

# LAND EVALUATION USING AHP

by


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B.Sc., University of Victoria, 1987

A Thesis Submitted in Partial Fulfillment of the  
Requirements for the Degree of

MASTERS OF SCIENCE

in the Department of Geography


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## Abstract

Land evaluation is the process of assigning an index to land areas representing a measure of the suitability of the land to a particular activity and is related to the land characteristics. The key challenge to researchers is the combination of data layers with non-commensurable data forms in a manner understandable to land managers. A survey of essayed techniques reveals a methodological extension to Saaty's (1977) Analytic Hierarchy Process (AHP) as a potential solution. This thesis develops an analytical tool to confirm the utility of AHP for land evaluation.

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## **Acknowledgements**

I wish to acknowledge the conceptual contribution made by Dr. I.F. Creed which resulted in the example 'forest fire' scenario.

Many thanks to all whom supported and encouraged this research. Thank you Peter for your guidance and understanding. Thank you Olaf for your enthusiasm and candor. Thank you Ze'ev for your questions and answers. Thank you Eleanor for always encouraging.

Thank you Deborah for love, laughter and happiness.

# 1 Introduction

Land evaluation seeks to score the ‘suitability’ or ‘susceptibility’ of land with respect to a particular action or a combination of activities (Goodchild 1976). Land evaluation is dependent on the requirements, preferences and predictors of the activity or set of activities being considered (Goodchild 1976, Hopkins 1977). The proposed research focuses on the development and testing of a method to evaluate land as part of the analytical functionality of a geographic information system (GIS).

Land evaluation can range from ‘tourism suitability’ (Keller et al. 1996) through ‘urban development’ (Zhu and Feng 1988) and ‘habitat’ (Peirera and Duckstein 1993, Bettinger et al. 1996) to ‘wildfire threat’ (Hawkes and Beck, 1997). Some land-based activities can be considered and evaluated in monetary terms, for example forestry or agriculture. Evaluation of land for these activities can be handled by traditional economic valuation methodologies driven by monetary supply and demand (Duerr et al. 1979). However, economic analysis is not always the most appropriate method of evaluating land, especially if it is necessary to judge the value of land for its combined value, or for suitability for activities difficult to quantify in monetary terms. For example, land evaluation for tourism suitability or wildlife habitat requires access to methodologies that can accommodate non-monetary measures (Keller et al. 1996).

Characteristics that are used to describe land vary from instrumentation measurements (e.g. elevation and soil content) to descriptive labeling (e.g. vegetation). These data can have different measurement scales and/or data forms (Yin and Pierce 1993, Bettinger et al. 1996). A fundamental challenge of land evaluation is the selection of an appropriate method to combine the various data forms that impact the land evaluation (Hopkins 1977).

The research question considered by this thesis is:

*What is a logical method to combine diverse and often non-monetary variant data for the purpose of land evaluation?*

This thesis seeks to conceptualize, implement and evaluate a generalized method for land evaluation. Based on research for decision analysis, the proposed method follows and develops ideas from the literature (Saaty 1970; Banai-Kashani 1989; Peirera and Duckstein 1993). The challenges of implementing a general method are addressed using current analytical and interface

technologies. The produced application is evaluated using sample data sets and hypothetical scenarios.

## 1.2 Academic Significance

The problem of land evaluation received considerable research attention in the 1960s and 1970s (CLI 1965,1970,1978; Goodchild 1976). The research agenda seems to have been more dormant in the latter part of the 1980s and early 1990s. This comes as a surprise given the advent of GIS in that time, and the potential of GIS to help in the land evaluation process. However, occasional research advancing land evaluation methodologies continues to be published (Keller et al. 1996).

The factors and variables that contribute to land suitability are *activity* specific and varies between localities, as do our perceptions of these factors. The literature contains a number of methodologies for the combination of factors. They can be argued to fall along the spectrum:

### Intuitive ... Data-Driven ... Axiom-Driven

- Intuitive:** The use of 'experts' to examine the land and decide relative areas of homogeneous suitability.
- Data Driven:** These reduction methods are based on characteristic data available for the area of interest and seek to derive a general formula for the 'land suitability' depending on some numerical combination of these data.
- Axiom Driven:** These computerized methodologies search the data for spatial patterns or land evaluations that are consistent with *a priori* knowledge.

A number of studies have looked at the mathematical validity, computational complexity and application viability of various proposed methods of combining land related data of different forms to yield some overall measure of land worth (Hopkins 1977, Burroughs 1986, Bania-Kashani 1989, Xiang 1994, Keller et al. 1996). The literature has revealed a number of considerations that can be used to evaluate a method's utility to assess the value of land. These considerations will be introduced and applied to evaluate land evaluation methodologies.

