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The prioritization of road maintenance projects is an important forest engineering task subject to limited budgets and competing investment needs. Large investments are made each year to maintain and upgrade forest road networks to meet economic and environmental goals. Many models and guidelines are available for single-criterion analysis of forest roads, but guidelines for multi-criterion analysis are rare. Additionally, even single-criterion approaches often rely on expert judgment to inform models of user preferences and priorities. These preferences are used to make tradeoffs between alternatives that contain data that are physical and biological, quantitative and qualitative, and measured on many different scales. The Analytic Hierarchy Process (AHP) has the potential to provide a consistent approach to the ranking of forest road investments based on multiple criteria. AHP provides a consistent, quantifiable approach to problems involving multi-criterion analysis, but it has not been applied to road management. The road investment problem differs from traditional AHP applications in that a large number of alternatives are compared at one time. AHP methodology is discussed, including the foundations, assumptions, and potential for use in prioritizing forest road investments to meet economic and environmental goals. Using AHP, the problem of scheduling maintenance and upgrade of forest roads is presented as a hierarchy and pairwise comparisons are elicited from decision makers to determine the relative importance of road characteristics to management goals. Issues regarding the use of the AHP to prioritize forest road investments are discussed. Three metrics are proposed to assist in evaluating the quality of a solution and to revise preferences when necessary. Various models using mathematical programming are used to incorporate the results of an AHP analysis into the scheduling of forest road maintenance and upgrade activities involving non-monetary benefits. Solutions to two non-linear integer programming formulations are found using a threshold accepting heuristic.

Setting Forest Road Maintenance and Upgrade Priorities Based on Environmental Effects and Expert Judgment

by

Elizabeth Dodson Coulter

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Elizabeth Dodson Coulter, Author

CONTRIBUTION OF AUTHORS

Dr. James Coakley assisted with the development of concepts as well as the design and editing of Chapters 2 and 5. Dr. Arne Skaugset assisted with the design of Chapter 4. Elizabeth Toman assisted with the development, design, and editing of Chapters 3 and 4. Dr. Mike Wing assisted in the development of the GIS-based figures and a GIS-based calculation of upslope drainage areas used in Chapter 6. Dr. John Sessions assisted with the development of concepts, interpretation of results, design, and editing of all chapters.

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Setting Forest Road Maintenance and Upgrade Priorities Based on Environmental Effects and Expert Judgment

1 Introduction

In recent years, the management of low-volume roads has transitioned from a paradigm where maintenance is designed to protect a capital investment in road infrastructure to one where other benefits of road maintenance, such as decreased negative environmental effects, are also important. These increased environmental concerns have lead many timberland owners to conduct inventories of their forest road networks. Managers use these datasets to better understand the condition of the road network and to set maintenance and upgrade priorities. These analyses generally focus on single problems such as barriers to fish passage, road-related landslides, chronic sediment input to streams, or drivability. Currently no methodology exists that can combine all of these concerns across the road network. This dissertation develops such a methodology based on the use of an existing multi-criterion decision analysis technique called the Analytic Hierarchy Process, or AHP. AHP was developed in the late 1970's by Thomas Saaty and has been used widely in many fields. Few applications of AHP within natural resource decision making have appeared in the literature despite an apparently good fit between the types of problems encountered in natural resources and the problems AHP was designed to solve.

1.1 Management of Existing Forest Road Networks

The management of existing forest road networks is often driven by single issues dictated by environmental concerns. Many models and decision rules exist for these analyses. For example, the Oregon Department of Forestry (ODF) publishes guidelines based on simple field measurements, to determine if a stream crossing structure is serving as a barrier to fish passage (Robison et al. 1999). The Washington Department of Natural Resources and Boise Corporation have created the empirically-based SEDMODL, used to estimate road-related sediment production and transport to streams (Dube et al. 2004).

However, even existing models and guidelines require significant professional judgment to implement.

ODF is currently testing a system of analysis for the road networks under its management. This system involves rating individual road segments across several categories using a five point scale. The rating values for separate categories of road performance, such as drainage and alignment, are kept separate and not combined. Once this rating has been completed, ODF then strives to upgrade all road segments with a critical rating in any of the several categories of road performance. This is perfectly adequate until resources are scarce enough that not all critical road segments can be upgraded at one time. When this is the case, there is no objective method within the current system for ODF managers to determine if a critical rating in one category is more or less important than a critical rating in another category. The method for using AHP to set priorities described here could be incorporated into ODF's existing system.

1.2 Previous Use of AHP in Natural Resources

AHP has been applied to natural resource decision making. A recent book, *The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making* (Schmoldt et al. 2001), contains descriptions of most of these applications. Many uses of AHP involve evaluating a set of forest plans generated using other means (such as linear programming) and various objective functions (Mendoza and Sprouse 1989, Kangas 1992, Kangas 1993, Pukkala and Kangas 1995, Leskinen and Kangas 1998, and Ananda and Herath 2003). Each of these is a traditional use of AHP where a small number of distinct alternatives are compared in order to determine the preferred alternative. Similarly, Anselin et al. (1989) used AHP to evaluate the ecological worth of potential conservation sites. Schmoldt et al. (1994) used AHP to develop an inventory and monitoring program for the Olympic National Park. In doing this, the authors applied AHP to a set of proposed projects and used the resulting values within a linear programming formulation to assign resources (money) to individual projects. Others have used the consensus-building features of AHP inherent in the development of a problem structure in large groups (Schmoldt and Peterson 2000) and using small groups of experts (Reynolds and Holsten 1994).

1.3 Using AHP to Manage Existing Forest Road Networks

The management of forest road networks currently suffers from a lack of methods and techniques to integrate multiple objectives and set priorities across these different goals. Additionally, the management of forest roads involves a mixture of quantitative data and models with expert judgment and qualitative data. These factors lead to AHP as a logical technique to assist with the integration of multiple criteria in the setting of priorities.

The traditional use of AHP is to compare a small number of alternatives to determine the best alternative based on some number of criteria. Mendoze and Sprouse (1989) used this traditional approach when they generated a ranking of six proposed forest plans. The six alternatives were generated using fuzzy linear programming and represent varying levels of importance of three objectives. The number of alternatives compared at any one time using a traditional AHP analysis is less than 10.

The forest road upgrade and maintenance problem differs from the traditional application of AHP in that a typical problem will contain a large number of potential alternatives. In the context of AHP, an individual alternative would include any maintenance or upgrade activity that could potentially take place on a given road segment. The application of AHP to large problems requires some special considerations as compared to traditional applications. These are discussed in theoretical terms in Chapter 2 and in application in Chapter 4.

A small body of literature exists that explores sensitivity analysis within the AHP. The analysis of problem sensitivity and the interaction between a decision maker's preferences and the specific alternatives under consideration are particularly important when problems become large and the decision maker is no longer able to intuitively evaluate the quality of a given solution. Existing sensitivity analysis methods deal exclusively with small problems. Chapter 5 presents the development of metrics that can be used with large problems. These metrics can help decision makers to better understand a problem and the interaction between his or her preferences and the alternatives under consideration.

The management of forest roads is limited by budgets. It is not practical to assume all high-ranking maintenance and upgrade alternatives identified by AHP can be completed. Chapter 6 presents various methods of incorporating the benefit for completing a given maintenance or upgrade project as derived using AHP to assign resources and schedule projects. The methods used include mixed integer mathematical formulations under both linear and non-linear objectives implemented using a heuristic technique.

1.4 Organization

This dissertation is organized as a series of four manuscripts that have or will be submitted to refereed journals for publication. Because each of these manuscripts is designed to stand alone, some redundancy exists.

Chapter 1 serves as an introduction to the dissertation. Gaps in current practice and techniques are briefly discussed as justification for this work.

Chapter 2 contains the manuscript "The Analytic Hierarchy Process: A Tutorial for Use in Prioritizing Forest Road Investments to Minimize Environmental Effects." This manuscript has been submitted to the *Journal of Forest Engineering* for publication.

A large body of AHP literature exists, however most of this literature has appeared in mathematical and operations research journals and is written in technical terms not appropriate for the practitioner that would benefit the most from a method like AHP. Many "user guide"-type literature are also available that describe the "how to" but rarely the "why." In the application of AHP there are decisions and assumptions that must be made. To understand the consequences of these assumptions and decisions, the user must understand the structure and theory of AHP. This manuscript is written for the non-mathematician and focuses on the specific problem of applying AHP to large problems such as a road inventory database. A small example using a subset of the data collected from the Oak Creek Drainage of the Oregon State University College of Forestry Research Forests for Chapter 4 is illustrated.

Chapter 3 is a non-manuscript chapter that provides a literature review, problem development, and preferences that are used in the manuscript contained in Chapter 4. Chapter 3 uses the literature to identify the factors that have been found to influence the adverse impacts of forest roads on soil and water. This is an example of using AHP to design an inventory system for forest roads where the structure of the problem developed from the literature guides the collection of data in the field.

Chapter 4 contains the manuscript "A Systems Approach to the Management of Existing Forest Road Networks Using the Analytic Hierarchy Process." This manuscript uses the problem formulation developed in Chapter 3 and applies it to a small example of 8.3 miles of road divided into 127 road segments. These 127 road segments translate into 127 alternatives to be considered for maintenance or upgrade using AHP. Practical issues and consequences of using AHP on problems with large numbers of alternatives will be examined, including model simplification, model validation, and the effects of preference consistency.

Chapter 5 contains the manuscript "Systems of User Feedback for Large Project Pools Using AHP: An Application to Setting Priorities for Road Maintenance." This manuscript develops metrics to be used in exploring problems with large numbers of alternatives. These metrics will include measures of sensitivity that recognize the differences between small and large problems. Additionally, metrics specific to the road maintenance and upgrade problem are developed that allow the user to better understand the interaction between his or her stated preferences and the resulting ranking of priorities. The metrics developed are based on the principle that a better understanding of the problem, including the input data and the interaction of this data with preferences, will increase the user's confidence in the results of an analysis.

The metrics developed in Chapter 5 use the complete road inventory data for the Oregon State University College of Forestry Research Forests. Chapter 6, containing the manuscript "Scheduling Road Maintenance Using the Analytic Hierarchy Process and

Heuristics," also used this data set. This road inventory was collected by the Research Forest staff in 2002 and contains data on approximately 140 miles of road divided into 2,389 road segments located on five tracts of forestland. The AHP problem formulation used in these two chapters is an example of using AHP to analyze existing datasets.

Chapter 6 explores uses of the results of an AHP analysis in the allocation of road budgets and the scheduling of road maintenance. These various applications of AHP use alternative objective functions. The problem is formulated as a ten period (year) allocation of road budget to three main activities: routine road maintenance on a fixed schedule, addition of aggregate surfacing in anticipation of timber sales, and special maintenance and upgrade projects as identified by AHP. Due to the size of the problem (approximately 50,000 decision variables), a heuristic was developed to solve two formulations of the non-linear scheduling problem.

Chapter 7 summarizes the results of the four manuscripts and suggests further research. This is followed by a bibliography listing all references used throughout the dissertation and an appendix on the Power Method for calculating eigenvalues and their associated eigenvectors.

1.5 Definitions

Several terms used throughout the dissertation warrant definition. These are listed below.

Alternative: An option to be considered using AHP. In the case of the road maintenance problems illustrated here, an alternative refers to an individual road segment. Each alternative has data (attributes) that correspond to the items at the base of the AHP hierarchy.

Attribute: Items at the base of an AHP hierarchy that correspond to the data used to compare alternatives.

Consistency: In general, there are two levels of consistency that are of concern within AHP: ordinal and cardinal consistency. Ordinal consistency states that if A > B and B > C, then A must be greater than C. Cardinal consistency is a more strict requirement that it A is two times B and B is three times C, then A must be six (two times three) times C. When pairwise judgments within AHP do not conform to this definition of cardinal consistency they are said to be inconsistent.

Criteria: An element of the AHP hierarchy.

Heuristic: The series of orderly taken to arrive at a solution. The heuristic used in Chapter 6 is illustrated in Figure 6.3.

Inconsistent: Judgments that do not meet the rules for ordinal consistency.

2 The Analytic Hierarchy Process: A Tutorial for Use in Prioritizing Forest Road Investments to Minimize Environmental Effects

Elizabeth Dodson Coulter[1], James Coakley[2], and John Sessions[3]

2.1 Abstract

The prioritization of road maintenance projects is an important forest engineering task due to limited budgets and competing investment needs. Large investments are made each year to maintain and upgrade forest road networks to meet economic and environmental goals. Many models and guidelines are available for single-criteria analysis of forest roads, however we have found no method for multi-criteria analysis. Additionally, even single criteria approaches often rely on expert judgment to inform models of user preferences and priorities. These preferences are used to make tradeoffs between alternatives that contain data that are physical and biological, quantitative and qualitative, and measured on many different scales. The Analytic Hierarchy Process (AHP) has the potential to provide a consistent approach to the ranking of forest road investments based on multiple criteria. AHP was specifically developed to provide a consistent, quantifiable approach to problems involving multi-criteria analysis, but it has not been applied to road management. AHP is composed of four steps: the hierarchical decomposition of a problem into a goal, objectives, and sub-objectives; the use of a pairwise comparison technique to determine user preferences; the scaling of attribute values for each of the alternatives; and the ranking of alternatives. The road investment problem differs from traditional AHP applications in that potentially thousands of alternatives are compared at one time. We discuss the AHP methodology including the foundations, assumptions, and potential for use in prioritizing forest road investments to

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meet economic and environmental goals, drawing from an example from the OSU Research Forest.

2.2 Introduction

Each year, large sums of money are spent to upgrade and maintain networks of forest roads. One of the primary tasks in the management of any forest road network is to set investment priorities. This is currently done in an ad hoc, often reactionary fashion as new laws, policies, and preferences arise. Models and methods have been developed to deal with individual aspects of forest roads, such as sedimentation (Dube et al. 2004) and fish passage (Robison et al. 1999), but currently there is no comprehensive framework available to managers to aid in setting priorities on a system-wide, multi-criteria basis. The Analytic Hierarchy Process (AHP) has potential for filling this gap.

Many land management agencies and companies have undertaken inventories of their forest roads. Publications such as "Roads Analysis: Informing Decisions About Managing the National Forest Transportation System" (USFS, 1999) help decision makers decide on attributes of concern, but give little direction in how these attributes should be combined and analyzed. This has led to the prevalence of informal decision methods to set investment priorities. While these approaches are able to capture expert judgment, there is no way of ensuring this judgment is applied consistently.

Many modeling approaches used in forest engineering rely on expert opinion and professional judgment to inform models of user priorities that are used to make tradeoffs between alternatives. Often these alternatives contain physical and biological, quantitative and qualitative data that are measured on many different scales. Expert judgment is necessary in cases where science has not determined quantifiable relationships between cause and effect. Multi-Criterion Decision Analysis (MCDA) is a field of theory that analyzes problems based on a number of criteria or attributes.

Some MDCA techniques require decision makers to set parameter weights and coefficients, such as goal programming and nonlinear optimization. The major drawback to these techniques is that weights placed on individual attributes (for example acres harvested, tons of sediment, and dollars of net present value) are required to serve two purposes. First, the weight must make the variables measured on different scales comparable, and second, the weight is used to adjust the relative importance of each variable to the problem. The contribution of the weight to each of these purposes can not be separated from the total value of the weight being used.

An alternative MCDA technique called the Analytic Hierarchy Process, or AHP, is presented here. Quoting Harker and Vargas (1987, p. 1383), "AHP is a comprehensive framework which is designed to cope with the intuitive, the rational, and the irrational when we make multiobjective, multicriterion and multiactor decisions with and without certainty for any number of alternatives."

When considering the forest road investment problem, models and guidelines exist for single-problem analysis such as road-related sediment or fish passage. However, when a decision maker needs to prioritize investments based on multiple problems the task becomes more difficult. For example, science has not produced quantifiable relationships to guide tradeoffs between road-related sediment production and road-related landslides. Thus the problem of setting priorities when presented with a road inventory is left to professional judgment. AHP is a framework for ensuring this judgment is applied consistently to all alternatives within a replicable, mathematically justifiable framework.

The traditional use of AHP is to rank a small number of alternatives. The road investment problem differs from these traditional problems in that a single analysis may include a large number of alternatives in the form of individual road segments or road features. We first discuss the AHP methodology, including the foundations and assumptions, and then formulate and solve a forest road investment problem.

2.3 The Analytic Hierarchy Process

The AHP involves the following four basic steps:

- Structuring the problem as a hierarchy;
- Completion of pairwise comparisons between attributes to determine user preference;
- Scaling of attributes; and
- Ranking of alternatives.

2.3.1 Step 1: Structure the Problem as a Hierarchy

The hierarchy is a basic structure used intuitively by decision makers to decompose a complex problem into its most basic elements, a process referred to as hierarchical decomposition. The top level of the hierarchy is the overall goal for the analysis (Figure 2.1). This goal is important in framing and focusing the problem. For example, if we are using AHP to determine the "best" forest road investments to make, we could use any of the following goals:

- Minimize environmental impacts of forest roads;
- Minimize impacts of forest roads on endangered runs of fish;
- Improve salmon habitat through upgrades in the forest road network; or
- Minimize transportation costs associated with forest roads.

While all of these are legitimate goals, each will require a different analysis and produce a different outcome.

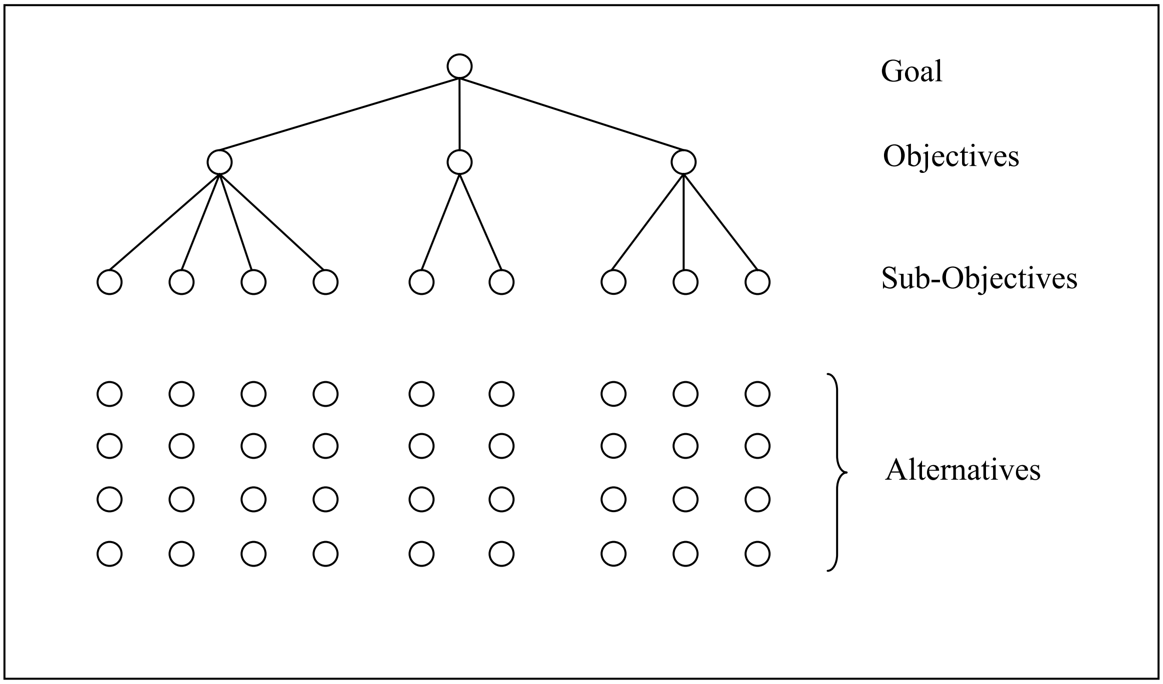

Figure 2.1: Generalized hierarchy depicting an overall goal, three objectives, and nine sub-objectives. Alternatives are not part of the problem hierarchy but have attributes that correspond to the elements in the lowest level of the hierarchy.

The second level of the hierarchy breaks the goal down into objectives. If the goal is to "minimize environmental impacts of forest roads," the second level in the hierarchy may contain the following objectives:

- Minimize sediment reaching waterways,
- Minimize the incidence of road-related landslides, and
- Minimize direct impacts to aquatic habitat.

The third and subsequent levels of the hierarchy further decompose the objectives into increasingly more specific sub-objectives.

Another way to look at the hierarchy is as a visual representation of an objective function where each objective is a function of its sub-objectives. This process of decomposition continues to successive layers of the hierarchy as far as is necessary to adequately represent the problem. It is not required that each objective be decomposed the same number of levels. An element that serves as an objective at one level may also serve as a sub-objective for the next higher level.

Below the hierarchy reside the alternatives to be considered. For our example these alternatives would be potential investments in a forest road network. Each alternative would have attributes that correspond to the criteria or sub-criteria at the lowest level of the hierarchy.

A hierarchy is termed complete if every element in each level connects to every element in both the layer above and below. The hierarchy shown in Figure 2.2b is an incomplete hierarchy because each sub-objective (third layer) is not relevant to each and every objective (second layer). The choice of a complete or an incomplete hierarchy depends on the independence of the individual elements. For example, consider two problem formulations where the overall goal is to choose restoration projects that will provide the most benefit to salmon habitat (Figure 2.2). In each of these formulations, the overall goal is subdivided into three objectives, or types of investments to be considered: investments associated with forest roads, investments related to silvicultural activities, and investments involving in-stream restoration. The bottom level of the hierarchy contains the attributes upon which the individual investments will be judged. For this example, let us consider only one of these factors: sediment.

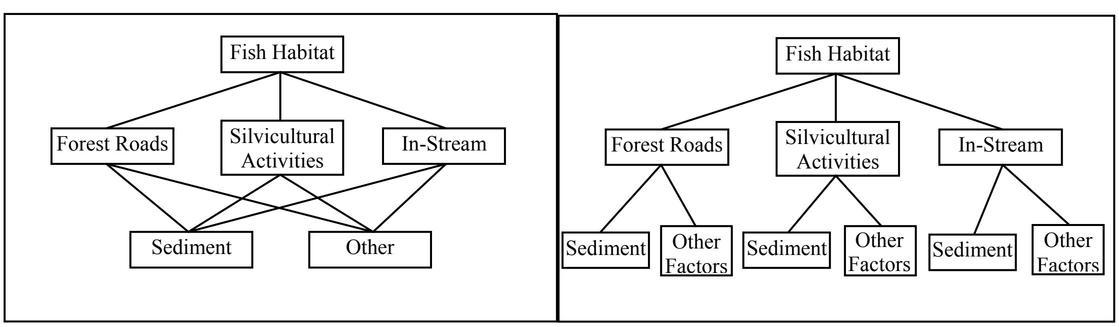

Figure 2.2: a) (left) Complete and independent problem formulation where the importance of sediment is independent of the sediment source. b) (right) Incomplete and dependent problem formulation where the importance of sediment is dependent on the sediment source.

While both formulations consider the same factor, sediment, in the first (Figure 2.2a) the worth of sediment in restoring fish habitat is independent of the source of sediment. In the second example (Figure 2.2b) the influence of sediment on the goal of restoring fish habitat would be dependent on its source, allowing the decision maker to treat sediment from roads differently from the sediment created through silvicultural activities or sediment that may already reside in a stream. The choice of hierarchical structure should follow the dependence or independence of the problem.

A classic psychological study conducted by Miller (1956) showed that the average individual has the capacity to keep only seven, plus or minus two, objects in mind at any one time without becoming confused. Therefore Saaty (1977) recommends that for each branch at each level of the hierarchy, no more than seven items be compared. For larger problems, this may mean that similar elements will need to be grouped and additional layers of hierarchy added in order to keep the problem formulation manageable.

This completes the first step of AHP. A hierarchical decomposition process is used to structure the goal as a hierarchy of objectives and sub-objectives. We now proceed to the second step which employs a pairwise comparison technique to derive the relative value of each objective and sub-objective.

2.3.2 Step 2: Pairwise Comparisons

In order to determine the relative importance of each objective and sub-objective, a pairwise comparison technique is used. Comparisons are performed between pairs of elements within each branch of each level of the hierarchy to determine the relative worth of one element as compared with another in relation to the element directly above. For example, a question that may be asked of a decision maker is "How much more important is sediment volume produced by the road than the distance between a road and the stream in predicting the volume of road-related sediment entering a stream?" The pairwise comparisons from each branch at each level of the hierarchy are entered into a matrix and used to determine a vector of priority weights. Only those elements that pertain to a common objective are compared against one another.

We use the following notation:

w_i = weight for attribute i, i=1,..,n where n = number of attributes

$a_{ij} = w_i / w_j$ = the result of a pairwise comparison between attribute i as compared to attribute j

A = matrix of pairwise comparison values, a_{ij}

A set of pairwise comparisons can be represented as:

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \qquad [2.1]$$

where w_1/w_2 is the importance of attribute *1* as compared to attribute *2*. Since the direct result of a pairwise comparison is a_{ij}, where a_{12} is equal to w_1/w_2, matrix A becomes:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad [2.2]$$

The goal of AHP is to uncover the underlying scale of priority values w_i. In other words, given a_{ij}, find the "true" values of w_i and w_j.

This A matrix has some special properties. First, A is of rank one. If we look at each column of A, we have:

$$A = \left\{ w_1^{-1} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}, w_2^{-1} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}, \cdots, w_n^{-1} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \right\} \qquad [2.3]$$

Each column of A differs only by a multiplicative constant, w_i^{-1}. If the A matrix is consistent only one column is required to determine the underlying scale ($w_1,\ldots,w_n$). The same evaluation could be undertaken in a row-wise fashion with the same result.

Second, if B is x times more important than C, then it follows that C is 1/x times as important as B. In other words, a_{ji} is the reciprocal of a_{ij} such that $a_{ij} = 1/a_{ji}$. This assumes the decision maker is consistent with respect to individual pairwise comparisons and is a fundamental assumption made by the AHP. With this assumption, matrix A is be reduced to:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{bmatrix} \qquad [2.4]$$

As seen in Equation 2.4, the diagonals are equal to unity (i.e. $w_1/w_1 = 1$). The above reduction means that only $\frac{n(n-1)}{2}$ pairwise comparisons need to be solicited from decision makers as compared with n^2 total entries in the completed A matrix. If the assumption that the decision maker is consistent with respect to individual pairwise comparisons does not hold, in other words if $a_{ij} \neq 1/a_{ji}$, then $(n^2 - n)$ pairwise comparisons would be required.

2.3.2.1 Deriving Weights

Once pairwise comparisons have been elicited from the decision maker, the next step is to use this matrix to estimate the underlying scale of preferences. In other words, given a_{ij}, find w_i and w_j. Because of the "random" error inherent in human judgment, even professional judgment, it can not be expected the true values of w_i and w_j can be found. The user will need to be content instead with good estimates of w_i and w_j (Fichtner 1986). Several methods have been proposed to estimate weights from matrices of pairwise comparisons. The two most common methods of deriving attribute weights are the eigenvector and the logarithmic least squares methods.

It can be shown by algebraic manipulations of the pairwise definitions that attribute weights can be obtained by finding the eigenvector corresponding to the largest eigenvalue of the A matrix. The eigenvector method was originally proposed by Saaty

(1977) and is one of the most popular methods of calculating preferences from inconsistent matrices of pairwise comparisons. Equation 2.3 showed a consistent matrix of pairwise comparisons. When this matrix is consistent it is of rank one, meaning that only one column or one row is necessary to derive the underling scale, w_i, of weights. When inconsistency is introduced into pairwise comparisons, more than one row or column of A is desired in order to derive a good estimate of the underlying scale of weights. The largest eigenvalue of A, λ_{max}, is used in consistency calculations (discussed below in Section 2.3.2.2 Consistency) and its corresponding eigenvector, normalized such that its components sum to one, represents the vector of attribute weights.

Elements of the eigenvector are normalized to sum to one as opposed to setting the largest element of the eigenvector equal to one. This is required in order to give the potential for equal weighting between branches of the hierarchy where the number of elements being compared may be different. This normalization ensures the weights within each branch of the hierarchy sum to one no matter the number of elements or the relationships between the elements of a branch. Assume a hierarchy with two branches with two and six sub-objectives, respectively. If the vector of weights were normalized such that the largest element is equal to one, the branch with six sub-objectives would be given more weight in total than the branch with only two sub-objectives. Likewise, a branch where there is little preference for one element over another would be given a higher total weight over a branch with the same number of elements but with larger differences in preferences between the individual elements.

Following the definition of $a_{ij} = w_i/w_j$ and $a_{ij} = 1/a_{ji}$:

$$a_{ij}a_{ji} = a_{ij}\frac{1}{a_{ij}} = a_{ij}\frac{1}{\frac{w_i}{w_j}} = a_{ij}\frac{w_j}{w_i} = 1 \qquad [2.5]$$

It follows that in the consistent case:

$$\sum_{j=1}^{n} a_{ij}\frac{w_j}{w_i} = n \qquad i = 1 \text{ to } n \qquad [2.6]$$

or, stated another way, multiplying Equation 2.6 through by w_i:

$$\sum_{j=1}^{n} a_{ij} w_j = n w_i \qquad i = 1 \text{ to } n \qquad [2.7]$$

These statements are equivalent to the matrix notation Aw = nw. If the goal is, given a positive reciprocal matrix A, to find w, the problem becomes (A - $n\boldsymbol{I}$) w = 0. This is a classical eigenvector problem and is non-trivial if and only if n is an eigenvalue of A. This method for deriving a vector of weights from a positive reciprocal matrix of pairwise comparisons uses the largest eigenvector, also termed the principal right eigenvector, and its corresponding eigenvalue.

One way to understand what eigenvectors and eigenvalues are is the following:

$$Aw = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \qquad [2.8]$$

where n, the eigenvalue of A (in the consistent case λ_{max} will equal n), is a matrix with diagonal values of λ_i, the components of the eigenvector of n, and zero elsewhere. In other words, the eigenvector of A is an equivalent, diagonalized form of A.

The Perron-Frobenius Theorem ensures that the components of the principal right eigenvector of a positive square matrix are real and positive (Aupetit and Genest 1993). Matrices of pairwise comparisons within AHP will always be positive because all elements will be greater than zero, and will always be square with both a column and a row for each element to be compared. Additionally, the Perron-Frobenius theorem states that the principal right eigenvector will be comprised strictly of positive entries and is unique up to a multiplicative constant. In other words, when the components of the resulting eigenvector are normalized to sum to one the solution will be unique. No other eigenvector of A, when normalized in a similar fashion, will be the same as the eigenvector corresponding to the largest eigenvalue of A.

Arriving at a close approximation to the eigenvalue and eigenvector of A is a relatively simple task. Most numerical methods for estimating eigenvalues require a symmetric, square, and positive matrix. AHP produces a square, positive matrix, but this matrix is reciprocal, not symmetric. This leaves the Power Method as the simplest method to implement (Hornbeck 1975). The Power Method can be used with a non-symmetric matrix as long as the dominant eigenvalue is not complex (see Appendix 1 for a description of the Power Method). Perron's Theorem ensures that the largest eigenvalue of a positive square matrix will be both simple and positive and has a corresponding positive eigenvector.

The other commonly used method for scaling a matrix of pairwise comparison data is the logarithmic least squares method (LLSM), first proposed by Crawford and Williams (1985). When pairwise comparisons are inconsistent, $a_{ij} = (w_i / w_j)$ becomes $a_{ij} = (w_i / w_j)(\varepsilon_{ij})$ where ε_{ij} is the error associated with inconsistent judgment. This relationship can also be expressed as:

$$\ln a_{ij} = \ln w_i - \ln w_j + \ln \varepsilon_{ij} \qquad i = 1, 2, \ldots, n;\ j > i \qquad [2.9]$$

This assumes the distribution of ε_{ij} is reciprocal such that $\varepsilon_{ij} = 1/\varepsilon_{ji}$ and lognormally distributed and leads to the minimization of the following equation (Crawford 1987):

$$\sum_{i=1}^{n} \sum_{j>i} \left[\ln a_{ij} - \left(\ln w_i - \ln w_j\right)\right]^2 \qquad [2.10]$$

Note that Equation 2.10 is nearly identical to the standard minimization of the sum of squares used in least-squares regression. The goal of LLSM is similar: to find the vector of weights that is the shortest distance from multiple estimates provided by pairwise comparisons. Equation 2.10 can be simplified so that for each row of A the geometric row mean is calculated:

$$w_i = \left[\prod_{j=1}^{n} a_{ij}\right]^{\frac{1}{n}} \qquad [2.11]$$

Like the eigenvector method the vector of resulting values is normalized so that the elements sum to one.

While some have strong feelings for either the eigenvector or LLSM (see Saaty and Hu (1998), Saaty and Vargas (1984), and Crawford (1987)), others consider this an extra-mathematical decision to be made when implementing AHP (Fichtner 1986). In the consistent case or when three or fewer elements are being compared, both the eigenvector and LLSM will give the same result after normalization. The question of the most appropriate scaling method arises when the matrices of pairwise comparisons are not consistent (see Fichtner 1984 and 1986). Both the eigenvector method and LLSM are accepted theoretically and used often in practice with little difference in the results (Crawford 1987). With pairwise comparisons completed and criteria weights calculated, we now look at methods for ensuring the preferences of the user are consistent enough to provide reliable criteria weights.

2.3.2.2 Consistency

Deviations from both ordinal and cardinal consistency are considered, and to a certain extent allowed, within AHP. Ordinal consistency requires that if *x* is greater than *y* and *y* is greater than *z*, then *x* should be greater than *z*. Cardinal consistency is a stronger requirement stipulating that if *x* is 2 times more important than *y* and *y* is 3 times more important than *z*, then *x* must be 6 times more important than *z*. If A is cardinally consistent, then $a_{ij}a_{jk} = a_{ik}$. Using the previous definition of a_{ij} we can see that this is true:

$$a_{ij}a_{jk} = \frac{w_i}{w_j}\frac{w_j}{w_k} = \frac{w_i}{w_k} \qquad [2.12]$$

If the relationship $a_{ij}a_{jk} = a_{ik}$ does not hold than A is said to be cardinally inconsistent. AHP has been designed to deal with inconsistent matrices (both cardinal and ordinal inconsistency), thus the problem becomes:

$$\frac{w_i}{w_j}\varepsilon_{ij} \cdot \frac{w_j}{w_k}\varepsilon_{jk} = \frac{w_i}{w_k}\varepsilon_{ik} \qquad [2.13]$$

where $\varepsilon_{ij} > 0$ and represents some perturbation causing A to be inconsistent, producing an A matrix that looks like the following:

$$A = \begin{bmatrix} 1 & \varepsilon_{12}a_{12} & \varepsilon_{13}a_{13} & \cdots & \varepsilon_{1n}a_{1n} \\ 1/\varepsilon_{12}a_{12} & 1 & \varepsilon_{23}a_{23} & \cdots & \varepsilon_{2n}a_{2n} \\ 1/\varepsilon_{13}a_{13} & 1/\varepsilon_{23}a_{23} & 1 & \cdots & \varepsilon_{3n}a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/\varepsilon_{1n}a_{1n} & 1/\varepsilon_{2n}a_{2n} & 1/\varepsilon_{3n}a_{3n} & \vdots & 1 \end{bmatrix} \quad [2.14]$$

Various methods have been devised to deal with inconsistency. Saaty (1977) suggests using the following consistency index (CI):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad [2.15]$$

where λ_{max} is the largest eigenvalue of A and n is the number of elements within a branch being compared. If A is perfectly consistent (cardinally) than λ_{max} will be at a minimum and equal to n, producing a CI equal to zero. As inconsistency increases λ_{max} will become increasingly large, producing a larger value of CI. This consistency index can also be expressed as a consistency ratio:

$$CR = \frac{CI}{CI_R} \quad [2.16]$$

where CI_R is the consistency index for a random square matrix of the same size. Saaty (2000) suggests that CR should be less than or equal to 0.1, but the choice is arbitrary. If after completion of a pairwise comparison matrix CR exceeds this threshold value then the user is instructed to go back and revise comparisons until the value of CR is acceptable.

Several methods for revising matrices to achieve an acceptable CR have been developed. The simplest method for identifying pairwise comparisons that are the most inconsistent is to compare the response from the pairwise comparison process (a_{ij}) with a ratio derived from the calculated weights (w_i / w_j). Those values of a_{ij} that are the most different from w_i / w_j are the pairwise comparisons that, if changed in the direction of w_i / w_j, will most improve consistency.

Karapetrovic and Rosenbloom (1999) have argued this approach measures the randomness of the user's preferences and that randomness of preferences is an inappropriate measure to use. The authors argue there are legitimate reasons for inconsistency and argue that instead the test should be to make sure no mistakes were made by the decision maker in entering pairwise comparisons into the matrix. Mistakes can be detected using tools borrowed from statistical quality control when more than one pairwise comparison matrix is computed for a given problem. Karapetrovic and Rosenbloom's method involves tracking CI over time using moving average and range control charts. This method is only valid when a sufficient number of pairwise comparison matrices are completed to allow the observation of a trend over time and assumes that a given decision maker is equally inconsistent throughout a given problem.

2.3.4 Step 3: Scaling Attributes

After pairwise comparisons have been made and priority weights calculated for each element within the hierarchy, the input data for each alternative must be transformed to a usable value before alternatives can be compared. A major strength of AHP is its ability to incorporate attributes that are measured on a number of different scales, at different intensities, and can include both numeric, descriptive, and categorical data.

AHP allows for a high degree of flexibility in the treatment of input data. This is achieved by converting all values to relative data. Relative values can be created by either comparing attribute values to other alternatives being compared or by comparing attributes to an "ideal" alternative. The choice of treatments will be dependent on the type of problem and available data.

When Saaty (1977) conceived AHP he carried pairwise comparisons through to the alternatives, termed relative scaling. Relative scaling has generated a large amount of criticism (see Belton and Gear 1983, 1985 and Millet and Saaty 1999) and will generally not be appropriate for the road investment problem or any other problem where more than a small number of alternatives are considered.

An alterative method proposed by Saaty for dealing with alternatives is the absolute, or ideal, mode of AHP. In the absolute mode, for a given attribute, each alternative is compared with an "ideal" alternative to determine its weight, termed "scoring." The score for each attribute of each alternative will range between zero and one. A common scoring technique involves dividing each attribute value by the maximum value for that attribute present among the alternatives. This assumes the decision maker's preference for that attribute is linear. Non-linear preferences can also be accommodated within AHP. These functions may be the result of scientific study, expert judgment, or pairwise comparisons between categorical variables.

We have now moved through the construction of the problem as a hierarchy, presented a technique of pairwise comparisons to estimate user preferences, and have discussed method to convert attribute data into a relative form. What remains is the synthesis of the information generated in the first three steps to develop a ranked list of alternatives.

2.3.5 Step 4: Synthesizing Priorities

Once relative values have been calculated for each attribute of each alternative, these attribute scores are combined with the attribute weights from pairwise comparisons to determine the overall ranking of each alternative. This is accomplished using a simple additive function. The products of each attribute score and its associated attribute weight are summed across each branch of the hierarchy. This sum becomes the attribute value for the node directly above and the process is repeated at the next level of the hierarchy.

Take, for example, a single objective with three sub-objectives. Using the pairwise comparison technique previously discussed, assume the weight for each of the three sub-objectives was determined to be equal to x_1, x_2, and x_3, respectively. Every alternative under consideration will have attributes that correspond to each of these three sub-objectives. Using techniques presented in the previous section, assume each attribute of each alternative has been reduced to a relative value. We will call this relative value for a general alternative y_1, y_2, and y_3, respectively. To calculate the overall score for the objective, S, the products of each attribute score and its associated attribute weight are summed, yielding the equation $S = x_1y_1 + x_2y_2 + x_3y_3$. If this objective is used as a sub-objective in the next higher level of the hierarchy, the relative value used for this attribute is S.

