The Analytic Hierarchy Process as a Means for Integrated Watershed Management

J.E. de Steiguer, Jennifer Duberstein, Vicente Lopes

Abstract

Integrated Watershed Management (IWM) has emerged worldwide as the preferred model for watershed planning. IWM uses the watershed as the basic geographic planning unit while integrating social, economic, ecological and policy concerns with science to develop the best plan. Stakeholder input is key to successful IWM. However stakeholder participation can present problems when the public is uncertain or unclear about the IWM planning criteria. The Analytic Hierarchy Process is a decision method for assisting IWM because it treats planning criteria and criteria weighting in an open and explicit manner.

Keywords: integrated watershed management, analytic hierarchy process, watershed planning, multi-criteria decision methods, multi-criteria decision models

Introduction

Today, the emerging field of integrated watershed management envisions the watershed as a holistic planning unit. However, while the integrated watershed management approach offers a process for solving watershed management problems, it also presents formidable challenges in terms of implementation. Thus, the purpose of this presentation is to explore the Analytic Hierarchy Process (AHP) as a means of assisting the implementation of integrated watershed management. The focus of this article is upon the AHP as a means for assisting in the plan selection process.

Watersheds and Integrated Watershed Management

The watershed is defined as, "the region draining into a river system, river or body of water" (Morris 1976). Watersheds are a highly desirable unit for planning because they are physical features ubiquitous across the landscape serving as the geographic foundation for political states. As planning units, watersheds transcend political boundaries. However, prior to the 1970's, most watershed management focused on solving localized problems without taking into account the interrelationship between those problems and the biophysical, economic and social elements of the larger watershed system (Heathcote 1998). Furthermore, during most of the mid- to late- 20th century, watershed management was, politically, a top-down planning process with national concerns pre-empting local (National Research Council 1999).

Today, however, countries everywhere are exploring bottom-up watershed planning for water, natural resource and environmental management through "integrated watershed management." Integrated watershed management (IWM) is a holistic problem-solving strategy used to protect and restore the physical, chemical and biological integrity of aquatic ecosystems, human health, and provide for sustainable economic growth (National Research Council 1999). IWM, in its most basic form, considers the interdependencies between science, policy and public participation (National Research Council 1999).

Over the past two decades, there have been numerous applications of IWM worldwide. For example, integrated watershed management approaches have been recently used for combating

DeSteiguer is a Professor, Duberstein is a graduate student, and Lopes an Associate Professor, all in the School of Renewable Natural Resources, University of Arizona, Tucson, AZ 85721. E-mail: jedes@ag.arizona.edu.

drought in the Jhabua watershed in India (Singh et al. 2002), assessing and managing water resources in the upper Chao Phraya in Thailand (Padma et al. 2001), assessing and managing agricultural phosphorus pollution on the Chesapeake Bay (Sharpley 2000), tackling the problem of land degradation in Australia (Ewing 1999), and managing the Truckee River in Nevada (Cobourn 1999). Also, in the United States, the USEPA has been quite instrumental in promoting the integrated watershed approach to management (National Research Council 1999):

> The lessons learned from these and other initiatives indicate that in order to succeed, integrated watershed management must be participatory, adaptive and experimental, integrating all the relevant scientific knowledge/data and user-supplied information regarding the social, economic and environmental processes affecting natural resources at the watershed level.

Plan Selection Using Stakeholder Values

The IWM process involves several distinct steps as follows (adapted from Heathcote 1998): 1) problem scoping and definition with decision-makers and professionals, 2) assessment of legal and institutional concerns, 3) consultation with stakeholders, 4) inventory of the geology, soil, streamflow, groundwater, water quality, plant and animal communities, land use, and the social and economic systems, 5) development of management options, with associated costs, to solve the problem(s), 6) assessment of management options, 7) environmental and social impact assessment as required by law, 8) selection of the best plan, 9) obtaining financial support, and 10) implementation and monitoring of the plan.

Due to page limitations, we will not attempt to discuss each of these steps in detail. For that detail, the reader is referred to Heathcote (1998). Taken together, all of these steps provide a comprehensive approach to IWM. This paper focuses on one especially critical step, that of "selecting the best plan." The selection of the best watershed plan is an especially important step because it represents the culmination of the IWM process and, thus, sets the course for the future of the watershed.