### **1.3 Practical Significance**

A defensible, understandable and responsive generalized method for land evaluation would provide a significant tool to the land management communities. Decision makers will be interested in any tool which provides a method of analyzing complex land and resource management decisions, especially if the method allows post-analysis and justification of the conclusions reached. An understandable method is preferable since its results can more easily be conveyed to management teams and other stakeholders. A responsive method will provide the basis for a sensitive analytical tool that can be used by a variety of users. A generalized method which makes a minimum number of assumptions regarding the size, complexity and form of the land evaluation process will be applicable to as wide a selection of problems as possible. Since land evaluation can be concerned with suitability, susceptibility, preference or likelihood of a land based action or process, a general land evaluation method will be equally applicable to evaluating such concepts as 'slope stability' or 'tourism potential'.

### **1.4 Summary of Chapters**

There are eight chapters to the thesis including this introduction. The sequence of chapters represents the logical developmental path of the land evaluation application researched.

Chapter Two discusses the concept of land evaluation and the spectrum of methodologies that have been considered in the literature. It explores the utility and viability of each method and details the reasons for selecting a particular technique for the purpose of the research presented in this thesis.

Chapter Three introduces the Analytic Hierarchy Process (AHP) as a general decision making method and discusses its computational form. Criticisms of the method appearing in the literature are discussed.

Chapter Four discusses the application of AHP within the GIS setting and an extension to the method is introduced to apply the technique to land evaluations.

Chapter Five details the application technique with particular attention paid to the practical problems of providing a responsive and understandable interface.

Chapter Six discusses considerations and hierarchy building techniques for one or more stakeholders.

Chapter Seven presents two simulated tests of the developed application: skiing potential and wildfire modeling.

The final chapter summarizes the thesis and outlines its research contributions.

## **Appendices**

Appendix A details the calculations associated with the AHP.

Appendix B details the calculations that the developed method for generalized land evaluation uses.

Appendix C describes the process of coding selection for the general land evaluation application development.

Appendix D provides further detail of the workings of the developed software and data file formats.

## **2 Land Suitability Analysis**

### **2.1 Introduction**

Land suitability is derived from the requirements, preferences and predictors of some activity (Hopkins 1977, Goodchild 1976, Steiner 1983, Gunton 1992, Watkins et al. 1997). The term 'land' refers to a region or set of regions defining the total area under consideration. The term 'suitability' often is associated with 'potential for development' though it applies more generally as areas have varying suitability habitat for wildlife, vegetation and humans.

Land evaluation is another term used to describe the general process of land suitability analysis. Land evaluation is not just the assigning of monetary values to land parcels but the general reference scoring (whether relative or absolute) of areas for different activities. In this thesis the term 'evaluation' is used in the broader sense.

To perform land suitability analysis current thinking appears to be that human expertise as well as a database of land characteristics is needed (Hopkins 1977, Burrough 1986). Human expertise is developed in part through exposure to, and experience with a particular land related activity. Others can compile this expertise through interviews, surveys and behavior observation. Land characteristics can take the form of physical, perceptual and emotional information linked to location. This information can be obtained through any number of techniques, with perceptual and emotional information more difficult to measure. The challenge is to combine the measurable characteristics with the expert knowledge in a meaningful manner (Steiner 1983).

A number of studies have made an overview of the mathematical validity, computational complexity and application viability of various methods of combining land related data of different forms to yield some measure of land worth (Hopkins 1977, Steiner 1983, Burroughs 1986, Bania-Kashani 1989, Xiang 1994, Keller et al. 1996).

Hopkins (1977) recognized the challenge of combining independent and non-commensurable data in a meaningful manner. This is the fundamental challenge to be addressed by this research so only methods that fulfill these criteria will be considered for further development.

The eventual goal of this land evaluation research is a method of obtaining the *relative* suitability of land for any given activity. This is therefore a primary requirement of any method under consideration.

It is understood that land characteristics change with time, whether gradually or catastrophically, and such changes may effect the suitability of land for a particular activity. Though, by definition, land evaluation methods are able to incorporate changing land characteristics, the operational difficulty of implementing these changes may pose a undesirable time constraints on the users of some methods. Some evaluation methods that are mathematically elegant may require enormous computational power (Keller et al. 1996) or massive input from the (Milot 1990). As a consequence, further desirable characteristics of a land evaluation method are moderate computational demands and realistic input expectations from the user.

As it is land managers who will be using the results of any developed method, it is desirable they are able to understand how the results are obtained and be able to interpret them in an effective manner. This not only means that they will need to follow the method themselves but also explain to others the assumptions, calculations and limitations of the method used. A method can be 'complex' due to the underlying mathematics, the required user input form or the difficulty of interpreting the output (Keller et al. 1996)

These method criteria represent a list of desirable characteristics envisioned for a general land evaluation method. The list is presented in no particular order and for the purposes of this chapter, all are considered of equal importance to the method selection. Table 2.1 summarizes these methodological criteria.

A Land Suitability method should:

- 1 handle interdependent data (Hopkins 1977; Wang 1994);
- 2 handle non-commensurable data (Hopkins 1977);
- 3 determine the relative suitability of land(Xiang and Whitley 1994);
- 4 respond quickly to updates in attribute values;
- 5 be calculated within a reasonable time frame (Keller et al. 1996);
- 6 demand only a reasonable amount of operator input (Milot 1990) and
- 7 be understandable to decision makers. (Keller et al. 1996)

**Table 2.1 - Key methodological measures**

Within the literature a number of methodologies have been considered, discussed and used for land evaluation. The methods cover a spectrum of application methods ranging from the intuitive (Gestalt) through combinatory to computational (Neural Networks). All the methods address some of the measures listed in Table 2.1 but none of the methodologies address all. A discussion of each method follows.