The overall score for a given alternative means nothing when standing alone. Only when compared with the overall scores for other alternatives does this number become meaningful. At this point, alternatives can be ranked by their importance in contributing to the goal of the analysis by simply sorting alternatives based on their overall score. Those alternatives with the higher score will receive a higher overall ranking.

2.4 Model Validation

Because AHP is based on the preferences of the decision maker, validation of the resulting weighting of alternatives is not possible or practical with traditional means. Kangas (1993, p. 285) points out that it "may be easier for the decision-maker to understand and accept this if he or she can be made aware of the fact that his or her preferences actually determine the outcome of the decision analysis."

The comparison of results from an application of AHP with historic results is not appropriate because it is assumed that past results are not based on consistently applied expert judgment, otherwise there would be no reason to implement AHP. Attempts have been made to compare the results from AHP with actual preferences. Cheung et al. (2001) used a line of questioning that provided additional information about the criteria decision makers were using to make their decisions. This information could then be used to refine the analysis.

In many cases the professional judgment required to structure the problem as a hierarchy and inform the model of preferences is the same professional judgment that determines if AHP is producing adequate results. The lack of a solid means of validating AHP results is one of the concerns that keeps many decision makers from utilizing the power of AHP. However, AHP is by nature designed to be used in situations where science has not yet been able to define quantifiable relationships and decisions rely, in large part, on professional judgment. As stated above by Kangas, a model built around human preferences should not be expected to produce a clear right or wrong answer.

2.5 Uses of the AHP in the Prioritization of Forest Road Investments

The traditional use of AHP is to rank a finite, generally small, number of alternatives. This has primarily been the focus of previous uses of AHP within natural resources. Several applications of AHP involve choosing between a small set of potential forest plans or projects (see Leskinen and Kangas (1998), Schmoldt et al. (1994), Kangas et al. (1993), Reynolds and Holsten (1994) for examples). While this remains a useful application, the forest road investment prioritization problem differs from the traditional AHP problem in that the number of alternatives to choose from may extend into the hundreds or even thousands. Additional constraints such as budget and time also need to be included in the scheduling of forest road investments. We illustrate our approach in a small example derived from data from the Oregon State University Research Forest in western Oregon.

We assume a goal of minimizing the environmental impacts of forest roads. We limit the impacts to road related sediment, landslides, and direct impacts to fish habitat for brevity. For this problem, an incomplete hierarchy structure has been constructed (Figure 2.3). The problem has been decomposed into three levels including the overall goal and three objectives, each with from two to six sub-objectives. Twelve sub-objectives form the base of the hierarchy. Figure 2.A1 in Appendix A describes and gives definitions for each of the twelve sub-objectives. Associated with this hierarchy are 20 potential road investments (alternatives) with attributes that correspond to the twelve sub-objectives at the lowest level of the hierarchy. Data for these alternatives are given in Figure 2.A2 in Appendix A.

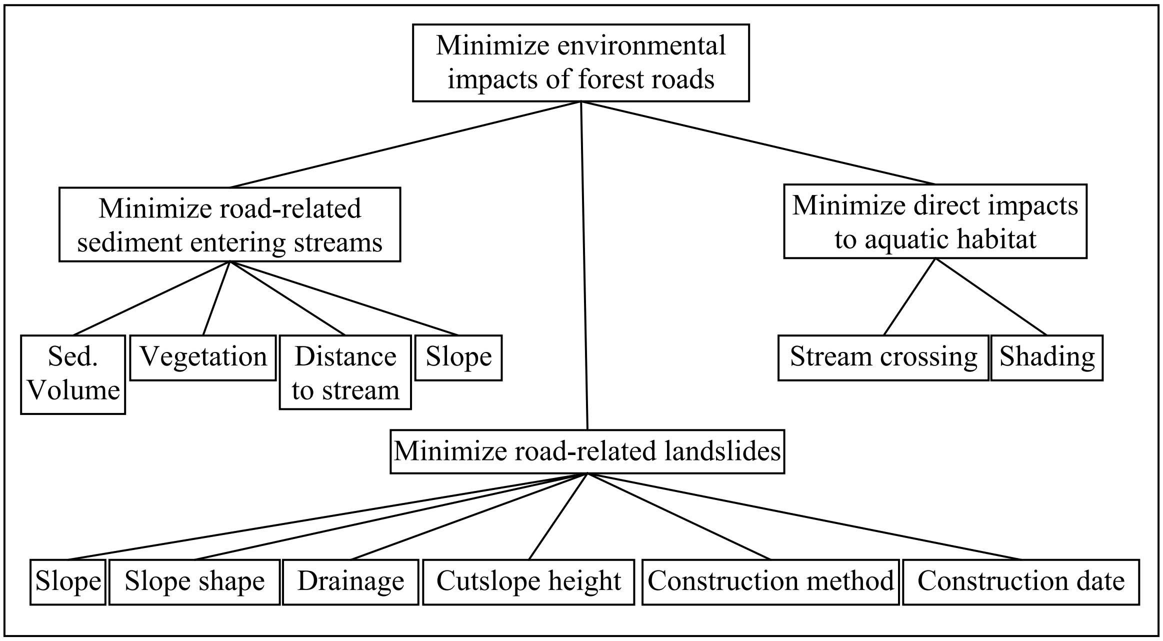

Figure 2.3: Hierarchy for the example problem containing an overall goal of minimizing the environmental impacts of forest roads, three objectives, and twelve sub-objectives.

To compare the elements within the second level of the hierarchy, a decision maker would be asked three questions:

- How important are direct impacts to fish as compared to sediment in reducing the environmental impacts of forest roads?
- How important are direct impacts to fish as compared to slope stability in reducing the environmental impacts of forest roads?
- How important is sediment as compared to slope stability in reducing the environmental impacts of forest roads?

If the response to the first question is “moderate importance”, to the second “very strong importance” and to the third “strong importance,” the A matrix would be structured as shown in Table 2.1.

Table 2.1: Pairwise comparison of the second level of example hierarchy using verbal responses corresponding to Saaty's linear 1-to-9 scale.

	Direct impacts to fish	Sediment	Slope stability
Direct impacts to fish	1	Moderate importance	Very strong importance
Sediment		1	Strong importance
Slope stability			1

The A matrix is completed by converting the verbal responses into a numerical value. One desirable quality of a chosen scale is that the decision maker should be able to keep all possible scale values in mind at one time. Returning to the findings of Miller (1956), the average individual has the capacity to keep only seven, plus or minus two, objects in mind at any one time without becoming confused (Table 2.2).

Saaty proposes a linear scale consisting of the integers from one to nine (Figure 2.2). The integer value is given to the more preferred attribute with the reciprocal of the integer recorded for the lesser preferred attribute. For the preferences stated above (Table 2.1), the resulting A matrix is shown in Table 2.3. The second row represents "sediment" as compared to "direct impacts to fish" in the first column. Here, "direct impacts to fish" was given moderate importance over "sediment", a value of 3 using Saaty's original 1-to-9 scale, so the inverse value, 1/3 is entered in the first column of the second row. The second column of the second row compares "sediment" to itself so a value of 1 is entered. For the third column of the second row the result of "sediment" compared to "slope stability" is recorded with a value of 5, representing the decision maker's view that "sediment" has strong importance over "slope stability" when minimizing the environmental impacts of forest roads.

Table 2.2: The scale used in the AHP to convert verbal responses to numeric values based on the integers between one and nine (adapted from Saaty 2000).

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above nonzero numbers	If activity A has one of the above nonzero numbers assigned to it when compared with activity B, then B has the reciprocal value when compared with A.	

Table 2.3: Pairwise comparison of second level of example hierarchy using Saaty's linear 1-to-9 scale to convert the verbal responses given in Table 2.2 to numeric values.

	Direct impacts to fish	Sediment	Slope stability	Weight
Direct impacts to fish	1	3	9	0.649
Sediment	1/3	1	5	0.279
Slope stability	1/9	1/5	1	0.072

Other methods and scales have been developed to convert verbal responses to numeric values. Lootsma (1991, 1993) introduced a geometric progression of values of the form $a_{ij} = e^{s\delta_{ij}}$, where $s > 0$ is a scale parameter and δ_{ij} are integers between -8 and 8, corresponding to Saaty's verbal scale. Lootsma's geometric progression was designed to be used only with the LLSM. The value of *s* can be calibrated to match scale values to the decision maker's preferences and is an additional parameter that must be set by the user. This additional variable *s* adds to the uncertainty in the results, increases the complexity, and adds little to no improvement in the results. While Lootsma's geometric scale is used, the most common scale is Saaty's linear 1-to-9 scale.

Using the matrix of pairwise comparisons, weights for each of the three objectives can be calculated using either the eigenvector or LLSM procedure (Table 2.3). Either method results in a weight of 0.649 for the objective "Minimize direct impacts to fish," 0.279 for "Minimize road-related sediment," and 0.072 for "Minimize road-related landslides." Before continuing, the consistency of judgments is checked using the Consistency Ratio approach presented previously. For this set of comparisons, λ_{max} is equal to 3.065, producing a CI of 0.032. The RI for a three by three square matrix is 0.52, leading to a CR of 0.062. If this CR value had been greater than a set threshold value, Saaty recommends pairwise comparisons be revised until the value of CR is acceptable. This same procedure is completed for the other three sets of pairwise comparisons needed to complete this example problem. The results of these comparisons are presented in Appendix A Tables 2.A4-2.A7.

In this example, the attribute value for "Minimize direct impacts to aquatic habitat" for each alternative is the sum of the relative value for "stream crossing" multiplied by the attribute weight for "stream crossing" and the relative value multiplied by the attribute weight for "shading." This same operation is carried out for the other two branches of the hierarchy. The overall score for "Minimize environmental impacts of forest roads" then becomes the sum of each objective's value multiplied by its weight. This is shown graphically for the first alternative in Figure 2.4 where each attribute score is presented in italics and each element weight is presented in bold type.

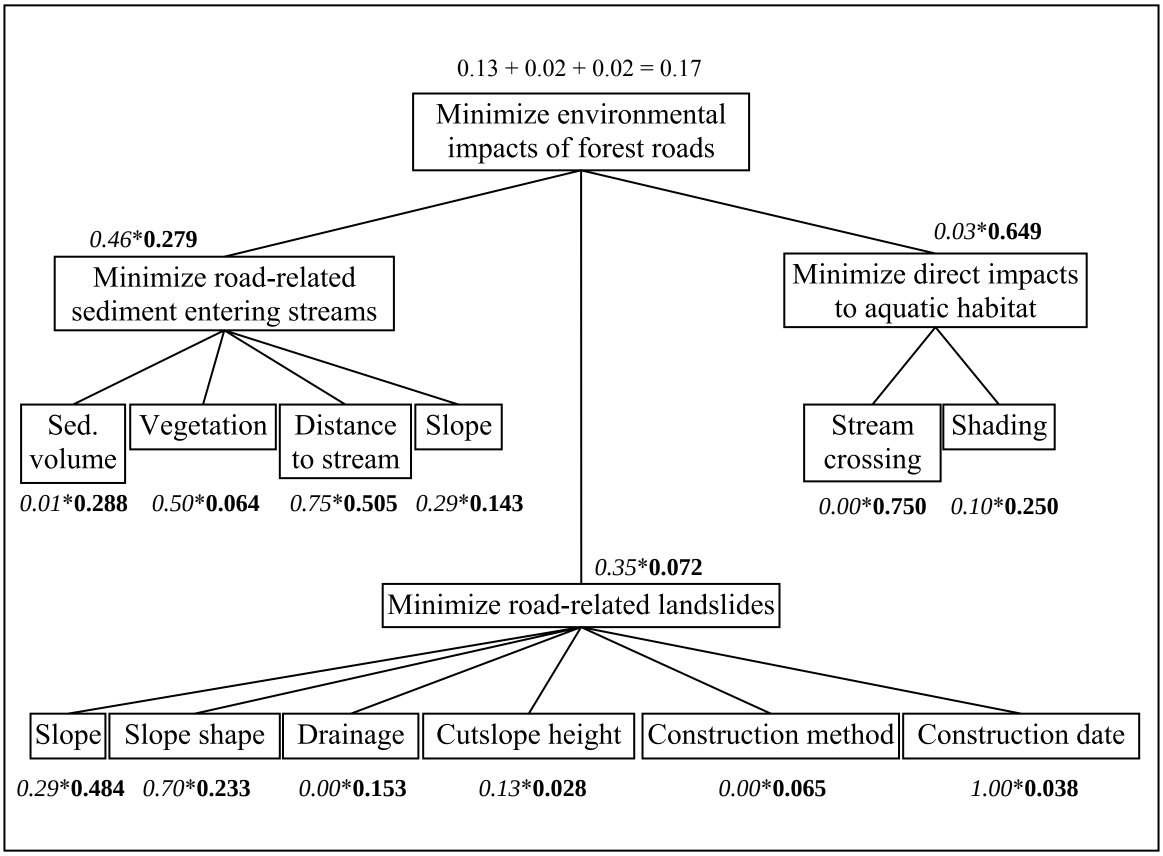

Figure 2.4: Calculation of overall score value for Alternative 1 of the example problem. Bold values indicate attribute weights, values in italics are relative attribute scores for Alternative 1.

When this synthesis of relative attribute values and attribute weights is completed for all 20 alternatives, the overall score for each alternative can be compared to the overall scores for the other alternatives and a ranking derived (Table 2.4). This ranking gives the user not only the ordinal rank of each alternative but a quantitative measure of the relative importance of each alternative. Note that the LLSM and eigenvector method produce identical rankings for this example.

Table 2.4: Overall score and ranking for the 20 alternatives in the example problem (data presented in Appendix A) using both the LLSM and eigenvector method of calculating weights from pairwise comparison data.

Alternative	LLSM Overall Score	LLSM Rank	Eigenvector Overall Score	Eigenvector Rank
1	0.167	10	0.168	10
2	0.243	4	0.244	4
3	0.180	9	0.181	9
4	0.190	8	0.189	8
5	0.202	7	0.202	7
6	0.114	16	0.114	16
7	0.047	20	0.047	20
8	0.087	18	0.087	18
9	0.137	14	0.136	14
10	0.402	2	0.403	2
11	0.152	12	0.151	12
12	0.214	5	0.213	5
13	0.666	1	0.666	1
14	0.355	3	0.355	3
15	0.142	13	0.142	13
16	0.206	6	0.207	6
17	0.082	19	0.081	19
18	0.101	17	0.101	17
19	0.116	15	0.116	15
20	0.162	11	0.162	11

2.5.1 Cost/Benefit Ratios

The overall score value can also be used as a measure of the relative worth of a given alternative as compared with other alternatives. This naturally leads to a cost/benefit ratio use of the overall score values combined with some measure of economic cost (Table 2.5). The numerator of the cost/benefit ratio is an estimated cost to fix a given problem represented by each alternative. The denominator, benefit, is the overall score generated using AHP. This score was calculated using the eigenvector method and absolute scoring. This comparison is possible because the benefit for a given project is a relative value calculated on the same scale as all other alternatives under consideration. The alternatives with the lower cost/benefit ratios would be the more favored alternatives, indicating those alternatives that will provide a greater benefit for every dollar spent. Combining the cost of a given investment and the benefit that investment will produce, a new ranking of alternatives can be made that considers both factors (Table 2.6).

Table 2.5: Cost/Benefit Ratio Example where cost is the estimated cost to complete a given alternative and the benefit is the overall score calculated using AHP, sorted by cost/benefit ratio.

Alternative	Overall Score	Price	Cost/Benefit ($1000/overall score)	Cost/Benefit Rank
13	0.666	$ 26,000	390.54	2
10	0.403	$ 8,000	198.72	6
14	0.355	$ 700	19.69	19
2	0.244	$ 7,500	307.13	4
12	0.213	$ 2,000	93.70	9
16	0.207	$ 350	16.92	20
5	0.202	$ 4,000	197.84	7
4	0.189	$ 750	39.59	15
3	0.181	$ 7,000	386.44	3
1	0.168	$ 750	44.68	11
20	0.162	$ 650	40.02	14
11	0.151	$ 4,500	297.42	5
15	0.142	$ 350	24.69	17
9	0.136	$ 1,500	109.98	8
19	0.116	$ 500	43.20	13
6	0.114	$ 500	43.85	12
18	0.101	$ 300	29.83	16
8	0.087	$ 200	22.99	18
17	0.081	$ 400	49.18	10
7	0.047	$ 3,000	643.05	1

2.5.2 Resource Allocation

The relative priorities derived using AHP can be used to allocate resources. For example, a simple three period integer programming allocation problem can be formulated using the benefits and costs for each alternative:

$$\text{Maximize } \sum_{j=1}^{3}\sum_{i=1}^{20} x_{ij} b_i$$

$$\text{s.t.} \quad \sum_{i=1}^{20} x_{ij} c_i < \$10{,}000 \quad \text{for every } j$$

$$\sum_{j=1}^{3} x_{ij} \leq 1 \quad \text{for every } i$$

$$x_{ij} \in \{0,1\} \quad \text{for every } i, j$$

Where *i* is the alternative (20 total), *j* is the period (3 total), b_i is the benefit derived though AHP for each alternative, c_i is the cost to repair each alternative (investment), and x_{ij} is a binary variable indicating if alternative *i* will be completed in period *j*.

The total dollar value to fix or complete all of the twenty alternatives is $68,950. For this example, only $10,000 is available to spend in each of the three time periods. The expenditures in each of the three periods were $7,450, $10,000, and $10,000, with a total benefit in each period of 1.318, 0.874, and 0.573, respectively (Table 2.6).

Table 2.6: Per alternative results of a three period allocation problem solved using linear programming sorted by period of completion.

Alternative	Overall Score	Price to Complete	Period Completed
7	0.047	$ 3,000	1
8	0.087	$ 200	1
9	0.136	$ 1,500	1
14	0.355	$ 700	1
15	0.142	$ 350	1
16	0.207	$ 350	1
17	0.081	$ 400	1
18	0.101	$ 300	1
20	0.162	$ 650	1
1	0.168	$ 750	2
4	0.189	$ 750	2
6	0.114	$ 500	2
10	0.403	$ 8,000	2
2	0.244	$ 7,500	3
12	0.213	$ 2,000	3
19	0.116	$ 500	3
3	0.181	$ 7,000	-
5	0.202	$ 4,000	-
11	0.151	$ 4,500	-
13	0.666	$26,000	-

Many of the large planning models used to manage forest roads use an objective function with many coefficients that must be decided upon and changed by the user. The value of these coefficients is heavily dependent on professional judgment and generally no formal process for deriving these coefficients is used. AHP provides a structured process to develop professional judgments and user preferences into coefficients that can be used in an objective function. This objective function can then be used to measure the "quality" of a given solution compared to solutions in previous or future model runs. The "ideal" against which each alternative would be compared to in order to determine an attribute's relative value would need to be set as a static value, not simply the maximum value present in a group of alternatives. These "ideal" attribute values would need to remain constant in order for overall alternative scores to be comparable. Once an "ideal" value is changed, a new comparison between overall scores would be required. This application of AHP has been introduced by Saaty (1986) and Schmoldt et al. (1995) but has not been demonstrated widely in the literature and may be a promising arena for future work.

2.6 Concluding Remarks

The Analytic Hierarchy Process appears to have potential for managing existing road systems where science has not yet uncovered quantifiable relationships between cause and effect, meaning the synthesis of road inventory data to set investment priorities must rely in part on professional judgment. AHP provides users with a structured means of incorporating both scientific data and professional judgments into a replicable process. Additionally, the overall score for each alternative can be used as a measure of the relative worth of a given alternative in relation to the overall goal as compared to the other alternatives under scrutiny. This relative benefit can be used to further incorporate costs into the decision analysis either through the use of a cost/benefit ratio or as a constraint used in scheduling investments.

The flexibility provided by AHP requires users to make several decisions in the formulation and implementation of an AHP solution. In order to make informed decisions concerning the correct application of AHP to a particular situation, it is necessary for the decision maker to have a clear understanding of the consequences of these decisions. This paper has presented the theoretical background, benefits, and drawbacks of many of these choices.

The forest road investment problem to minimize the environmental impacts of roads differs from the traditional applications of AHP in that the potential exists for large numbers of alternatives to be compared simultaneously. The measures of relative benefit of each alternative can then be used in subsequent models to allocate scarce resources such as budget and time.

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2.8 Appendix A

The following problem is used in many examples throughout the paper. Table 2.A1 gives a description of the variables used. Data is presented for the 20 alternatives considered in Table 2.A2. This data is reduced to relative values in Table 2.A3. Verbal responses to pairwise comparisons are presented in Tables 2.A4, 2.A5, 2.A6, and 2.A7.

Table 2.A1: Variable descriptions for the example problem.

Variable	Abbreviation	Description
Volume	Vol	Tons of sediment produced by given road segment
Vegetation	Veg	Qualitative rating of vegetative cover between the road segment and the stream, rated on a scale of 1 to 10 where 1 represents no vegetation and 10 represents complete vegetative cover
Distance	Dist	Distance in feet from the road segment to a stream
Slope1	S1	Slope in percent between the road and the stream
Slope2	S2	Slope in percent of the natural hillslope (excluding the road prism)
Slope shape	Shape	Categorical description of the shape of the natural hillslope (excluding the road prism)
Drainage	Drainage	Qualitative categorical description of the road drainage, ranging from poor to good
Cutslope height	CSH	Average height of the cutslope in feet
Construction method	Method	Categorical description of the construction method used, either sidecast or endhaul
Construction date	Date	Decade of initial road construction
Stream crossing	Xing	Description of fish passage through a stream crossing structure, N/A indicates the road segment does not include a stream crossing
Shading	Shade	Percent reduction in stream shading due to the presence of the road segment

Table 2.A2: Raw data for the 20 alternatives compared in the example problem.

	Vol	Dist	S1	Veg	S2	Shape	Drainage	CSH	Method	Date	Xing	Shade
1	7800	28	100	4	100	Convex	Average	5	Sidecast	Pre-1960	N/A	0
2	7200	0	9	5	9	Planar	Poor	6	Sidecast	1970	YES	40
3	8500	248	117	6	117	Concave	Average	16	Sidecast	Pre-1960	N/A	0
4	700	0	88	6	88	Planar	Average	7	Endhaul	1980	NO	15
5	450	0	44	8	44	Planar	Average	9	Sidecast	1970	YES	60
6	6400	30	119	8	119	Convex	Average	12	Endhaul	1990	N/A	0
7	2000	0	119	8	119	Convex	Average	3	Sidecast	1990	YES	80
8	270	62	120	1	120	Planar	Average	7	Sidecast	1960	N/A	0
9	860	0	46	1	46	Concave	Poor	19	Sidecast	1970	YES	10
10	570	488	101	7	101	Concave	Average	15	Endhaul	1970	N/A	0
11	110	0	58	3	58	Planar	Average	10	Endhaul	1980	YES	5
12	4500	0	82	3	82	Convex	Poor	15	Endhaul	1980	NO	75
13	600	495	106	10	106	Planar	Poor	14	Sidecast	Pre-1960	N/A	0
14	1700	0	27	7	27	Planar	Good	0	Sidecast	1960	YES	90
15	260	0	83	9	83	Planar	Average	20	Sidecast	Pre-1960	NO	35
16	40	482	101	2	101	Planar	Average	14	Endhaul	1960	N/A	0
17	600	320	77	7	77	Planar	Average	11	Sidecast	1980	N/A	0
18	3700	0	4	7	4	Convex	Good	2	Sidecast	1990	YES	40
19	30	0	19	8	19	Concave	Poor	2	Sidecast	1960	NO	5
20	630	0	44	7	44	Planar	Good	5	Sidecast	1970	NO	80

Table 2.A3: Relative data used in example problem.

	Vol	Dist	S1	Veg	S2	Shape	Drainage	CSH	Method	Date	Xing	Shade
1	0.92	0.06	0.83	0.40	0.83	0	0.3	0.23	1	1	0	0.00
2	0.85	0.00	0.08	0.50	0.08	0.7	1	0.31	1	0.7	0	0.44
3	1.00	0.50	0.98	0.60	0.98	1	0.3	0.83	1	1	0	0.00
4	0.08	0.00	0.73	0.60	0.73	0.7	0.3	0.36	0	0.3	1	0.17
5	0.05	0.00	0.37	0.80	0.37	0.7	0.3	0.46	1	0.7	0	0.67
6	0.75	0.06	0.99	0.80	0.99	0	0.3	0.62	0	0	0	0.00
7	0.24	0.00	0.99	0.80	0.99	0	0.3	0.17	1	0	0	0.89
8	0.03	0.13	1.00	0.10	1.00	0.7	0.3	0.35	1	0.9	0	0.00
9	0.10	0.00	0.38	0.10	0.38	1	1	0.95	1	0.7	0	0.11
10	0.07	0.99	0.84	0.70	0.84	1	0.3	0.79	0	0.7	0	0.00
11	0.01	0.00	0.48	0.30	0.48	0.7	0.3	0.50	0	0.3	0	0.06
12	0.53	0.00	0.68	0.30	0.68	0	1	0.76	0	0.3	1	0.83
13	0.07	1.00	0.88	1.00	0.88	0.7	1	0.71	1	1	0	0.00
14	0.20	0.00	0.23	0.70	0.23	0.7	0	0.02	1	0.9	0	1.00
15	0.03	0.00	0.69	0.90	0.69	0.7	0.3	1.00	1	1	1	0.39
16	0.00	0.97	0.84	0.20	0.84	0.7	0.3	0.72	0	0.9	0	0.00
17	0.07	0.65	0.64	0.70	0.64	0.7	0.3	0.56	1	0.3	0	0.00
18	0.44	0.00	0.03	0.70	0.03	0	0	0.11	1	0	0	0.44
19	0.00	0.00	0.16	0.80	0.16	1	1	0.10	1	0.9	1	0.06
20	0.07	0.00	0.37	0.70	0.37	0.7	0	0.24	1	0.7	1	0.89

Table 2.A4: Pairwise comparison for the second level of hierarchy (CR = 0.06).

	Direct impacts to fish	Sediment	Slope stability	Weight
Direct impacts to fish	1	Moderate importance	Very strong importance	0.649
Sediment		1	Strong importance	0.279
Slope Stability			1	0.072

Table 2.A5: Pairwise comparisons for sub-objectives of "Minimize sediment input to streams" objective (CR = 0.074).

	Distance from road to stream	Amount of sediment	Slope between road and stream	Vegetation between road and stream	Weight
Distance from road to stream	1	Moderate importance	Moderate importance	Strong importance	0.505
Amount of sediment		1	Moderate importance	Strong importance	0.288
Slope between road and stream			1	Moderate importance	0.143
Vegetation between road and stream				1	0.064

Table 2.A6: Pairwise comparisons for sub-objectives of "Minimize road-related landslides" objective (CR = 0.072).

	Hill-slope	Slope shape	Road drainage	Construct-ion method	Construct-ion date	Cutslope height	Weight
Hillslope	1	Strong importance	Strong importance	Strong importance	Absolute importance	Very strong importance	0.484
Slope shape		1	Moderate importance	Strong importance	Very strong importance	Very strong importance	0.233
Road drainage			1	Strong importance	Strong importance	Very strong importance	0.153
Construct-ion method				1	Moderate importance	Moderate importance	0.065
Construct-ion date					1	Moderate importance	0.038
Cutslope height						1	0.028

Table 2.A7: Pairwise comparison for the objective of "Minimize direct impacts to fish" objective (CR = 0.000).

	Stream crossing	Stream shading	Weight
Stream crossing	1	Moderate importance	0.750
Stream shading		1	0.250

3 Model Formulation to Minimize Adverse Environmental Impacts to Soil and Water from Forest Roads

3.1 Introduction

This chapter lays out the formulation of an AHP hierarchy for the goal of minimizing the environmental impacts to soil and water resources by forest roads as well as the associated pairwise comparisons. The literature review presented here serves as background for the hierarchy and preferences used in the manuscript "A systems approach to the management of existing forest road networks", Chapter 4.

3.2 Problem Formulation

The first step in formulating any solution is to define the context within which the solution is to take place. For example, the context may be the public management of lands devoted to multiple use, the private management of non-industrial timberlands, or the private management of industrial timberlands. The formulation of this problem will be within the context of a private ownership of industrial timberlands. The implications of choosing this context will be discussed in the following sections.

After articulating the management context within which a solution will take place, the problem is hierarchically decomposed into an overall goal, objectives, sub-objectives, and so on until the base of the hierarchy contains only measurable attributes.

3.2.1 Setting the Management Goal

Setting the overall goal for the management of forest roads serves to focus and direct the remainder of the analysis. For example, a goal may be to minimize maintenance costs, maximize the efficiency of timber harvesting operations, minimize the hydrologic impacts caused by forest roads, minimize the environmental impacts to soil and water resources, or to minimize all environmental impacts of the forest road network. All of these are legitimate goals but each would necessitate a very different problem formulation. The goal chosen for this formulation will be the minimization of environmental impacts to soil and water resources caused by forest roads.

3.2.2 Identifying Environmental Impacts

Descriptions of the potential adverse impacts associated with forest roads abound. For intensively managed, private industrial forest land, the most salient environmental impacts are to soil and water, which includes impacts due to landslides, fine sediment, fish passage, and riparian habitat. Adverse impacts include an increase in the occurrence of shallow, translational landslides (Swanson and Dryness 1975, Megahan and Kidd 1979, Lyons and Beschta 1983, Sessions et al. 1987, Robsison et al. 1999a, Rosenfeld 1999, Jones et al. 2000), and the production of fine sediment in excess of natural levels (Rice et al. 1972, Dunne 1979, Megahan and Kidd 1979, Megahan et al. 1983, Reid and Dunne 1984, Luce and Black 1999, Cornish 2001, MacDonald et al. 2001). The impacts may result in a reduction in the amount and quality of aquatic habitat available to fish (Beechie et al. 1994, Robison et al. 1999b), and changes in peak flows (Lyons and Beschta 1983, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Jones 2000, La Marche and Lettenmaier 2001).

The goal to minimize environmental impacts to soil and water is the highest level of the hierarchy. At the second level of the hierarchy are the individual resource objectives that include sediment-producing impacts and direct impacts to aquatic habitat (Figure 3.1). The third layer of the hierarchy is a comparison of risk for each of the elements in the second level of the hierarchy, with the exception of the loss of riparian habitat. In this context, risk is the combination of the probability of an event occurring and the impacts a failure could have if it were to occur. For some organizations the probability of occurrence alone, say a road-related landslide, is the extent of risk they are willing to take, regardless of the potential impacts. Other organizations are willing to tolerate a higher probability of occurrence if the resulting impacts are likely to be minor.

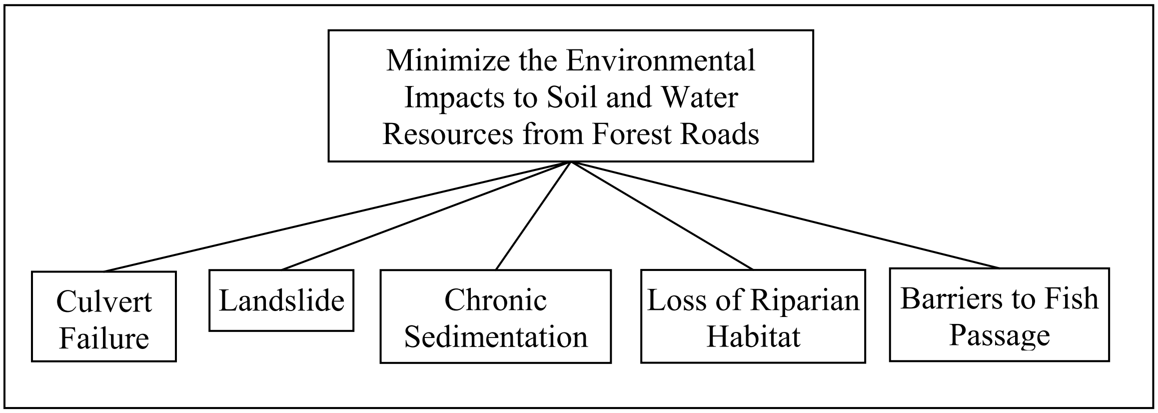

Figure 3.1: Top two levels of the road investment hierarchy where the top level represents the overall goal for the analysis and the second level describes the objectives included in meeting that goal.

3.2.2.1 Sediment-Producing Impacts

The production of sediment from forest roads occurs in the form of frequent delivery of fine sediment from the travelway, cut and fill slopes, and ditches, and from episodic inputs of sediment. Episodic events occur when some portion of the road prism fails either through the initiation of a landslide or fluvial erosion resulting from the diversion of a stream down a road travelway after a failure of the road drainage system.

Numerous studies have shown that not only do forest roads contribute to an increase in landslide incidence as compared with natural hillslopes (Swanson and Dryness 1975, Skaugset and Wemple 1999, Rosenfeld 1999) but also they are generally larger in size (Swanson and Dryness 1975, Robison et al. 1999a). Roads in steep terrain necessitate significant excavation that steepens portions of the slope within the road prism (Robison et al. 1999a). Additionally, forest roads collect and reroute water (Montgomery 1994, Wemple 1996). Robison et al. (1999a) found a large percentage of road-related landslides occurred where drainage systems had failed. Failure occurs when oversteepened portions of the road prism become saturated and weakened or when drainage structures become inoperative and stream water is rerouted down the road travelway. Landslides are more prevalent on steep terrain whereas washout-type failures occur primarily at road-stream crossings. Because different mechanisms are at work, these two types of road failure are presented separately in the problem hierarchy (Figure 3.1).

3.2.2.1.1 Culvert Failure

When considering the importance of a potential road failure due to a culvert failure, several factors of concern (Figure 3.2). The first of these factors is the probability of a drainage system failure causing a washout to occur. The factors included in predicting the occurrence of a culvert failure form a branch of the hierarchy directly below culvert failure occurrence.

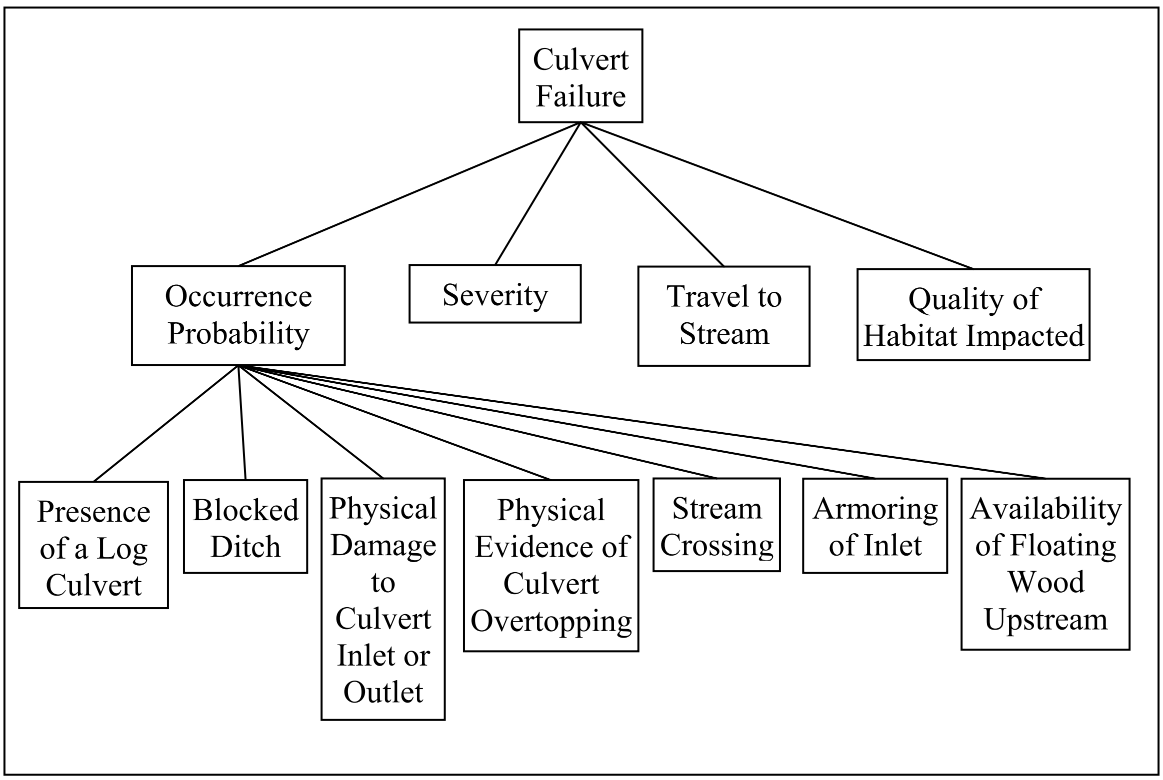

Figure 3.2: Factors included in determining the probability of a culvert failure occurring.

The occurrence of a culvert failure is more likely when a log culvert or other significant organic debris is buried in the road fill; when ditches are blocked by small cutslope failures, vegetation, or inadequate maintenance; when culvert inlets or outlets are damaged and their capacity reduced; when culverts are too small to handle large flows as evidenced by overtopping of the culvert; when a drainage structure passes a live stream; when culvert inlet structures are inadequately armored allowing the erosion of material surrounding a culvert; or when large amounts of floating wood are available upstream that could be dislodged during a storm event and transported downstream to block a drainage structure.

The risk a decision maker is willing to take with respect to culvert failures is a combination of the probability of failure and the potential for resource impacts. Potential resource impacts in the case of a culvert failure includes the likelihood a culvert failure will damage stream habitat, the severity of that damage, and some measure of the quality of habitat that would likely be impacted. Including these other factors beyond probability of occurrence allows a decision maker to tailor a solution to an appropriate level of risk tolerance.

The severity of a given culvert failure occurrence depends on the volume of water available to erode the road prism (Figure 3.3). The availability of water is greatest at a stream crossing. Deeper fills provide a greater volume of erodible material (Haupt 1959). As the depth of fill at the culvert inlet, or the head depth, increases, so does the likelihood that the debris blocking the drainage structure will float, clearing the blockage. Additionally, as the depth of water increases above the culvert inlet, the increase in head encourages a greater flow of water through the culvert, allowing it to pass a larger volume of water and debris (Robison et al. 1999b).

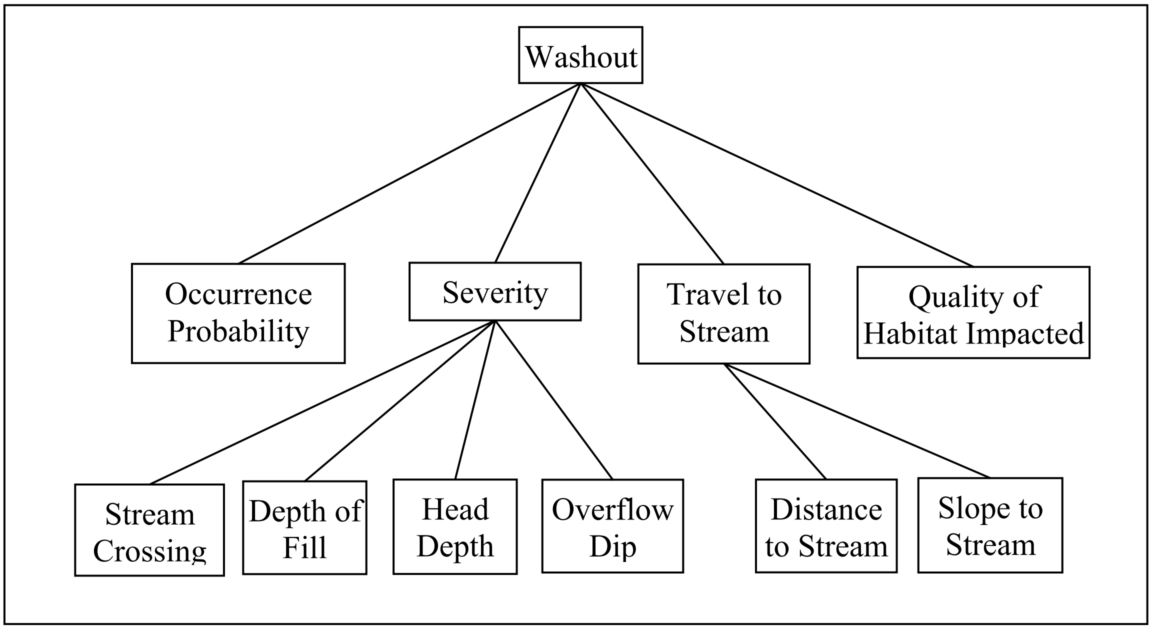

Figure 3.3: Attributes used to describe the severity of a culvert failure and the predicted travel of culvert failure debris to a nearby stream.