Observers and practitioners agree that it is crucial for stakeholders to be involved in developing and selecting the best plan (National Research Council 1999). Otherwise, it is said, the entire process may be ineffective. This is true because a strict top-down planning and plan selection process (*sans* stakeholders) can create implementation barriers due to the lack of public support of, or even opposition to, the final plan.

However, as important as stakeholder participation is to the plan selection, this same stakeholder involvement renders this step the "most difficult and controversial" in the IWM process (Heathcote 1998). Difficulty and controversy in "selecting the best plan" arise when stakeholders do not fully understand the criteria used for the IWM process. A group of stakeholders may well agree upon the overall watershed problem. They may also understand the goal of the IWM process. Furthermore, they may very well accept the information and data brought to the process. However, they may not understand the criteria, nor the criteria weights, used to determine the best plan. As a result, they may not always agree upon the choice of the best watershed plan.

As Heathcote (1998) states: "In some decision processes, these…criteria are not made explicit, with the result that participants disagree about the acceptability of an option without a clear understanding of the reasons for their dissatisfaction. Explicit discussion of…evaluation criteria encourages better citizen understanding and more focused decision making and can strengthen…support." Indeed, better understanding of the decision criteria can manage stakeholder conflict.

To illustrate the role of criteria in plan selection, consider a hypothetical watershed planning problem adapted from Heathcote (1998). The situation concerns the implementation of best management practices (BMPs) on farmland to prevent non-point source pollution of a river. Thus, the IWM goal is to select BMPs to prevent non-point source pollution.

There are eight alternative management options being considered: 1) "do nothing", 2) construct buffer strips, 3) construct fencing, 4) use conservation tillage, 5) construct buffer strip and fencing, 6) construct fencing, use conservation tillage, 7) construct buffer strips, use conservation tillage, and 8) construct fencing, buffer strips, use conservation tillage. Each represents a mutually exclusive, potentially independent project for managing non-point source pollution. Each alternative would have a unique budget, schedule and associated considerations.

Finally, there are criteria used to help select the best alternative. Criteria are measures of the effectiveness or suitability of the possible management actions. They must be: 1) measurable by mutually agreed upon methods, and 2) they must vary between, and thus differentiate, the alternatives. In this case, the criteria were: 1) cost, 2) time to implement the BMPs, 3) meets legal requirements.

Thus, in order to choose the best plan, each alternative would be evaluated according to the criteria and the alternative that scored highest would be selected and implemented.

The Analytic Hierarchy Process and IWM

A tool that permits explicit presentation of evaluation criteria and, thus, possibly improves IWM plan selection is the Analytic Hierarchy Process (AHP). The AHP is a Multi-Attribute Decision Method (MADM). MADM refers to a host of quantitative techniques used to facilitate decisions that involve multiple competing criteria. MADM methods use multiple criteria rather than relying on a single criterion to make a decision as in, say, cost-benefit analysis (max net present value). Thus, MADM methods are ideally suited to address decision situations such as our hypothetical BPM problem that featured multiple criteria for selecting the best alternative.

MADM examples include Multi-Attribute Utility Theory, the Novel Approach to Imprecise Assessment and Decision Environments, the Outranking Method, and the Analytic Hierarchy Process (DeMontis et al. 2000).

The AHP is perhaps the most widely-used of the MADM methods. We choose it for study here because it has a number of desirable attributes, such as: 1) the AHP is a structured decision process quantitative process which can be documented and replicated, 2) it is applicable to decision situations involving multi-criteria, 3) the AHP is applicable to decision situations involving subjective judgment, 4) it uses both qualitative and quantitative data, 5) it provides measures of consistency of preference, 6) there is ample documentation of AHP applications in the academic literature, 7) commercial AHP software is available with technical and educational support, and 8) the AHP is suitable for group decision-making.