## 2.2 Gestalt Method

The Gestalt method of determining and judging 'homogeneous regions' relies on the opinion of an expert land evaluator. This expert views the land in question, either in person or using topological maps and/or ortho-photos and indicates, for example, the regions of high, medium and low suitability for a given activity. These regions are identified as polygons and are assumed to be internally homogeneous by definition, with all contributing factors integrated by the expert. The clarity of the delineation of the homogenous areas is dependent upon the expert. Factors such as terrain, accessibility, scenic quality, water features, aspect and vegetation may all be contributing factors, but are not specifically referenced (Hopkins 1977).

The Gestalt method provides a means of gathering knowledge directly from experts without re-interpretation by intermediary data forms. The analysis is holistic and may or may not incorporate intangibles, for example ambiance and scene quality (Keller et al., 1996).

Experts with the experience necessary for such work are rare and becoming rarer as training emphasis appears to be moving away from such general landscape interpretation. Another concern is the repeatability of evaluations by different experts in the same area, as personal bias is inevitable. Studies that only use a single expert are subjective, and the results could be difficult to reproduce. Also, the suitability of using experts to evaluate areas outside their specific region of expertise is questionable.

With respect to the method measures (Table 2.1):

- this method produces only ordinal suitabilities (fails #3);
- requires the original *Gestalt* expert to evaluate any change to the study region (fails #4);
- and is based on an understanding of land suitability which cannot easily be transferred to another person (#7 is undetermined).

### 2.3 Land Characteristic Analysis

Study of the Gestalt method has resulted in the reductionist view that the intuitive and land feature components the 'experts' used to derive their valuations can be identified. If the process of integration used by the experts were understood then the method could be automated and exported to areas of similar terrain elsewhere (McHarg 1969; Goodchild 1976). This complex task requires the identification, measurement and storage of the contributing factors as well as the development of a reasonable method for measuring and combining the influence of dissimilar and non-commensurable factors.

Identification of factors in land suitability necessitates a clear understanding of the requirements of the activity under consideration (Goodchild 1976). The quality of these factors throughout the area of study can be obtained by consulting specialized experts who have deep understanding of their field, but lack the encompassing experience of the Gestalt expert.

Once gathered, the physical and perceptual characteristics of an area can be combined together to give a representation of the land suitability. The challenge is the development of a method that allows the combination of dissimilar and non-commensurable data forms while remaining computationally and intellectually approachable. The discussion of land evaluation methodologies continues with methods using a reductionist approach.

#### 2.3.1 Ordinal Combination Method

Consider  $n$  data layers  $A_1, A_2, \dots, A_n$ , each reflecting a land characteristic in nominal or ordinal form. That is, each data layer reflects the distribution of a particular factor (soil types, vegetation types, etc.). The suitability of a factor is then matched with its suitability for the activity under consideration. Typically, the values 'High', 'Medium' and 'Low' are used to produce the factor-suitability layers  $B_1, B_2, \dots, B_n$ . Since the combination of descriptive strings is not meaningful, a hash pattern, grayscale or numeric value is assigned to each 'High', 'Medium' and 'Low' in the layers  $B_1, B_2, \dots, B_n$  with denser patterns, darker grays and higher numeric value indicating greater suitability.

Ordinal combination methods combine the individual factor suitability layers to produce a combination data layer,  $C$ , using some form of the basic formula:

$$C = B_1 + B_2 + \dots + B_n \quad (2.1)$$

The key advantages of this method are its simplicity, both conceptual and computational. McHarg (1986) used this method in the Richmond Parkway study with good results. There are, however, fundamental problems with this method. When the data layers are combined it is implicitly assumed the numbers (or hashes or grayscales) are in the same interval system. This clearly is not the case when combining a set of land characteristics. It is also assumed the ratings of each factor are independent, which is not always the case. In addition, the simple process of summing ordinal data violates fundamental statistical assumptions of levels of measurement. Specifically, the intervals between the values are not necessarily equal. As a result of these considerations the ordinal combination method is *not* a good method of generating suitability maps (Hopkins, 1977).

With regard to the method measures (Table 2.1):

- this method does not handle inter-dependent data (fails #1); and
- uses an invalid mathematical operations when considering non-commensurable data (fails #2).

Failing these two measures which are crucial to the production of a meaningful suitability measurement eliminates this method as a viable alternative.

### 2.3.2 Linear Combination Method

Following the process already described for the *ordinal combination method*, the data layers  $B_1, B_2, \dots, B_n$  are produced with ordinal scale *numeric* values. The layers are then combined to produce the composite suitability layer, C, using the formula:

$$C = w_1 B_1 + w_2 B_2 + \dots + w_n B_n \quad (2.2)$$

with the weighting factors  $w_1, w_2, \dots, w_n$  (real number values) specified to reflect the relative importance of the data layers.