If a culvert failure occurs at a drainage structure not associated with a stream crossing, there is the probability that the sediment resulting from the culvert failure would reach a stream. This depends on the distance between the road and the stream combined with the slope between the road and the stream.

As part of an assessment of risk, a decision maker may be more tolerant of damage to low quality habitat as compared to known high quality habitat. The specific habitat considered here is in-stream aquatic habitat (Figure 3.4). The quality of aquatic habitat can be predicted based on the presence or absence of fish, stream order, stream gradient, and stream confinement (Barbour et al. 1999).

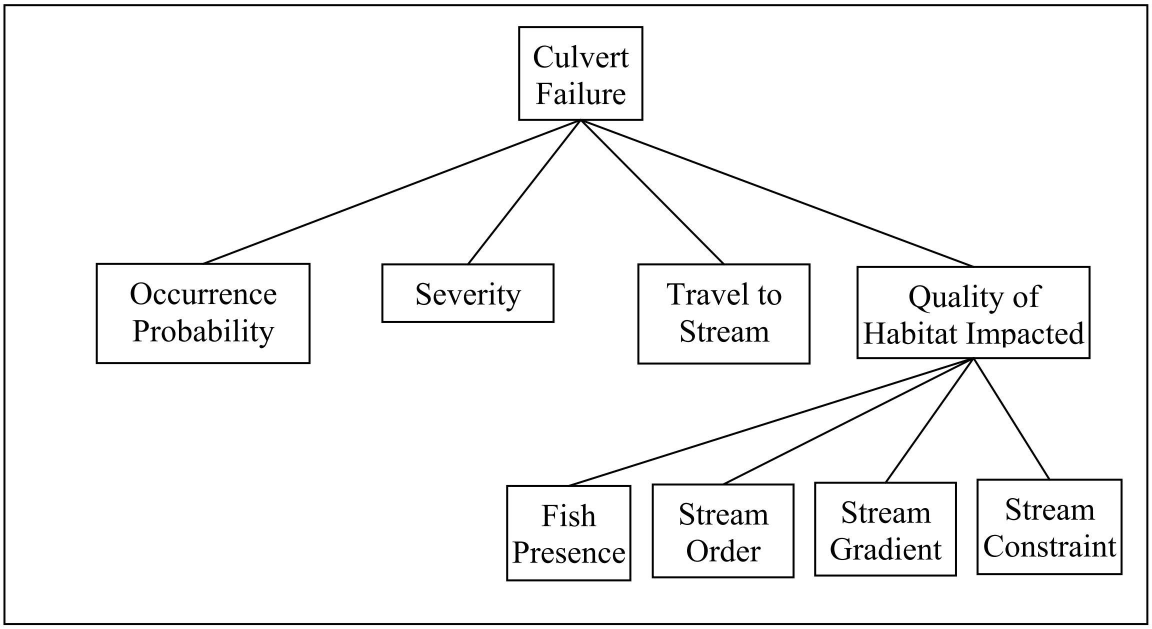

Figure 3.4: Quality of habitat impacted if a culvert failure were to occur.

3.2.2.1.2 Landslides

As with culvert failures, the analysis of road-related landslides must include an assessment of risk that includes the probability a given landslide will reach a stream and the quality of the aquatic habitat within that stream, in addition to an estimate of occurrence probability (Figure 3.5). This allows the decision maker to assess the level of risk tolerable and does not require the decision maker's risk level to be the same for culvert failures as for landslides. For example, a decision maker may be primarily concerned with culvert failures that occur near high quality aquatic habitat but wishes to address all road segments with a significant risk of slope instability regardless of the potential for aquatic habitat impacts. These seemingly inconsistent preferences are allowable only when the comparison between occurrence probability and potential impacts are made for each type of impact separately as opposed to for all impacts combined.

Robison et al. (1999a) found that over half of all road-related landslides occurred at drainage points, therefore the functioning and adequacy of the road drainage needs to be assessed to determine the potential for failure leading to a landslide. A surrogate for drainage adequacy is contributing road length (Haupt 1959, Harr and Nichols 1993, Johansen et al. 1997). This is the road length that contributes ditch flow to a given drainage point. Adequacy of the road drainage system also includes the identification of damage to the system such as blocked ditches (Harr and Nichols 1993, Veldhuisen and Russell 1999), reduced culvert capacity, and evidence that past storm events have overwhelmed the structure's capacity.

Robison et al. (1999a) observed that landslides occurring at locations away from drainage points were generally fill slope failures. The same study cited cutslope height as a predictor of road instability (also Skaugset and Wemple 1999).

Several studies have found a strong correlation between underlying geology and the occurrence of road-related landslides (Swanson and Dryness 1975, Bourgeois 1978, Sessions et al. 1987, Veldhuisen and Russell 1999, Wemple et al. 2001) as well as hillslope gradient (McCashion and Rice 1983, Sessions et al. 1987, Montgomery 1994, Robison et al. 1999a), slope position (Sessions et al. 1987, Skaugset and Wemple 1999, Wemple et al. 2001) and slope shape (Veldhuisen and Russell 1999). Fillslope depth is a measure of interaction between construction method and hillslope gradient. Construction method is a description of the design and construction practices implemented when building the road and includes factors such as the amount of cut and fill (Sessions et al. 1989, Wemple et al. 2001) and adequacy of fill compaction (Megahan and Kidd 1979).

The presence, size, and location of tension cracks in a road prism may indicate an impending failure and may be able to help predict the magnitude of the failure. For example, if tension cracks are located on the edge of a fill it can be reasoned less of the road prism is on the verge of failure than if the tension cracks encompass much of the road surface. The presence or absence of tension cracks is a potential symptom of failure as opposed to a mechanism and therefore is not included in models predicting road-related landslides. Likewise, little research has been documented that determines if tension cracks are predictive of failure or are a result of fill consolidation.

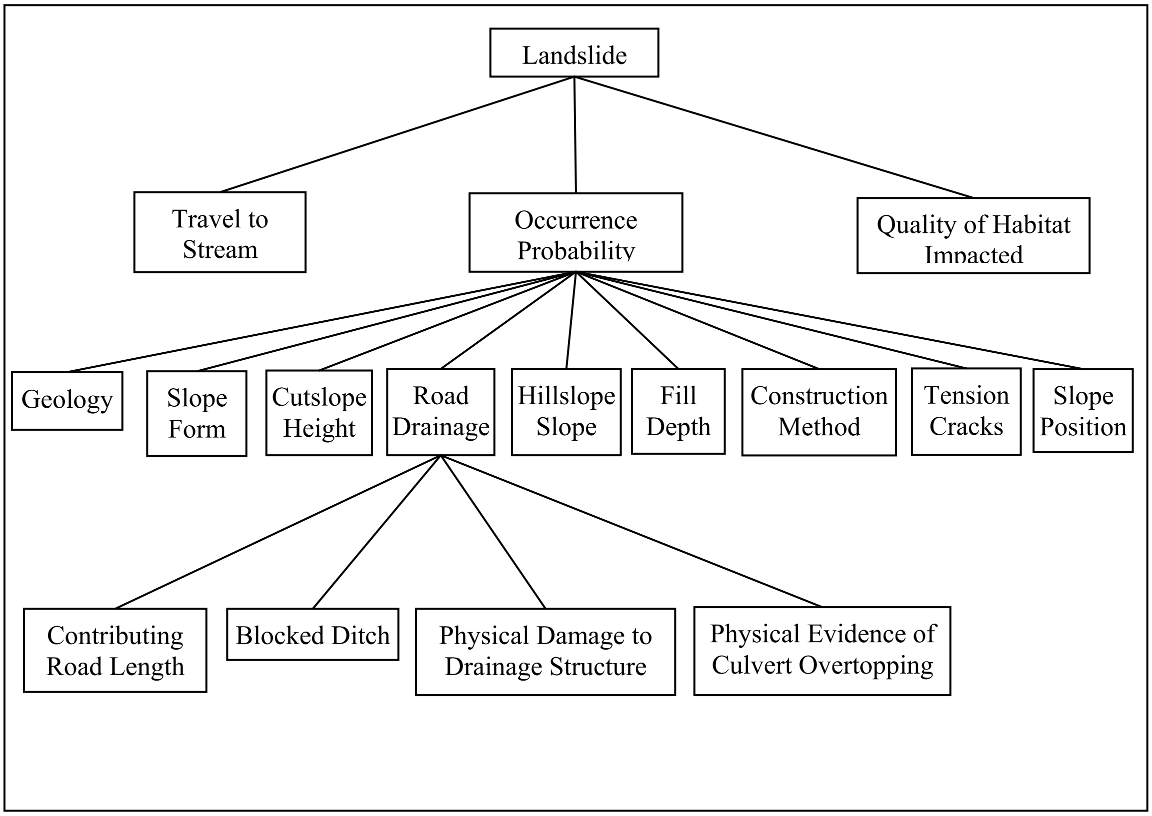

Figure 3.5: Factors included in estimating the relative probability of a road-related landslide occurring.

Factors influencing the quality of potentially impacted aquatic habitat are the same for landslides as they were for culvert failures (Figure 3.6). Likewise, the factors included in determining the likelihood a landslide will travel far enough to reach a stream channel are the same for landslides as for culvert failures with the addition of tributary junction angle. Benda and Cundy (1990) found the travel of landslides to be severely restricted when the junction angle between the landslide path and a stream channel exceeded 70 degrees.

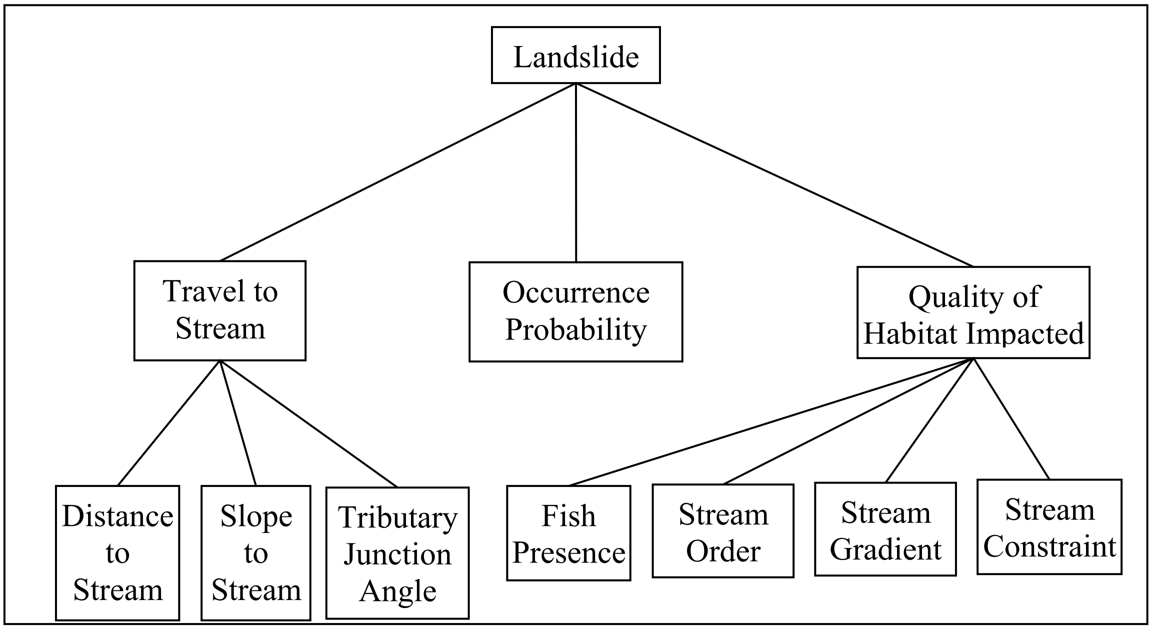

Figure 3.6: Attributes used in determining the probability a landslide will travel to a stream and the quality of the habitat potentially impacted by such a mass movement.

3.2.2.1.3 Chronic Sediment Production

The third type of event causing sediment release by forest roads is the chronic production of fine sediment from road prism surfaces (Figure 3.7). As with both landslides and culvert failures, risk is taken into consideration by including not only a predictor of the amount of sediment a given road segment is likely to produce but also the likelihood sediment will find its way to a stream and the quality of the habitat impacted once sediment does reach a stream.

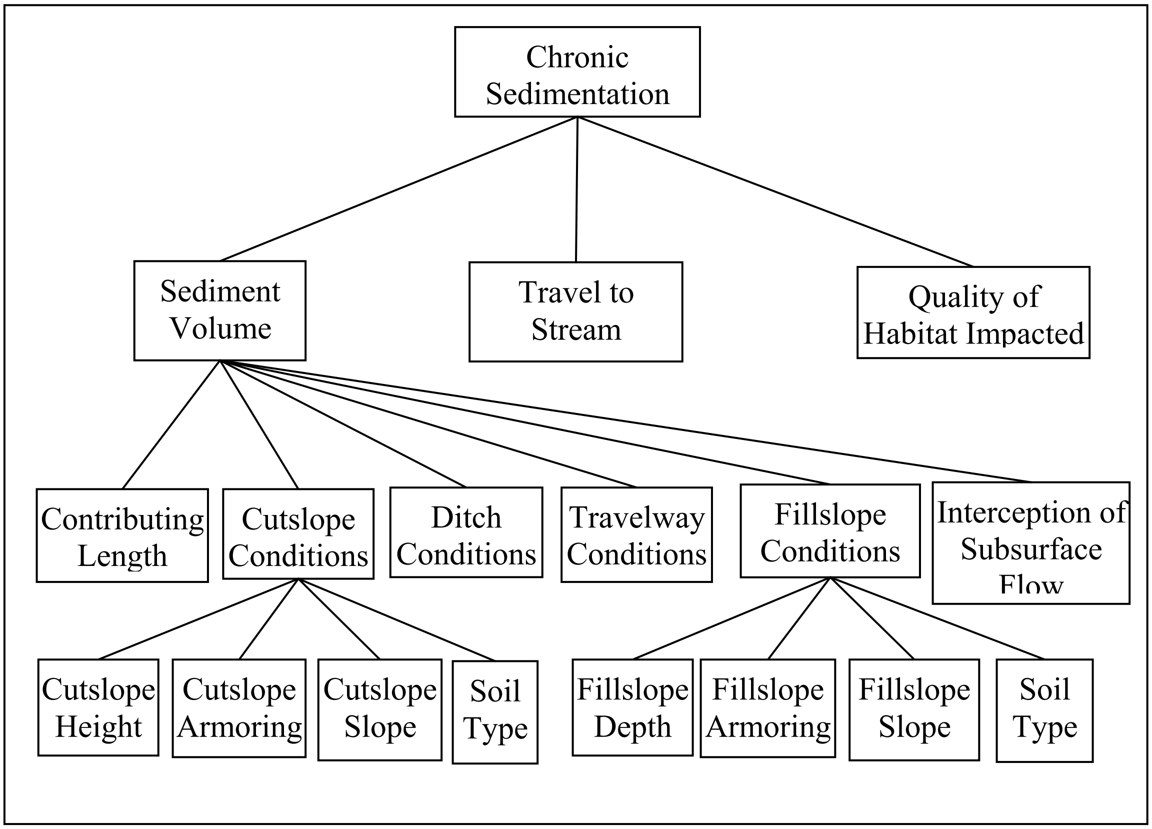

Figure 3.7: The effect of cutslope and fillslope conditions on the volume of sediment produced through chronic sedimentation.

The volume of sediment produced by a given road segment can be partitioned into the sediment produced by each of the components of the road prism. This is done to reduce the number of attributes that need to be compared simultaneously. From psychological studies pioneered by Miller (1956), we know that the average human mind can consider only seven, plus or minus two, items at any one time without becoming confused. In order to keep the number of pairwise comparisons between factors influencing sediment production feasible, we differentiate between sources of sediment within the road prism at this level of the hierarchy (the third level in Figure 3.7). Additionally, contributing road length and interception of subsurface flow are included as they impact the total sediment produced and transported regardless of the source of sediment within the road prism.

Sediment production from cutslopes and fillslopes increases with increasing cutslope height and fillslope depth (Haupt 1959, Amann 2004), ineffective armoring that increases soil exposure (Swift 1984, Burroughs and King 1989, Fahey and Coker 1989, Luce and Black 1999, Fransen et al. 2001, Megahan et al. 2001), increasing cutslope and fillslope gradient (Burroughs and King 1989, Megahan et al. 2001), and more erosive soil types (Burroughs and King 1989, Elliot and Tysdal 1999, Luce and Black 1999, Fransen et al. 2001).

Ditch conditions (Figure 3.8) dictate the amount of energy available to transport sediment. As ditch slope increases so does the power available to transport sediment (Bilby 1985). In most cases the slope of the ditch will be equal to the road gradient. The presence of gullies or large drops within the ditch or at a culvert inlet serves to increase energy available to dislodge and transport sediment. The armoring of a ditch with vegetation can aid in trapping sediment (Bilby 1985, Bilby et al. 1989, Luce and Black 1999) but can at the same time reduce ditch capacity if too much vegetation is present or if too much sediment is deposited in the ditch. Both of these potential effects of ditch vegetation are considered in the attributes “ditch armoring” and “reduction in ditch capacity.”

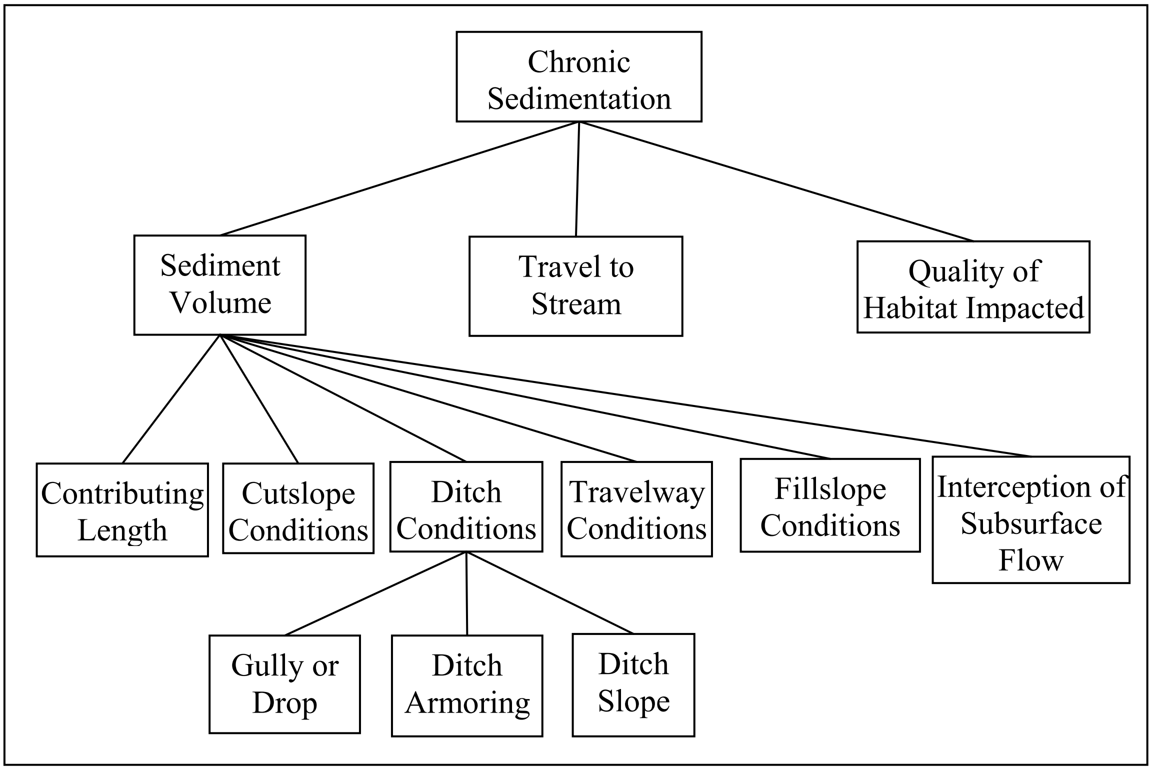

Figure 3.8: Factors used in determining the effect of ditch conditions on the volume of sediment produced through chronic sedimentation.

Ten characteristics of the travelway that impact total sediment production were identified, again exceeding the number of elements that can be effectively compared at one time. Therefore, these attributes were clustered into three groups relating to the road surface, road age, and the use and management of the travelway (Figure 3.9).

Sediment from the travelway increases with the road grade (Packer 1967, Swift 1984, Vincent 1985, Bilby et al. 1989, Elliot and Tysdal 1999, Luce and Black 1999) and more erosive soil types. The type and quality of the road surfacing has an impact on sediment production (Packer 1967, Swift 1984, Bilby et al. 1989, Burroughs and King 1989, Fahey and Coker 1989, Grayson et al. 1993, Ziegler et al. 2001) with parent material having higher erosion rates than rocked surfaces. Rock quality is also a factor and is generally measured in terms of rock hardness and the amount of fines present. The amount of fines present in rock surfacing on older roads is partially a function of the depth of rock surfacing, and the adequacy of the subgrade (Bilby et al. 1989, Burroughs and King 1989, Grayson et al. 1993). When the depth of rock is not sufficient and traffic is allowed on the road during wet weather, fines are pumped up to the surface, thereby becoming available for transport beyond the road prism.

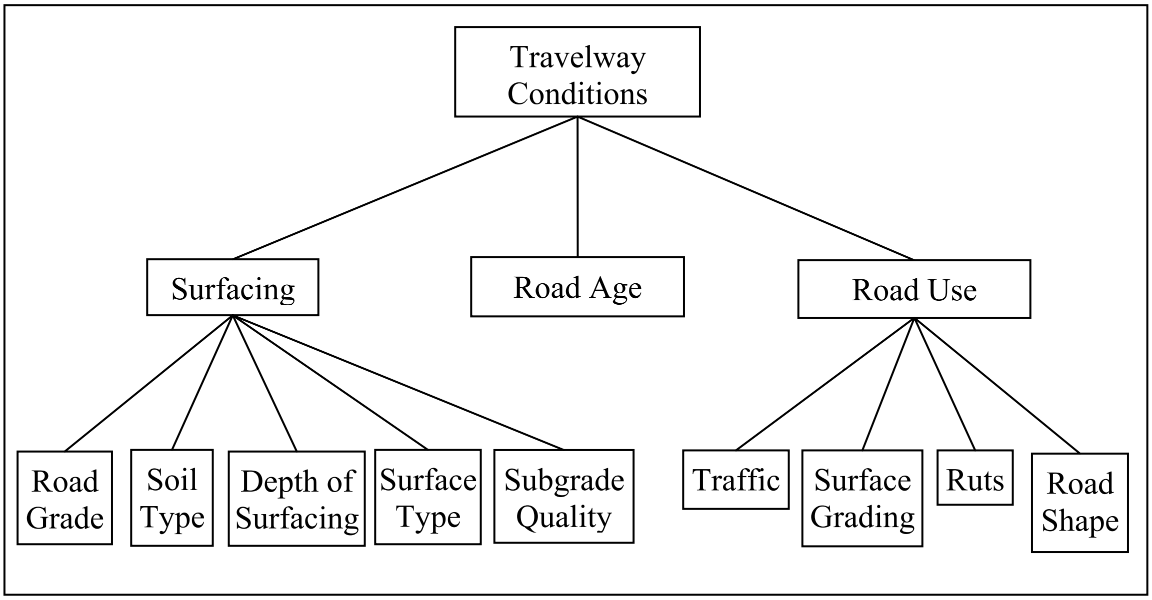

Figure 3.9: The components of travelway conditions that impact the production of fine sediment.

Newly built roads tend to produce large volumes of sediment in the first few years of existence. Studies, including Brown and Krygier (1971) and Vincent (1985), have found that suspended sediment levels increase dramatically after road construction and generally return to levels approaching pre-treatment within the first decade after construction.

Studies have demonstrated that the interception of subsurface flow by a road prism increases the amount of sediment produced by a forest road (Megahan et al. 2001, Amann 2004). The interception of subsurface flow is also quite variable in both time and space. Some road segments may intercept flow only during storm events that exceed a certain threshold while others may collect subsurface flow year-round (Veldhuisen and Russell 1999).

Numerous studies have looked at the effects of fine sediment on aquatic habitat, particularly the habitat of anadromous salmonids. High levels of sediment are known to fill up spawning gravels reducing, and in some cases eliminating, oxygen delivery to eggs and fry (Phillips et al. 1975, Platts and Megahan 1975, Rieser and Bjornn 1979, Johnson 1980, Platts et al. 1989, Lisle and Lewis 1992, Montgomery et al. 1996, Davies-Colley and Smith 2001). High levels of suspended sediment are a source of stress to fish causing decreased vigor and, at high enough levels, death (Rieser and Bjornn 1979, Redding et al. 1987, Daview-Colley and Smith 2001). Additionally, suspended sediment can increase stream power leading to streambed scour, reducing the quality of and eliminating habitat (Montgomery et al. 1996). Factors to be considered when estimating the likelihood fine sediment produced within a road prism will be transported to a live stream can be clustered into characteristics of the hillslope below the forest road and the quantity of water available to transport sediment (Figure 3.10).

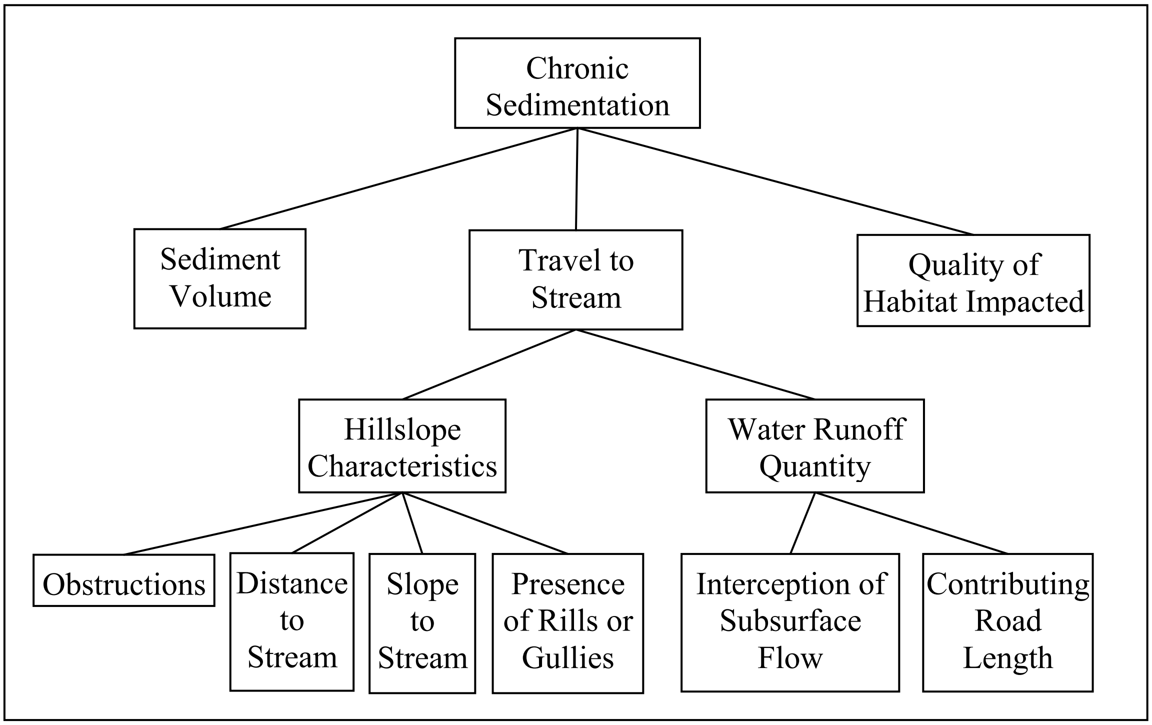

Figure 3.10: Factors affecting the transportation of chronic sediment from the road to a stream.

Similar to the transport of mass movements of soil from road failures, the slope and distance between the road and a live stream must be considered. Because fine particles resulting from chronic sedimentation are transported in relatively small quantities as compared to landslides and culvert failures, the opportunity to store this sediment on the hillside is greater. This storage depends on the presence of obstructions to trap sediment. Haupt (1959) used an obstruction index to describe the potential for storing sediment on the hillside. This index value was approximately equal to the spacing between logs and other materials that could serve to trap sediment. Similar methods and observations have been made by others (Swift 1986, Burroughs and King 1989, Megahan and Ketcheson 1996, Croke and Mockler 2001). The presence of a rill or gully below a drainage structure increases the likelihood sediment will reach a stream channel by greatly reducing the obstructions and roughness between the road and a stream (Bilby et al. 1989, Burroughs and King 1989, Elliot and Tysdal 1999). The quantity of water available to move sediment from its origin to a stream is determined by the quantity of subsurface water intercepted by the road prism and the length of contributing road.

Describing the habitat that could potentially be impacted by fine sediment produced by forest roads is conducted in the same manner as previously described for both culvert failures and landslides and uses the same variables.

3.2.2.2 Direct Modification of Aquatic Habitat

When forest roads are close to streams there is significant opportunity for direct, negative impacts to aquatic habitat. These impacts include the modification of habitat and road-stream crossing structures that do not allow the passage of fish during portions or all of the year.

The loss of riparian habitat (Figure 3.11) due to the proximity of forest roads to streams includes the loss of stream shading which can lead to increases in stream temperature (Holtby 1988), road encroachment that impedes the natural movements of the stream channel, the loss of riparian forest that would have otherwise provided inputs of large wood to the stream, and increased peak flows (Harr et al. 1975, Wemple et al. 1996, Jones et al. 2000, La Marche and Lettenmaier 2001). Increased peak flows have the potential of causing increased scour and flooding of aquatic habitat.

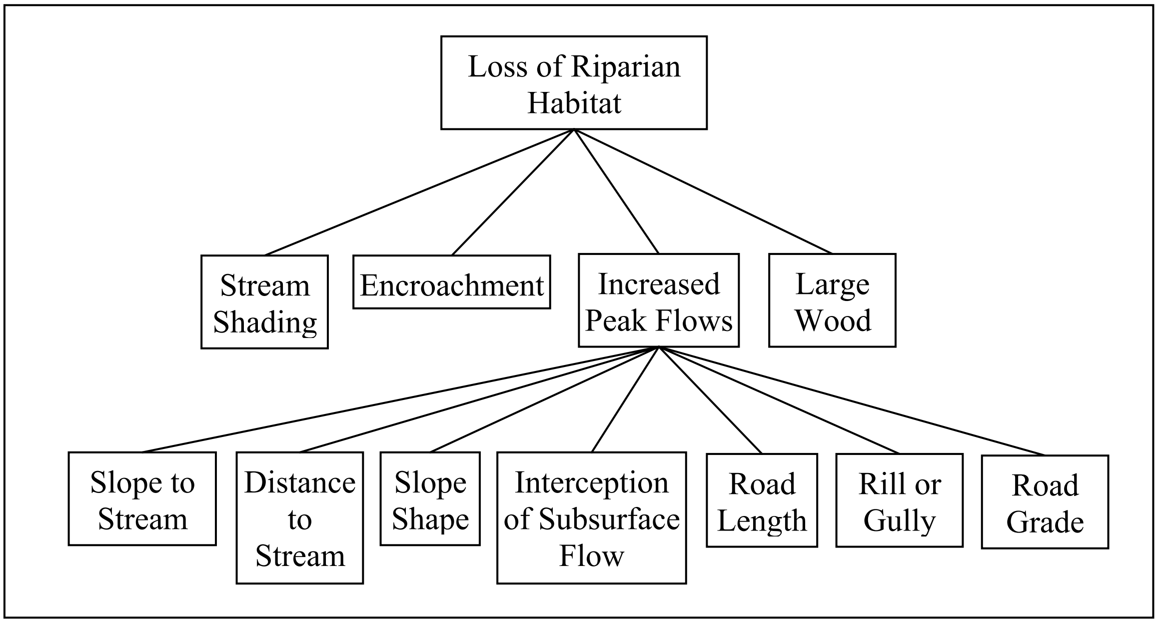

Figure 3.11: Factors describing the direct loss of aquatic habitat due to the proximity of roads to streams.

The magnitude of peak flow increases due to forest roads is a hotly debated topic (see Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000). The factors purported to lead to this augmentation include many of the factors already discussed, including the slope and distance between the road and stream, the contributing road length, road grade, the presence of a rill or gully (defined channel) between the road and stream, and the interception of subsurface flow. The interception of subsurface flow is hypothesized to greatly accelerate the speed at which groundwater reaches a stream by moving water from relatively slow, subsurface flow pathways, into ditches that provide rapid transport to road drainage structures (Wemple et al. 1996). The shape of the slope between the road and the stream has also been used to describe the speed at which water is transported from the road surface to a stream channel (La Marche and Lettenmaier 2001).

While many land managers have made a concerted effort to upgrade existing stream crossing structures that do not allow for the passage of fish of all life stages during all or portions of the year, many of stream crossing structures do still serve as barriers to fish passage (Conroy 1997). Landslides, culvert failures, and chronic sediment all contain an assessment of risk. The issue of fish passage includes an analogous assessment of how important a given barrier to fish passage is by additionally considering the quality of habitat the given road structure is blocking access to, the quantity, or length, of stream beyond the barrier that could be available as habitat if the barrier were not present, and the severity of the barrier. The severity of the barrier to fish passage is generally described as either partial, meaning the passage of fish is disallowed during a portion of the year or a portion of the fish life cycle, or complete (Figure 3.12).

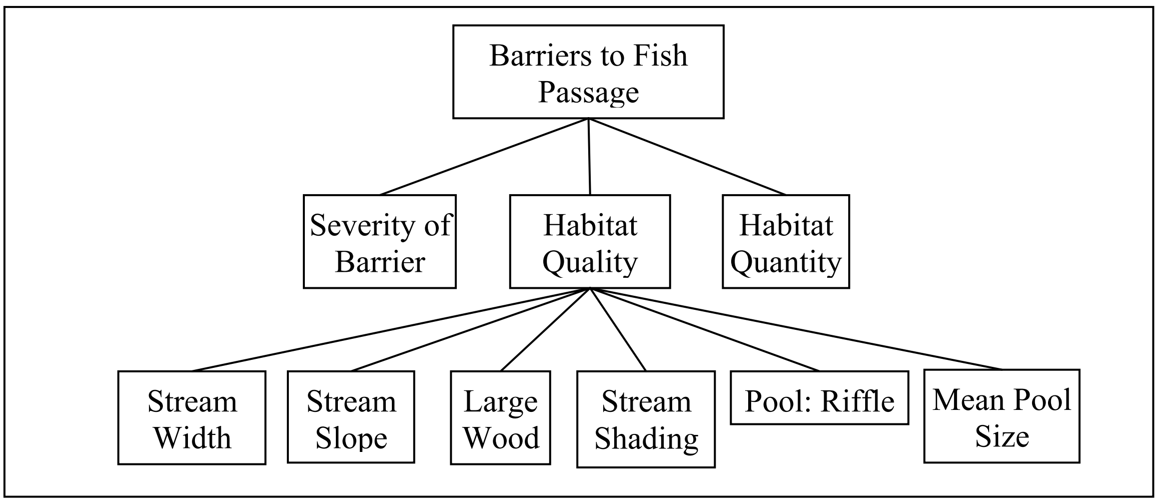

Figure 3.12: Factors describing the loss of aquatic habitat due to road-stream crossing structures that serve as barriers to fish passage.

Reiser and Bjornn (1979) describe the habitat requirements per life stage and activity for anadromous salmonids and include the width of a stream, steam slope, the presence of large wood, stream shading, the ratio of pool habitat to riffle habitat, and the average size of pools. While many of these factors are correlated, such as the presence of large wood and the ratio of pools to riffles, they are not direct substitutes.

3.3 Assessing Priorities

With the problem defined as a hierarchy, the next task is to inform the model of decision maker preferences. Some of the relationships discussed in the previous section have been investigated scientifically. When available, these results should be incorporated. This is particularly the case with the lower levels of the hierarchy. Within the higher levels of the hierarchy described here, scientific questions of probability of occurrence give way to questions of risk, policy, and politics. For example, how should a decision maker balance the probability of a landslide occurring with the probability the landslide will reach a stream channel? How important is the mass movement of soil from a road-related landslide as compared to the chronic production of fine sediment to the health and vigor of aquatic species? How should a balance be struck between habitat quantity and quality? These are questions science has not yet answered. If these were questions that could be answered in an objective fashion through scientific study then there would be no reason to use a method such as AHP that relies on judgment.

Many questions of preference and relative importance will depend on the specific geographic area under consideration and will necessarily rely on local knowledge. For some factors preferences may change with each analysis depending on local peculiarities and conditions.

Priority is assessed within the AHP through pairwise comparisons between each of the elements within each branch of each level of the hierarchy. These pairwise comparisons are conducted by asking the decision maker questions such as "In the minimization of environmental impacts to soil and water resources caused by forest roads, how important is sediment production as compared to direct habitat modification?" Responses to these questions follow Saaty's (1977 and 2000) linear scale (Figure 3.1). Pairwise comparisons can be made in any order.

Table 3.1: The Fundamental Scale used in the AHP (adapted from Saaty 2000).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above nonzero numbers	If activity A has one of the above nonzero numbers assigned to it when compared with activity B, then B has the reciprocal value when compared with A.	

While studies such as Robison et al. (1999) have identified factors involved in past occurrences of culvert failures, no literature can be found that looks at the relative importance of these factors as compared to one another in predicting where a culvert failure is likely to occur. The exact magnitude of each pairwise comparison is then left up to the decision maker. These comparisons have been made based on professional judgment. All pairwise comparisons are presented below in Section 3.4.

As with culvert failures, much of the literature that has looked at road-related landslides has identified individual factors that influence the incidence of mass failures but rarely consider the relative importance of these factors. Robison et al. (1999a) and Skaugset and Wemple (1999) both found slope steepness, road drainage, cutslope height, and fill depth to all have a strong correlation with landslide occurrence. Swanson and Dryness (1975) found a strong relationship between landslide frequency and geology while Veldhuisen and Russell (1999) found only a weak relationship. The magnitude of importance of geology in predicting landslide occurrence will likely change depending on the specific geographical area under consideration. If sharp contrasts exist between the strength of underlying soils within the road inventory area, then geology will likely be given higher preference than if there is little variation in geology.

Slope shape and slope position have both been shown to have significant predictive ability concerning road-related landslides. However, both of these factors are strongly correlated to other variables under consideration such as cutslope height, fillslope depth, and hillslope slope. In general, mid-slope roads tend to have steeper cross slopes, higher fills, and higher cutslopes than either ridge top or valley bottom roads. For the same average slope this is also true for roads on a concave hillslope as compared to either a planar or convex hillslope. Choice of specific preference levels will then necessarily depend on how tightly these factors correlate within a given inventory. The preferences given to factors involved in the analysis of road-related landslides are given in Appendix A, Tables 3.A5 through 3.A7.

When predicting the production of fine sediment, the main source of this sediment is the travelway. However, in order for the sediment produced within the travelway to leave the road prism it must travel through the ditch. This assumes the road segment in question has a functioning ditch and tread that allows runoff to move off the travelway. When this is the case, both Luce and Black (1999) and Reid and Dunn (1984) found the condition of the ditch to have as much influence as the travelway in determining the total amount of sediment leaving the road prism. Ditches that are armored with grass or other material are able to slow water down and trap sediment produced by the travelway before it has an opportunity to leave the road prism. When a road prism intercepts subsurface flow, this increase in flow augments the ability of a given road segment to transport sediment from the road prism (Amann 2004).