The steps in the AHP method are as follows:

Step 1: The AHP begins with the development of a decision hierarchy with an *objective*, *alternatives* and *criteria*. Decision hierarchies are most effective if all stakeholders are involved in the development process. An AHP hierarchy can have as many levels as needed to fully characterize a particular decision situation. For example, consider the following hypothetical two-level (i.e., one set of choice criteria and one set of choice alternatives) IWM decision situation (Figure 1). Assume that a watershed councils' objective is to select the best possible watershed plan from three alternatives: Plans A, B and C. Assume also that there are four choice criteria that enter into this decision: 1) water quality, 2) timber production, 3) riparian protection, and 4) cost. The alternatives, although not explicit in this example, could provide the decision-makers with information of either a quantitative nature or a qualitative nature.

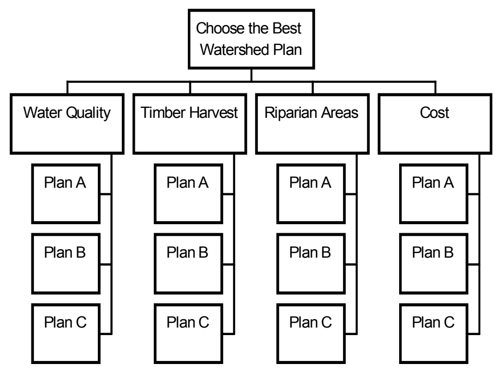

Figure 1. Decision hierarchy for a hypothetical watershed.

Step 2: Next, the decision-makers individually express their opinions regarding the relative importance of the criteria and preferences among the alternatives using *pairwise* comparisons and a 9-point system ranging from 1 (the two choice options are equally preferred) to 9 (one choice option is extremely preferred over the other). If, however, one criterion is preferred *less* than the comparison criterion, the reciprocal of the preference score is assigned. The 9-point scale has been the standard rating system used for the AHP (Saaty 2000). Its use is based upon research by psychologist George Miller (1956) which indicated that decision makers were unable to consistently repeat their expressed gradations of preference finer than "seven plus or minus two."

Step 3: These preference scores next undergo a synthesis process in order to calculate a priority weight vector for the criteria. There are different possible methods for synthesizing preference scores (Anderson et al. 1994, Saaty 2000). Whichever method is used, the final result, illustrated by this example, is a 1 x 4 vector (designated as **X**) of normalized, i.e., summing to 1, criteria preference scores. Once the scoring and synthesis process has been completed for the criteria, it is conducted for the alternatives. In this example, there are three alternatives, hence three vectors of weights, which are arranged to form a 4 x 3 (i.e., four criteria by three alternatives) matrix (designated as **Y**) of normalized preference scores.

Step 4. The final step in the AHP process is to complete the synthesis by multiplying the 1 x 4 "criteria vector" by the 4 x 3 "alternatives matrix" in order to obtain a 1 x 3 vector (designated as **XY**) of normalized unit-less weighted preference scores for each of the three plan options. For example, this hypothetical AHP exercise might have yielded final weighted preference scores for the three plans as follows: Plan A = 0.35 + Plan B = 0.25 + Plan C = 0.40 = 1.0. Plan C then is the decision-makers' preferred plan based upon their subjective judgment. The score (i.e., 0.40 out a possible 1.0) indicates the relative strength of that preference. Hämäläinen and Salo (1997) state that the final weights that result from the AHP represent the priority ordering of the alternatives and, thus, permit determination of the most preferred alternative. Another interpretation of possible "meanings" of the AHP weights is a more complex issue (Hämäläinen and Salo 1997).

In addition to final preference weights, the AHP permits calculation of a value called the consistency index (Anderson et al. 1994, Saaty 2000). This index measures transitivity of preference for the person doing the pairwise comparisons. To illustrate the meaning of transitivity of preference, if a person prefers choice A over B, and B over C, then do they in consistent fashion prefer A over C? Furthermore individual scores can be aggregated to obtain a composite group score (Saaty 2000).

AHP Examples, Drawbacks

Applications of the AHP to complex decision situations number in the thousands (Zahedi 1986). However, the application of the AHP to natural resource problems has been "surprisingly limited" according to Schmoldt, Kangas and Mendoza (2001). Unfortunately, page limitations do not permit a review of this literature.