This method is conceptually and computationally simple, which allows it to be implemented quickly. Also, the method corrects one of the key problems of the *ordinal combination method*,

the assumption that the interval scales are directly comparable. However, the method does not address the possibility that the data layers may be interdependent. Despite this fundamental weakness the *linear combination method* is a common method used for combining thematic map layers of data (Hopkins 1977), and forms a part of some of the more complex methods yet to be discussed. The key to this method is the determination of the weighting factors since the validity of the analysis is directly related to the rigor of the process used to determine weighting factors.

Rating schemes have been proposed (Lyle and von Wodtke, 1974) which scale the resulting map layer values onto the [0,1] or [1,100] interval for computational reasons. These transformations do not change the relative placement of values along the scale and so do not correct the fundamental weakness of this method: its inability to handle explicitly interdependent data layers.

With regard to the method measures (Table 2.1):

- this method does not handle inter-dependent data (fails #1);
- will require extensive research to determine the weighting factors (#6 is undetermined); and
- those derivations may not be understood by the decision maker (#7 is undetermined).

Finally, even a weighted summation of ordinal data violates the assumption, with ordinal measurement, that the interval between ordered values is not generally uniform.

### 2.3.3 Nonlinear Combination Method

The inter-dependence of data layers could be accommodated if the combination method was not linear. If rigorously formulated relationships among the data layers can be expressed in mathematical terms the nonlinear method is workable. The general formula would follow the form:

$$C = fn(B_1, B_2, \dots, B_n) \quad (2.3)$$

with '*fn*' representing the nonlinear function combining the data layers  $B_1, B_2, \dots, B_n$ .

The key weakness of this method is the difficulty in deriving the nonlinear function. The inter-relationships between the various data layers are probably not known, most likely impossible to model and difficult to justify to decision makers.

With regard to the method measures (Table 2.1):

- this method demands the quantification of relationships between very different factors which may be impossible to accomplish (fails #6); and
- will likely be extremely difficult to explain to decision makers (#7 is undetermined).

## 2.4 Homogenous Regions

The mathematical methods above have all treated the data layers separately, then combined them to form the composite suitability layer, C. The recurring problem of factor inter-dependence can be avoided by segmenting the area into regions of homogeneous properties. By considering like-areas as a single group (even if they are discontinuous) produces a finite set land-factor-combinations that can be examined individually.

The next two methods form homogeneous land areas before combining factors to calculate the composite suitability.

### 2.4.1 Factor Combination Method

With this method a logical intersection is made across all the data layers, creating areas of homogeneous factors  $h_1, h_2, \dots, h_m$  and allowing the explicit consideration of all occurring factor combinations by an expert. In some ways this is a partial return to the *Gestalt* method, except the expert would consider each homogeneous parcel of land separately. Inter-dependence between data layers is integrated by the expert who assigns a suitability index to each homogeneous area  $h_1, h_2, \dots, h_m$  using a gestalt evaluation. The assumption is that an expert exists who could complete the evaluations.

Though attractive in a theoretic sense, the definition and subsequent consideration of the homogeneous areas becomes unmanageable for all but very simple data sets. Consider that for  $n$  data layers with  $D_n$  discrete values, the minimum number of homogenous areas  $M_{\min} = \text{maximum} \{ D_i ; i = 1, 2, \dots, n \}$  while the maximum is no larger than the product of the discrete value counts (ie.  $D_n$ ) as given by:

$$M_{\max} \leq \prod_{i=1}^n D_i \quad (2.4)$$

$M_{\max}$  describes the maximum number of uniquely homogeneous regions in the data set and its value grows geometrically with each additional data layer added to the land evaluation.

As the number of data layers is increased the expert would be expected to weight each of these combinations individually and consistently which, for even a moderately complex scenario, would take a long time and be difficult to complete objectively. Since this method is a reformulation of the *Gestalt* method there remain the issues of expert availability, consistency, repeatability and regional validity. In reality, it is unlikely that an expert exists capable of performing the task.

With regard to the method measures (Table 2.1):

- this method handles inter-related data (passes #1);
- and non-commensurable data (passes #2);
- but fails all the remaining measures (#3-#7) due to the exhaustive nature of the factor combinations created before evaluation.

#### 2.4.2 Cluster Analysis Method

A method proposed to reduce the number of homogeneous areas created by the *factor combination method* utilizes cluster analysis to group areas of similar factor values into a single region of essentially homogeneous nature. Cluster analysis groups the two most similar areas (or groups of areas) based on an index of similarity across the set of factors considered for all areas. The process is repeated until either the desired number of regions (groups of areas) is reached or the regions are judged to have reached an acceptable level of diversity. It is possible to use statistical methods to measure the 'index of similarity' (Hopkins 1977). Once created the regions can be assigned suitability rating by an expert.