Most studies have found that contributing road length has little influence over the total amount of sediment produced and exported by a segment of forest road (Reid and Dunn 1984, Luce and Black 1999, Amann 2004). While fillslopes generally have the ability to generate as much sediment as cutslopes, this sediment is generally dispersed below the road whereas sediment from cutslopes generally congregates in ditches and is susceptible to movement when ditch flows are great enough to entrain sediment within the ditch. These relationships are shown in Tables 3.A8 through 3.A17.

Reid and Dunn (1984) and Bilby et al. (1989) found road gradient to have a small influence on total sediment production when compared with other factors such as surfacing type (quality, hardness, and the presence of fines), depth of surfacing, and soil type. Bilby et al. (1989) showed the depth of surfacing to be approximately as important as soil type in predicting sediment quantity.

Road use, both traffic levels and maintenance activities (road grading and ditch clearing) have strong impacts on the total amount of sediment produced (Reid and Dunn 1984, Bilby et al. 1989) with traffic levels being the most constant and therefore the more important factor of the two for predicting long-term sediment production levels.

By far the most important factor in determining if sediment produced by a forest road reaches a live stream is the presence of a defined channel between the drainage structure and the stream (Megahan and Ketcheson 1996). In the case of a road-stream crossing this channel is the stream itself. When a defined channel is not present, obstructions between the road and the stream and the slope between the road and the stream are measures of the hillslope’s ability to trap and store sediment (Haupt 1959, Megahan and Ketcheson 1996).

The most serious direct impact forest roads can have on streams is encroachment, limiting the natural migration of the stream channel and, in the worst situations, rerouting the stream into a narrow, often straight channel. While roads have been found to increase peak flows at stream crossing structures (Toman 2004) it is unlikely this increase is of sufficient magnitude to cause detectable modification of aquatic habitat. Increases in peak flows are caused by the interception of subsurface flows and the routing of that flow to stream channels more rapidly than would otherwise be the case (Wemple et al. 1996, Toman 2004).

Studies of the relative importance of different attributes to habitat quality have been undertaken for some individual aquatic species. Several aquatic habitat inventory methods exist in the literature such as the Rapid Bioassessment Protocol (RBP) (Barbour et al. 1999). The RBP rates several variables and conditions such as those included here on a scale 20-point scale where one represents poor conditions and 20 optimal conditions. The scores for all categories are added together to achieve an overall habitat score for a given stream reach. No weighting of individual categories takes place, therefore all attributes are considered to be equal in their importance. Other approaches have found fish to favor pool habitats over riffle habitats (Modde et al. 1991). As with the other branches of the hierarchy, decision makers will need to rely on significant local knowledge and the opinion of experts in order to complete pairwise comparisons appropriate to the problem at hand.

3.4 Pairwise Comparisons

The following matrices of pairwise comparisons are based on the literature where possible (see section 3.5 Assessing Priorities) and on professional judgment where no such information was available.

Table 3.2 gives the pairwise comparisons for the main objectives. The following questions, with the response in parenthesis, are as follows:

a) How important is landslide risk as compared with fish passage in determining the environmental impacts of forest roads on soil and water resources? (equal importance, 1)

b) How important is landslide risk as compared with sediment in determining the environmental impacts of forest roads on soil and water resources? (moderate importance, 3)

c) How important is landslide risk as compared with culvert failure risk in determining the environmental impacts of forest roads on soil and water resources? (moderate importance, 3)

d) How important is landslide risk as compared with loss of habitat in determining the environmental impacts of forest roads on soil and water resources? (strong to very strong (strong plus) importance, 6)

e) How important is fish passage as compared with sediment in determining the environmental impacts of forest roads on soil and water resources? (moderate importance, 3)

f) How important is fish passage as compared with culvert failure risk in determining the environmental impacts of forest roads on soil and water resources? (strong importance, 5)

g) How important is fish passage as compared with loss of habitat in determining the environmental impacts of forest roads on soil and water resources? (very strong importance, 7)

h) How important is sediment as compared with culvert failure risk in determining the environmental impacts of forest roads on soil and water resources? (moderate importance, 3)

i) How important is sediment as compared with loss of habitat in determining the environmental impacts of forest roads on soil and water resources? (moderate importance, 3)

j) How important is culvert failure risk as compared with loss of habitat in determining the environmental impacts of forest roads on soil and water resources? (strong importance, 5)

These questions can be asked in any order. The responses to these questions are recorded in a square matrix as shown in Table 3.2. Also indicated is a reference to the question that produced the given result and the resulting weight for each factor. For all of the following tables, the weights given in plain type are weights for the full hierarchy. Weights in italics are weights for the reduced, or "pruned" hierarchy, discussed further in Chapter 4. All weights were derived using the principal right eigenvector. The attributes that were deleted to determine weights for the pruned hierarchy are those indicated by the shaded rows and columns. Weights were derived for the pruned hierarchy using the un-shaded values (i.e. Table 3.4).

Table 3.2: Pairwise comparisons for objectives related to minimizing the environmental impacts to soil and water resources by forest roads (CR = 0.0642).

	Landslide Risk	Fish Passage	Chronic Sediment	Culvert failure Risk	Loss of Habitat	Weight
Landslide Risk	1	a) 1	b) 3	c) 3	d) 6	0.3256
Fish Passage	a) 1	1	e) 3	f) 5	g) 7	0.3703
Chronic Sediment	b) 1/3	e) 1/3	1	h) 3	i) 3	0.1674
Culvert failure Risk	c) 1/3	f) 1/5	h) 1/3	1	j) 5	0.0993
Loss of Habitat	d) 1/6	g) 1/7	i) 1/3	j) 1/5	1	0.0375

For the remainder of the pairwise comparisons, questions similar to those above were asked of the decision maker: How important is attribute A compared to attribute B in relation to the element directly above in the hierarchy. If the dominant element is element B, the appropriate integer between one and nine is recorded in row B, column A, and the inverse of the same integer recorded in row A, column B.

Table 3.3: Pairwise comparisons for objectives related to culvert failure risk (CR = 0.1024).

	Culvert failure Occurrence	Travel to Stream	Habitat Quality	Severity	Weight
Culvert failure Occurrence	1	3	5	5	0.5481
Travel to Stream	1/3	1	7	1	0.2826
Habitat Quality	1/5	1/7	1	1/3	0.0599
Severity	1/5	1	3	1	0.1594

Table 3.4: Pairwise comparisons for attributes related to culvert failure occurrence (CR = 0.948).

	Log Culvert	Blocked Ditch	Inlet Damage	Over-topping	Stream Crossing	Inlet Armor	Floating Wood	Weight
Log Culvert	1	1/5	1/2	1/3	1/9	1/2	1/8	0.0295
Blocked Ditch	5	1	5	1/3	1	9	1/3	0.1508 *0.1250*
Inlet Damage	2	1/5	1	1/3	1/9	3	1/8	0.0456
Over-topping	3	3	3	1	1	5	1	0.2019 *0.2971*
Stream Crossing	9	1	9	1	1	9	1/4	0.2032 *0.1639*
Inlet Armor	2	1/9	1/3	1/5	1/9	1	1/8	0.0290
Floating Wood	8	3	8	1	4	8	1	0.3399 *0.4140*

Table 3.5: Pairwise comparisons for attributes related to the probability a culvert failure will travel to a stream (CR = 0).

	Distance to Stream	Slope to Stream	Weight
Distance to Stream	1	3	0.7500
Slope to Stream	1/3	1	0.2500

Table 3.6: Pairwise comparisons for attributes related to habitat quality. The results of this set of pairwise comparisons are used for the quality of potentially impacted habitat from culvert failures, landslides, and sediment (CR = 0.0579).

	Fish	Stream Order	Stream Gradient	Constrained	Weight
Fish	1	9	9	9	0.7405 *0.8182*
Stream Order	1/9	1	1/3	1/3	0.0484
Stream Gradient	1/9	3	1	1	0.1056 *0.0909*
Constrained	1/9	3	1	1	0.1056 *0.0909*

Table 3.7: Pairwise comparisons for attributes related to culvert failure severity (CR = 0.3439).

	Stream Crossing	Depth of Fill	Head Depth	Overflow Dip	Weight
Stream Crossing	1	9	9	9	0.6967 *0.9000*
Depth of Fill	1/9	1	1	1/7	0.0423
Head Depth	1/9	1	1	1/7	0.0595
Overflow Dip	1/9	7	7	1	0.2016 *0.1000*

Table 3.8: Pairwise comparisons for objectives related to culvert failure risk (CR = 0).

	Landslide Occurrence	Travel to Stream	Habitat Quality	Weight
Landslide Occurrence	1	9	9	0.8182
Travel to Stream	1/9	1	1	0.0909
Habitat Quality	1/9	1	1	0.0909

Table 3.9: Pairwise comparisons for attributes related to landslide occurrence (CR = 0.1260).

	Drainage	Tension Cracks	Cutslope Height	Hillslope Slope	Fill Depth	Percent Sidecast	Geology	Slope Position	Slope Form	Weight
Drainage	1	9	9	9	1	9	9	9	9	0.4125 *0.5391*
Tension Cracks	1/9	1	1/9	1/9	1/9	1/5	1/7	1/5	1/5	0.0126
Cutslope Height	1/9	9	1	1	1/2	5	5	5	7	0.1236 *0.0973*
Hillslope Slope	1/9	9	1	1	1	5	3	7	9	0.1279 *0.1091*
Fill Depth	1	9	2	1	1	3	3	9	9	0.1730 *0.2133*
Percent Sidecast	1/9	5	1/5	1/5	1/3	1	1/3	1	3	0.0349
Geology	1/9	7	1/5	1/3	1/3	3	1	5	7	0.0681 *0.0412*
Slope Position	1/9	5	1/5	1/7	1/9	1	1/5	1	1	0.0255
Slope Form	1/9	5	1/7	1/9	1/9	1/3	1/7	1	1	0.0219

Table 3.10: Pairwise comparisons for attributes related to drainage adequacy, used in determining probability of landslide occurrence (CR = 0.0227).

	Contributing Road Length	Blocked Ditch	Physical Damage	Evidence of Overtopping	Weight
Contributing Road Length	1	1/9	1/9	1/9	0.0350
Blocked Ditch	9	1	1/2	1/2	0.2241 *0.2000*
Physical Damage	9	2	1	1	0.3705 *0.4000*
Evidence of Overtopping	9	2	1	1	0.3705 *0.4000*

Table 3.11 Pairwise comparisons for attributes related to the probability a landslide will travel to a stream (CR = 0.0625).

	Distance to Stream	Slope to Stream	Tributary Junction Angle	Weight
Distance to Stream	1	1/3	1/7	0.0812
Slope to Stream	3	1	1/5	0.1884 *0.1667*
Tributary Junction Angle	7	5	1	0.7306 *0.8333*

Table 3.12 Pairwise comparisons for objectives related to sediment risk (CR = 0).

	Sediment Production	Travel to Stream	Habitat Quality	Weight
Sediment Production	1	1	5	0.4546
Travel to Stream	1	1	5	0.4506
Habitat Quality	1/5	1/5	1	0.0909

Table 3.13: Pairwise comparisons for attributes related to the production of fine sediment (CR = 0.2806).

	Contributing Road Length	Cutslope Conditions	Ditch Conditions	Travelway Conditions	Fillslope Conditions	Subsurface Flow	Weight
Contributing Road Length	1	1/3	1/3	1/3	1/5	1/9	0.0291
Cutslope Conditions	3	1	1/7	1/9	5	1/9	0.0560
Ditch Conditions	3	7	1	1	9	1/9	0.1556 *0.0965*
Travelway Conditions	3	9	1	1	9	1/7	0.1723 *0.1049*
Fillslope Conditions	5	1/5	1/9	1/9	1	1/9	0.0376
Subsurface Flow	9	9	9	7	9	1	0.5494 *0.7986*

Table 3.14: Pairwise comparisons for attributes related to cutslope condition, used in determining the production of fine sediment (CR = 0.1856).

	Cutslope Height	Cutslope Armoring	Cutslope Slope	Soil Type	Weight
Cutslope Height	1	1/5	3	1/9	0.0665
Cutslope Armoring	5	1	5	1/9	0.1741
Cutslope Slope	1/3	1/5	1	1/9	0.0392
Soil Type	9	9	9	1	0.7203

Table 3.15: Pairwise comparisons for attributes related to ditch condition, used in determining the production of fine sediment (CR = 0.2834).

	Presence of Gully or Drop	Ditch Armoring	Ditch Slope	Weight
Presence of Gully or Drop	1	9	9	0.7968 *0.9000*
Ditch Armoring	1/9	1	5	0.1514 *0.1000*
Ditch Slope	1/9	1/5	1	0.0518

Table 3.16: Pairwise comparisons for attributes related to travelway condition, used in determining the production of fine sediment (CR = 0.2005).

	Surfacing	Road Use	Road Age	Weight
Surfacing	1	1/5	7	0.2271
Road Use	5	1	9	0.7219
Road Age	1/7	1/9	1	0.0510

Table 3.17: Pairwise comparisons for attributes related to travelway surfacing, used in determining the production of fine sediment (CR = 0.2007).

	Road Grade	Surfacing Type	Surfacing Depth	Soil Type	Subgrade Quality	Weight
Road Grade	1	1/3	1/3	1/5	1/5	0.0547
Surfacing Type	3	1	1/5	5	5	0.4708 *0.5548*
Surfacing Depth	3	5	1	1/3	1	0.1169 *0.1161*
Soil Type	5	1/5	3	1	1/3	0.1603 *0.1449*
Subgrade Quality	5	1/5	1	3	1	0.1974 *0.1842*

Table 3.18: Pairwise comparisons for attributes related to road use, used in determining the production of fine sediment (CR = 0.3194).

	Traffic	Grading	Ruts	Road Shape	Weight
Traffic	1	9	9	9	0.7003 *0.9000*
Grading	1/9	1	1/7	5	0.0681
Ruts	1/9	7	1	7	0.2005 *0.1000*
Road Shape	1/9	1/5	1/7	1	0.0312

Table 3.19: Pairwise comparisons for attributes related to fillslope condition, used in determining the production of fine sediment (CR = 0.2184).

	Depth of Fill	Fillslope Slope	Fillslope Armoring	Soil Type	Weight
Depth of Fill	1	1/3	1/7	1/9	0.0345
Fillslope Slope	3	1	1/7	1/9	0.0575
Fillslope Armoring	7	7	1	1/9	0.1973
Soil Type	9	9	9	1	0.7107

Table 3.20: Pairwise comparisons for attributes related to the probability sediment will travel to a stream (CR = 0).

	Downslope Conditions	Water Quantity	Weight
Downslope Conditions	1	1/3	0.2500
Water Quantity	3	1	0.7500

Table 3.21: Pairwise comparisons for attributes related to downslope conditions used in determining the travel of fine sediment (CR = 0.2385).

	Obstructions	Distance to Stream	Slope to Stream	Rill/Gully	Weight
Obstructions	1	7	1/3	1/9	0.1014 *0.0623*
Distance to Stream	1/7	1	1/5	1/9	0.0341
Slope to Stream	3	5	1	1/9	0.1523 *0.1295*
Rill or Gully	9	9	9	1	0.7122 *0.8082*

Table 3.22: Pairwise comparisons for attributes related to the quantity of water available to transport sediment (CR = 0).

	Interception of Subsurface Flow	Contributing Road Length	Weight
Interception of Subsurface Flow	1	9	0.9000
Contributing Road Length	1/9	1	0.1000

Table 3.23: Pairwise comparisons for attributes related to the direct loss or degradation of aquatic habitat due to the proximity of road to riparian areas (CR = 0.0227).

	Stream Shading	Stream Encroachment	Loss of LWD	Peak Flows	Weight
Stream Shading	1	1/9	1	1/2	0.0686
Stream Encroachment	9	1	9	9	0.7462 *0.9000*
Loss of LWD	1	1/9	1	1/2	0.0685
Peak Flows	2	1/9	2	1	0.1167 *0.1000*

Table 3.24: Pairwise comparisons for attributes related to the increase in peak flows due to forest roads (CR = 0.1159).

	Slope to Stream	Distance to Stream	Slope Shape	Subsurface Flow	Contributing Length	Rill or Gully	Road Grade	Weight
Slope to Stream	1	1/9	3	1/9	3	1/9	1	0.0394
Distance to Stream	9	1	9	1/7	9	1/5	9	0.1720 *0.0778*
Slope Shape	1/3	1/9	1	1/9	1/3	1/9	1/3	0.0189
Subsurface Flow	9	7	9	1	9	1	9	0.3761 *0.4869*
Contributing Length	1/3	1/9	3	1/9	1	1/9	1	0.0288
Rill or Gully	9	5	9	1	9	1	9	0.3328 *0.4353*
Road Grade	1	1/9	3	1/9	1	1/9	1	0.0321

Table 3.25: Pairwise comparisons for attributes related to fish passage (CR = 0).

	Severity of Barrier	Habitat Quality	Habitat Quantity	Weight
Severity of Barrier	1	1	1	0.3333
Habitat Quality	1	1	1	0.3333
Habitat Quantity	1	1	1	0.3333

Table 3.26: Pairwise comparisons for attributes related to habitat quality when fish passage issues are present (CR = 0.1324).

	Stream Width	Stream Gradient	LWD	Stream Shading	Substrate	Pool:Riffle	Mean Pool Size	Weight
Stream Width	1	1/3	3	1/3	1	1/5	1/7	0.0588
Stream Gradient	3	1	5	3	3	1	1/3	0.1662 *0.1960*
LWD	1/3	1/5	1	3	3	1/5	1/7	0.0662 *0.0668*
Stream Shading	3	1/3	1/3	1	1/3	1/5	1/7	0.0508
Substrate	1	1/3	1/3	3	1	1/5	1/7	0.0591 *0.0523*
Pool:Riffle	5	1	5	5	5	1	1/3	0.2079 *0.2153*
Mean Pool Size	7	3	7	7	7	3	1	0.3911 *0.4697*

3.5 Data Collection and Definitions

The following road attributes were collected for 127 road segments in Oak Creek. For each attribute, the description, collection method, scale of measurement, and method used to convert raw data to a relative values is listed. Many of these attributes are used multiple times in the hierarchy. Unless otherwise noted, the same conversion to relative value was used each time the attribute appears in the hierarchy.

Table 3.27: General road location variables.

Variable	Description	Scale	Collection Method	Relative Value
Road Segment	Descriptive Title			
Slope Position	Categorical description of road location	Valley bottom, Mid-slope, Ridge top	Field	Mid-slope = 1.0 Valley bottom = 0.1 Ridge top = 0.03 (Skaugset and Wemple 1999)
Soil Type	Soil classification	Categorical	GIS	For sedimentation: based on K_f For landslide occurrence: based on Plasticity Index (Knezevich 1975)
Hillslope Slope	Slope of the hillslope traversed by road	Percent slope	Field/GIS	Slope to stream: (% Slope)/(max slope in survey) For landslide occurrence: Function based on Robison et al. (1999) favoring steeper slopes

Table 3.28: Road surface variables.

Variable	Description	Scale	Collection Method	Relative Value
Surface Type	Categorical description of road surfacing	Dirt, Dirty gravel, Clean gravel, Paved	Field	Dirt = 1 Dirty = 0.7 Clean = 0.5 Paved = 0
Depth of Surfacing	Depth of rock on road surface	Inches	Field estimate	1-(depth/max depth)
Subgrade	Categorical quality of subgrade	Base course of 3"+, Compacted parent material, Poor	Field	0 – same for all roads in survey area
Traffic	Categorical description of traffic level	Heavy (32+ axles/day), Moderate (8-32 axles/day), Light (<8 axles/day), Abandoned, (Reid and Dunne 1984)	Field	Function based on Figure 6 of Reid and Dunne (1984)
Road Grade	Gradient of travelway	Percent slope	Field	Grade/max grade
Frequent Maint-enance	Is the road frequently graded?	Yes, No	Field or GIS	Yes = 1 No = 0
Ruts	Categorical description of depressions in the travelway	Yes mineral soil exposed, Yes no mineral soil exposed, No	Field	Mineral soil exposed = 1 No mineral soil exposed = 0.5 No = 0
Road Shape	Categorical description of road shape	Crowned, Insloped, Outsloped	Field	Insloped = 1 Crowned = 0.8 Outsloped = 0.5
Construction Method	Percent of road travelway that has been sidecast	Percent	Field	Decimal percentage
Road length	Length of road draining to structure	Feet	Field or GIS	Length/max length
Tension cracks	Presence of tension cracks	Yes, No	Field	Yes = 1 No = 0

Table 3.29: Ditch variables.

Variable	Description	Scale	Collection Method	Relative Value
Ditch armoring	Categorical description of ditch armor	Yes, No	Field	No = 1 Yes = 0
Down cutting	Evidence of ditch erosion	Along length of ditch, At culvert inlet, None	Field	Along length of ditch = 1 At culvert inlet = 1 No = 0
Interception of groundwater	Evidence of interception of subsurface flow	Yes, No	Field	Yes = 1 No = 0
Ditch Capacity	Percent reduction in ditch capacity	Percent	Field	Decimal percentage

Table 3.30: Cutslope Variables.

Variable	Description	Scale	Collection Method	Relative Value
Cutslope Height	Height of the cutslope from the base of the ditch to the top of the cut	Feet	Field	For sediment: height/max height For landslide occurrence: function based on Robison et al. (1999)
Cutslope slope	Slope of the cutslope	Degrees	Field	Slope/max slope
Armoring of cutslope	Categorical description of cutslope armor	Yes, No	Field	No = 1 Yes = 0

Table 3.31: Drainage variables.

Variable	Description	Scale	Collection Method	Relative Value
Drainage type	Categorical description of drainage structure type	CMP, CPP, Bridge, Water bar, Grade reversal	Field	For information only - not used
Mechanical damage	Reduction in drainage structure capacity due to damage	Percent	Field	Decimal percentage
Head depth	Depth of fill over the top of drainage structure	Meters	Field	Depth/max depth
Overtopping	Evidence of culvert overtopping or other indications the culvert is too small	Yes, No	Field	Yes = 1 No = 0
Log culvert	Evidence of log culvert or other large accumulation of organic mater in fill	Yes, No	Field	Yes = 1 No = 0
Armoring of culvert inlet	Categorical description of culvert inlet armor	Yes, No	Field	No = 1 Yes = 0
Overflow dip	Presence of an overflow dip	Yes, No	Field	No = 1 Yes = 0
Floating wood	Availability of floating wood upstream from drainage structure	Rank on a scale from 1 to 10 with 1 indicating no floating wood, 10 maximum floating wood	Field	Floating wood scale value divided by 10
Rill/Gully	Presence of a defined channel below the drainage structure	Gully drains to stream, Rill not draining to stream, None	Field	Gully = 1 Rill = 0.5 None = 0

Table 3.32: Fillslope variables.

Variable	Description	Scale	Collection Method	Relative Value
Fillslope depth	Vertical depth of the fillslope from the travelway to the natural hillslope	Feet	Field	Function based on Robison et al. (1999)
Fillslope slope	Slope of the fillslope	Percent slope	Field	Slope/max slope
Fillslope Armoring	Categorical description of fillslope armor	Yes, No	Field	No = 1 Yes = 0

Table 3.33: Variables descriptive of the conditions between the road and stream.

Variable	Description	Scale	Collection Method	Relative Value
Obstructions	Obstructions between the drainage outlet and stream that could serve to trap sediment	Average number of obstructions per 100 feet	Field	Obstructions/ 100
Slope shape	Categorical description of slope below the road	Planar, Convex, Concave	Field or GIS	Concave = 1 Planar = 0.6 Convex = 0 (Veldhuisen and Russell 1999)
Encroach-Ment	Is the road encroaching on the stream?	Yes, No	Field	Yes = 1 No = 0
Stream Shading	Reduction in stream shading due to the location of the road	Percent	Field	Decimal percentage
Tributary Junction	Junction angle of stream to the path a landslide would take, measured from upstream	Degrees	GIS	< 70 degrees = 1 > 70 degrees = 0 (Benda and Cundy 1990)
Distance to Stream	Distance from the drainage structure to stream	Feet	GIS	1-distance/max distance
Slope to Stream	Average gradient between road and stream	Percent	GIS	Slope/max slope

Table 3.34: Variables describing the stream that could potentially be impacted by failures of a forest road.

Variable	Description	Scale	Collection Method	Relative Value
Stream size	Classification of stream size	Small, Medium, Large	GIS	Medium = 1 Small = 0 (only medium and small streams present in example)
Fish	Classification of stream as fish or non-fish	Fish, Non-fish	GIS	Fish = 1 Non-fish = 0
Stream gradient	Gradient of stream	Percent	GIS	1- (gradient-min gradient)/(max gradient – min gradient)
Constraint	Is the stream constrained?	Yes, No	GIS or field	No = 1 Yes = 0

Table 3.35: Variables describing the quality of habitat behind a barrier to fish passage.

Variable	Description	Scale	Collection Method	Relative Value
Fish passage	Is the drainage structure a barrier to fish passage	Total, Partial, Temporary, No, N/A, (Robison et al. 1999)	Field	0 – no fish passage barriers were found for this example
Length	Length of stream	Feet	GIS or field	Length/max length
Width	Width of stream	Feet	Field	Width/max width
Slope	Stream gradient	Percent	Field	1-Slope/max slope
Shade	Stream shading	Percent	Field	Decimal percentage
LWD	Is large wood preset?	Abundant, Present, Rare, None	Field	None found
Substrate	Description of stream substrate	Cobble/gravel, Bedrock, Embedded, cobble/gravel, Silt	Field	None found
Pool Volume	Mean pool volume	Gallons	Field	None found
Pool: Riffle	Ratio of pools to riffles	Ratio	Field	Ratio/max ratio

4 A Systems Approach to the Management of Existing Forest Road Networks Using the Analytic Hierarchy Process

Elizabeth Dodson Coulter[4], Arne Skaugset[5], John Sessions[6], and Elizabeth Toman[4]

4.1 Abstract

Inventories of forest roads are used to manage road networks. Currently, there is no decision support tool to help land managers develop priorities for the maintenance and upgrade of forest roads. The Analytic Hierarchy Process, AHP, is a flexible technique that integrates expert judgment with data and is well suited to this problem. Using AHP, the problem of maintenance and upgrade of forest roads is presented as a hierarchy. Pairwise comparisons were elicited from decision makers to determine the relative importance of road characteristics to management goals. The solution is applied to a forest road network in western Oregon. Modifications to the hierarchy and issues regarding the use of the AHP to prioritize forest road investments are discussed.

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4.2 Introduction

Forest land managers use inventories of forest roads to identify potential problems from the roads they manage. This is increasingly true in the USA, with programs like the Oregon Plan for Salmon and Watersheds (see http://www.oregon-plan.org). The analysis of road inventories often focus on one issue at a time, such as sediment production (Dube et al. 2004), unstable road fills (Sessions et al. 1987), or fish passage (Robison et al. 1999b). A road inventory contains potentially hundreds of miles of road divided into thousands of road segments that can cause multiple impacts. By focusing on single issues at a time, many of the potential impacts may be overlooked. Miller (1956) has shown that most individuals are able to consider five to nine items at any one time, far fewer than the total number of road segments contained in a typical road inventory that have the potential to cause negative environmental impacts.

Publications such as "Roads Analysis: Informing Decisions About Managing the National Forest Transportation System" (USFS, 1999) attempt to help decision makers include multiple environmental impacts in their analysis of forest road systems, but give little direction in how these attributes should be combined and analyzed. This has led to the prevalence of informal decision methods that rely on expert judgment to analyze road inventory databases and set road maintenance and upgrade priorities. Expert judgment is necessary in cases where science has not determined quantifiable relationships between cause and effect. While these informal approaches are able to capture expert judgment, there is no way of ensuring this judgment is applied consistently. The Analytic Hierarchy Process (AHP) is a technique that combines data with expert judgment and applies this information to large data sets consistently, allowing decision makers to evaluate alternatives based on multiple criteria. AHP was developed by Saaty (1977) and is used in fields such as business and operations research (Saaty 2004). This study uses AHP to prioritize road segments for their potential to cause soil and water problems.

4.3 Analytic Hierarchy Process

AHP involves four steps: 1) structuring the problem as a hierarchy by identifying related attributes and goals; 2) pairwise comparisons among attributes to determine the user's preferences; 3) the reduction of attributes to relative values; and 4) the ranking of alternatives.

AHP requires that problems are constructed as a hierarchy. A process called hierarchical decomposition is used that puts the overall goal at the top of the hierarchy with more specific objectives and sub-objectives below. One way to look at a hierarchy is as a visual representation of an objective function where each objective is a function of its sub-objectives. This process of decomposition continues to successive layers of the hierarchy as far as is necessary to adequately represent the problem. It is not required that each objective be decomposed the same number of levels. An element that serves as an objective at one level may also serve as a sub-objective for the next higher level. Objectives are decomposed until the base of the hierarchy is composed of the attributes that are used to compare alternatives. Attributes can be quantitative or qualitative and can be measured on any scale as long as that scale remains constant for a given attribute.

Pairwise comparisons are made between the attributes within each group at each level of the hierarchy based on the contribution of each attribute to the element directly above them in the hierarchy. The most prevalent scale used to carry out these comparisons is a linear scale that is composed of integers between one and nine. One signifies equal importance between the attributes and nine is used when one attribute is strongly more important than the other. Reciprocals are used to express the strength of the weaker of the two attributes. AHP does not require the decision maker to be completely rational or consistent in completing these pairwise comparisons.

The result of each set of pairwise comparisons is a positive reciprocal matrix such that $a_{ij} = a_{ji}$, $i, j \leq n$, where n is equal to the number of elements being compared within one set of pairwise comparisons. Various methods for calculating attribute weights from this matrix have been proposed. Saaty (1977, 2000) uses the principal right eigenvector while others (Lootsma 1996) have used the normalized geometric mean of the rows of the priority matrix, also called the Logrithmic Least Squares Method (LLSM). Both the eigenvector and LLSM have strong mathematical and theoretical backing (Fichtner 1986) and both are used extensively in practice with little difference in results (Crawford 1987, Coulter et al. in review).

The magnitude of the decision maker's inconsistency in completing pairwise comparisons is measured using a Consistency Ratio (CR). The CR is formed by the ratio of the Consistency Index (CI) of a matrix of pairwise comparisons and the Random Consistency Index (RI) for a matrix of the same size. The CI is found using the largest eigenvalue, λ_{max}, corresponding to the principal right eigenvector and is equal to $(\lambda_{max} - n)/(n-1)$ where n is the number of attributes being compared to create a n by n square matrix. The RI is the average CI of many matrices completed with random entries (see Saaty 2000). In practice, pairwise comparisons are adjusted until the CR of each matrix is less than or equal to 0.1, or ten percent.

Weights are derived through a pairwise comparison technique and are multiplied by the relative value for each attribute of each alternative. Relative values for individual attributes can be derived in many ways including pairwise comparisons between categorical data, linear interpolations based on the maximum or minimum value under consideration, or utility functions as defined by the decision maker. The overall score for each alterative is aggregated using an additive function of the product of each attribute weight and its associated relative attribute value.

AHP allows for the inclusion of less than perfect data in both the attribute values and in pairwise comparisons. Input values can include both quantitative and qualitative data, measured on any continuously applied scale. For example cutslope height can be a continuous, directly measured value, an estimate to the nearest meter, or a categorical variable with ranges of values (i.e. 3-7 meters). The more precise and certain both attribute values and pairwise comparisons are, the more certainty the user has in the outcome of an analysis.

4.4 Study Site

The Oak Creek Watershed is part of the McDonald-Dunn Research Forest west of Corvallis, Oregon. The watershed is actively managed by the College of Forestry at Oregon State University and is used for teaching, research, demonstration, and recreation.

There are approximately 8.3 miles of road in the Oak Creek Watershed. Attributes of the road system were inventoried during the summer of 2004. The road system was divided into road segments so that each road segment consisted of the length of road that drained to a common point.

The mainline road that parallels Oak Creek was built by the Civilian Conservation Corps in 1939. Ridgetop roads in the northwest corner of the Oak Creek watershed were built in 1946 and upgraded in the 1970's. The other roads in the watershed were built between 1963 and 1967, except for the mid-slope road in the western portion of the drainage that was built in the early 1980's. The road system, especially the drainage system, has been updated many times since the roads were constructed. Road segments were determined by drainage points that included culverts, ditch-outs, grade reversals, and waterbars (Figure 4.1).

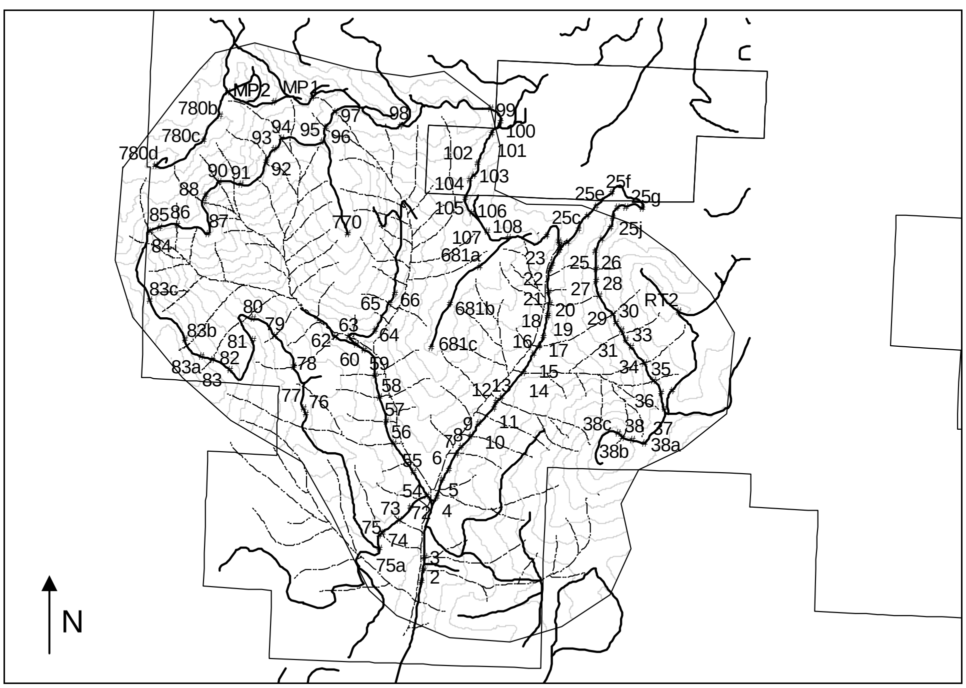

Figure 4.1: Road segments surveyed within the Oak Creek watershed. Labels refer to individual road segments. Roads were divided into segments bounded on each side by drainage structures. Drainage structures include culverts, ditch-outs, waterbars, and grade reversals.

The average road segment in the Oak Creek Watershed drained 156 meters (512 feet) and was between 16 and 1025 meters (54 to 3362 feet) long. Roads traversed hillslopes with grades that averaged 26 percent and ranged from zero percent in the valley bottom to 60 percent on some mid-slope roads. Road grades ranged from 0 to 15 percent and averaged 6.3 percent. All roads are surfaced with crushed aggregate. Most drainage structures are either plastic (CPP) or metal (CMP) culverts.

Fish are reported to be present in the main stems of Oak Creek up to the stream junctions downstream from road segment 60 on the west fork and road segment 14 on the east fork. The road system crosses a fish-bearing stream in only one location and the culvert at that location meets current guidelines for passing fish, thus no fish passage problems exist.

4.5 Developing the Problem Structure

Descriptions of the potential adverse impacts associated with forest roads abound. For intensively managed, private industrial forest land, the most salient environmental impacts are to soil and water, which includes impacts due to landslides, fine sediment, fish passage, and riparian habitat. Adverse impacts include an increase in the occurrence of shallow, translational landslides (Swanson and Dryness 1975, Megahan and Kidd 1979, Lyons and Beschta 1983, Sessions et al. 1987, Robsison et al. 1999a, Rosenfeld 1999, Jones et al. 2000), and the production of fine sediment in excess of natural levels (Rice et al. 1972, Dunne 1979, Megahan and Kidd 1979, Megahan et al. 1983, Reid and Dunne 1984, Luce and Black 1999, Cornish 2001, MacDonald et al. 2001). The impacts may result in a reduction in the amount and quality of aquatic habitat available to fish (Beechie et al. 1994, Robison et al. 1999b), and changes in peak flows (Lyons and Beschta 1983, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Jones 2000, La Marche and Lettenmaier 2001). Using attributes of forest roads that have been identified in the literature to influence the magnitude of negative impacts to soil and water resources (Table 4.1), a hierarchy was constructed with a goal of minimizing the environmental impacts to soil and water resources from forest roads (Figure 4.2).

Table 4.1: Literature sources used in the construction of the road inventory problem hierarchy with an overall goal of minimizing environmental impacts to soil and water resources from forest roads.

Objective	Issue	Literature Source
Culvert failure	Stream crossing, floating wood, head depth	Robison et al. 1999b
	Fill depth	Haupt 1959
Quality of aquatic Habitat	Presence of fish, stream order, stream gradient, stream confinement	Barbour et al. 1999
	Stream width, stream gradient, large wood, stream shading, pool habitat, riffle habitat	Rieser and Bjornn 1979
Landslide occurrence	Road drainage	Robison et al. 1999a
	Contributing road length	Haupt 1959, Harr and Nichols 1993, Johansen et al. 1997
	Blocked ditch	Harr and Nichols 1993, Veldhuisen and Russell 1999
	Fill depth	Robison et al. 1999a
	Cutslope height	Robison et al. 1999a, Skaugset and Wemple 1999
	Geology	Swanson and Dryness 1975, Bourgeois 1978, Sessions et al. 1987, Veldhuisen and Russell 1999, Wemple et al. 2001
Landslide travel	Tributary junction angle	Benda and Cundy 1990
Fine sediment production	Cutslope height, fillslope depth	Haupt 1959, Amann 2004
	Cutslope armoring, fillslope armoring	Swift 1984, Burroughs and King 1989, Fahey and Coker 1989, Luce and Black 1999, Fransen et al. 2001, Megahan et al. 2001
	Cutslope slope, fillslope slope	Burroughs and King 1989, Megahan et al. 2001
	Soil type	Burroughs and King 1989, Elliot and Tysdal 1999, Luce and Black 1999, Fransen et al. 2001
	Ditch gradient	Bilby 1985
	Ditch armoring	Bilby 1985, Bilby et al. 1989, Luce and Black 1999
	Road gradient	Packer 1967, Swift 1984, Vincent 1985, Bilby et al. 1989, Elliot and Tysdal 1999, Luce and Black 1999
	Road surfacing	Packer 1967, Swift 1984, Bilby et al. 1989, Burroughs and King 1989, Fahey and Coker 1989, Grayson et al. 1993, Ziegler et al. 2001
	Depth of rock surfacing, adequacy of surfacing	Bilby et al. 1989, Burroughs and King 1989, Grayson et al. 1993
	Road age	Brown and Krygier 1971, Vincent 1985
	Interception of subsurface flow	Megahan et al. 2001, Amann 2004

(Table 4.1 cont.)

