population. Interviews with experts established 5 ppm as the critical value for the quality existence of the four species. As multiple dissolved oxygen measurements are taken including measurements at multiple sites and multiple times of the year, the evaluation measure takes the percentage of these measurements that are below the critical 5 ppm to measure the quality of water for four classes of wildlife.

The percentage of water pH measurements below 4.5 was selected to measure water quality with respect to amphibians. pH is a measure of water acidity. pH measures the relative amount of free hydrogen and hydroxyl ions in the water. In the United States the pH of most natural waterways ranges from 6.5-8.5. This is considered to be the optimal range for most indigenous organisms. Changes in acidity can make water unfit to support aquatic and terrestrial life. Amphibians are very sensitive to high levels of acidity. More specifically, excess acidity can cause amphibian egg membranes to thicken; leading to the reduced hatching, increasing deformity, and possible death of amphibian embryos. For the water quality of amphibians, experts selected 4.5 pH as the minimum suitable level and again took the percentage of multiple measurements that surpassed this level.

For this study, a riparian zone (RZ) is defined as a hundred-foot region extending from the banks of the Upham Brook's waterways. Vegetation within a RZ increases infiltration and ground water storage and decreases soil erosion. The vegetation functions as living, breeding, and foraging habitat for the wildlife residents. Due to their high value for fish and wildlife habitat, proper maintenance and protection of the RZ is of extreme importance. The percentage of the riparian zone with natural vegetation or underdeveloped was selected to measure the quality of the riparian zone and floodplain. The percentage of the watershed outside the RZ underdeveloped or with natural vegetation was selected to measure land use within the watershed. The area in question consists of the land, within the watershed, outside of the riparian zones. This includes the housing developments, public buildings, industry, wooded regions, parking lots, and roads that exist outside the 100-foot buffer.

Urbanization can have a direct impact on the quality of a watershed. The impervious area in a drainage basin provides a quantitative measure of this potential impact: it is a measure of the total area where water does not infiltrate into the soil, including roads; rooftops; sidewalks; and compacted soil (Arnold & Gibbons, 1996). The percentage of impervious surface within the watershed was selected to reflect the measure of attainment of the natural stream flow objective. This indicator can be used to estimate the cumulative urbanization impacts on the natural flow of water within the watershed. Buildings, parking lots, man-made stream channels, and roads built

within the watershed impede the natural flow of water and disrupt the natural habitat of all the wildlife in the Upham Brook.

The average EPA Rapid Bioassessment (RBP) metric score was selected to evaluate the natural stable channel for fish, invertebrates, mammals, and birds. The EPA's RBP is an integrated assessment comparing habitat, water quality, and biological measures with empirically defined reference conditions. The reference conditions are actual sites that represent minimally disturbed aquatic ecosystems. Siltation or sedimentation is defined as the accumulation of finely divided particles of soil or rock and minerals in waterways. Siltation build up alters the depth of water and severely alters the aquatic habitat. In addition, silt can transfer potentially toxic pollutants into waterways from sources not adjacent to a watershed's streams.

The percentage of channel in a natural state (no redirection or channelization) was chosen to measure the natural stream channel within the Upham Brook for amphibians. A stream channel is defined as the bed where a natural stream of water runs or may run. Modification or construction within the stream channel usually occurs to control the path of the moving water. Amphibian habitats and food sources are directly influenced by the alteration of the stream channel, particularly spawning areas.

The percentage of fecal coliform measurements in violation of EPA standards was selected to measure the attainment of the safe for designated use objective. The presence of fecal coliform in water is an indicator of potential health risk to exposed individuals. The presence of fecal coliform in aquatic environments indicates that the water has been contaminated with the fecal material of man or other animals. Fecal coliform bacteria may be present in urban watersheds as a result of the overflow of sewage pipes. Ordinarily, fecal coliform does not pose a danger to humans. However, the presence of fecal coliform usually indicates the presence of pathogens or disease-causing bacteria. The State of Virginia Department of Environmental Quality sets as a general requirement for all surface waters (except shellfish waters): that fecal coliform bacteria shall not exceed a geometric mean of 200 fecal coliform bacteria per 100 ml of water for two or more samples over a 30-day period, or a fecal coliform bacteria level of 1,000 per 100 ml at any time.