The method does, however, pose significant challenges. The specification of 'similarity' is a complex task and requires a deep understanding of the inter-dependence of the factors. Expert input would be needed to complete this analysis and the formulation of a 'similarity index' will have to be carefully constructed to avoid violating ordinal assumptions. Finally, the product will require detailed explanation to convey to the decision makers the methods and assumptions used.

With regard to the method measures (Table 2.1):

- this method shows many good features but does not determine the relative suitability of land areas (fails #3);
- the complex calculation must be recalculated if factor values are updated (fails #4); and
- is conceptually challenging (fails #7).

## 2.5 Hybrid Methods

Hybrid techniques combine features from more fundamental methodologies to address the weaknesses of any one individual method by combining the strengths of contributing techniques.

### 2.5.1 Rules of Combination

A compromise between the *nonlinear* and *factor* combination methods is derived by assigning suitability indices to sets of factor-combinations rather than to a single combination. Avoiding numbers and arithmetic by using verbal logic terms, *rules of combination* does not require the numerous comparisons of the *rules of combination* method nor the exact mathematical relationship between all the factors as the *nonlinear combination* method does (Hopkins 1977). The powerful concept that the knowledge of experts can be formalized in descriptive verbal terms for later re-use on other evaluations is the central theme of *Expert Systems*, whose study has become large and energetic (Expert Systems 1984-present, Quinlan 1996) defining a field of study of its own.

A typical expert system is constructed by a *knowledge engineer* consulting with some domain expert or experts. Through a series of interviews and consultations the engineer iteratively constructs the expert system to solve the narrow range of questions which are of interest (Doyle 1984). The end result is a large system of conditional statements that a computer program will evaluate for each homogeneous area of land. Examples of such conditional statements for land value could be:

```

if (soil = clay) and (slope > 20) --> (building_suitability = poor)
    else (building_suitability = moderate)
endif
if (aspect > 180 and aspect < 290) --> (outlook = westerly)
    else (outlook = other)
endif
...
if (outlook = westerly and building_suitability <> poor) then (land_value = high)

```

Using this method, it is possible to identify special case scenarios and assign a specific value for the output - effectively over-riding the rest of the conditional statements. This makes the system extremely flexible. The individual statements generally are easy to explain to decision makers and the implicit logic of the method is appealing. Using raster map algebra (Tomlin 1990) the implementation of this method is straightforward, once the rules are established.

The development and testing of an expert system is a challenging task and will involve the coordination and cooperation of the decision maker, knowledge engineer, domain expert(s) and a systems programmer. The process of consultation is iterative and will demand a large amount of time from the domain expert(s). The definition of the *rules of combination* can be difficult to quantify and justify. The overall structure of the expert system can become large and unwieldy (Pereira and Duckstein, 1993), making adjustments difficult to accomplish. The structure of the rule tends to be in the form : if A and B and C and D then E which leads to multiple instances of almost identical rules such as: if A and B and not C and D then F. The number of combination of factors grows exponentially and can lead to extremely large rule structures where errors will be difficult to track and coding modifications may have unintended results.

With regard to the method measures (Table 2.1):

- this method addresses most of the issues but may be difficult to adjust to accommodate new factors (#4 is undetermined); and
- the development of the rules and the software to emulate the domain expert's evaluation process will be demanding (fails #6).

### 2.5.2 Hierarchical Rules of Combination

A more structured form of the *rules of combination* has been developed following the premise that the composite rating can be developed hierarchically (Alexander 1964). The method first considers the combination of types *within* each subset of the factor-set that exhibit strong interdependencies. These combinations are rated for suitability *as combinations* within the subset. Higher order combinations of 'combinations of the factors within each factor subset' are then considered and rated according to suitability. This process is continued until all factors are included in the rating.

Hierarchical restructuring of the question removes the redundant rules found in the *rules of combination* method. The comparisons are made between combinations with similar

interdependencies. That is, comparisons are made between similar sets of factors using *common* characteristics. The next level of comparisons is made between ‘combinations of combinations’ with distinct *common* characteristics. In general, comparisons are made between factors (or combinations of factors) of common form.

Though the comparisons are more efficient than those of *rules of combination* method, the number of required comparisons can rise dramatically for more complex problems.

With regard to the method measures (Table 2.1) this method passes most of the measures listed but care will need to be taken to keep the amount of operator input to a reasonable level since the number of pairwise comparisons rises geometrically with each considered homogeneous area (# is undetermined).

## 2.6 MCDM Methods

Multi-criteria decision making (MCDM) can be applied to the problem of assessing land suitability. The decision to be considered is: “what is the most suitable area of land?” and the criteria are the various data layers. Phrased in this general fashion the considerable research on decision making, applicable to all can be focused on land suitability analysis decisions (Pereira and Duchstein, 1993). There are three basic groups of MCDM (Vincke, 1986) based on either:

- graph theory (Outranking method)
- utility theory (Multi-attribute Utility Methods)
- mathematical programming (n-dimensional distance minimization)

The particular form of the MCDM techniques that lends itself to computerization is the outranking method due to its well-defined method.