Objective	Issue	Literature Source
Transport of fine sediment	Obstructions	Haupt 1959, Swift 1986, Burroughs and King 1989, Megahan and Ketcheson 1996, Croke and Mockler 2001
	Presence of a defined channel	Bilby et al. 1989, Burroughs and King 1989, Elliot and Tysdal 1999
Habitat loss	Stream shading	Holtby 1988
Change in peak flows	Interception of subsurface flow	Wemple et al. 1996, Gilbert 2002, Marbet 2003, Wemple and Jones 2003, Toman 2004
	Slope shape	La Marche and Lettenmaier 2001

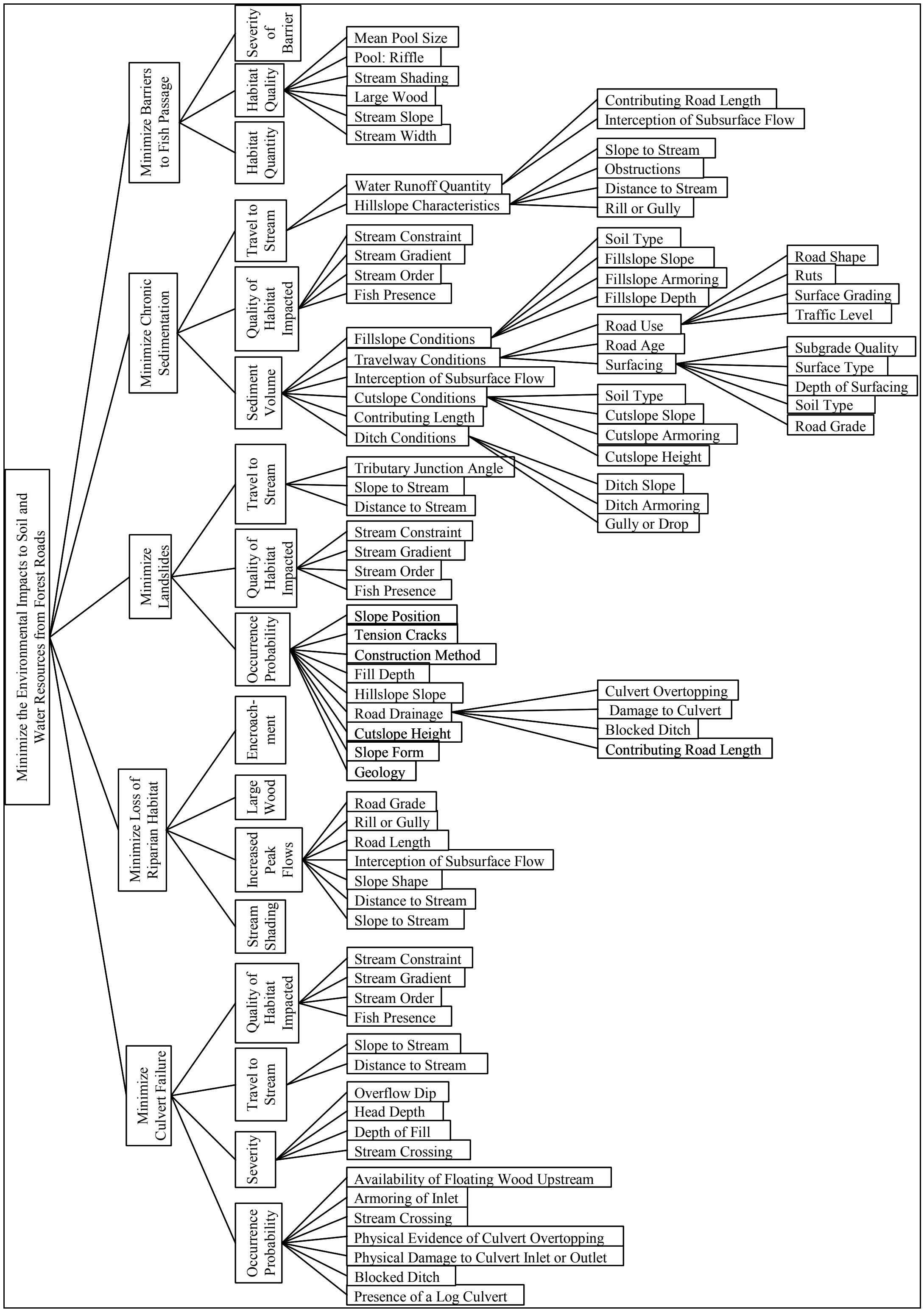

Figure 4.2: Hierarchy developed for the goal of minimizing the environmental effects of forest roads on soil and water resources.

The goal to minimize environmental impacts to soil and water is the highest level of the hierarchy. At the second level of the hierarchy are the individual resource objectives that include: 1) Minimize culvert failures; 2) Minimize loss of riparian habitat; 3) Minimize landslides; 4) Minimize chronic sedimentation; and 5) Minimize barriers to fish passage. The third layer of the hierarchy is an evaluation of risk for each of the objectives in the second level of the hierarchy, with the exception of the loss of riparian habitat. In this context, risk is the balancing of the probability of an event occurring and the impacts a failure could have if it were to occur. The base of the hierarchy is composed of the attributes that were measured in the field for each road segment represented in the road inventory. Each of these attributes was measured using an appropriate scale, such as feet for the height of a cutslope, percent slope for the road grade, or meters for the length of a road segment. The 84 attributes that describe each road segment were then reduced to relative, dimensionless values that range from zero to one, where one signifies higher importance. The rule used to reduce each attribute to a relative value differed for each attribute. For example, if the ditch along road segment A was reduced in capacity by 45%, the relative value for that attribute was computed as 0.45 (Tables 3.27-3.35).

4.6 Results and Discussion

The attribute data from the 127 road segments in the Oak Creek watershed was analyzed using the hierarchy developed to minimize the adverse impacts of forest roads on soil and water. Matrices of pairwise comparisons for the Oak Creek watershed were completed using the relationships found in the literature where possible (Table 4.1). Using the preferences of the authors for the resource objectives in the second level of the hierarchy (the level of attributes directly below the overall goal), the following weights were calculated: Minimize Culvert Failure, 0.993; Minimize Landslides, 0.3256; Minimize Chronic Sediment, 0.1674; Minimize Loss of Habitat, 0.375; and Minimize Barriers to Fish Passage, 0.3703. The road segments that posed the greatest risk to soil and water resources within the Oak Creek watershed are listed in Table 4.2 and shown graphically in Figure 4.3.

Table 4.2: The 25 road segments in the Oak Creek Watershed that pose the greatest risk to adverse impacts to soils and water using the full problem hieararchy. The rank for each road segment for each of the five objectives is given and the most important objective for each road segment is listed.

Road Segment	Overall Score	Overall Rank	Culvert failure Rank	Landslide Rank	Chronic Sediment Rank	Habitat Loss Rank	Fish Passage Rank	Major Issue
4	0.2930	1	8	50	1	2	1	Encroachment/sediment
5	0.2766	2	14	13	2	6	1	Sediment
9	0.2632	3	20	20	4	19	1	Sediment
90	0.2573	4	26	5	20	37	1	Landslide/exposed ruts
12	0.2529	5	12	41	7	22	1	Sediment
7	0.2520	6	18	28	8	23	1	Sediment
6	0.2456	7	16	56	5	12	1	Sediment
89	0.2437	8	30	6	23	39	1	landslide/sediment
10	0.2345	9	21	81	3	14	1	Sediment
64	0.2323	10	50	21	21	29	1	Multiple
11	0.2316	11	10	83	6	24	1	Sediment
91	0.2284	12	39	17	22	36	1	Multiple
58	0.2265	13	19	69	10	32	1	Sediment
26	0.2241	14	71	30	17	34	1	Multiple
57	0.2209	15	32	77	9	26	1	Sediment
33	0.2191	16	89	34	18	40	1	Sediment
34	0.2098	17	95	54	19	42	1	Sediment
14	0.2094	18	3	7	38	3	1	Culvert failure/habitat
80	0.2085	19	78	60	16	33	1	Sediment
18	0.2045	20	33	85	13	17	1	Sediment
29	0.2019	21	111	73	11	46	1	Sediment
17	0.2015	22	46	89	12	16	1	Sediment
83b	0.2015	23	51	1	54	99	1	Landslide
54u	0.2003	24	5	9	29	4	1	Sediment
56	0.1936	25	1	49	26	8	1	Culvert failure

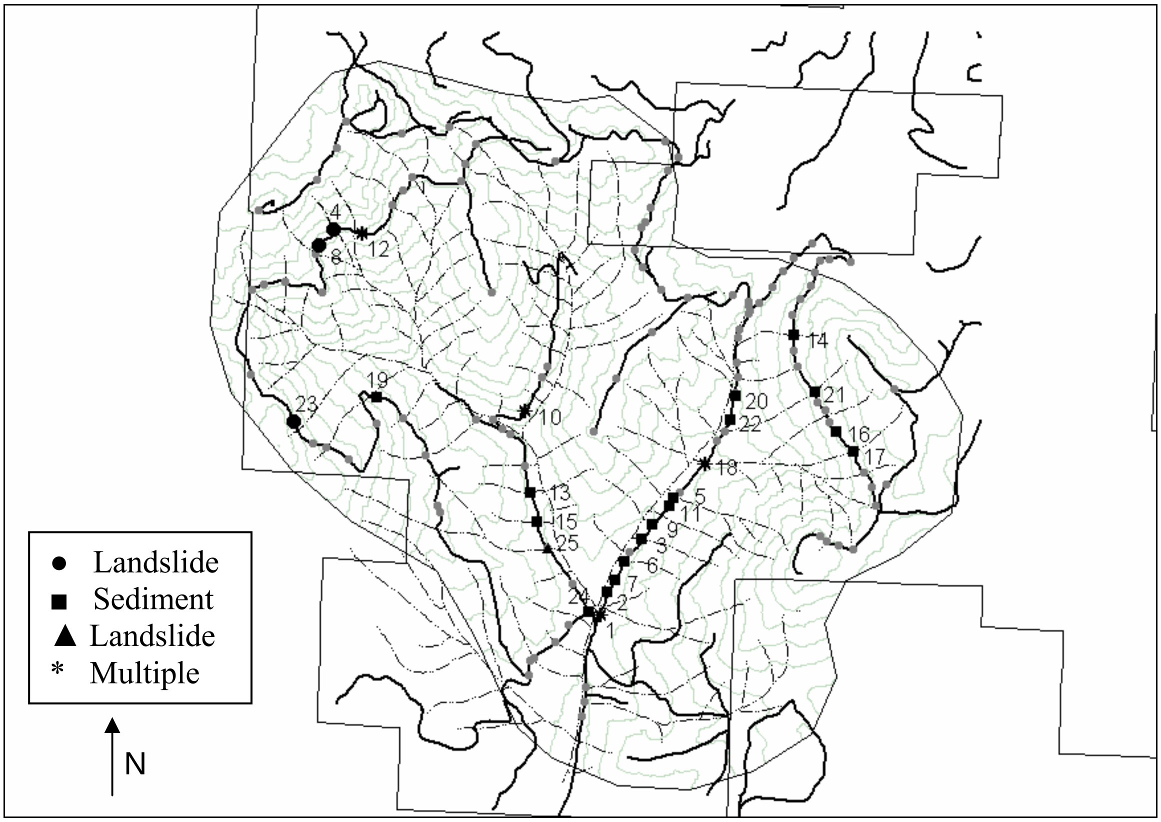

Figure 4.3: The location of the 25 road segments that pose the greatest risk to soil and water in the Oak Creek watershed. Symbols indicate the dominant cause of adverse impacts for each road segment. Numbers represent the overall rank of the twenty highest-ranked road segments.

Note that all road segments are ranked the same (1) for fish passage. This is because there were no structures blocking fish passage in Oak Creek. Road segments that rank moderately high on several objectives may receive a higher overall score, and thus a higher overall rank, than those road segments that may, for example, only rank moderately high on one objective.

Fifteen of the 25 road segments that pose the greatest risk to soil and water in the Oak Creek watershed are valley-bottom roads. The reason for this lies primarily in the preferences used in this analysis which weight potential for impacts to fish habitat higher than the potential for landslide occurrences.

Objective validation of a model that is based on the preference of a decision maker is not possible, but it is possible to validate branches of the hierarchy to determine if the results appear reasonable. The results of the analysis for the landslide objective alone were compared to field evidence and professional judgment regarding how well the model predicted risk due to road-related landslides (Table 4.3 and Figure 4.4).

Table 4.3: The 20 road segments that pose the highest risk of landslides (fifth column from left). The ranking for fish passage has been omitted because it is the same for all road segments.

Road Segment	Overall Score	Overall Rank	Culvert failure Rank	Landslide Rank	Chronic Sediment Rank	Habitat Loss Rank
83b	0.2015	23	51	1	54	99
87	0.1652	29	44	2	121	90
93	0.1615	32	29	3	126	81
88	0.1539	38	34	4	122	70
90	0.2573	4	26	5	20	37
89	0.2437	8	30	6	23	39
14	0.2094	18	3	7	38	3
25k	0.1445	42	41	8	47	69
54u	0.2003	24	5	9	29	4
25i	0.1342	49	84	10	18	73
25j	0.1339	50	86	11	19	77
83	0.1245	57	113	12	79	123
5	0.2766	2	14	13	2	6
13	0.1512	39	23	14	43	53
77	0.1439	43	91	15	37	114
25h	0.1299	52	85	16	59	67
91	0.2284	12	39	17	22	36
25f	0.1238	58	103	18	81	98
25g	0.1254	56	92	19	83	85
9	0.2632	3	20	20	4	19

Most of the road segments that have a high risk due to landslides are located on mid-slope roads in steep terrain (Figure 4.4). The roads identified on the western edge of the Oak Creek watershed (road segments numbered 76 through 94) were witnessed to have experienced small cutslope and fillslope failures and one failure of the road fill at the time the road inventory was taken. This road fill failure occurred on road segment 87, which is calculated to pose the second greatest risk to soil and water in the Oak Creek watershed.

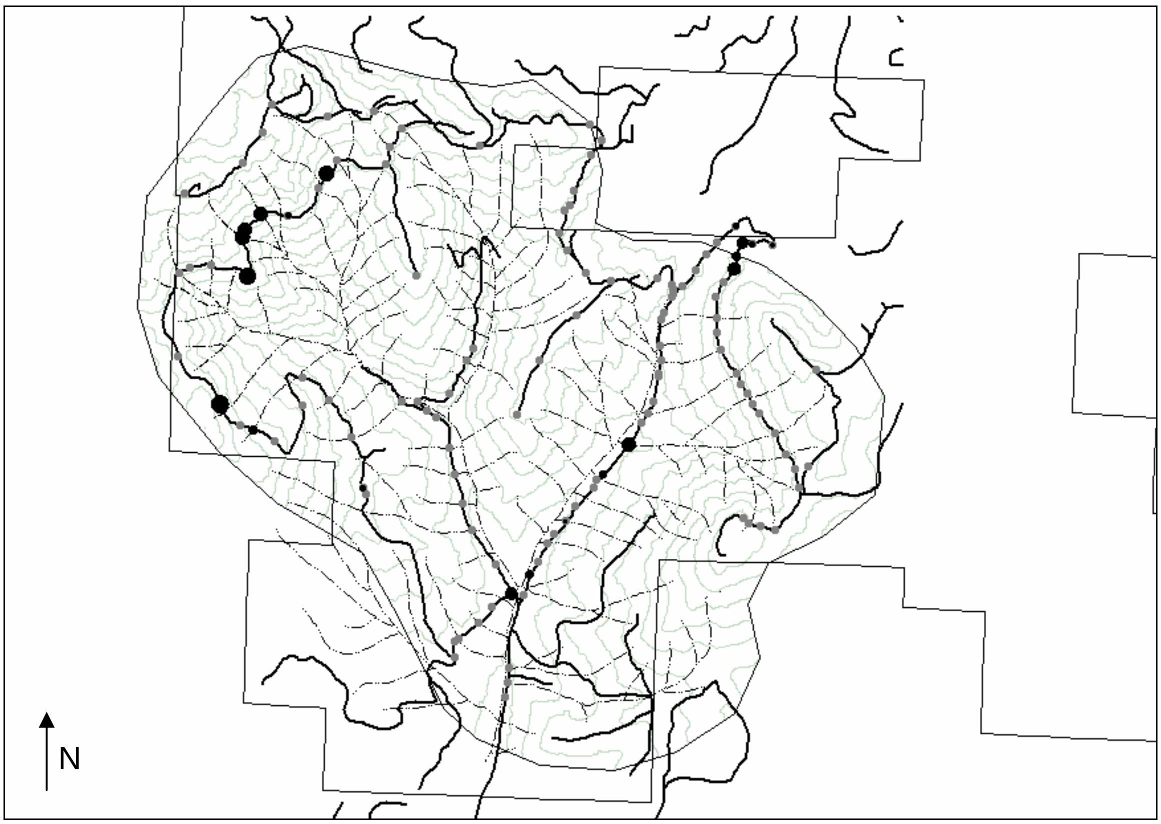

Figure 4.4: Location of the 20 road segments that pose the greatest risk due to landslides, with larger circles indicating greater risk.

Several road segments of the mainline road on the valley bottom are also ranked in the top twenty road segments for landslide risk. These are road segments 5, 9, 13, and 14. The attributes of these segments that influence the landslide risk are shown in Table 4.4. These segments are ranked relatively high not because they are at particular risk of a landslide occurring, but because of their proximity to a fish stream and the high likelihood that if a landslide were to occur that stream would be impacted.

Table 4.4: Attributes of four valley-bottom roads with high landslide risk rankings.

Segment	Hillslope Gradient	Percent Sidecast	Cutslope Height	Fillslope Depth	Distance to Stream	Rill or Gully
5	20%	30%	8 ft.	2 ft.	80 ft.	Gully
9	10%	40%	2 ft.	5 ft.	184 ft.	Rill
13	30%	35%	7 ft.	5 ft.	201 ft.	None
14	30%	50%	2 ft.	15 ft.	0 ft.	Gully

Currently in the pairwise comparison for landslide risk (third level of the hierarchy), landslide occurrence is given extreme importance over both the likelihood of a landslide traveling to a stream and the quality of habitat that could potentially be impacted, yet still some road segments with a low probability of failure are present at the top of the landslide risk rankings. If the decision maker wishes to weight the analysis more toward landslide occurrence and less toward potential impacts, there are several options. First, the attributes “travel to stream” and “habitat quality” could be eliminated entirely from the hierarchy. In this case the user would be making the decision that landslide occurrence alone is the extent of risk they are willing to tolerate when it comes to road-related landslides. If this is not the case, the second option would be to add an additional branch to the hierarchy (Figure 4.5). This will lower the overall influence of potential impacts as compared with landslide occurrence. This is a technique known as clustering and is a method for dealing with the constraints of requiring that pairwise comparisons be based on the integers between one and nine.

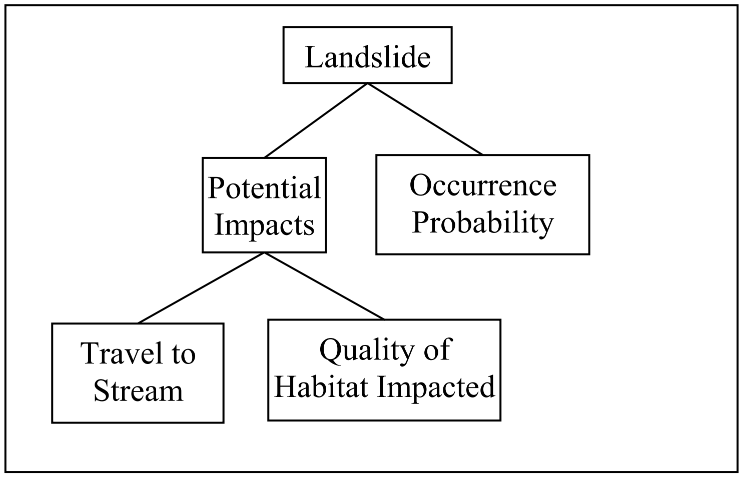

Figure 4.5: Alternate method for dealing with landslide risk.

If the same relative priorities as before are applied, "occurrence probability" having extreme importance over "potential impacts" and "travel to stream" and "habitat quality" equally as important, occurrence probability will be given a weight of 0.9 and risk a weight of 0.1. The attributes "travel to stream" and "habitat quality" will both receive a weight of 0.5. This gives an overall relative value for landslides of 0.9(occurrence probability) + 0.1[0.5(travel to stream) + 0.5(habitat quality)], which is equal to 0.9(occurrence probability) + 0.05(travel to stream) + 0.05(habitat quality). Compare this to the previous case where the overall relative value for landslides was equal to 0.8(occurrence probability) + 0.1(travel to stream) + 0.1(habitat quality). When this new weighting is applied, only road segment 14 with its 3 meter fill is still listed in the top twenty road segments for risk of landsliding. The choice of hierarchical structure is based on the professional judgment of the decision maker. The lower in the hierarchy a given element is located the lower its potential for influencing the overall goal, and conversely, the higher in the hierarchy an element is placed the greater influence that attribute will have on the analysis. Therefore the choice of model structures, in terms of how the hierarchy is constructed, has a controlling influence over the resulting rankings. This is an important point to consider when constructing a problem hierarchy.

An alternate approach would be to eliminate all road segments not on steep side slopes from the landslide analysis. This would be accomplished by setting the relative values for the attributes within the landslide branch of the hierarchy equal to zero for all road segments that do not pass some filter. A potential filter would be to assume that the risk of a landslide will be equal to zero for all road segments located on a cross slope less than 50 percent (Robison et al. 1999a). When this is done, only seventeen road segments receive a score for the objective of minimizing landslides.

4.6.1 "Pruning" the Hierarchy

Many of the factors identified in the literature and included in the full version of the hierarchy were assigned low weightings through the pairwise comparison process. In many cases this was because of relationships between attributes. For example, the assessment of landslide probability included the factors hillslope gradient, fillslope depth, cutslope height, and percent sidecast (construction method). Each of these factors is important when predicting road-related landslides. The following questions were asked during pairwise comparison of these attributes:

- "How important is hillslope gradient compared to percent sidecast in determining the probability of a landslide occurring?"
- "How important is fillslope depth compared to percent sidecast in determining the probability of a landslide occurring?"
- "How important is cutslope height compared to percent sidecast in determining the probability of a landslide occurring?"

In all of these cases, sidecast construction is less important that the specific geometry of a road segment. Additionally, fillslope depth can be seen as a surrogate for percent sidecast meaning this variable is not necessary.

One of the advantages to setting up a problem using AHP prior to data collection is that extraneous variables can be discarded. This was done for the hierarchy created here. In general, those attributes with a weighting of less than 0.1 were discarded. A lower threshold was set for larger hierarchies where weights are spread over more attributes. The original hierarchy and weighting for the "landslide occurrence" branch of the problem are shown in Figure 4.8. Shaded attributes in Figure 4.6 were removed from the hierarchy.

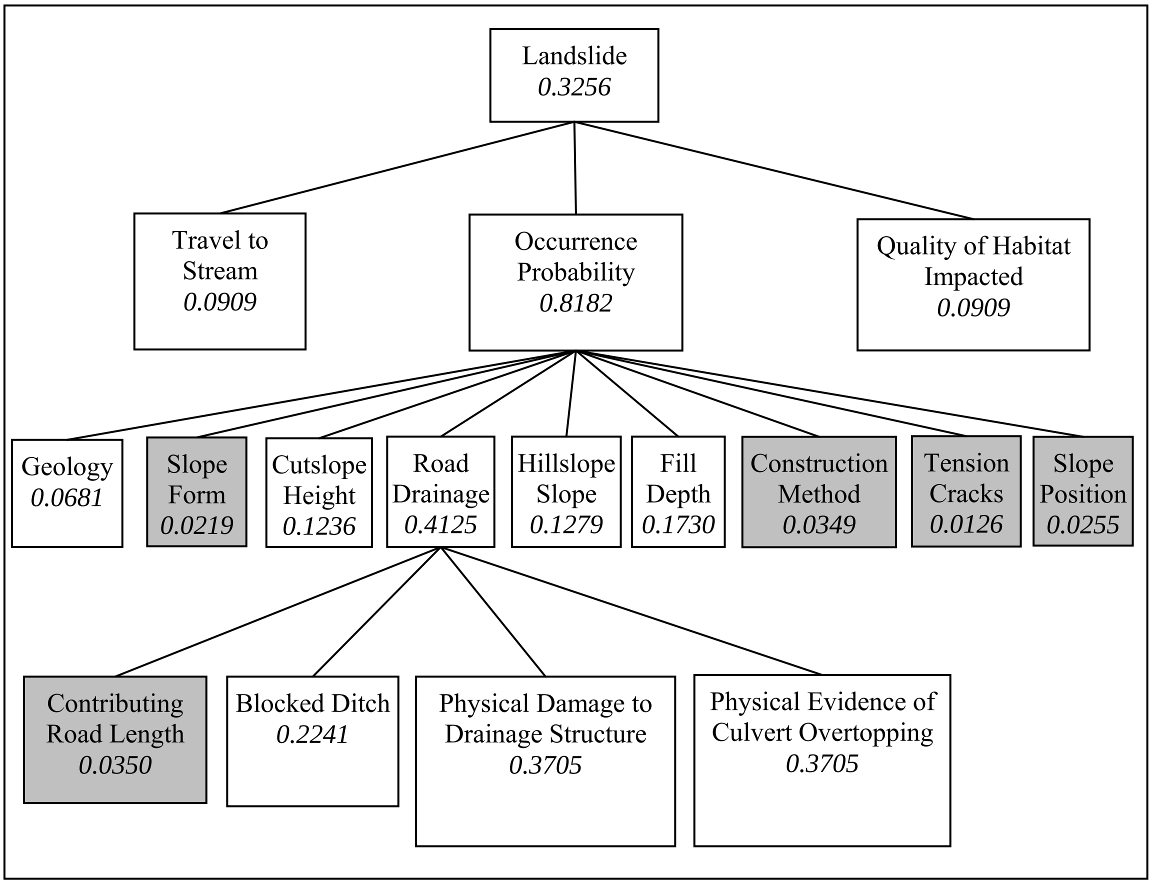

Figure 4.6: Pruning the road-related landslide occurrence branch of the problem hierarchy based on weights from the first round of analysis, shown in italics. "Pruned" boxes are shaded grey.

Pruning was conducted for each level of each branch of the hierarchy. The full hierarchy contained 87 attributes requiring 219 pairwise comparisons. Some of these attributes were based on the same road inventory data, such as the distance from the road to the stream or the interception of subsurface flow, but were included in multiple branches of the hierarchy and therefore needed to be included in multiple sets of pairwise comparisons. The pruned version of the hierarchy retained 50 attributes requiring 79 pairwise comparisons. This represents a 43% reduction in the number of attributes with a 64% reduction in the number of comparisons required of the decision maker. This is a significant savings in the amount of work required by a decision maker to complete an analysis and reduces the complexity of the problem hierarchy considerably. The realization of this reduction in work would occur only if new pairwise comparisons were elicited for subsequent analysis of other areas using the same solution hierarchy.

The road segments were reanalyzed using the reduced hierarchy in order to determine the impact in results of this reduction in complexity. Pairwise comparisons were unchanged from the original example with the rows and columns corresponding to the pruned attributes simply removed from the matrices of pairwise comparisons. New weightings (eigenvectors) were calculated using these reduced matrices. This “pruned” hierarchy is shown in Figure 4.7.

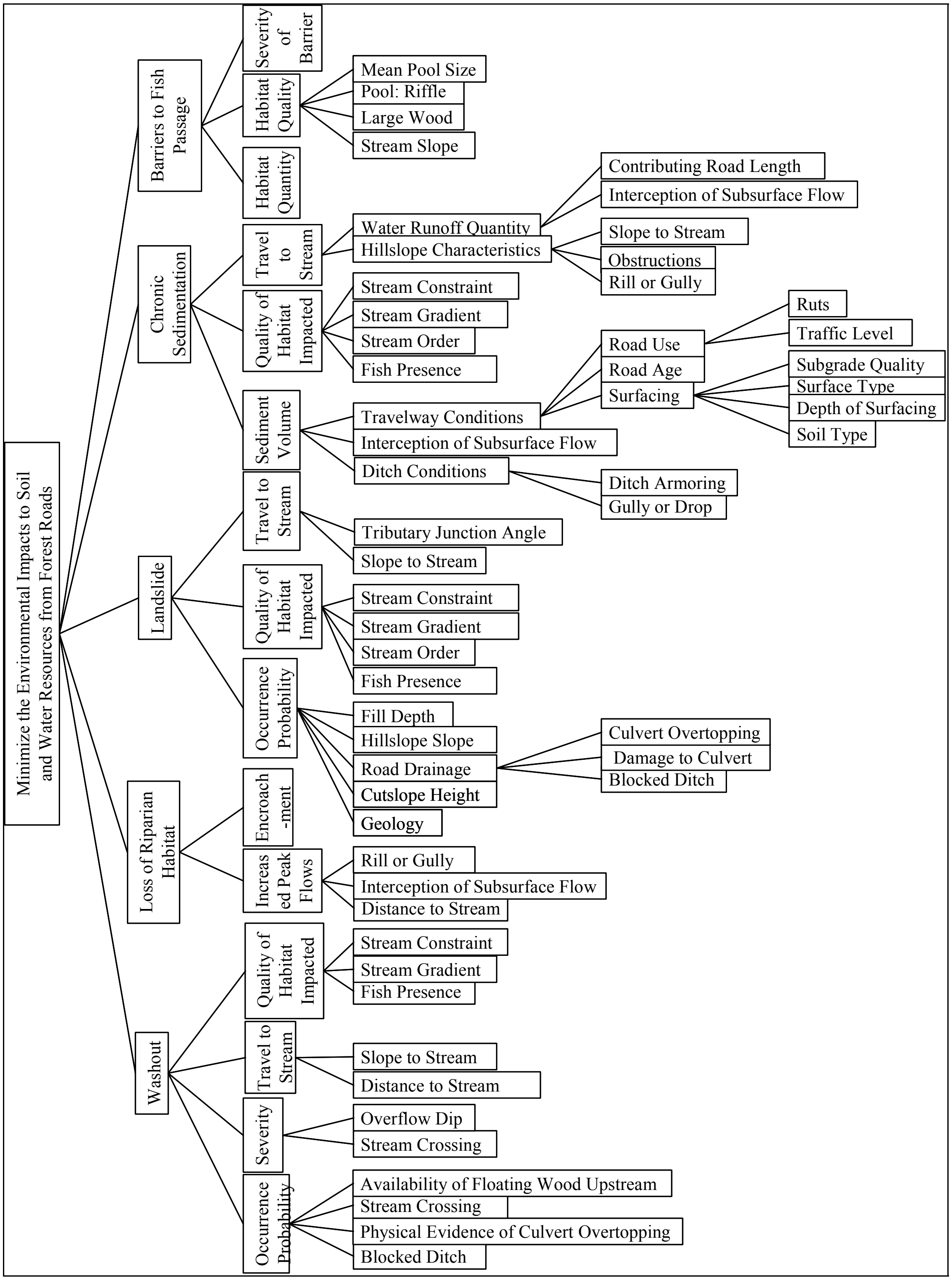

Figure 4.7: Pruned hierarchy for the minimization of adverse effects to soil and water resources from forest roads after all attributes with minimal contribution to the overall goal were removed.

For those road segments that either scored high or low, their rank using the full hierarchy was similar to their rank using the pruned hierarchy (Figure 4.8). For those road segments with moderate to moderately low ranking, the rank using the full hierarchy was not as similar to their rank using the pruned hierarchy. This difference resulted primarily from inconsistency in stated preferences in the original matrices of pairwise comparisons. Because only those attributes with minimal contribution to the overall goal were removed, only minor differences in the rank of individual attributes using the two hierarchies should have resulted from their relative performance on these attributes.

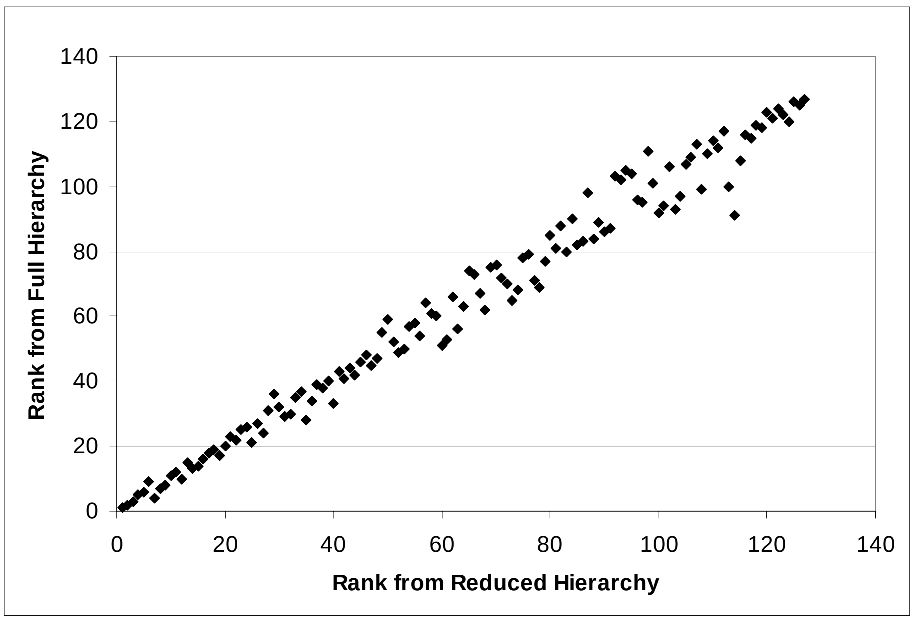

Figure 4.8: Comparing the resulting ranking of individual road segments within the Oak Creek watershed using the full and reduced hierarchical structures.

Each decision maker will need to make the trade off between complexity of the hierarchy and differences in the ranking of alternatives using more and less complex hierarchical structures. Changes in the overall score values (the values calculated using AHP that are used to generate a ranked list of road segments) for individual road segments within the Oak Creek watershed appears to be small. Overall score values generated using the full hierarchy are not comparable to those generated using the reduced hierarchy because each is based on a different set of attributes.

One reason for the larger discrepancies between rank using the full and pruned hierarchies among the moderate to moderately-low ranked road segments is due to the closeness in relative value of these road segments. Road segments with the greatest difference in rank between the two analysis are located in the region where a change in rank results from a small change in relative value (Figure 4.9).

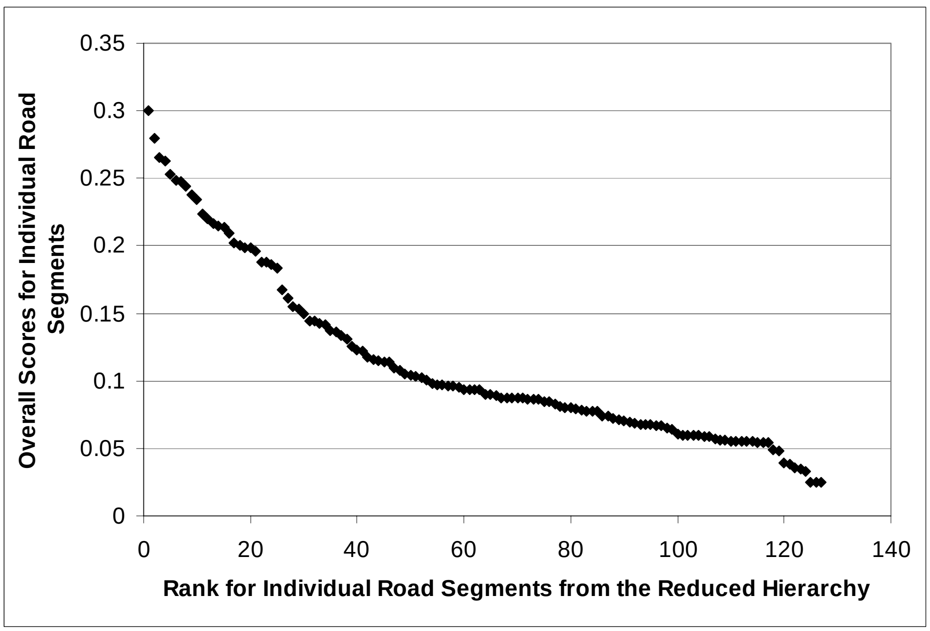

Figure 4.9: Rank versus overall score for individual Oak Creek road segments.

4.6.2 Customizing the Hierarchy

Because there are no barriers to fish passage due to stream crossing structures in the Oak Creek watershed and because this analysis will not be combined with data from another road system that may include barriers to fish passage, fish passage does not need to be in the hierarchy. The removal of fish passage from the hierarchy removes seven attributes and 13 pairwise comparisons from the reduced hierarchy.

When fish passage is removed from the hierarchy, the resulting analysis shows a change in the rank of a number of road segments within the Oak Creek watershed. These differences were similar in pattern and magnitude to those found when moving from the full to the reduced hierarchy. The rank of individual road segments under each of the four remaining objectives (culvert failures, landslides, chronic sediment, and habitat modification) did not change, however the relative weights of these objectives did change. If the original set of pairwise comparisons between these objectives had been perfectly consistent then no changes in rank would have occurred when the fish passage objective was removed. While the inconsistency in comparisons among these objectives is within acceptable levels, meaning CR is less than 0.1 (Saaty 2000), there is still some inconsistency in judgments present. The main advantage to removing fish passage from the hierarchy is that relative values are dispersed over a wider range of values, resulting in greater distinction in relative value between road segments (Figure 4.10).

For example assume five objectives where the first objective is two times more important than the second objective, the second objective is equally as important as the third objective, the third objective is two times more important than the fourth objective, and the fourth objective is twice as important as the fifth objective (Table 4.5). The relative importance of each objective relative to the other objectives remains constant regardless of which objective is dropped (Table 4.6).

Table 4.5: Matrix of pairwise comparisons between five objectives when the first objective is two times more important than the second objective, the second objective is as important as the third objective, the third objective is twice as important as the fourth objective, and the fourth objective is twice as important as the fifth objective.

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Weight
Objective 1	1	2	2	4	8	0.3256
Objective 2	1/2	1	1	2	4	0.3703
Objective 3	1/2	1	1	2	4	0.1674
Objective 4	1/4	1/2	1/2	1	2	0.0993
Objective 5	1/8	1/4	1/4	1/2	1	0.0375

Table 4.6: Weights resulting from eliminating one or more of the objectives depicted in Table 3.5 when the relative importance of the alternatives is kept constant.

	Objective 5 Removed	Objectives 4 and 5 Removed	Objectives 3, 4, and 5 Removed	Objective 2 Removed
Objective 1	0.4444	0.5000	0.6667	0.5333
Objective 2	0.2222	0.2500	0.3333	0.2667
Objective 3	0.2222	0.2500	-	-
Objective 4	0.1111	-	-	0.1333
Objective 5	-	-	-	0.0667

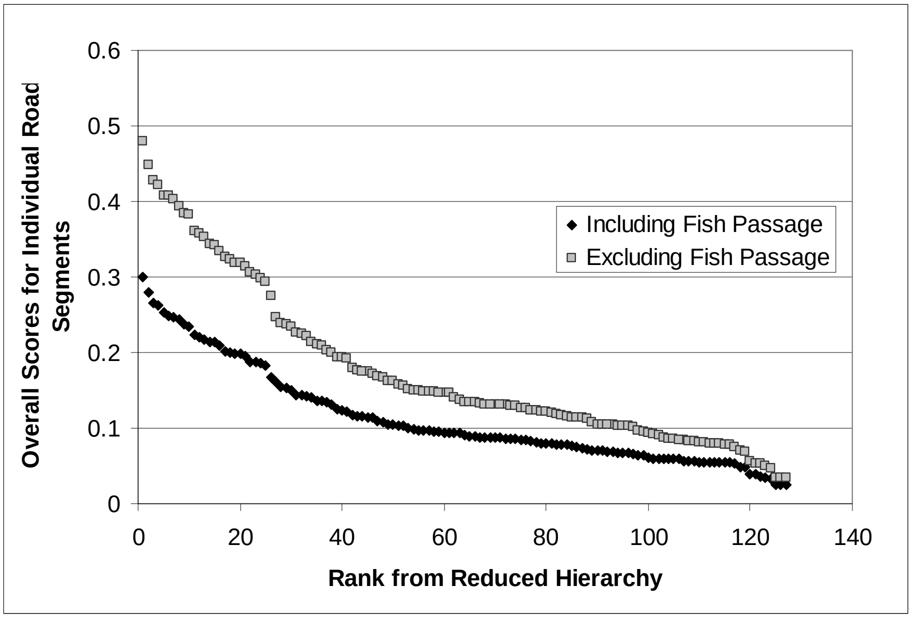

Figure 4.10: A comparison of overall score values for individual road segments when fish passage is included and when fish passage is excluded from the hierarchy.