Despite its widespread use as a decision method, the AHP has received some criticism (Hill and Zammit 2000): 1) because no theoretical basis exists for the formation of hierarchies, decision makers, when faced with identical decision situations, can derive different hierarchies, thus different solutions, 2) the rankings produced by the AHP are arbitrary because they are produced by a subjective opinion using a ratio scale and these arbitrary rankings can lead to "rank reversal," 3) flaws exist in the methods for aggregating individual weights into composite weights, and 4) an absence of a sound underlying statistical theory. Despite these concerns, the AHP remains immensely popular among private and public sector decision-makers.

Conclusions

Integrated watershed management situations consist of multiple criteria and alternatives that must be evaluated by a decision-maker in order to achieve an objective. The AHP provides a systematic method for comparison and weighting of these multiple criteria and alternatives by decision-makers. AHP is thought to be a method and planning framework with potential for implementation of IWM. An advantage of the AHP is that it is capable of providing numerical weights to options where subjective judgments of either quantitative or qualitative alternatives constitute an important part of the decision process. Such is often the case with IWM. A disadvantage is that the AHP method can be time-consuming and tedious if there are many levels in the decision hierarchy. Commercial software is available to simplify the AHP rating process, consistency indices and to perform matrix calculations. Also, the context of the decision and the sophistication of the decision-makers is crucial to the use and success of AHP.

Acknowledgments

Thanks to Isobel Heathcote and Donald Dennis for review comments. However, all errors and opinions are those of the authors.

References

Anderson, D.R., D.J. Sweeney, T.A. Williams. 1994. An Introduction to Management Science: Quantitative Approaches to Decision-making. West Publishing, Minneapolis-St. Paul, MN.

Ewing, S. 1999. Landcare and community-led watershed management in Victoria, Australia. Journal of the American Water Resources Association 35(3):663-674.

Cobourn, J. 1999. Integrated watershed management on the Truckee River in Nevada. Journal of the American Water Resources Association 35(3):623-632.

De Montis, Andrea, Paquale De Toro, Bert Droste-Franke, Ines Omann, and Sigrid Stagl. 2000. Criteria for quality assessment of MCDA methods. In Proceedings of the 3rd Biennial Conference of the European Society for Ecological Economics, Vienna, Austria, May 3-6, 2000, pp. 1-32. International Institute for Ecological Economics (www.kfunigraz.ac.at/vwlwww/omann/ESEE_group.pdf)

Hämäläinen, R.P., A.A. Salo. 1997. Rejoinder: The issue of understanding the weights. Journal of Multi-Criteria Analysis 6:340-343.

Heathcote, Isobel W. 1998. Integrated Watershed Management: Principles and Practices. John Wiley & Sons, Inc. New York.

Hill, S., and C. Zammet, 2000. Identification of community values for regional land use planning and management. Paper presented at the International Society of Ecological Economists Congress, Canberra, Australia, July 5-8, 2000. Australian National University.

Morris, William, ed. 1976. The American Heritage Dictionary of the English Language. Houghton-Mifflin Company, Boston.

Miller, George. 1956. The magical number of seven plus or minus two: Some limits on our capacity for processing information. Psychological Review. 63:81-97.

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

Padma, L., H. Lim-Applegate, and M. Scoccimarro. 2001. The adaptive decision-making process as a tool for integrated natural resources management: Focus, attitudes, and approach. Conservation Ecology 5(2):11. http://www.consecol.org/vol5/iss2/art11

Saaty, T.L. 2000. Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process, Volume 6. RWS Publications, Pittsburgh, PA.

Schmoldt, Daniel L., Jyrki Kangas, and Guillermo A. Mendoza. 2001. Basic principles of decision making in natural resources and the environment. In The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making, pp. 1-13. Kluwer Academic Publishers, London.

Sharpley, A. N. 2000. Agriculture and phosphorus management: The Chesapeake Bay and Boca Raton, FL. Lewis Publishers, London.

Singh, A. K., T.J. Eldho, and D. Prinz. 2002. Integrated watershed management approach for combating drought in a semi-arid region in India: The case of Jhabua watershed. In 2nd World Water Congress: Integrated Water Resources Management, pp. 85-92. Alliance House, London.

Zahedi, F. 1986. The analytic hierarchy process: A survey of the method and its application. Interfaces 16: 96-108.