The percentage of stream length accessible to the public was selected to measure the increase of access and recreation sub-objective. Accessible areas are defined as regions of the watershed that are available to the public without the obstacles of urban development. These include parks, walking and bike trails, recreational areas, and wilderness regions. The percentage of the 100-year floodplain with construction was chosen to measure the safety and flood conveyance sub-objective. A 100-year floodplain is defined as the area adjoining a river, stream, or water body covered by water in the event of a 100-year flood. This area is determined by defining a region that has a one-percent or greater chance of being inundated by water in any given year. A natural floodplain with limited or no urbanization is essential for the safety of the human habitat. The percentage of stream length with trash was selected to measure the aesthetics of the Upham Brook. It is believed the elimination of trash along streams will increase the value of the watershed for the human inhabitants. Unpolluted areas of the watershed will become both pleasing to the eye and a valuable area for the surrounding communities. The data recorded for this evaluation measure will rely on the judgment of the evaluator.

References

Arnold, CL Jr., Gibbons CJ. 1996. Addressing Barriers to Watershed Management. Environmental Protection Agency, Baltimore, Maryland, 8-12 June 1996. Accessed 25 January 2000. Internet. www.epa.gov/owow.watershed/Proceed/adler.html.

Adler R. 1996. Addressing Barriers to Watershed Management. Proceedings of *Watershed 96'*, 1-5.

Belton V. 1984. The Use of a Simple Multiple-Criteria Model to Assist in Selection from Shortlist. *O.R. Society National Conference*, University of Lancaster.

Clemen, R. T., T. Reilly. 2001. *Making Hard Decisions with Decision Tools Suite*, 1st Edition. Duxbury Press, Pacific Grove, California.

Davis, DG. 1998. EPA's Watershed Approach. Water and Watersheds Program of the EPA/NSF Partnership for Environmental Research. Covallis, Oregon, 28-29

Edwards W. 1978. Use of multiattribute utility measurement for social decision making. In *Conflicting Objectives in Decisions*, Bell D, Keeney R, Raiffa H (eds), Wiley: New York.

Environmental Protection Agency. 1995. Watershed Protection: A Project Focus. EPA-841-R-95-003. Accessed 25 February 2000 on the Internet at www.epa.gov/owow/watershed/focus/.

Garcia M. 1999. Anatomy of a Watershed. Technical Report of the Department of Urban Studies and Planning, Virginia Commonwealth University.

Keeney, R. L. 1992. *Value Focused Thinking*. Cambridge, Mass: Harvard University Press.

Kenney R. and Raiffa H. 1993. *Decisions with Multiple Objectives, Preferences and Value Tradeoffs*. Cambridge University Press: New York.

Kirkwood, C. W. 1997. *Strategic Decision Making, Multiobjective Decision Analysis with Spreadsheets.* Duxbury Press: Belmont CA.

Merrick, J. R. W., M. Garcia. 2004. A Value Focused Thinking Approach to Watershed Improvement. *Journal of the American Planning Association* **70**(3) 313-328.

National Research Council. 1999. *New Strategies for America's Watersheds.* National Academy Press: Washington DC.

Parnell, G., Conley H., Jackson J., Lehmkuhl L., and Andrew J. 1998. Foundations 2025: A Framework for Evaluating Future Air and Space Forces. *Management Science* **44**(10) 1336-1350.

Parnell, G. 2004. Value-Focused Thinking using Multiple Objective Decision Analysis. In *Methods for Conducting Military Operational Analysis: Best Practices in Use Throughout the Department of Defense*, Military Operations Research Society: Washington, DC.

Prato T. 1999. Risk-based Multiattribute Decision Making in Property and Watershed Management. *Natural Resource Modeling* **12**.

Prato T, Hajkowicz S. 1999. Selection and Sustainability of Land and Water Resource Management Systems. *Journal of the American Water Resources Association* **35** 739-752.

Qiu Z, Prato T, Fulcher C, Barnett Y. 1998. WAMADSS – An Agricultural Resource Management Tool for Evaluating Sustainable Agriculture. *Journal of Soil and Water Conservation* **53** 159.

Warner A. 1996. Developing an Applied System of Ecological Indicators for Measuring Restoration Progress in an Urban Watershed. EPA, Baltimore, MD 8-12 June 1996. Accessed 25 February 2000 on the Internet at www.epa.gov/OWOW.watershed/Proceed/warner.html.