4.7 Conclusions

AHP allows large complex problems to be refined into successively smaller problems using hierarchical decomposition. The full hierarchy and the pruned hierarchy, are large and complex. Once the hierarchy is structured, pairwise comparisons are performed between small clusters of attributes within each branch and level of the hierarchy with reference to the element above it. This allows the decision maker to focus on one small portion of the problem at a time. Ensuring pairwise comparisons remain manageable, that is to say between a small number of attributes, is paramount. When too many attributes or dissimilar attributes are compared it becomes difficult for the decision maker to maintain consistency and fatigue becomes a concern, leading to errors and indifference.

The structure of the hierarchy has an influence over analysis results. This provides a large amount of flexibility to ensure the results of an analysis match scientific findings and professional judgment. Care must be taken, however, to minimize the unintended effects of hierarchical structure. As attributes are placed higher up in a multilevel hierarchy they will have a greater relative influence on the overall score of each alternative. Additionally small changes in the hierarchy structure can have large consequences in the resulting rankings, as evidenced by the example of landslide risk. The decision maker (and analyst) needs to understand these consequences when the hierarchy is structured.

AHP is a flexible technique that generates a problem formulation that should be allowed to change as analysis moves from one geographic area to another and as goals, policies, laws, and concerns change. It is reasonable to assume a single problem formulation such as either the full or reduced hierarchy presented here could be used as the basis for many analyses. It is also reasonable to assume that this base hierarchy would be modified as the need arises, such as the example in the Oak Creek watershed where no barriers to fish passage were found. Priorities will change depending on the specifics of the analysis being conducted. One example presented earlier was geology. Swanson and Dryness (1975) found that geology had a strong influence over landslide rates in the H.J. Andrews Experimental Forest where two geologic formations with very different strength characteristics were found side by side. This difference in landforms is not present in Oak Creek, therefore geology was not a large determinate in the occurrence of road-related landslides. Local knowledge is essential in informing these modifications of both the problem structure and pairwise comparisons. Once either the hierarchy or preferences have been modified the relative values produced by the AHP are no longer directly comparable with the relative values from a previous analysis.

The most limiting factor in applying the AHP to a problem such as the prioritization of road investments is a lack of specific scientific data to inform pairwise comparisons. This means that these comparisons often must be made on the basis of professional judgment. These judgment calls are already being made in the management of forest road networks. What AHP does is provide a framework within which scientific knowledge, professional judgment, and local expertise can be applied consistently and in a replicable fashion to large, complex problems. The source of pairwise comparison values should be referenced and updated as new science becomes available.

AHP can be used to select road attributes of concern as a first step in designing a road inventory. By completing the problem hierarchy and conducting pairwise comparisons prior to designating the road characteristics to be collected, decision makers can help to ensure the information collected will be used and the specific road characteristics important to the analysis are available. By pruning the hierarchy of those attributes that do not significantly contribute to the designated goal, extraneous data can be eliminated and complexity can be reduced. The main advantage to this pruning is that this streamlining of the hierarchy should make data collection in the field more productive by eliminating unneeded attributes.

AHP uses multiple comparisons of each attribute to inform attribute weights. When these comparisons provide conflicting information the reliability of the weights decreases. This is most evident during the pruning of a hierarchy where inconsistency in pairwise comparisons is the major cause of rank shifts. This was demonstrated when fish passage, an objective all alternatives scored the same on, was removed from the hierarchy. Because of inconsistency in the pairwise comparisons of the objectives, rank shifts occurred. Inconsistency should not be completely avoided but should be kept to a reasonable level.

Many organizations have road inventory databases that have already been collected and are currently being used in single-problem analysis. For example, these databases may be queried to determine the location of barriers to fish passage or to determine road segments that are most susceptible to landslides. Current systems do not allow the comparison of multiple road-related problems or impacts. Structuring AHP to use existing road inventory data would allow the integration of multiple issues into a single, comprehensive analysis.

AHP is a flexible method that has promise in the management of existing forest road networks by allowing the prioritization of investments based on multiple criteria. AHP can be used both in the development of new road inventory protocol and the analysis of existing road networks. This paper presents a formulation of the minimization of environmental impacts on soil and water resources caused by forest roads. The structure of the hierarchy and pairwise comparisons were informed by a combination of the scientific literature and expert opinion. The application of this problem structure to 8.3 miles of roads within the Oak Creek watershed appears to produce reasonable results. Additionally, a pruned hierarchy was shown to maintain predictive ability while significantly reducing complexity. The importance of hierarchical structure and consistency in pairwise comparisons was shown. Decision makers who choose to use AHP in the analysis of forest road investments must be aware of these consequences.

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5 Systems of User Feedback for Large Project Pools Using AHP: An Application to Setting Priorities for Road Maintenance

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5.1 Abstract

The Analytic Hierarchy Process, or AHP, is a multi-criterion decision analysis method used to set priorities based on multiple criteria and expert judgment. The traditional use of AHP is to rank a limited number of alternatives. In these applications the decision maker is able to evaluate the quality of solution intuitively. When, however, the number of alternatives becomes large this evaluation becomes difficult. AHP involves structuring the problem as a hierarchy followed by the decision maker performing series of pairwise comparisons to determine preferences. These preferences are then applied consistently to all alternatives to produce a ranked list of alternatives. Few metrics are available to provide user feedback in problems constructed as incomplete hierarchies with large numbers of alternatives. Three metrics are proposed to assist decision makers in evaluating the quality of a solution and to revise preferences when necessary. These metrics are applied to a forest road inventory with 2,389 alternatives consisting of road segments to be considered for upgrade or maintenance.

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5.2 Introduction

The Analytic Hierarchy Process, or AHP is a multi-criterion decision analysis method that uses expert judgment to evaluate a set of alternatives based on multiple, dissimilar attributes. AHP was introduced by Saaty (1977) and since then has seen wide use in many fields. The traditional use of AHP is to rank a small number of alternatives.

Because AHP is based on expert judgment there is often no way to objectively validate model results. With traditional applications of AHP, users are often able to look at the results and intuitively decide if the model is adequately representing their preferences. Based on this intuitive analysis, users can then revise preferences until model output is consistent with the user's intentions.

When AHP is applied to problems with large numbers of alternatives, this intuitive review of the results becomes difficult, if not impossible. Metrics that provide decision makers with feedback about the nature of the specific problem and the influence of user preferences on the results is needed for users to make informed decisions about how to revise preferences and ensure solutions adequately represent their preferences. Paulson and Zahir (1995) state that the main source of uncertainty in the results of an AHP analysis "result from the limited amount of information available to the decision maker and the level of his or her understanding of the problem" (p. 45). Therefore, the better a decision maker understands a given problem, specifically the interaction between their preferences and the alternatives under consideration, the greater that user's confidence in the results.

Existing methods of sensitivity analysis within AHP are designed specifically for use with complete hierarchies applied to problems with small numbers of alternatives. This study presents sensitivity analysis methods that are applicable to problems described by incomplete hierarchies containing large numbers of alternatives. We provide an overview to AHP, introduce a road investment problem, and the use this problem to develop systems of user feedback to be used with large problems.

5.3 The Analytic Hierarchy Process

AHP involves four steps: structuring the problem as a hierarchy; pairwise comparisons among attributes to determine the user's preferences; the reduction of attributes to relative values; and the ranking of alternatives.

AHP requires that problems be constructed as a hierarchy, a process termed hierarchical decomposition, such that the overall goal is represented at the top of the hierarchy with objectives and sub-objectives below. Objectives are decomposed until the base of the hierarchy is composed of the attributes that are used to compare alternatives. These attributes can be quantitative or qualitative and can be measured on any scale as long as that scale remains constant for a given attribute.

Pairwise comparisons are made between the attributes within each group of each level of the hierarchy based on the contribution of each attribute to the element directly above them in the hierarchy. The most prevalent scale used to carry out these comparisons is Saaty's Fundamental Scale. The Fundamental Scale is composed of the integers between one and nine where one signifies equal importance between the attributes and nine is used when one attribute is strongly more important than the other. Reciprocals are used to express the strength of the weaker of the two attributes. AHP does not require the decision maker to be completely rational or consistent in completing these pairwise comparisons.

The result of each set of pairwise comparisons is a positive reciprocal matrix such that $a_{ij} = a_{ji}$, $i, j \leq n$, where n is equal to the number of elements being compared within one set of pairwise comparisons. Various methods for calculating attribute weights from this matrix have been proposed. Saaty (1977, 2000) uses the principal right eigenvector while others (Lootsma 1996) have used the normalized geometric mean of the rows of the priority matrix, also called the Logrithmic Least Squares Method (LLSM). Both the eigenvector and LLSM have strong mathematical and theoretical backing (Fichtner 1986) and both are used extensively in practice with little difference in the results (Crawford 1987).

The magnitude of the decision maker's inconsistency in completing pairwise comparisons is measured using a Consistency Ratio (CR). The CR is formed by the ratio of the Consistency Index (CI) of a matrix of pairwise comparisons and the Random Consistency Index (RI) for a matrix of the same size. The CI is found using the largest eigenvalue, λ_{max}, corresponding to the principal right eigenvector and is equal to $(\lambda_{max} - n)/(n-1)$ where n is the number of attributes being compared to create a n by n square matrix. The RI is the average CI of many matrices completed with random entries (see Saaty 2000). Saaty suggests pairwise comparisons should be adjusted until the CR of each matrix is less than or equal to 0.1, or ten percent.

The CR can be thought of as analogous to the R^2 value used in linear regression. Both values have an optimal value, zero for CR and one for R^2. As the difference increase between actual and predicted values in the case of linear regression or calculated and expressed preferences in the case of AHP, the value of R^2 and CR depart from their optimal values. As each of these values departs from optimal, the user's confidence in the results decreases.

Weights are derived through a pairwise comparison technique and are multiplied by the relative value for each attribute of each alternative. Relative values for individual attributes can be derived in many ways including pairwise comparisons between categorical data, linear interpolations based on the maximum or minimum value under consideration, or utility functions as defined by the decision maker. The overall score for each alterative is aggregated using an additive function of the product of each attribute weight and its associated relative attribute value.

AHP allows for the inclusion of less than perfect data both in the attribute values and in pairwise comparisons. Input values can include both quantitative and qualitative data, measured on any continuously applied scale. For example, data for cutslope height could be included as a continuous directly-measured value, an estimate to the nearest foot, or as a categorical variable that describes a range of values (i.e. 3-7 meters). The more precise and certain both attribute values and pairwise comparisons, the more certainty the user can have in an analysis outcome.

5.4 Sensitivity Analysis

Several methods of sensitivity analysis within the AHP have been presented in the literature. Sensitivity analysis within AHP generally involves determining ranges of attribute weights or preferences that will produce a given ranking of alternatives. Saaty and Vargas (1987) used interval assessments of priority judgment, as opposed to the point estimates generally used within AHP, to determine the likelihood a rank reversal will occur. This method would require the decision maker to give a range of likely preferences during pairwise comparisons as opposed to a single estimate. Saaty and Vargas then randomly chose priority values within this range to determine the probability that across the given range of priority values a change in the ranking of the alternatives will occur. Paulson and Zahir (1995) randomly generated matrices of criteria weights and used these to examine the scope of results possible for a given set of alternatives. Aguaron and Moreno-Jimenez (2000) present a formulation to calculate local stability intervals for individual criteria. These are intervals within which either the top-ranked alternative or all alternatives do not change rank.

Masuda (1990) used the concept of a reachability matrix to analyze the impact of variations in the weights at one level of the hierarchy. The results for a problem with three criteria can be shown as an equilateral triangle with irregular polygons representing combinations of the three weights that will produce a top ranking for a given alternative. Erkut and Tarimcilar (1991) included additional spatial information to this weight space. Sanchez (1992, 1994) built upon the work of Masuda by expanding the definition of critical criteria and by providing an analytic technique to determine the location of points at which rank reversal will occur.

All of these approaches specifically require the problem be structured as a complete hierarchy (see Chapter 2 for a discussion of complete and incomplete hierarchies). Masuda proposes a method to convert an incomplete hierarchy to a complete hierarchy (Figure 5.1) that involves the inclusion of dummy nodes and dummy links. The problem with this method lies in the normalization of weights. In the original formulation, $S_{21}+S_{22}=1$ and $S_{31}+S_{32}=1$. In the converted hierarchy, the correct weighting (not used by Masuda or Sanchez) would be $S_{31}+S_{32}+S_{33} = S_{31}+S_{32}+S_{22}=1$, clearly not the same problem as was represented by the original, incomplete hierarchy. Additionally, these methods become impractical, if not impossible, to implement when problems become large.

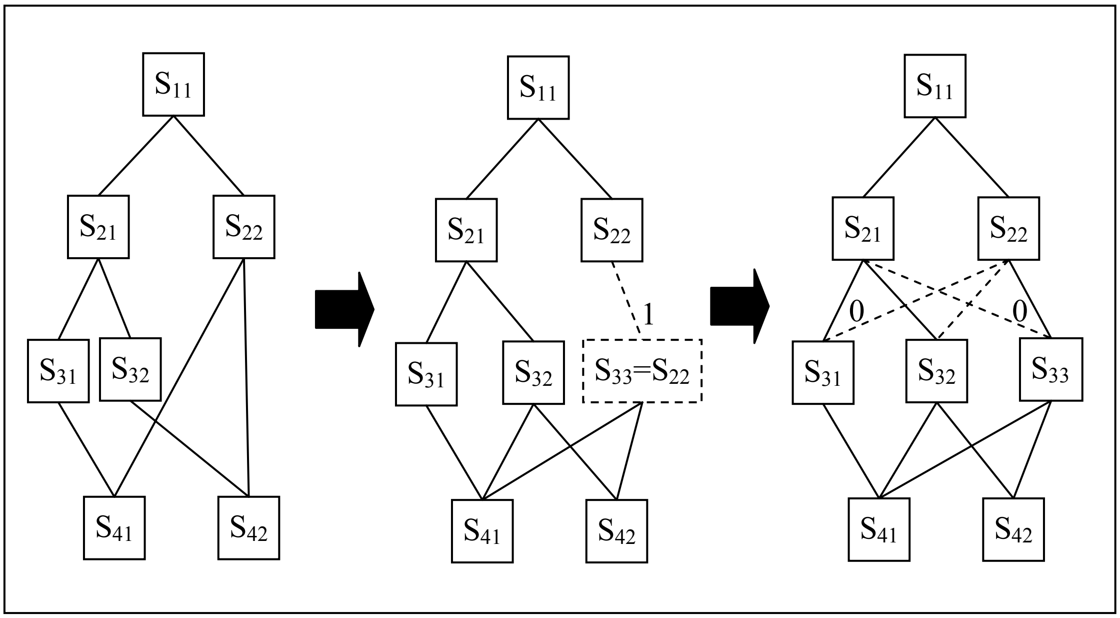

Figure 5.1: Masuda's (1990, Figure 2, p. 418) proposed method for converting an incomplete hierarchy to a complete hierarchy for sensitivity analysis.

These methods also consider either the change in rank of the top-ranked alternative only or the probability that a change in rank will occur within any of the alternatives. With large problems neither of these conditions may be sufficient to adequately describe the sensitivity of the problem.

A large problem that is well suited for analysis via AHP is the prioritization of road maintenance. A common technique to collect information about road maintenance needs is a road inventory. During the road inventory, roads are divided into segments at points of road drainage or changes in road condition such as surfacing type, road gradient, or drivability. This type of a problem quickly grows too large for the analysis techniques previously mentioned.

5.5 Example

A road inventory for 140 miles of forest road, divided into 2,389 road segments, was used in this analysis. The roads are located in western Oregon within five tracts managed by the Oregon State University College of Forestry Research Forests.

A hierarchy was developed that had an overall goal to minimize environmental and economic costs of the forest road network (Figure 5.2). Three objectives were recognized: minimize impacts to streams (environmental cost), minimize forest road failures (both an environmental and economic cost), and minimize violations to the Oregon Forest Practices Act (both an environmental and economic cost). These objectives were further decomposed into 31 attributes that were used to assess each of the 2,389 alternatives (road segments). An incomplete hierarchy is the most appropriate hierarchical form to use for this problem.

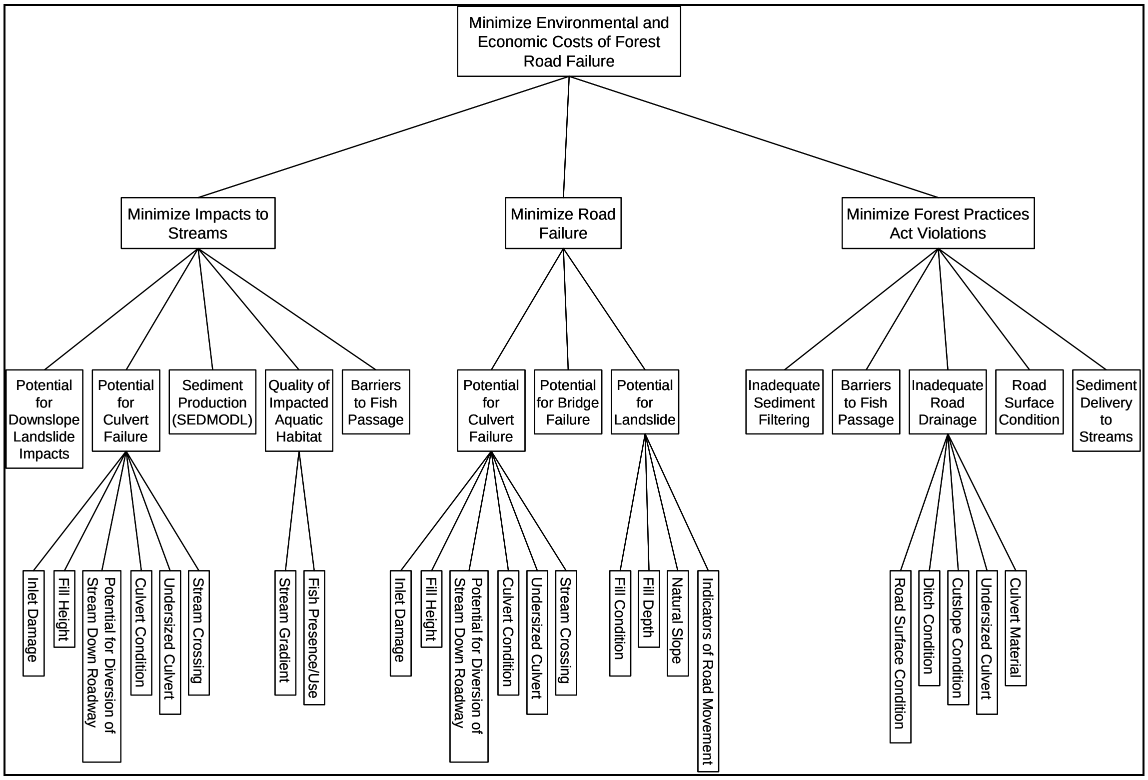

Figure 5.2: Hierarchy used in the road maintenance problem for 140 miles of forest road.

Nine sets of pairwise comparisons are required for the example problem, however only eight need be completed by the decision maker. Note that only one set of pairwise comparisons for the sub-objective of minimize culvert failure is required. While the importance of a culvert failure for the objectives to minimize stream impacts and minimize road failure may be different, the factors that lead to a culvert failure that impacts a stream and a culvert failure that leads to a road failure remain the same.

5.6 Consistency

When sets of pairwise comparisons are too inconsistent, meaning the CR is too high, Saaty (2000) suggests preferences be modified by comparing the judgments made by the decision maker, a_{ij}, to the calculated weights, w_i/w_j and a_{ij} be adjusted in the direction of w_i/w_j. The pairwise comparison with the largest difference between w_i/w_j and a_{ij} is the most inconsistent judgment and the judgment that, if changed in the correct direction, will produced the greatest improvement in consistency. Saaty states that any change in a_{ij} in the direction of w_i/w_j will improve consistency. This is true up to a point. A critical interval exists where an adjustment of a_{ij} in the direction of w_i/w_j will improve consistency but beyond which consistency will decrease.

The values of w_i and w_j can not be used directly to determine how far a_{ji} can be adjusted before improvements in consistency are no longer made. This is due to the dependence of calculated weights on the original estimates of priority. Therefore, $w_i/w_j - a_{ij}$ for each pairwise comparison is used to first, rank judgments according to how inconsistent they are and second, to determine the direction each preference needs to be changed in order to improve consistency. Once the direction of change has been established, simulation can be used to vary the judgment in question and calculate a new set of criteria weights used to determine consistency measured in terms of CR. This continues until the value of CR no longer decreases.

Take, for example, a problem with three criteria, C_1, C_2, and C_3. The initial set of pairwise comparisons for these three criteria is:

$$A = \begin{bmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 5 \\ 1/3 & 1/5 & 1 \end{bmatrix} \qquad [5.1]$$

This leads to criteria weights of $w = [0.61, 0.28, 0.11]^T$, an eigenvalue of $\lambda_{max} = 3.41$, and a consistency ratio of CR = 0.40. In order to determine the most inconsistent judgment, the following comparisons are made:

$$\begin{aligned} \frac{w_1}{w_2} - a_{12} &= \frac{0.61}{0.28} - 4 = -1.86 \\ \frac{w_1}{w_3} - a_{13} &= \frac{0.61}{0.11} - 3 = 2.65 \\ \frac{w_2}{w_3} - a_{23} &= \frac{0.28}{0.11} - 5 = -2.36 \end{aligned} \qquad [5.2]$$

The largest absolute difference between judgment and the calculated weight is for a_{13}, followed by a_{23}, then a_{12}. The positive value of the comparison for a_{13} indicates the decision maker should consider increasing a_{13}. The maximum amount a_{13} can be adjusted and still continue to decrease CR is found by successively increasing a_{13} until CR no longer improves. For our application, decision makers only have the ability to choose preference values corresponding to the integers between one and nine, thus a maximum of 16 values are considered. Sixteen values would only be considered in the case where the preference for C_1 over C_2 was given as nine when, for example, the user made an error and C_2 should have been recorded as being preferred nine times over C_1. In this situation, the preference for C_1 over C_2 would be systematically decreased to a minimum value of one. If CR is still decreasing, the order of the preferences would be swapped such that C_2 was preferred over C_1 and the preference value for C_2 over C_1 would be increased until CR stopped decreasing.

The first iteration of the example above would look like the following:

$$A = \begin{bmatrix} 1 & 4 & 4 \\ 1/4 & 1 & 5 \\ 1/4 & 1/5 & 1 \end{bmatrix}, \lambda_{\max} = 3.2476 \qquad [5.3]$$

giving a CR of 0.1656. This process is completed until either CR increases or the end of the scale, 9, is reached. Sets of pairwise comparisons at all levels of the hierarchy are treated in the same way as CR is a measure of the consistency of one set of pairwise comparisons independent of the remainder of the problem.

While providing useful information, the danger in making consistency guidance too prominent is that users will change pairwise comparisons solely to improve consistency as opposed to revisions to better reflect their true preferences. Therefore, it is recommended that decision makers record their preferences first for all sets of pairwise comparisons prior to making adjustments due to concerns over consistency. To support this mode of revisions, a control chart is provided to visually show the decision maker which of their sets of pairwise comparisons is more inconsistent than others. Karapetrovic and Rosenbloom (1999) state that setting an absolute maximum CR to accept is inappropriate because it measures the randomness of the decision maker's preferences. Instead, what they suggest is that tests for consistency should be looking for cases where the decision maker has either made a mistake or is illogical in their choice of preferences. The solution provided by Karapetrovic and Rosenbloom is to calculate the same measure as advocated by Saaty, CR, but use tools borrowed from statistical quality control to identify cases where the user has potentially made an error or has been illogical in their statement of preferences. This assumes a decision maker will be consistently inconsistent throughout all sets of pairwise comparisons in a given problem. Tools such as range and control charts will identify those sets of pairwise comparisons that have values of CR outside the range of the other sets of comparisons made by the decision maker. The example illustrated in Figure 5.3 would lead the decision maker to go back and take a look at the "Road Drainage" set of pairwise comparisons. From the chart it can be seen that for this decision maker within this problem, CR should be less than 0.26, or the mean CR plus one standard deviation. Any set of pairwise comparisons with a CR value greater than 0.26 should be revisited. It is at this time that the tools discussed above would be used to indicate to the user the most inconsistent comparison within the set, the direction comparisons should be revised in to improve consistency, and the distance each comparison can be revised and still improve CR.

Note that Habitat Quality has a CR of zero and is thus outside the consistency limits set by the mean CR and standard deviation. In this application, sets of pairwise comparisons less than the lower control limit should not be revised. This is a set of pairwise comparisons between only two attributes, therefore the CR value will always be equal to zero no matter the preference stated by the user.

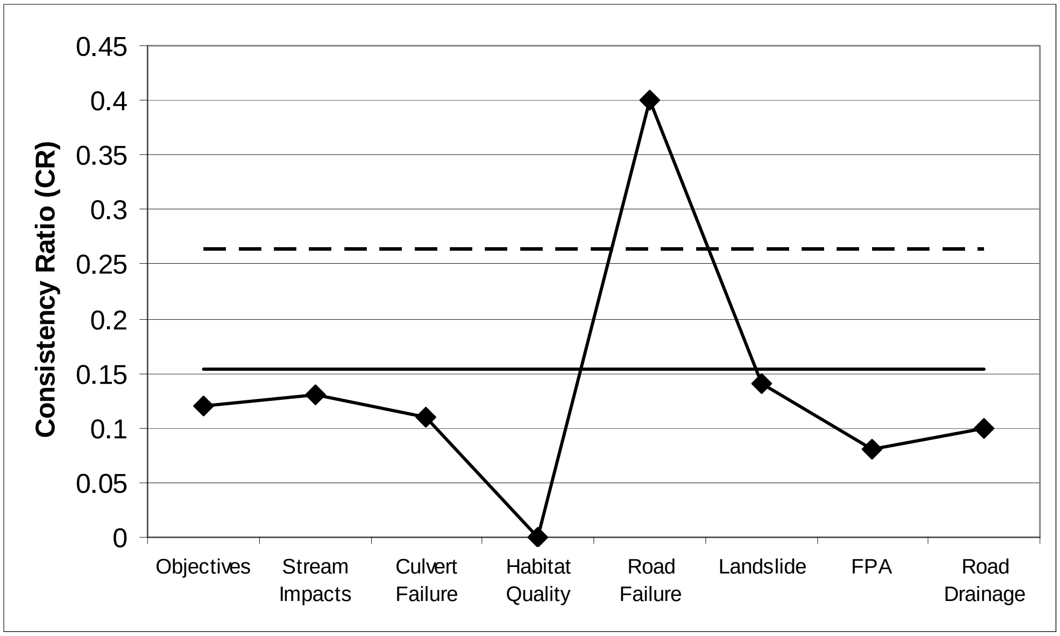

Figure 5.3: Example of using a control chart to indicate to the decision maker when one or more sets of pairwise comparisons has a CR outside the range indicated by the mean CR (solid line) plus or minus one standard deviation (dashed line).

Once pairwise comparisons are completed and revised for consistency if needed, weights are calculated for each of the elements within the problem hierarchy. The eigenvector method of reducing pairwise comparisons to weight vectors was used for this example (Table 5.1).

Table 5.1: Attribute weights used with the example problem. Column offsets indicate levels of the hierarchy.

Minimize Stream Impacts: 0.665		
	Downslope Landslide Impacts: 0.066	
	Culvert Failure: 0.127	
		Inlet Damage: 0.251
		Fill Height: 0.125
		Diversion Potential: 0.213
		General Culvert Condition: 0.128
		Undersized Pipe: 0.129
		Stream Crossing: 0.154
	Sediment Production (SEDMODL): 0.146	
	Habitat Quality: 0.130	
		Fish Use: 0.833
		Stream Gradient: 0.167
	Barrier to Fish Passage: 0.531	
Minimize Road Failure: 0.225		
	Culvert Failure: 0.444	
		Inlet Damage: 0.251
		Fill Height: 0.125
		Diversion Potential: 0.213
		General Culvert Condition: 0.128
		Undersized Pipe: 0.129
		Stream Crossing: 0.154
	Bridge Failure: 0.070	
	Landslide: 0.489	
		Fill Condition: 0.510
		Fill Depth: 0.128
		Natural Slope: 0.073
		Indicators of Movement: 0.290
Minimize Forest Practices Act Violations: 0.090		
	Barriers to Fish Passage: 0.515	
	Inadequate Sediment Filtering: 0.077	
	Inadequate Road Drainage: 0.183	
		Culvert Material: 0.027
		Undersized Pipe: 0.153
		Cutslope Condition: 0.209
		Ditch Condition: 0.411
		Road Surface Condition: 0.200
	Road Surface Condition: 0.076	
	Sediment Delivery: 0.150	

Data for the alternatives was taken from an inventory of 140 miles of forest road. Roads were divided into segments based on road or cultural features (Table 5.2). The length of road between endpoints was described and any problems recorded. For use in AHP this data was reduced to relative values for each of the 31 attributes included at the base of the problem hierarchy. These relative values were combined with the attribute weights to produce an overall score for each alternative (Figure 5.4).

Table 5.2: Road features used as beginning or end points of road segments and their number of occurrences.

Feature	Number of Occurrences
Ditch Relief Culvert	886
Road Junction	355
Water Bar	304
Road Start	233
Road End	218
Stream Crossing Culvert	144
Trail Crossing	48
Gate	44
Road Blocked	38
Property Line	19
Slide	15
Bridge	12
Ruts	12
Surface Change	9
Rock Pit	6
Stream	6
Hole in Road	3
Ford	2
Other	35

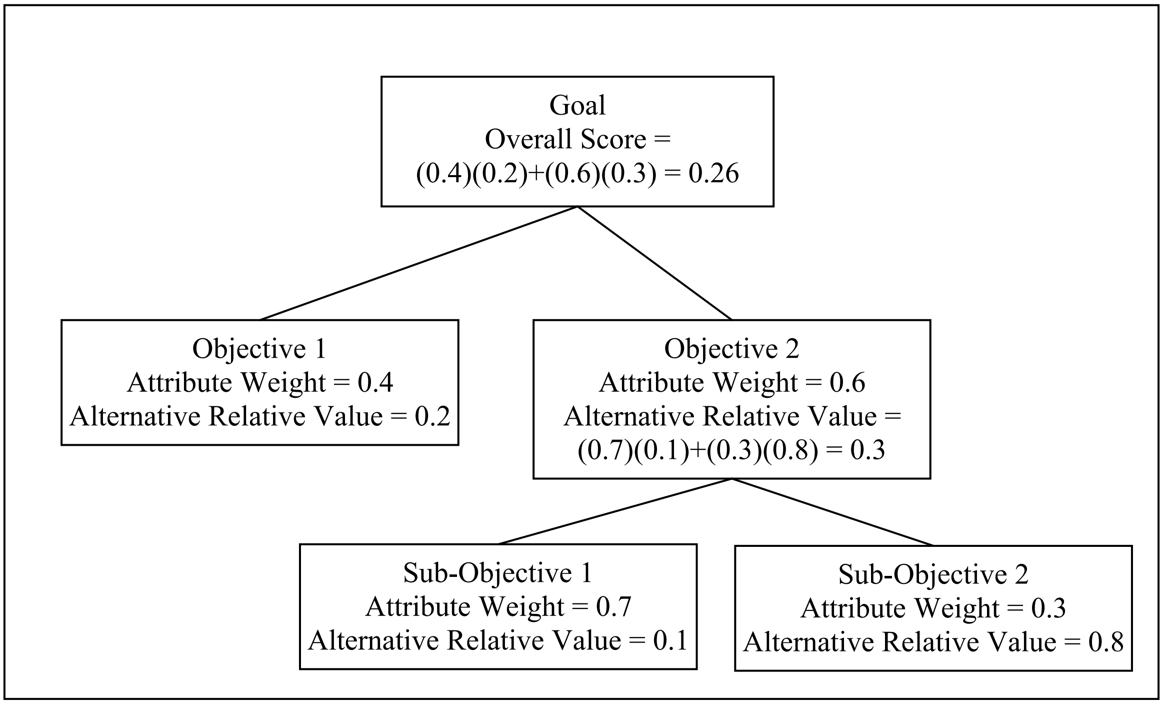

Figure 5.4: Calculating the overall score for an alternative in a small example hierarchy.

5.7 Sensitivity Analysis

After overall score values have been calculated for all alternatives, sensitivity analysis is used to assist the decision maker to understand how their preferences interact with the alternatives to create the final ranking of alternatives. The sensitivity analysis uses three metrics. Two of these metrics are calculated over a user-defined interval described in the next section.

5.7.1 Analysis Interval

One characteristic of large problems is that there will likely exist a large number of low ranking alternatives. For the road maintenance example, there will be a small sub-set of alternatives that are "hot spots" (areas that should be given high maintenance priority), another sub-set of alternatives with moderate importance, and a large sub-set of alternatives where no problems currently exist (low maintenance priority). These sub-sets of alternatives may or may not be identifiable prior to analysis. Within these sub-sets there will likely be regions where the overall score varies little or not at all for some range of rankings. Within these regions extremely small changes in weights with correspondingly small changes in the overall scores of alternatives can cause many alternatives to change rank. Changes in the ranking of alternatives under these conditions will have little significance to the user. Therefore, the user may be interested in selecting the minimum overall project score to include in sensitivity analysis calculations (Figure 5.5).

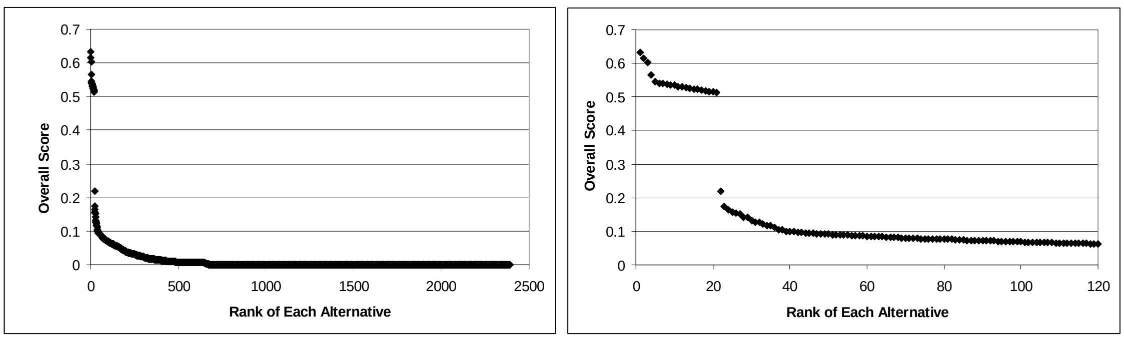

Figure 5.5: Projects ranked by overall score for the road maintenance problem for a) all projects, and b) the top 5% of the alternatives based on overall ranking.

Three metrics are proposed and include a measure of potential, an analysis of the sensitivity of the problem to objective weights, and a spatial, problem-specific analysis designed for the road investment problem. Each of these metrics is designed to assist the decision maker to better understand the implications of their preferences as applied to a set of alternatives using the rational that the better the decision maker understands the problem and how his or her preferences impact the outcome, the more confidence the decision maker will have in the results.

5.7.2 Potential

For our purposes, potential defines the ability of a given set of pairwise comparisons to influence the overall ranking of alternatives. This is a function of both the data and the criteria weights. The form of the metric is:

$$P_k = \sum_{i=1}^{n} \frac{\left|Rank_{ik} - Rank_i\right|}{\log\left(Rank_i\right)} \qquad [5.3]$$

Where P_k is the potential for set k of pairwise comparisons to influence the overall ranking of alternatives, $Rank_{ik}$ is the ranking of alternative i within set k of pairwise comparisons, and $Rank_i$ is the overall rank of alternative i for all n alternatives within the analysis interval. The log term in the denominator gives more weight to differences in rank for those alternatives ranked higher overall. P_k can be calculated for any attribute for which pairwise comparisons are required.

Lower values of P_k signify those criteria within the problem hierarchy which have the greater potential to influence the overall ranking of alternatives. Thus if the ranking resulting from set of pairwise comparisons is equal to the overall ranking for the problem, P_k for that attribute would be equal to zero. The overall ranking of alternatives will, therefore, be more sensitive to those criteria, either in terms of weights or attributes, with lower P_k values and less sensitive to those criteria with higher P_k values.

Little additional work is required to calculate P_k. After overall scores have been calculated and alternatives ranked according to their overall score, rankings are determined for each set of pairwise comparisons based on the values used in the calculation of overall score. These rankings are then compared with the overall ranking for each alternative within the analysis interval.

Based on the distribution of overall scores for the example problem, several analysis intervals were chosen and are described by the minimum overall score included in the given analysis (Table 5.3). P_k was calculated over each of these intervals for all attributes requiring pairwise comparisons. More alternatives will be included in the analysis interval with a minimum score of 0.1 than will be considered in the analysis interval with a minimum score of 0.4.

Table 5.3: Potential (P_k) calculated across four analysis intervals (minimum overall scores to be included in the analysis) for the road maintenance problem where n is the number of alternatives included in each.

Minimum Overall Score Included in Analysis	**0.05**	**0.1**	**0.2**	**0.4**
n	**248**	**84**	**23**	**21**
Minimize Stream Impacts	5	3	1	1
Minimize Culvert Failure	18	16	32	33
Habitat Quality	69	19	7	6
Minimize Road Failure	12	16	36	38
Minimize Landslides	211	282	370	375
Minimize FPA Violations	35	17	5	5
Inadequate Road Drainage	88	114	172	185

The absolute values of P_k are not as important as the relative value of each. Two clear points come out of the P_k analysis. First, within all intervals Minimize Stream Impacts has the lowest potential value indicating that the Minimize Stream Impacts branch of the hierarchy has the greatest potential impact on the overall ranking of alternatives. Second, the Minimize Landslides branch of the hierarchy has the least potential to influence the overall ranking of alternatives. This is due more to the specific road projects included in the analysis than to the user's preferences. The criteria weight for Minimize Landslides is slightly higher than the criteria weight for Minimize Culvert Failure under the Minimize Road Failure objective yet Minimize Culvert Failure has an intermediate potential value.

It is interesting to note the relative changes in the other P_k values. The relative potential influence of Habitat Quality is greater when only the highest ranking alternatives are considered (the analysis interval with a minimum overall score of 0.4) and decreases as more lower-ranking alternatives are brought into the analysis. The opposite effect occurs with Minimize Culvert Failure, Minimize Road Failure, and Inadequate Road Drainage.

5.7.3 Sensitivity of Criteria Weights

With the road maintenance example used previously, the set of pairwise comparisons with the largest amount of subjectivity is the layer of objectives directly below the overall goal of the analysis. This is often the case with AHP applications and has been noted by others (Erkut and Tarimcilar 1991). The following method for sensitivity analysis could be easily adapted for any level of the hierarchy.

While some authors have formulated mathematical models to calculate the sensitivity of AHP solutions to individual criteria weights (see Aguaron and Moreno-Jimenez 2000), the most straight-forward approach to sensitivity analysis is simulation. In other words, vary weights until some threshold activity occurs. Published studies of sensitivity within AHP have concentrated on two activities. The first is that the alternative that is ranked highest with the current weights no longer is the preferred alternative. The second activity that is considered is that a shift in rank occurs among any of the alternatives under consideration. As discussed earlier, large problems will likely contain sub-sets of alternatives with nearly identical overall scores. Within these regions, very small absolute changes in weights can cause many alternatives to change relative rank. Therefore, it is reasonable to set threshold values that trigger a "significant" change in rank. Two such threshold values were considered. These are the number of rank shifts occurring and the size of the change in rank, both expressed in relative terms. For example, a decision maker may not be concerned with a one or two place change in rank when a total of 2,389 alternatives are under consideration, many of which will be chosen for funding. Therefore, the decision maker can specify that only those shifts in rank greater than one percent of the total number of alternatives under consideration, for example, be considered significant. Additionally, the decision maker can specify a threshold value for the number of rank shifts that must occur before they are considered significant. This value is expressed as a percentage of the total number of alternatives within the analysis interval.