### 2.6.1 Outranking Method

The *outranking method* involves the pairwise comparison among alternatives. The pairwise comparison component of this technique has been refined by Saaty (1977,1980, 1982, 1987) in his Analytic Hierarchy Process (AHP). Saaty (1980) formally develops a method for decision decomposition and explains how a complex question can be broken down into a hierarchy of simple comparisons: those made between two alternatives with respect to a common criteria.

Banai-Kashani (1989) suggested the AHP could be used for site evaluation, which is a restricted form of general land suitability analysis.

The Analytic Hierarchical Process (AHP) (Saaty 1970-1993) has been considered for land evaluation since it is ideally suited for handling multi-criteria decisions (Banai-Kashani 1989). With the pairwise comparisons that are fundamental to the AHP, the operator can input the inter-relations between factors in a consistent fashion. The hierarchical nature of the process allows the evaluation problem to be structured in an organized and understandable way, eliminating the need for an overall expert in land suitability with the Gestalt method. The ratings for individual land tracts can be quickly calculated and visually presented even when there are inconsistencies in the input preference structure. In addition, methods of accommodating multiple stakeholders with conflicting opinions (Saaty 1990b, Saaty and Alexander 1989), inconsistent operator input (Saaty 1970-1993), missing data (Parkan et al. 1996) and extremely large decision structures (Millet 1990) have been proposed as refinements to the method.

With regard to the method measures (Table 2.1) this method passes all the criteria listed though the number of pairwise comparisons demanded by the method can grow quickly. Millet (1990) developed a method of limiting the number of comparisons needed to complete the AHP in complex scenarios to a manageable level without substantially altering the resultant priorities.

The combination of the mathematical rigor of AHP development and the accepted efficiency of the hierarchical method of analyzing complex problems highlight this method as the choice for further development.

A detailed explanation of the Analytic Hierarchy Process comprises Chapter 3.

### **2.6.2 MCDM compromise method**

Pereira and Duckstein (1993) present a method which combines priority assessment of alternatives with a mathematical programming technique called *compromise programming* (Zelany 1982). Compromise programming involves the minimizing of a Minkowski distance from some optimal point to the individual alternatives to determine which is optimal. The key challenges posed by this method are the formulation of an appropriate distance metric, delineation of justifiable thresholds denoting changes in land suitability and the handling of inter-dependent factors.

With regard to the method measures (Table 2.1):

- the complex calculations demanded by this method need to be recalculated to include updated factor values or new factors (fails #4);
- the method demands a deep understanding of the inter-relationships between the factors which need to be converted into a justifiable distance metric (fails #6); and
- is likely to be far too complex and abstract to be convincingly conveyed to decision makers (#7 is undetermined) especially as it involves non-conventional metrics.

## 2.7 Fuzzy processing

Zahed (1965) proposed the idea of incorporating the uncertainties of data into the analysis. With respect to land evaluation, the homogeneous nature of areas is questioned, as are the boundaries of those areas. Utilizing fuzzy logic provides a method of smoothing the discontinuous transitions between areas with the hope of providing more realistic output. Fuzzy processing may be used to provide a means of assessing the impact of uncertainty with the data source and by the decision maker. Though the technique may be used in land evaluation process (Davidson 1994), it does not address the fundamental problem of combining data of different forms. Decision makers may not find it straight forward to follow all the steps of fuzzy logic data processing.

## 2.8 Computer Inference

These methodologies attempt to allow the computer to search for solution sets while assuming a bare minimum about the structure and form of the land suitability scoring. These solutions may minimize the divergence from some fundamental understanding of the data set or provide a structure for the clustering of the data into more manageable pieces.

### 2.8.1 Bayesian Modeling

The bayesian method assumes the various data layers are not spatially correlated and conditionally independent. In addition, an idea of the probability of an outcome is required to start the process. This *a priori* probability is monitored, as each factor is added into the calculation, to see if the addition of factors supports the *a priori* probability. Iterating through the factors the method calculates the total weight of all the supportive factors to produce maps

showing maximum likelihood. This method has been used to derive potential maps for mineral deposits (Bonham-Carter, 1994).

It has already been noted that the one of the key problems we seek to overcome is inter-dependent factors so *Bayesian Modeling* is limiting in this respect. In addition, the *a priori* probability may not be available or unreliable and pre-supposes a gestalt evaluation.

With respect to the other measures listed in Table 2.1 this method only satisfactorily addresses #2 (handle non-commensurable data), #3 (produces clearly delineated suitability areas) and #3 (determines the relative suitability of land).

### **2.8.2 Neural Networks**

Wang (1994) proposes using the pattern recognition capabilities of neural systems to find areas of similar land suitability. He argues the patterns can be recognized as vectors of land-physiography attributes. A Gestalt expert could then, as with cluster analysis, evaluate these patterns.

Though intriguing as a method, its computational and conceptual complexity will make it difficult to develop as a reliable, understandable method of deriving relative land suitabilities. In addition the criteria used to determine which patterns are dominant and which patterns are complimentary has still to be defined by some other method. These difficulties are similar to the conceptual challenges posed by *cluster techniques*. Decision makers may not find the computer generated patterns easy to accept and will likely follow the theoretic development with difficulty.