Sensitivity analysis involves increasing or decreasing one weight at a time until a "significant" change in ranking occurs. Normalization conventions within AHP are followed such that the criteria weights within the analysis will always sum to one. When one weight is increased, the other weights within the analysis are decreased proportional to their importance. For example, assume three attributes with scores $w_1 = 0.48$, $w_2 = 0.35$, and $w_3 = 0.17$. If we are to increase w_1 by 0.01, the resulting weights would be as follows:

$$w_1 = 0.48 + 0.01 = 0.49$$
$$w_2 = 0.35 - 0.01\left(\frac{w_2}{w_2 + w_3}\right) = 0.35 - 0.01\left(\frac{0.35}{0.35 + 0.17}\right) = 0.343$$
$$w_3 = 0.17 - 0.01\left(\frac{w_3}{w_2 + w_3}\right) = 0.17 - 0.01\left(\frac{0.17}{0.35 + 0.17}\right) = 0.167$$

Using these weights, new overall scores are calculated for each alternative, a new ranking generated, and the new rank for each alternative within the analysis interval is compared with its old ranking. Once the threshold activity has occurred, this signals the limit of that criteria has been reached.

Smaller sensitivity intervals indicate that overall rankings are more sensitive to the weight of that criteria. As with potential, this approach to sensitivity analysis informs the decision maker about the interactions between the user's preferences and the specific alternatives under consideration. Armed with this new information the decision maker can refine pairwise comparisons, concentrating on those comparisons with the greatest influence on the overall ranking of alternatives. This sensitivity analysis has been conducted for a number of different analysis intervals and minimum change criteria (Table 5.4). For each of these analysis, it is required that at least 1% of the total number of alternatives within the analysis interval change rank. For the analysis interval with a minimum overall score of 0.05, at least 3 alternatives (1% of the 248 alternatives within the analysis interval) would need to change rank to be considered "significant". Two levels of the minimum change in rank an individual alternative would need to make in order to be considered a "significant" rank change were also included, 1% and 10%. For the analysis interval with a minimum overall score of 0.05, a shift in rank of 3 and 30 places, respectively, would need to occur in a single alternative in order for that change in rank to be considered significant. For those analysis intervals that include fewer than 100 alternatives, a shift in rank of an alternative one place is considered significant when the minimum change in rank is set at 1%.

Table 5.4: Sensitivity analysis of the three objectives in the second level of the road maintenance hierarchy for different analysis intervals and threshold values for the minimum change in rank required for a single alternative to be considered significant. All analyses require 1% of the alternatives within the analysis interval to change rank where *n* is the number of alternatives included in the analysis interval.

Minimum Score	**0.00**	**0.05**		**0.10**		**0.20**		**0.55**	**0.60**
n	**2,389**	**248**		**84**		**23**		**16**	**3**
Minimum Change in Rank	0%	1%	10%	1%	10%	1%	10%	1%	1%
Minimize Stream Impacts									
Low	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Current	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665
High	0.977	0.977	0.977	0.977	0.977	0.977	0.977	0.977	0.977
Range	0.972	0.972	0.972	0.972	0.972	0.972	0.972	0.972	0.972
Minimize Road Failure									
Low	0.245	0.225	0.205	0.235	0.205	0.215	0.105	0.145	0.135
Current	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245
High	0.245	0.255	0.275	0.245	0.275	0.245	0.595	0.415	0.985
Range	0.000	0.030	0.070	0.010	0.070	0.030	0.490	0.270	0.850
Minimize Forest Practices Act Violations									
Low	0.090	0.000	0.00	0.000	0.000	0.000	0.000	0.000	0.000
Current	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090
High	0.090	0.100	0.130	0.100	0.120	0.100	0.160	0.140	0.890
Range	0.000	0.100	0.130	0.100	0.120	0.100	0.160	0.140	0.890

The analysis that includes all alternatives with an overall score of 0.00 or greater and a minimum change threshold of one alternative one place is analogous to the traditional sensitivity analysis presented in the literature. This analysis does tell us that this example problem is insensitive to the weight for Stream Impacts and sensitive to the weights of both Minimize Road Failure and Minimize Forest Practices Act Violations. However, it does not tell us any more than this.

The final ranking of alternatives is insensitive to Minimize Stream Impacts throughout the potential range of criteria weights. Depending on the specific definition of a significant change in rank used, the problem is sensitive to both Minimize Road Failure and Minimize Forest Practices Act Violations. With higher analysis threshold values the problem becomes less sensitive to both these criteria weights.

This sensitivity analysis could be carried out on additional sets of pairwise comparisons within the problem hierarchy. From the results of the sensitivity to the objective weights, little additional information would be gained from a sensitivity analysis of the Minimize Stream Impacts branch of the hierarchy. Analysis of the other two branches would, however, lead to a deeper understanding of the interactions between the decision maker’s preferences and the alternatives under consideration.

5.7.4 Problem-Specific Spatial Metrics

With problems such as road maintenance, a decision maker will likely be interested in clusters of high-ranking alternatives as opposed to single alternatives. Certainly when spatial information is available, data such as overall score or rank can be shown visually in a Geographic Information System (GIS) where projects with particular rank or overall score values are highlighted. A visual display helps to locate clusters of problem areas, for example a generally good road with localized problems. Additional metrics can be developed to fit the specific problem. For our road maintenance problem, most roads are located within one of eight road networks, each with varying lengths of total roads. Therefore the metric we used to inform the decision maker of clusters of higher-priority maintenance problems was average overall score per length of road:

$$RS_j = 100\left[\frac{\sum_{i=1}^{n} OverallScore_{ij} * SegmentLength_{ij}}{TotalRoadSystemLength_j}\right] \qquad [5.4]$$

The overall score for each alternative was used as opposed to rank because of the issues discussed above concerning regions where many alternatives have similar overall score values across a wide range of final rankings. Therefore, overall score is a better metric when considering the relative difference between alternatives.

This metric RS_j was calculated for each road system j across all n alternatives. Multiplying by 100 is simply for ease of use as all overall scores are values between zero and one. RS_j gives the decision maker insight into the road systems with the grouping of highest-priority maintenance alternatives. Larger RS_j values indicate a greater concentration of higher-priority alternatives. This metric assumes the use of road length to weight scores is appropriate.

The majority of the roads used in this analysis, 108.5 out of a total of 140 miles, are located within the McDonald-Dunn Research Forest. Within the forest, eight relatively distinct road networks exist. Maintenance activities are generally confined to one of these eight road networks at a time. Thus, it would be useful for a decision maker to determine which of these eight road systems should receive attention first. The metric RS_j is used to determine the road systems with the highest average overall score. This metric is calculated for all road segments, not just those within the user-defined analysis interval (Table 5.5).

Table 5.5: RS_j calculated for the eight road systems within the McDonald-Dunn Research Forest.

Road System (j)	RS_j
100-Road	1.865
200-Road	1.904
300-Road	1.159
400-Road	1.656
500-Road	2.081
600-Road	3.745
700-Road	2.765
800-Road	5.067

Because RS_j is a weighted average of the overall score of each road segment (alternative) within a system, weighted by total road system length, it can be used to determine the road system with the highest average score. The 800-Road system clearly has the highest average overall score value (RS_j), followed by the 600-Road, 700-Road, and 500-Road. This would indicate to a road manager that he or she would see the greatest benefit, both environmental and economic, from focusing maintenance activities on the 800-Road system.

5.7.5 Use of Sensitivity Metrics

Each of the three sensitivity metrics presented here provides a different view of the interaction between the decision maker's preferences and the alternatives under consideration and are best used in concert with one another. If a decision maker were to look solely at the P_k values for the example problem used here, it would be difficult to determine if the high potential value for Minimize Stream Impacts is due to the high criteria weight or the specific alternatives under consideration. If the decision maker combines the potential analysis results with the results from the sensitivity analysis, it is clear that the high agreement between the ranking under Minimize Stream Impacts and the overall ranking of alternatives (P_k) is, in this case, more a function of the specific alternatives under consideration than criteria weights. By exploring these interactions using all three metrics developed here, a decision maker is able to better understand the consequences of his or her preferences and how these interactions change depending on the alternatives considered.

5.8 Concluding Comments

In addition to guides to help decision makers revise preferences to improve consistency (a necessary requirement in the AHP), three metrics were developed to aid decision makers in exploring the interaction of their preferences and the alternatives under consideration. These three metrics are potential (P_k), a sensitivity analysis using simulation and user-defined criteria of a significant change in rank, and a problem-specific spatial metric of overall alternative score per road system weighted by road length (RS_j).

Each of these metrics was designed specifically for large problems and incomplete hierarchical formulations, cases that have thus far been ignored in the literature. Large problems often have regions where small changes in overall score values can produce large changes in rank, making traditional sensitivity analysis, concerned with the change in rank of one alternative one place, of little value. The inclusion of bounds on sensitivity analyses, both in terms of the number of alternatives included in the analysis and criteria for significant changes in rank, allow a more meaningful analysis of large problems. Additionally, each of these three metrics is quick to calculate, even with large problems. This allows a decision maker tools to fully explore the problem and revise preferences accordingly.

After a decision maker is satisfied that his or her preferences are being correctly represented, the allocation of resources to projects can be done by one of several methods, including mathematical programming. This is where factors such as budgetary and spatial constraints can be taken into consideration.

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6 Scheduling Road Maintenance Using the Analytic Hierarchy Process and Heuristics

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6.1 Abstract

The management of low-volume roads has transitioned from a paradigm where maintenance is designed to protect a capital investment in road infrastructure to one where other benefits of road maintenance, such as decreased negative environmental effects, are also important along with road roughness and drivability. In this study, two models using mathematical programming are applied to schedule forest road maintenance and upgrade activities involving non-monetary benefits. Model I uses a linear objective function formulation that maximizes benefit subject to budgetary constraints. Model II uses a non-linear objective function equal to the sum of benefits divided by the sum of all costs in a period. Because of the non-linearity of the constraints and the requirements that the decision variables be binary, the solutions to both problem formulations are found using a threshold accepting heuristic. The benefit for completing a given road maintenance or upgrade project is determined using the Analytic Hierarchy Process (AHP), a multi-criterion decision analysis technique. This measure of benefit is combined with the economic cost of completing a given project to schedule maintenance and upgrade activities for 140 miles of road in forested road systems within western Oregon.

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6.2 Introduction

Maintenance systems for low-volume road networks have a long history in practice and in the literature. Most of these systems, such as the World Bank's Highway Design and Maintenance Standards Model (HDM-4), focus on maintaining adequate drivability standards (Riley and Bennett 1995) to benefit local industries and communities (Conrad 1987). In recent years, the forest sector in the western United States and elsewhere has been moving away from a model of maintenance programs designed to protect capital investments in road infrastructure (Long et al. 1987) towards maintenance programs that also consider the environmental impacts caused by poorly maintained roads.

Models such as the HDM-4 use a benefit-cost approach to prioritizing maintenance projects. The cost is a direct economic estimate of what it will take to complete a given project and the benefit is a reduction in the Vehicle Operating Cost (VOC) to all users of the road. VOC is a purely economic measure that takes into consideration repair and maintenance of vehicles, fuel costs, travel time, and the price of vehicular accidents (Riley and Bennett 1995). Each of these components increases as the road roughness increases with road deterioration. Empirically derived models have been completed for most road surfacing types that describe the deterioration of the road surface with factors such as traffic patterns, weather, and maintenance strategies (Paterson 1987). While non-economic reasons for road maintenance are occasionally mentioned in passing (Faiz and Staffini 1979), they are not typically incorporated into decision models.

An alternate approach to setting maintenance priorities is presented here. We use a multi-criterion decision analysis method called the Analytic Hierarchy Process, or AHP, to determine the benefit gained from completing a given maintenance project. This measure of benefit is then used in two separate formulations of a road maintenance scheduling problem. The first formulation maximizes benefit received from completing a set of maintenance and upgrade projects, the second maximizes a benefit-cost ratio. The strength of these approaches is that non-economic and subjective factors can be incorporated in the analysis.

The problem presented here considers 2,389 potential maintenance and upgrade projects over a 10-year planning horizon requiring routine maintenance, additions of crushed aggregate in preparation for timber extraction, and maintenance and upgrade projects, resulting in 47,780 integer decision variables to be considered. Heuristic search techniques based on threshold acceptance have been developed to solve the problem. Threshold acceptance is a neighborhood search technique that accepts all solutions that are either better than the current solution or within an acceptable interval from the current solution. This acceptable interval, or threshold, decreases with time until only solutions that are better than the current solution are accepted. The algorithm will stop when a given number of iterations have been completed with no improvements made in the solution. Threshold acceptance has been shown to be a simple, efficient heuristic that produces solutions as good as more complicated techniques such as simulated annealing for certain types of problems (Dueck and Scheuer 1990). In this paper, we will first present a brief introduction to AHP, followed by an example of applying AHP to the analysis of road maintenance and upgrade scheduling.

6.3 The Analytic Hierarchy Process

The AHP involves four steps: structuring the problem as a hierarchy; making pairwise comparisons among attributes to determine the user's preferences; reducing attributes to relative values; and ranking alternatives. AHP requires that problems be constructed as a hierarchy, a process termed hierarchical decomposition, such that the overall goal is represented at the top of the hierarchy with objectives and sub-objectives of that goal below. Objectives are decomposed until the base of the hierarchy is composed of the attributes that are used to compare alternatives. An attractive benefit of AHP is that attributes can be quantitative or qualitative and can be measured on any scale as long as that scale remains constant for a given attribute.

Pairwise comparisons are made between the attributes within each group at each level of the hierarchy based on the contribution of each attribute to the element directly above them in the hierarchy. The most prevalent scale used to carry out these comparisons is Saaty's Fundamental Scale. The Fundamental Scale is composed of the integers between one and nine where one signifies equal importance between the attributes and nine is used when one attribute is strongly more important than the other. Reciprocals of these scale values are used to express the strength of the weaker of the two attributes. AHP does not require the decision maker to be completely rational or consistent in completing these pairwise comparisons.

The result of each set of pairwise comparisons is a positive reciprocal matrix such that $a_{ij} = a_{ji}$, $i, j \leq n$, where n is equal to the number of elements being compared within one set of pairwise comparisons. Various methods for calculating attribute weights from this matrix have been proposed. Saaty (1977, 2000) advocates using the principal right eigenvector while others (Lootsma 1996) have promoted the use of the normalized geometric mean of the rows of the priority matrix, also called the Logrithmic Least Squares Method (LLSM). Both the eigenvector and LLSM have strong mathematical and theoretical backing (Fichtner 1986) and both are used extensively in practice with little difference in the results (Crawford 1987).

The magnitude of the decision maker's inconsistency in completing pairwise comparisons is measured using a Consistency Ratio (CR). The CR is formed by the ratio of the Consistency Index (CI) of a matrix of pairwise comparisons and the Random Consistency Index (RI) for a matrix of the same size. The CI is found using the largest eigenvalue (λ_{max}) corresponding to the principal right eigenvector and is equal to $(\lambda_{max} - n)/(n-1)$ where n is the number of attributes being compared to create a n by n square matrix. The RI is the average CI of many matrices completed with random entries (see Saaty 2000). In practice, pairwise comparisons are adjusted until the CR of each matrix is less than or equal to 0.1, or ten percent. As CR increases, confidence that the resulting vector of weights accurately represents the decision maker's preferences decreases correspondingly.

Weights are derived through a pairwise comparison technique and are multiplied by the relative value for each attribute of each alternative. Relative values for individual attributes can be derived in many ways including pairwise comparisons between categorical data, linear interpolations based on the maximum or minimum value under consideration, or utility functions as defined by the decision maker. The overall score for each alterative is aggregated using an additive function of the product of each attribute weight and its associated relative attribute value.

AHP allows for the inclusion of less than perfect data both in the attribute values and in pairwise comparisons. For example, data for cutslope height could be included as a continuous, directly measured value, an estimate to the nearest foot, or as a categorical variable that describes a range of values (i.e. 3-7 feet). The more precise and certain both attribute values and pairwise comparisons, the more certainty the user can have in the outcome of an analysis.

6.4 Application

The Oregon State University (OSU) College of Forestry maintains approximately 140 miles (225 km) of primarily gravel surfaced low volume roads located in five separate forested tracts in Western Oregon. Most of these roads are closed to vehicular public access but are maintained for timber extraction and the support of teaching and research activities.

A road inventory was completed for all roads within OSU ownerships in 2002. The inventory data were stored in a Microsoft Access database. Each road was divided into one or more road segments where each segment is the length of road between road drainage structures, intersections with other roads or trails, or other changes in road condition. The 140 miles of road were divided into a total of 2,389 road segments.

The benefits of road maintenance were assessed based on the negative impacts of current road conditions. In this light, AHP was used to structure the problem as a hierarchy with an overall goal of minimizing the total cost, both environmental and economic, of forest road ownership (Figure 6.1). This goal was decomposed into three objectives, minimizing the environmental impacts to streams, minimizing the incidence of road failure that could potentially lead to both environmental and economic costs, and minimizing Forest Practices Act violations. Each of these three objectives was further decomposed into a total of 31 attributes used to compare each of the alternatives.

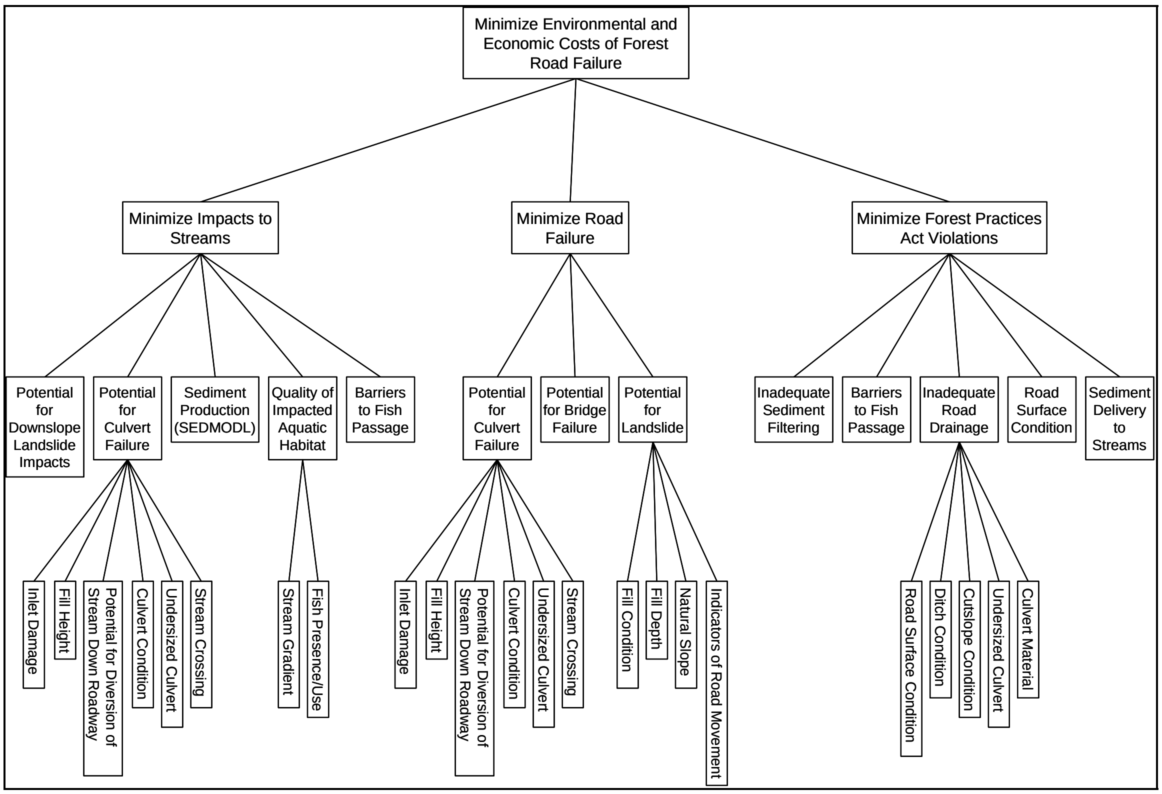

Figure 6.1: Hierarchy used to minimize environmental and economic costs of forest road failure.

Pairwise comparisons were completed at each level of each branch of the AHP hierarchy and the eigenvector method was used to derive weights for each attribute. The attribute weights were then applied to each of the 2,389 road segments to calculate an overall score value. The overall score for each alternative was a value between 0 and 1 where higher overall score values indicate greater benefit than lower overall score values.

Out of the total 2,389 road segments, projects were identified for each road segment (Table 6.1). Of these projects, the majority involved the upgrade of the road drainage system, including the installation or replacement of cross-drain culverts, stream crossing culverts, bridges, and overflow dips. The replacement of a cross drain culvert is triggered when the existing culvert is either damaged, smaller than 18 inches in diameter, or constructed of material other than double-walled plastic. The new installation of a cross drain culvert is also recommended when the existing road design does not adequately filter road runoff prior to a stream crossing, for example when a ditch drains directly to a stream. For stream crossings when fish are not present, culvert replacement is encouraged when the recommended culvert size based on drainage area exceeds the current culvert size. When fish are known to inhabit a stream or when fish use is unknown and either the culvert is blocking fish passage or the culvert is too small based on drainage area, replacing the current culvert with a bridge is the only option considered in this example. Barriers to fish passage were determined based on the depth of the downstream resting pool and the jump from the resting pool to the culvert outlet, both measurements collected during the road inventory. The construction of an overflow (broad-based) dip was included any time the road inventory stated a moderate or high risk of diverting a stream down the length of the road if a culvert were to fail.

Table 6.1: Summary of the types of maintenance and upgrade projects identified.

Type of Project	Number of Road Segments
Install a cross-drain culvert	693
Install a stream crossing culvert	58
Install a bridge	20
Blade and roll	10
Construct an overflow (broad-based) dip	42
Pull unstable fill	8
Total	831

Where road surface conditions were indicated to be a problem, such as the existence of ruts or berms, it was assumed that additional grading and compaction in addition to the regular maintenance would be sufficient. Within road segments where unstable fill was indicated, the maintenance and upgrade project included removing the unstable fill.

6.4.1 Problem Formulation

The current management system of the OSU forests requires that all but abandoned roads (those roads that have been closed between timber harvests) receive regular maintenance once every three years. This regular maintenance includes grading and compaction of the road surface and brush clearing along either side of the roadway. Three-year contracts are let for this routine maintenance. Crushed aggregate is placed on haul routes prior to timber extraction in an amount equivalent to the depth of rock that is expected to deteriorate during hauling. Whenever possible, upgrades to the road system are completed in conjunction with a timber sale. When road maintenance and upgrade projects are completed outside of routine maintenance or a timber sale contract, prevailing wage rates as set by the State of Oregon must be paid to the contractors. This additional expense is equivalent to approximately 25% of the project cost. The current OSU budget is $300,000 per year for road maintenance and upgrades.

The 2002 road inventory data were used to determine the maintenance or upgrade activity required for each road segment. These activities included replacing or installing cross-drain culverts, replacing stream crossing structures, providing extra grading of the road surface to improve drainage, and the removal of unstable fill. Average costs for each of these activities were generated using current contractor costs gathered during telephone interviews with road contractors (Table 6.2).

Table 6.2: Maintenance and upgrade activity costs used in scheduling road maintenance.

Activity	Range of Current Costs	Cost Used in Modeling
Replace one cross-drain culvert (18 inch diameter)	$17-19 per linear foot of culvert, installed	$350 per cross drain culvert
Replace one stream crossing culvert when no fish are present (24 inch diameter)	$23-24 per linear foot of culvert, installed	$460 per stream crossing culvert
Install and furnish a new bridge	$26,000	$26,000 per bridge
Construct a broad-based overflow dip on an existing road	$100	$100 per occurrence
Grade and roll existing roads (routine maintenance)	$430-475 per mile	$8.15 per station
Brushing (routine maintenance)	$300 per side per mile	$11.50 per station
Addition of crushed aggregate surfacing on existing roads	$12 per delivered ton for aggregate and hauling, $0.50-2.00 per ton to place aggregate	$13.50 per ton
Pull unstable road fill	Contracts are conducted by the hour	$7,500 per station

While the scheduling algorithm has the option of choosing any of the 2,389 potential maintenance and upgrade projects, not all potential projects will provide a benefit. For example, some of the road segments in the road inventory database that were used to generate potential projects include the span of road between a road junction and a gate used to control access and may only be 0.01 miles in length. Other road segments may be functioning properly and require nothing more than routine maintenance. In both cases, the benefit for activities outside regular maintenance, as derived using AHP, will be near zero. Only a relatively small number of potential projects have significant benefit values (Figure 6.2).

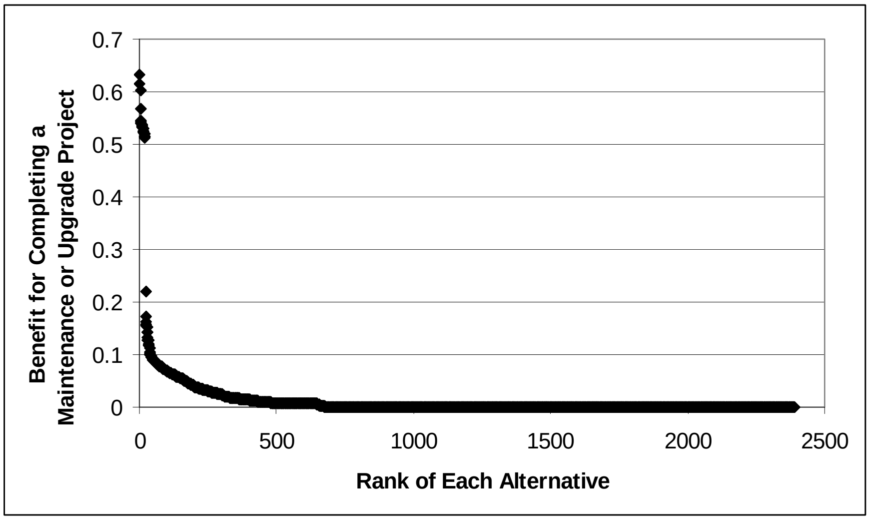

Figure 6.2: Distribution of benefit values (overall score generated using AHP for individual projects) for the 2,389 maintenance and upgrade projects under consideration, sorted by rank.

Routine maintenance requirements, aggregate surfacing requirements, costs for maintenance and upgrade activities, and the benefit for completing maintenance and upgrade activities were combined to create a 10-year plan for the management of all roads within the management area. The current timber harvest plan for the next 10 years, as determined by OSU, was used to determine the location of haul routes and volumes of timber to be extracted over each of these routes.

Two separate objective functions were evaluated. Model I maximizes benefit subject to budgetary constraints:

Maximize $\sum_{j=1}^{10}\sum_{i=1}^{2389} b_i x_{ij}$

Subject to:

$$\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij} < Budget \text{ for every } j$$

$$\sum_{j=1}^{10} x_{ij} \leq 1 \quad \text{for every } i$$

$$\sum_{j=1}^{3} y_{ij} = 1 \quad \text{for every } i, j$$

$$y_{ij} = y_{i(j+3)} \quad \text{for } j = 1..7 \text{ and every } i$$

$$p_i = f_1(x_{ij}, z_{ij})$$

$$m_i = f_2(y_{ij})$$

$$x_{ij}, y_{ij}, z_{ij} \in \{0,1\} \quad \text{for every } i, j$$

Where:

b_i: the benefit derived from AHP for completing project i

x_{ij}: 1 if project i will be completed in period j, 0 otherwise

p_i: cost of completing project i, $p_i = a_i$ if a timber harvest is scheduled in the same road system in the same period, $p_i = c_i$ otherwise, where $c_i > a_i$

m_i: cost of routine maintenance for road segment i, $m_i = d_i$ if more than 75 percent of the active road segments in a road system are maintained in the same period, $m_i = e_i$ otherwise, where $e_i > d_i$

y_{ij}: 1 if road segment i will receive routine maintenance in period j, 0 otherwise

r_i: cost to rock (add crushed aggregate) to road segment i

z_{ij}: 1 if road segment i will receive additional aggregate in period j, 0 otherwise

Budget: dollars allocated in each year (period) for all maintenance and upgrade activities

This maximization of benefit subject to budgetary constraints is a mixed integer programming formulation with a linear objective function. However, in this formulation, the cost of routine maintenance and projects are functions of other decision variables, creating a non-linear problem. Therefore, the heuristic was used.

Model II maximizes:

$$\text{Maximize } \sum_{j=1}^{10}\left[\frac{\sum_{i=1}^{2389} b_i x_{ij}}{\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij}}\right]$$

Subject to:

$$\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij} < Budget \text{ for every } j$$

$$\sum_{j=1}^{10} x_{ij} \leq 1 \text{ for every } i$$

$$\sum_{j=1}^{3} y_{ij} = 1 \text{ for every } i, j$$

$$y_{ij} = y_{i(j+3)} \text{ for } j = 1..7 \text{ and every } i$$

$$p_i = f_1(x_{ij}, z_{ij})$$

$$m_i = f_2(y_{ij})$$

$$x_{ij}, y_{ij}, z_{ij} \in \{0,1\} \text{ for every } i, j$$

This objective function seeks to maximize the sum of benefits divided by costs over each of the 10 years and thus is non-linear. The benefit-cost ratio is calculated for each year as the sum of the benefits received from completing maintenance and upgrade projects during the year divided by the sum of all road-related costs. The objective function was the only difference between the two models, all constraints and costs were the same. For the undiscounted versions of both Model I and Model II, benefits were assumed to occur only in the period of project completion.

Formulations of both Model I and Model II that included a time preference for the achievement of benefits were also considered. For some projects, such as replacing a stream crossing structure that is currently serving as a barrier to fish passage, benefits may be realized into the future. Therefore, for those projects that included the replacement of a physical structure, benefits were assumed to occur annually in the period in which the project is funded and every year after until period ten. This assumption that benefits terminate at year ten does bias the solution by not including the same stream of benefits for a project scheduled later as compared to a project scheduled earlier. These two additions modify the objective functions as follows:

Model I: Maximize $\sum_{j=1}^{10}\sum_{i=1}^{2389}(b_i disc_i)x_{ij}$

Model II: Maximize $\sum_{j=1}^{10}\left[\frac{\sum_{i=1}^{2389}(b_i disc_i)x_{ij}}{\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij}}\right]$

where $disc_i = \left[\frac{(1+i_{Rate})^{10-j} - 1}{i_{Rate}(1+i_{Rate})^{10-j}(1+i_{Rate})^{j}}\right]$ if the project involves a structure replacement, and $1/(1 + i_{Rate})^j$ otherwise. For both models, an interest rate (i_{Rate}) of 10 percent was used. In these formulations costs are not discounted. The discounting of costs in the Model I formulation would not change the solution because the model has no reason to consider a time preference for costs. For Model II, discounting costs at the same rate as benefits are discounted would have no impact on the solution as compared to the undiscounted solution. In this case, costs are pushed further into the future at the same rate as benefits are moved up in time.

6.4.2 Solution Method

The non-linear nature of the constraints and discrete decision variables for both Model I and Model II ensure the solution space will not be convex but instead may contain local optima. Additionally, the objective function of Model II is non-linear. A solution technique that allowed the model to escape from these local optima was needed. Several techniques exist to solve problems of this nature, each of which allows the algorithm to accept inferior solutions in order move away from local optima (Reeves 1993, Glover and Kochenberger 2003). For both model formulations, a threshold accepting heuristic (Dueck and Scheuer 1990) was used to set a yearly schedule for road maintenance and upgrades. Dueck and Scheuer have shown that for some problems threshold accepting performs as well or better than similar heuristics such as simulated annealing that require more control variables. Threshold accepting is a neighborhood search technique, meaning the algorithm will perturb an existing solution slightly, in this case by choosing a new starting period for routine maintenance activities on one active road and by choosing if and when to complete one or more projects, and comparing this new solution to the old solution. If the new solution is better than the old solution, it will automatically be accepted. If the new solution is worse than the old solution, but not that much worse, it will also be accepted. The criteria for "not that much worse" is set by the threshold. The heuristic is willing to accept larger disimprovements early in the search and is less willing to accept disimprovements as the search progresses. The acceptance of large disimprovements at the beginning of the process is introduced to make the starting condition less important. For this algorithm, the threshold value was initially set at 10% of the current objective function value. After 100 solutions have been accepted at each threshold level, the threshold value is multiplied by 0.75 until it becomes less than 10^{-4}, at which time the threshold is set to zero. When the threshold value is zero, only those solutions better than the current solution are accepted. After the model has rejected 1000 solutions in a row, the model run is complete and the best solution recorded. This process is repeated 100 times from random starting points with the best solution retained.

Parameters such as the initial threshold value and the schedule of threshold decreases were set through trial and error. For example, when the initial threshold value was set either higher or lower than 10% the algorithm would produce inferior solutions as compared with those produced with a threshold of 10%. When the threshold was set higher, the algorithm would bounce around with little direction. Lower threshold values were too restrictive and the algorithm terminated before adequately exploring potential solutions. Even though the thresholds were set by trial and error to determine a good threshold schedule, the results for individual runs were variable (Figure 6.5). As part of the strategy to avoid being stalled in a local maximum, 100 runs were examined at different starting points. The randomly generated initial solution was the only difference in the starting conditions of each run.

The initial solution randomly assigned a start period for routine maintenance to each whole road and maintenance was scheduled every three years thereafter (Figure 6.3). Only entire roads were considered for routine maintenance as opposed to individual road segments. No projects are scheduled in the initial solution. Both routine maintenance and the addition of crushed aggregate to road surfaces were requirements that incurred cost yet received no benefit. Therefore, because no projects were scheduled for completion in either model formulation, the algorithm starts with an initial objective function value of zero.

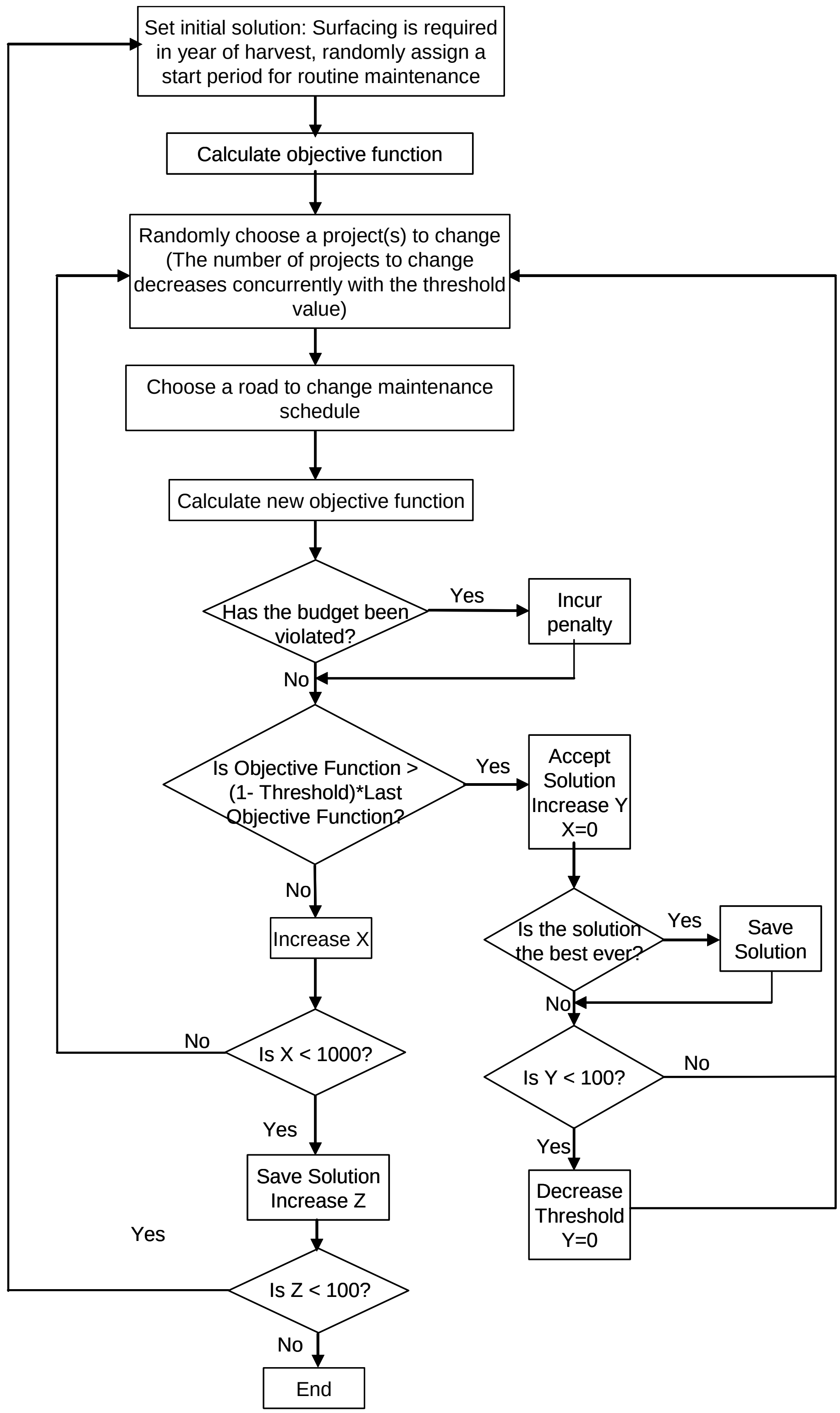

Figure 6.3: Solution algorithm used to schedule road maintenance and upgrade activities.

As the model searched for new solutions, it had the option of deselecting projects for completion. The other option the model had was to vary the start year for the maintenance schedule of each road. The model did not have the option of not surfacing a road in the year of timber extraction or not performing routine maintenance.

The roads under consideration were divided into twelve road systems. The four smaller tracts were each assigned a unique road system and the largest tract was divided into eight separate road systems. Each road system consists of a mainline road with numerous collector roads branching off to access different areas. Within the main tract of forestland, some of these collector roads connect with collector roads from other road systems. In order for a project to be considered as part of a timber sale contract it must be located within the same road system and scheduled during the same period as a proposed harvest. If a project was not included in a timber sale contract, a surcharge equivalent to 25% of the project cost was added to the total cost to complete that project. Additionally, if fewer than 75% of the total road segments within a road system were scheduled for routine road maintenance in a given year, this same surcharge was added to account for increased mobilization costs and decreased productivity of maintenance operations. Figure 6.4 shows the procedure the algorithm used to calculate the objective function value for both Model I and Model II.