## 2.9 Summary

Recalling Table 2.1 for direct comparison a summary of the literature evaluation of the methodologies fills Table 2.2.

- 1 handle interdependent data;
- 2 handle non-commensurable data; (such as temperature and road access)
- 3 determine the relative suitability of land;
- 4 respond quickly to updates in attribute values;
- 5 be calculated within time limits imposed by current technology;
- 6 demand only a reasonable amount of operator input and
- 7 be understandable to decision makers.

Table 2.1 - Key method measures

Method	1	2	3	4	5	6	7	Y-count
Gestalt	Y	Y	n	n	Y	Y	~	4 - 5
Ordinal Combination	n	n	Y	Y	Y	Y	Y	5
Linear Combination	n	Y	Y	Y	Y	~	~	4 - 6
Nonlinear Combination	Y	Y	Y	Y	Y	n	~	5 - 6
Factor Combination	Y	Y	n	n	n	n	n	2
Cluster Combination	Y	Y	n	n	Y	Y	n	4
Rules of Combination	Y	Y	Y	n	Y	n	Y	5
Hierarchical Combination	Y	Y	Y	Y	Y	~	Y	6 - 7
MCDM Outranking	Y	Y	Y	Y	Y	~	Y	6 - 7
MCDM Compromise	Y	Y	Y	n	Y	n	~	4 - 5
Fuzzy Logic	~	Y	~	~	Y	n	~	2 - 6
Bayesian Modeling	n	Y	Y	n	n	n	n	2
Neural Network	Y	Y	n	n	n	~	n	2 - 3

Y: Yes

n : no

~ : undetermined

Table 2.2 - Method comparison (adapted from Keller et al. 1996)

Land suitability analysis involves the quantification of the utility or predisposition of land for a particular activity. Both physical and perceptual attributes of a site can influence its suitability and are gathered through measurement of feature and interviews with experts respectively. The merging of the numerous data forms to generate a single meaningful suitability index poses a serious challenge.

The *Gestalt* method of consulting with an area expert presents an attractive means of quickly obtaining an evaluation. Justifying the validity of the produced suitability indices to decision makers may be difficult and repetition of the study by another expert may yield different results.

Lack of replicability therefore is a dominant critique. This method cannot be used to create a general method for deriving defensible suitability indices for arbitrarily large and complex areas and activities.

The three mathematical models (*ordinal*, *linear* and *nonlinear*) each lack key functionality. The *ordinal* method uses an invalid mathematical addition to combine layers, the *linear* method fails to deal with interdependent factors and the *nonlinear* method assumes the existence of generally unknown complex relationships linking all pertinent data forms. These techniques all violate mathematical assumptions of ordinal level data summation.

The *factor combination* and *cluster analysis* methods rely on expert input to assign suitability ratings to the homogeneous units created. In addition the *factor combination* method requires a possibly overwhelming number of unique factor-combinations which need to be individually considered while the *cluster analysis* demands a large amount of interpretation. Both methods are computationally complex and challenging to explain to decision makers.

The *rules of combination (expert system)* and *hierarchical combination* method have many good features including being piece-wise comprehensible to the decision maker. The construction of these methods is, however, non-trivial and for the expert system involves a small team of developers to complete. The *hierarchical* method is preferred since it reduces the problem to a hierarchy reflecting the different levels of interaction between factors.

*Fuzzy processing*, though interesting, does not address the key problems of suitability analysis (combination of inter-dependent and non-commensurable data) but may be useful in the fine tuning of a method which does.

*Bayesian modeling* has key deficiencies with its requirements for an initial probability of likelihood of an outcome and conditional independence that can be difficult to obtain within realistic data sets.

*Neural network* pattern recognition methodologies could, theoretically, find patterns within the data set but the questions of ‘what patterns are the most important?’ and ‘when can two patterns be considered complimentary and not contrary?’ remained unanswered by this method.

Established *Multi-criteria decision making* (MCDM) methods show the most promise for the development of a general method to derive defensible suitability indices. The firm theoretical basis for these methods lend credence to the analysis while the decomposition of the land evaluation question yields a formulation understandable to decision makers. The Analytic Hierarchy Process (AHP) uses efficient and understandable hierarchies to represent decision structures and has been used by researchers (Banai-Kashani 1989, Xiang, 1994) to illustrate the utility of MCDMs.

Based on the discussion presented in this chapter a method using MCDM techniques may produce the most effective results. Saaty's AHP (1970-1993) provides a strong theoretic foundation on which to build a land evaluation method.

Chapter 3 details the Analytic Hierarchy Process (AHP) and discusses the key features and weaknesses of this general decision making method. The theoretic extension of the AHP for the purpose of land suitability analysis is detailed in Chapter 4.