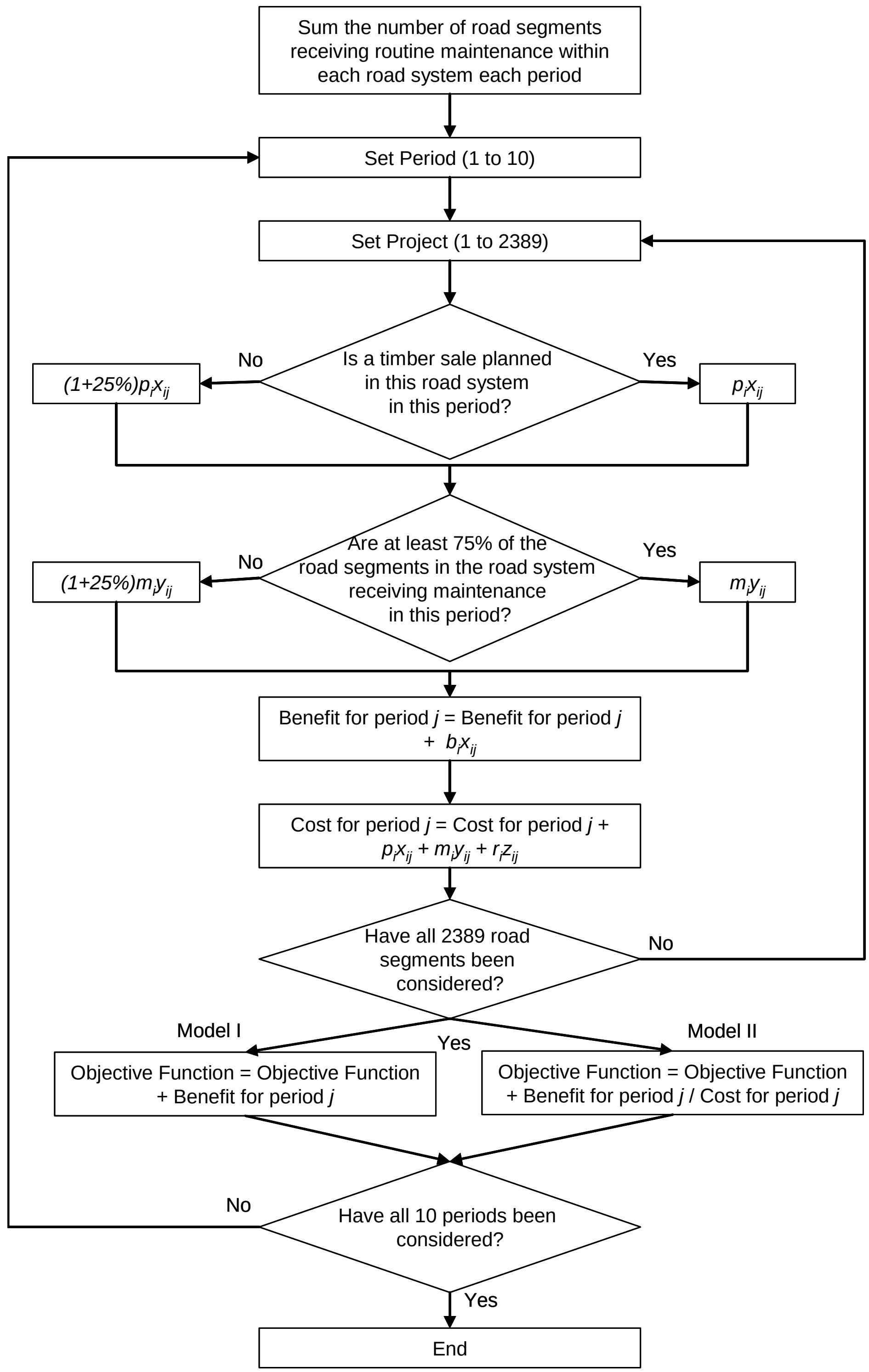

Figure 6.4: Calculation of the objective function value.

The model was coded in Visual Basic within a Microsoft Access database application and run on a 2.4 GHz Pentium 4 computer. Run times varied between Model I, Model II, and budget levels but were less than one hour for a single application of the heuristic which included 100 runs of the threshold accepting algorithm.

6.5 Results

The models were solved using a budget of $250,000 per year. The optimal solution found after each run of Model II showed more variations between runs than the objective function value of the optimal Model I solution after each run (Figure 6.5). Model II also produced a bi-modal distribution of objective function values. Those runs with low objective function values either conducted routine maintenance in all periods or grouped maintenance activities to start in years one and three. The lower objective function values indicate runs when the algorithm was unable to escape from local maximums and illustrate why the algorithm included multiple runs of threshold accepting in order to identify superior solutions.

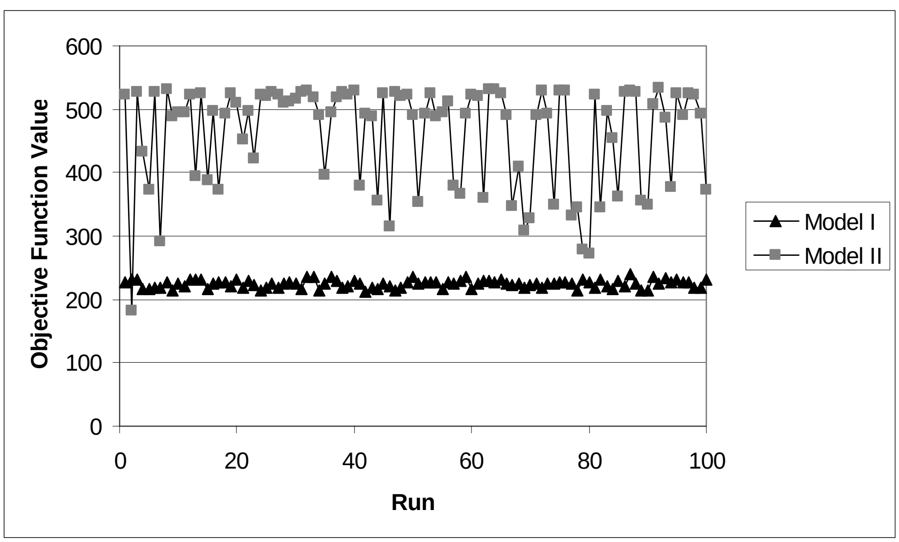

Figure 6.5: Optimal objective function values for 100 runs each of Model I and Model II. The absolute values of the objective functions are not comparable between the two model formulations.

The absolute value of the two objective functions is not comparable. The objective function value for Model I is the sum of the benefit values and nearly all projects were chosen for funding. At this budget level, 100 runs may not have been necessary for the Model I formulation. At lower budget levels when not all projects can be funded, the variation in objective function values between model runs is nearly identical between the two formulations.

The Model I formulation achieved nearly 100% of the total benefit using 94% of the total budget. The Model II formulation produced a solution that achieved 96% of the total benefit while using only 65% of the total budget (Figure 6.6). Across the 10-year planning horizon, the benefit-only formulation (Model I) funded all maintenance and upgrade projects while the benefit-cost formulation funded 724. The difference in projects selected for funding that made the largest difference in total project expenditures between the two solutions is the exclusion of five bridge installations from the Model II solution. Each of these five projects would replace a stream-crossing culvert, at the cost of $26,000 each, that is either currently passing fish but has some minor damage or a culvert spanning a stream with unknown fish use that would act as a fish passage barrier if fish were present. Additionally, the benefit-cost solution excluded a project to pull (repair) potentially unstable road fill that currently shows no signs of failure and would have cost nearly $100,000. These are projects that do provide benefit, but benefits which are not economically justified in the benefit-cost solution.

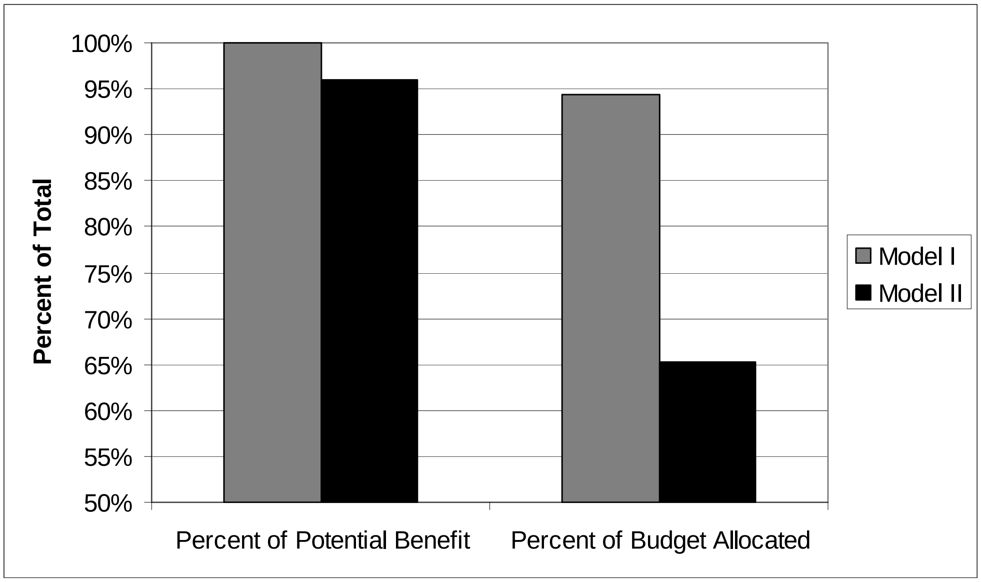

Figure 6.6: Comparison of the potential benefit achieved and budget allocated during the 10-year planning period for Model I and Model II using an annual budget of $250,000.

At the $250,000 budget level, all but two projects were funded with the Model I formulation. Within the Model II solution, there was a distinct difference between the benefit-cost ratio of individual projects chosen for funding and those not chosen for funding (Figure 6.7). The benefit-cost ratio for individual projects was calculated as $100{,}000 b_i x_i / p_i$. Projects with benefit-cost ratios less than 5 were funded opportunistically. For example, many of the projects within this range were ditch relief culverts that provide marginal benefit if replaced. If it was possible to schedule these projects in conjunction with a timber sale, they were scheduled. If it was not possible to schedule one of these projects in a period in which a timber sale was occurring within the same road system, the project would have been subjected to a 25% cost premium and therefore was not often scheduled.

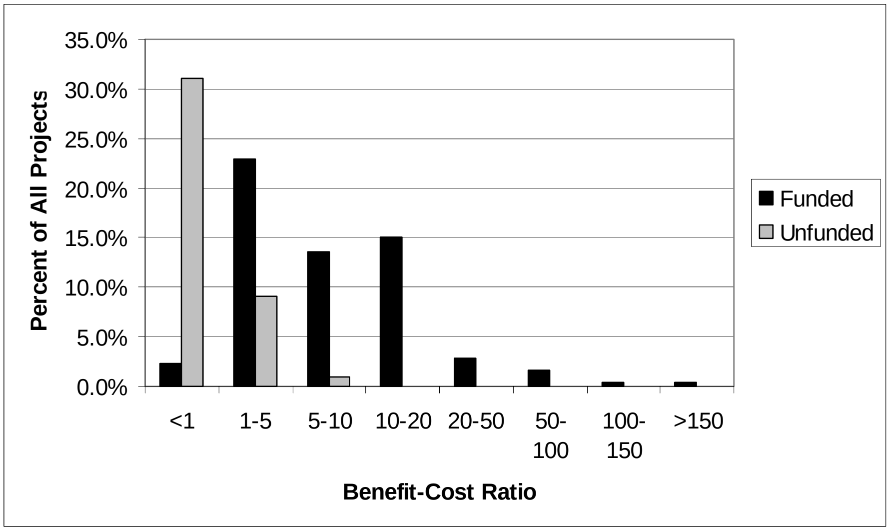

Figure 6.7: Comparison of the benefit-cost ratios of funded and non-funded projects using the undiscounted Model II assuming a $2500,000 budget.

The benefit-cost formulation was able to decrease maintenance costs as well as project expenditures as compared to the benefit-only solution. This is a result of the cost minimization portion of the benefit-cost objective function that is absent in the benefit-only formulation.

The Model I solution allocated 47% of total expenditures to project work with 37% and 16% of total expenditures allocated to routine maintenance and new road surfacing, respectively (Figure 6.8). The Model II solution allocated 37% of total expenditures to project work with 39% and 24% of total expenditures allocated to routine maintenance and new road surfacing, respectively. This solution also moves all routine maintenance activities into the second and third year of the three-year maintenance cycle (Figure 6.9). An artifact of using a 10-year planning horizon and a 3-year maintenance cycle is that maintenance activity in Year 1, 4, 7, and 10 are minimized. If a road is first maintained in Year 1 three more maintenance applications will be required. If, instead, a road is first maintained in Year 2 or 3, only two more maintenance applications will be required within the planning period.

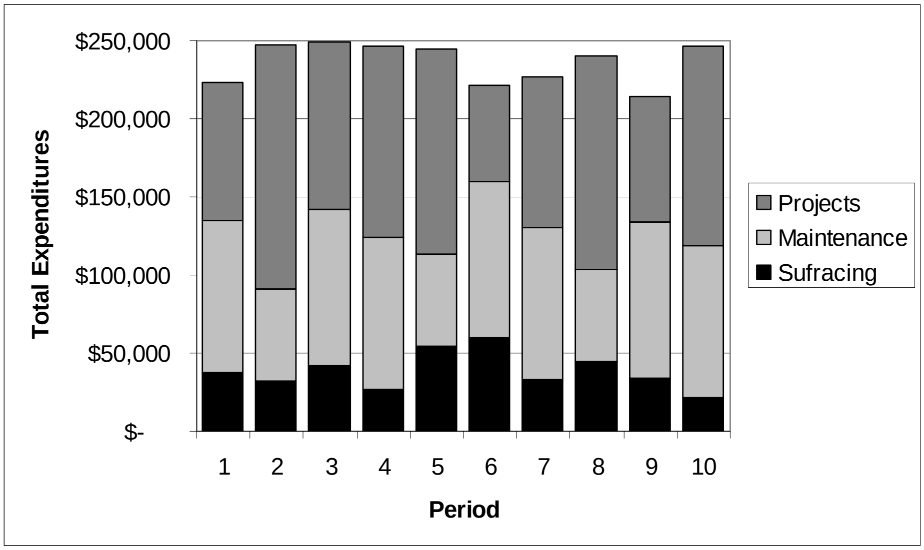

Figure 6.8: Allocation of budget to projects, routine maintenance, and surfacing activities for each of the ten planning periods for Model I ($250,000 annual budget).

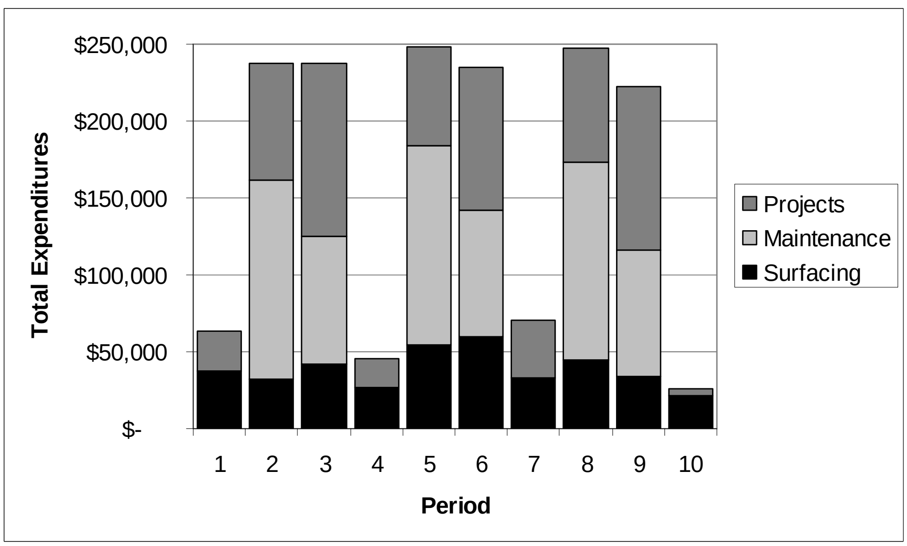

Figure 6.9: Allocation of budget to projects, routine maintenance, and surfacing activities for each of the ten planning periods for Model II ($250,000 annual budget).

Due to the constraints placed on routine maintenance activities (added cost if entire road networks were not maintained at one time), preference in scheduling was given by the algorithm to these activities in order to minimize costs. As a result, maintenance and upgrade projects were scheduled more opportunistically to coincide with timber sales. Since many road systems have timber sales planned for more than one year, this approach provided greater flexibility in scheduling.

Comparing expenditures and benefits for the two model formulations using both discounted and undiscounted benefits, not only do benefits occur earlier (Figure 6.10), but total benefit is greater for both Model I and Model II formulations over the undiscounted models using the same $250,000 annual budget level (Table 6.3). In all cases, the Model I formulation produces a solution with a higher cost and higher total benefits then the Model II formulation with the same budget and discounting strategy. The reduction in cost between the Model I and Model II formulations is three to six times greater than the reduction in benefit for the same budget and time preference combination.

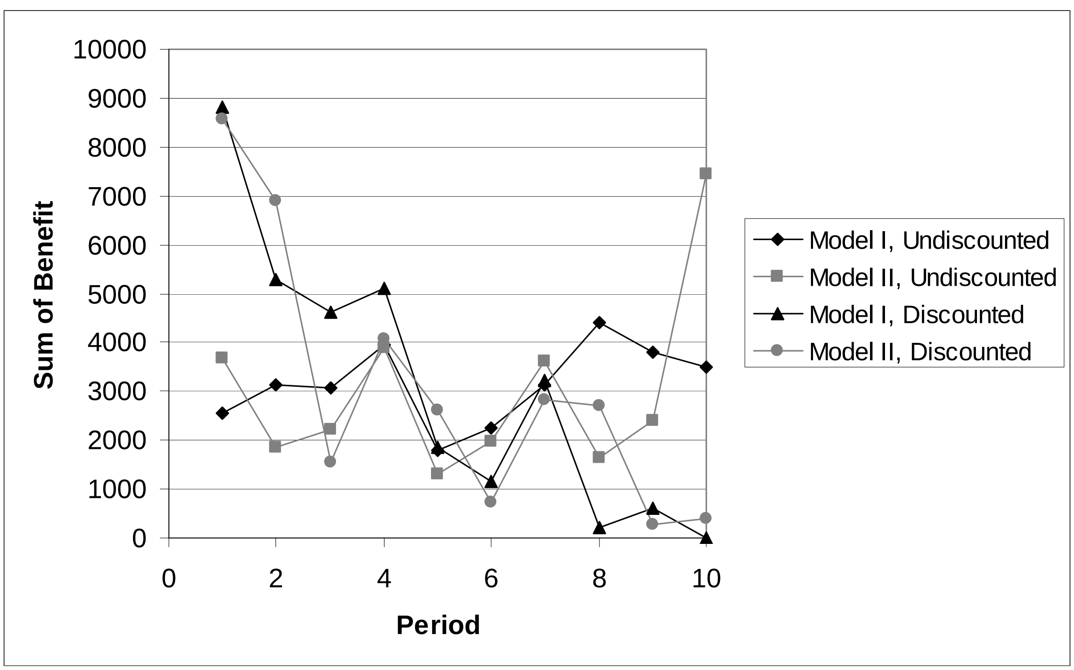

Figure 6.10: Comparison of total benefit realized from completing maintenance and upgrade projects by period with and without a time preference for when benefits occur. For comparison purposes, the sum of benefits in each year for the discounted formulations show benefits only in the year of completion.

Table 6.3: Comparison of total expenditures and total benefit realized across the 10 year planning horizon for two budget levels, with and without a time preference for when benefits occur.

	$250,000 Budget, Undiscounted		$250,000 Budget, Discounted		
	Total Expenditures	Total Benefit	Total Expenditures	Total Benefit	Discounted Benefit
Model I	$2,360,361	31.3	$2,128,260	30.9	499.5
Model II	$1,6330,084	30.0	$1,850,074	30.6	476.7
Percent Difference	31%	5%	13%	1%	5%

It is not reasonable to assume Model I would produce a solution similar to Model II with the same algorithm and budget constraints. Model II was able to reduce costs by eliminating routine maintenance in the maintenance cycle starting in year one. In the other years, however, Model II allocated a large percentage of the available budget to road activities. In order to get a similar solution using Model I, budgets would need to be set separately for each year.

6.6 Conclusion

AHP was used to define the benefit of maintenance and upgrade projects for low-volume forest roads. Two model formulations were compared that used this benefit term. A threshold accepting technique was used to schedule routine maintenance, aggregate surfacing replacement, and maintenance and upgrade projects for 140 miles of road in western Oregon considering formulations with and without time preferences. Both of these formulations are examples of how environmental benefits that are not defined monetarily can be incorporated into road maintenance scheduling. AHP provides a useful framework to provide quantitative measures of environmental benefit that can be used in modeling and scheduling algorithms. This paper has presented several examples of how these types of problems can be formulated and solved.

The reduction in cost between the Model I (maximize benefit subject to budget constraints) and Model II (maximize a benefit-cost ratio) formulations was three to six times greater than the reduction in benefit for the same budget and time preference combination. The choice between these objective functions remains with the decision maker and involves tradeoffs between budget expenditures and minimizing environmental impacts. Other objective functions and constraints can be substituted for the ones illustrated here. The heuristic search technique provides a flexible platform for scheduling activities that can be subject to both linear and non-linear objectives and constraints.

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7 Summary and Future Research

7.1 Summary

A common tool used by forest land managers to track the maintenance needs of large forest road networks is road inventories. These inventories help managers to identify potential problems from the roads they manage. The analyses of road inventories often focus on one issue at a time, such as sediment production, unstable road fills, or fish passage. This has led to the prevalence of informal, ad hoc decision methods that rely on expert judgment to analyze road inventory databases and set road maintenance and upgrade priorities. While these informal approaches are able to capture expert judgment, there is no way of ensuring this judgment is applied consistently.

The Analytic Hierarchy Process, AHP, has been in use for nearly 30 years. In this time it has been widely applied in many areas of business and operations research. AHP has been applied to problems within natural resources, as discussed in Chapter 1, but these applications have covered only a few of the many situations within forest engineering and natural resources where a technique such as AHP is well suited. The traditional AHP application involves creating a ranked list of a small number of alternatives. While this is a useful application, it does limit the user to the solution of problems with few alternatives.

Natural resource decision making often requires the use of professional judgment to make tradeoffs between a large number of alternatives when resources are limited and relationships between cause and effect have not been quantified. The problem of prioritizing and scheduling road maintenance and upgrade projects is one such case. A road inventory contains potentially hundreds of miles of road divided into thousands of road segments that can cause multiple impacts. By focusing on one single issue at a time, many of the potential impacts may be overlooked. Miller (1956) has shown that most individuals are able to consider five to nine items at any one time, far fewer than the total number of road segments contained in a typical road inventory that have the potential to cause negative environmental impacts. AHP combines data with expert judgment and applies this information to alternatives consistently, allowing decision makers to evaluate alternatives based on multiple criteria.

While it has not been demonstrated in the literature, AHP is also well suited to the analysis of large problems, such as the road maintenance problem. The work presented here explored the use of AHP to solve road maintenance problems with a large number of alternatives. It was found that no modifications of the basic AHP methodology are required in order to apply AHP to problems with large numbers of alternatives. The only difference between applications of AHP to large problems and traditional applications is that the option of using Saaty's relative mode (where the attributes of one alternative are compared with the attributes of all other alternatives using pairwise comparisons) is not appropriate.

In the first five chapters I applied AHP methodology to the problem of prioritizing and scheduling forest road maintenance and upgrade activities. This is a specific problem that faces nearly all landowners and managers who must manage and maintain low volume roads. The methodology developed here uses the existing multi-criterion decision analysis technique AHP to solve large, complex problems that require the integration of scientific data and expert judgment.

Chapter 2 provided a description of AHP methodology as applied to large problems. Much of the literature on AHP has appeared in mathematical and operations research journals and is generally written to these audiences. The manuscript in Chapter 2 presents AHP methodology, including the theoretical background and key assumptions, in technical language for non-mathematicians.

AHP is not a difficult technique to implement and can easily be used by field personnel to set project priorities. Knowledge of the technique, however, is essential to the choice of model structures and assumptions. This was illustrated through the application of AHP to the roads in the Oak Creek Watershed (Chapter 4). When the original problem hierarchy was applied to the road inventory several road segments of the mainline road on the valley bottom were ranked high for landslide risk. By most standards, this was clearly erroneous and resulted from segments ranking relatively high not because they were at particular risk of a landslide occurring, but because of their proximity to a fish stream and the high likelihood that if a landslide were to occur that stream would be impacted. These results were an unintended consequence of the choice of hierarchical structure. The lower in the hierarchy a given element is located the lower its potential for influencing the overall goal, and conversely, the higher in the hierarchy an element is placed the greater influence that attribute will have on the analysis. This is an issue that will arise any time a hierarchy with more than two layers (overall goal and attributes) is used. As the depth of the hierarchy increases, so to does the sensitivity of the results to the hierarchical structure increase. Therefore the choice of model structures, in terms of how the hierarchy is constructed, has a controlling influence over the resulting rankings and these influences must be understood by decision makers.

The importance of maintaining adequate consistency in pairwise comparisons was demonstrated when the hierarchy developed in Chapter 3 was pruned. The pruning process involved removing the rows and columns within the matrices of pairwise comparisons that corresponded to attributes with low weights. A new set of attribute weights was then calculated using the remaining pairwise comparisons. If pairwise comparisons are perfectly consistent (CR = 0) then the removal of one attribute will not change the relative weighting of the remaining attributes. Essentially the vector of weights will be rescaled to sum to one. When pairwise comparisons are not consistent, the relative weight of one attribute as compared with another will change. The more inconsistent the original matrix of pairwise comparisons were the larger the change in the relative weighting of attributes. In some cases, an attribute that was weighted higher than another attribute prior to pruning would weigh less than that other attribute after the punning process. Watching attribute weights through the punning process when inconsistency is high, a decision maker could quickly loose faith in AHP and the process of using pairwise comparisons to develop attribute weights. This underscores the importance of maintaining adequate levels of consistency in pairwise comparisons. As consistency increases, so should the decision maker's confidence in the attribute weights.

Two different approaches were used to develop a framework for the analysis of forest road inventory data. The first, presented in Chapters 3 and 4, constructed the problem hierarchy first. After the hierarchy was developed, a road inventory was conducted that collected data on each road segment corresponding to the attributes at the lowest level of the hierarchy. In the second approach (Chapter 6), a road inventory had already been conducted and a problem structure was developed to work with the existing road attributes. Both of these situations arise in practice. A benefit of AHP is that it can both work with existing inventories as well as serve as a tool to develop new road inventories to meet land manager's goals.

The first application (Chapters 3 and 4) presented a formulation and illustration of a problem designed to minimize the negative environmental effects to soil and water caused by forest roads. The problem hierarchy was developed using the literature. The adverse impacts forest roads can have on soil and water were identified along with the attributes that can help explain and predict these impacts. Where possible, the relative importance of attributes relative to one another was also determined using scientific evidence. This analysis of the literature produced a large hierarchy that required the comparison of alternatives based on 87 attributes, meaning 87 pieces of data needed to be collected for each road segment. Attributes of the road system within the Oak Creek Watershed were inventoried during the summer of 2004. The watershed is actively managed by the College of Forestry at Oregon State University and is used for teaching, research, demonstration, and recreation. There are approximately 8.3 miles of road in the Oak Creek Watershed. The road system was divided into road segments so that each road segment consisted of the length of road that drained to a common point.

The hierarchy was "pruned", discarding those attributes that contributed little to the final analysis result. The pruned hierarchy contained 50 attributes. In practice, the hierarchy would likely be pruned back further. For example, professional judgment may be used to estimate directly the risk of a culvert failure at a stream crossing as opposed to predicting the likelihood of a culvert failure within AHP using several road attributes.

The second application (Chapters 5 and 6) applied AHP to an existing forest road inventory. The Oregon State University (OSU) College of Forestry maintains approximately 140 miles (225 km) of primarily gravel surfaced low volume roads located in five separate forested tracts. The road inventory was completed for all roads within OSU ownerships in 2002. The 140 miles of road were divided into a total of 2,389 road segments. Based on this road inventory, the benefits of conducting road maintenance were assessed based on the potential negative impacts resulting from current road conditions. The problem was structured as a hierarchy with an overall goal of minimizing the total cost, both environmental and economic, of forest road ownership. This goal was decomposed into three objectives; minimizing the environmental impacts to streams, minimizing the incidence of road failure that could potentially lead to both environmental and economic costs, and minimizing Forest Practices Act violations. Each of these three objectives was further decomposed into a total of 31 attributes used to compare each of the alternatives.

Each attribute at the base of the hierarchy was available from the existing road inventory, either directly, or in the case of sediment, indirectly. To assess the relative sediment contribution of each road segment, data from the road inventory was input into the model SEDMODL to predict sediment volumes. The output from SEDMODL was then scaled to a value between zero and one for each of the road segments. An alternate approach would have been to include the prediction of sediment production in the AHP hierarchy, as was done with the prediction of culvert failure. This illustrates the flexibility of AHP to handle different types of data and different levels of sophistication all within the same problem solution.

With traditional applications of AHP, the goal of analysis is generally to rank a small number of alternatives. Once this ranking is completed the analysis is generally also completed. This approach, however, leaves useful information on the table in the form of the overall scores. The overall score values give a measure of the relative importance of one alternative as compared to another. Chapter 6 used the overall score values for each alternative to define the benefit for completing a given road maintenance or upgrade activity. In this way, it was possible to compare the worth of one alternative to other potential alternatives and to allocate scarce resources.

Two model formulations were presented that used different objective functions. These formulations were intended as illustrations of how the results of an AHP analysis could be included in scheduling and resource allocation. The first, Model I, maximized benefit (the sum of the overall score values of the maintenance and upgrade projects chosen for funding) subject to budget constraints. The second formulation, Model II, maximized a benefit-cost ratio subject to the same budget constraints. Model II did not use the traditional benefit-cost ratio of the individual projects but instead maximized an aggregate benefit-cost ratio for each period equal to the sum of the benefit for a period divided by the total expenditures for all road-related activities for the period.

The constraints applied to both model formulations were non-linear because the costs for completing both routine maintenance and project work varied depending on other activities. These were the choice of other roads to maintain in the same period in the case of routine maintenance and the harvesting schedule in the case of maintenance and upgrade projects. The non-linearity of the constraints combined with the binary restrictions on the decision variables meant that the solution space for each model formulation would not be convex and therefore mixed-integer programming solvers were not appropriate.

The lack of a convex solution space required a technique to avoid becoming stalled at a local maximum. The heuristic chosen was threshold accepting, a neighborhood search with acceptance criteria for non-improving moves. Threshold accepting begins by accepting a large number of solutions that may not be better than the current solution. As the algorithm progresses, the number of worse solutions accepted decreases until only those solutions that improve the objective function are accepted. To further reduce the importance of the starting solution, the search strategy was modified to repeat the search 100 times from random starting points and to retain the best solution.

The scheduling algorithm considered three activities. The first activity was that aggregate surfacing was required on all haul routes prior to a timber harvest. The amount of surfacing required was proportional to the timber volume expected to be trucked over each haul route. The model had no latitude to choose when or where to add surfacing as this was tied to the harvest schedule, assumed to be a fixed input. The second activity considered was the routine maintenance of all active roads within the ownership. All active roads were required to be maintained once every three years. For this routine maintenance the model was not allowed to choose not to maintain a road but could choose when to start maintenance. The price of road maintenance depended on how much of each road system was to be maintained in a given period. The third activity considered were the maintenance and upgrade projects identified by the road inventory. The model could choose both if and when to complete these projects. These projects were the individual alternatives, or road segments, identified by the road inventory and analyzed using AHP. While all three activities incurred costs, only the projects provided benefits.

The choice of Model II's objective function had two effects on the solution in relation to Model I. The first was that projects with high benefit as compared to their costs were chosen for funding over those projects with low benefit-cost ratios. The second was that the model minimized routine maintenance costs. With the Model I solutions, the model had no reason to be concerned with costs as long as they were less than the budget in each period.

Several new techniques to aid decision makers in better understanding how their preferences interact with the alternatives to create a solution within AHP were introduced. The first of these is a methodology for improving judgment consistency that expands on Saaty's (2000) identification of the most inconsistent judgment (Chapter 5).

When sets of pairwise comparisons are too inconsistent, meaning the CR is too high, Saaty (2000) suggests preferences be modified by comparing the judgments made by the decision maker to the calculated weights and adjust the preference in the direction of the weight. The pairwise comparison with the largest difference between the calculated weight and the stated preference of the decision maker is the most inconsistent judgment and the judgment that, if changed in the correct direction, will produced the greatest improvement in consistency. Saaty states that any change in the preference in the direction of the calculated weight will improve consistency. This is true up to a point, yet Saaty gives no guidance as to how to find this critical interval within which an adjustment of the preference will improve consistency but beyond which consistency will decrease. Because the value of the calculated weights depend on the other preferences as stated by the user, simulation was used to determine the largest change in a preference that can be made before consistency, as measured using the CR begins to decrease. This allows the user to concentrate on those judgments that are the most inconsistent.

Two forms of sensitivity analysis for use with large problems were also developed in Chapter 5. The first of these was Potential (P_k), a measure of the potential for one objective to influence the outcome of the analysis. Potential tells the decision make which of the criteria in the hierarchy is most important in determining the ultimate outcome of the analysis. The Potential value for a given criteria may be caused by a strong preference by the decision maker for that criteria or it may be a function of the specific alternatives under consideration. Combined with the other methods for sensitivity analysis developed in Chapter 5, the user can better understand which of these may be the case and thereby develop a deeper understanding of the problem.

The second builds upon established methods for sensitivity analysis within AHP by adding thresholds that define a significant change in the final ranking of alternatives. Published studies of sensitivity within AHP have concentrated on two activities. The first is that the alternative that is ranked highest with the current weights no longer is the preferred alternative. The second activity considered is that a shift in rank occurs among any of the alternatives under consideration. However, with large problems there will likely be sub-sets of alternatives with nearly identical overall scores. Within these regions, very small changes in weights can cause many alternatives to change rank. Therefore two threshold values that trigger a “significant” change in rank were developed. These were the number of rank shifts occurring and the size of each instance of a change in rank. Simulation is conducted by varying the weights until a significant change in rank occurs. The sensitivity analysis then reports the upper and lower bound of each criteria weight that first causes a significant change in rank. These bounds, and specifically the range between the minimum and maximum weight values, help the user to determine which of the user's preferences have a greater influence on the final ranking of alternatives. Those weights that have small ranges within which weights produce essentially similar rankings are those weights the decision maker should concentrate on and ensure the weights accurately reflect the decision maker's preferences. If a criteria weight has a large range within which the final ranking of alternatives is similar there is little call for the decision maker to spend his or her time improving preferences.

7.2 Recommendations for Future Study

The analysis of forest road maintenance and upgrade needs presented here primarily focuses on minimizing the environmental impacts of forest roads on soil and water. However, road management must also consider how road conditions affect current or proposed road use, costs, and equipment logistics. These are not explicitly considered in the AHP applications developed here. There is no reason, other than added complexity, why these other factors can not also be included in an analysis of road maintenance needs using AHP.

The work presented here assumed that either there was only one decision maker or a group of decision makers was able to unanimously construct a hierarchy and set preferences through pairwise comparisons. This will not be the case for most applications of AHP. A large body of literature exists that deals with group decision making using AHP. In order for many organizations to adopt a methodology such as AHP, these group decision-making techniques will need to be demonstrated with large problems.

A concern many have with the implementation of a preference-based model is model validation. Opportunities may exist to validate at the least portions of analysis such as those presented here in Chapters 3 and 4 with field measurements. For example, how well does the predicted ranking of road-related sediment production using AHP correspond to measured sediment values in the field? Studies and models of road-related sediment production do exist, however, each in interested in a different measure of sediment in both space and time.

The applications demonstrated in Chapter 6 assumed the harvest schedule was fixed as an input value. It would be useful to explore the benefits of simultaneously scheduling timber harvest activities with road maintenance and upgrade needs. Such a schedule could potentially take advantage of efficiencies that are not currently realized when timber harvest and road activities are scheduled separately.

The algorithm used in Chapter 6 to schedule road activities was not an efficient solution technique at lower budget values. This was due to the difficulty of remaining within the budget constraints at the early stages of a model run. This might be remedied by using a penalty function so that solutions that violate the budget constraint could still be accepted. A penalty function could be tied to the threshold value such that the penalty of violating the budget increases as the solution progresses. Even at higher budget levels, the algorithm used tended to stall at local optima about one-third of the time. Changes in the control parameters or other heuristic techniques may be more efficient at moving away from these local maximums.

The flow of benefits through time resulting from the completion of a road maintenance or upgrade project is not well understood and therefore can not be meaningfully included in current scheduling algorithms. This lack of quantifiable relationships points to a need to better understand the behavior of forest roads over time. For example, if a road segment is maintained so as to eliminate ruts that are currently producing large amounts of fine sediment, what will the sediment output from that road segment look like over time? How likely are the ruts to reappear? In general, how does a road deteriorate over time and what are the controlling factors that dictate this deterioration?

Many other problems exist within forest engineering specifically, and the management of natural resources in general, for which AHP would appear to be a useful analysis technique. Examples include forest planning, watershed restoration, restoration after fire, fuel reduction activities, choice of silvicultural prescription, and decisions concerning appropriate road standards. I proposed a methodology for solving both small and large problems, including sensitivity analysis and solution exploration. Each application will reveal specific issues with both the framing of the problem and the setting of priorities. The resolution of these issues will both increase the applicability of AHP to natural resource decision analysis as well as, hopefully, the acceptability of preference models such as AHP to deal with the variety of problems encountered in the management of natural resources.

8 Bibliography

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Appendix

Appendix 1: The Power Method

The Power Method (Muntz 1913) is often used to estimate the largest eigenvalue of a matrix and its corresponding eigenvector. The Power Method can be used to find additional eigenvalues and eigenvectors of a matrix but, for applications of eigenvectors to AHP, only the largest eigenvalue is necessary.

The Power Method requires that a matrix be square and have a simple (not complex) eigenvalue. Perron's theorem assures a simple, positive eigenvector for any square positive matrix, such as the matrices created through the process of pairwise comparisons in AHP. Let us call a matrix of pairwise comparisons A. This matrix A is a square matrix with n columns and n rows, and is reciprocal symmetric such $a_{ij} = 1/a_{ji}$ where a_{ij} is an individual element within A.

When A is raised to a sufficiently high power, ordinal consistency will emerge. Thus, any initial vector V_0 can be chosen and A^kV_0 will converge to $A^kV_0 \approx \lambda V$ where λ is an eigenvalue of A.

Let us assume a column vector V_0 with a dimension of n rows with all elements equal to one. If we multiply A by V_0 we will have the vector V_1. This vector V_1 is the first approximation of the eigenvector of A with the first approximation of the eigenvalue, λ, equal to the largest component of V_1. Each element in V_1 is divided by λ to normalize V_1 such that the largest element is equal to one. This process is repeated, multiplying A by V, taking the largest component of V as the new estimate of λ, and dividing the elements of V by λ, until the difference in λ between iterations is less than some given threshold value, say 0.00001. For use in the AHP the final estimate of the eigenvector is normalized such that the components sum to one.

For example, let us assume the following matrix A is the result of pairwise comparisons between three attributes:

$$A = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1 \end{bmatrix}$$

The initial V is:

$$V_0 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

For the first iteration:

$$AV_0 = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1*1+3*1+7*1 \\ 1/3*1+1*1+5*1 \\ 1/7*1+1/5*1+1*1 \end{bmatrix} = \begin{bmatrix} 11.000 \\ 6.333 \\ 1.343 \end{bmatrix}$$

Giving a first approximation of λ=11.000 and V_1 equal to:

$$V_1 = \begin{bmatrix} 11.000 \\ 6.333 \\ 1.343 \end{bmatrix} = \begin{bmatrix} 11.000/11.000 \\ 6.333/11.000 \\ 1.343/11.000 \end{bmatrix} = \begin{bmatrix} 1.000 \\ 0.576 \\ 0.122 \end{bmatrix}$$

This process is repeated:

$$AV_1 = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1 \end{bmatrix} \begin{bmatrix} 1.000 \\ 0.576 \\ 0.122 \end{bmatrix} = \begin{bmatrix} 3.582 \\ 1.519 \\ 0.380 \end{bmatrix} = \begin{bmatrix} 1.000 \\ 0.424 \\ 0.106 \end{bmatrix}, \lambda = 3.582$$

Assuming the stopping criteria is a change in λ no more than 0.00001 between iterations, the Power Method converges after eight iterations to a value of λ equal to 3.06489 with the corresponding eigenvector:

$$V = \begin{bmatrix} 1.000 \\ 0.430 \\ 0.111 \end{bmatrix}$$

When used in the AHP, this vector of weights is normalized such that the sum of the elements is equal to one. This is accomplished by dividing each element in the vector by the sum of all elements:

$$W = \begin{bmatrix} 0.649 \\ 0.279 \\ 0.072 \end{bmatrix}$$