## **3 Analytic Hierarchy Process**

### **3.1 Introduction**

The Analytic Hierarchy Process (AHP) is a theory of measurement (Saaty 1970, 1986, 1987, 1988; Harker 1986; Harker and Vargas 1987). Within the field of decision making, AHP aids in the description of the general decision operation through the decomposition of a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria and alternatives. AHP represents judgments through pairwise comparison of hierarchy elements relative to the next dependent hierarchy level. Using a “fundamental scale of relative magnitudes expressed in dominance units” (Saaty 1990a, p.47) the comparisons are collected from the user and organized in matrix form. Calculating the eigenvector of the comparison matrices yields a ratio scale of relative magnitudes for the hierarchy elements. The ranking of alternatives is obtained through the amalgamation of these scales for the entire hierarchy.

This chapter expands this terse description of AHP into general mathematical terms and presents some of the key criticisms of the method. For a complete worked example of the AHP method see Appendix A.

### **3.2 A theory of measurement**

The AHP is a general theory of measurement and is used to derive ratio scales for paired comparisons. Developed to accommodate both physical (tangible quantities distinct from the measuring observer) and psychological events (ideas and beliefs of the individual) AHP can be used to establish measures in both the physical and social domains (Saaty 1977-1990, Harker and Vargas 1987, Zehadi 1986,1987).

### 3.3 Hierarchical Structure

The analysis of a system may lead to the situation where the number of criteria and their mutual relationships exceeds the ability of the researcher to understand all the pieces of information simultaneously. Mazzota and Opaluch (1995) showed the performance of decision makers is reduced when tackling difficult problems. It is common, in these cases, to break the system into smaller sub-systems, each more manageable than the larger system. Hierarchies are a common method of organizing reality into manageable groups with dependencies implicit in the structure.

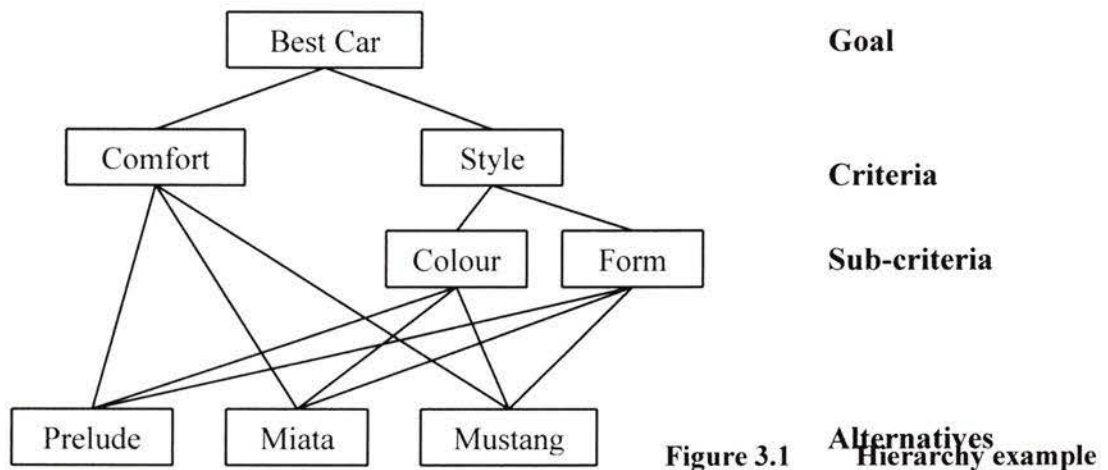
“The immense scope of hierarchical classification is clear. It is the most powerful method of classification used by the human brain-mind in ordering experience, observations, entities and information. Though not yet definitely established as such by neurophysiology and psychology, hierarchical classification probably represents the prime mode of coordination or organization (i) of cortical processes, (ii) of their mental correlates, and (iii) of the expression of these in symbolism and languages. The use of hierarchical ordering must be as old as human thought, conscious and unconscious...” (Whyte 1969 p. 116)

There are a number of advantages for using a hierarchy to represent systems:

- hierarchical representations describe how changes in the importance of upper level criteria affect the priority of elements at lower levels (element influence);
- hierarchical representations provide a large amount of structural detail of the system (element details);
- top-down development methods produce hierarchies quickly (efficiency of representation);
- small changes have small effect (model stability);
- additions to the hierarchy are quickly incorporated (model flexibility).

For AHP a hierarchy is constructed to represent a decision making situation. The topmost level is termed the *focus* or *goal*. All other, supporting, levels of the hierarchy are made of criteria and sub-criteria (which are independent parts of a criteria). The choice options appear at the lowest level of the hierarchy.

Consider the decision (Figure 3.1) “What car to buy?”;



This representation of the decision illustrates:

- the goal of the decision is to choose the best car;
- the first level of criteria are ‘car comfort’ and ‘car style’;
- ‘Colour’ and ‘Form’ are sub-criteria of ‘Style’. We say that ‘style’ is dependent on ‘colour’ and ‘form’;
- the cars between which we will decide are ‘Prelude’, ‘Miata’ and ‘Mustang’; and
- all criteria lacking sub-criteria are directly dependent on the alternatives.

### 3.4 Judgment Scale

The AHP uses a nine (9) value scale to convert from the descriptive comparative judgments of the decision maker into the ratio values used in the computation phase of the method. Saaty (1980) lists a number of reasons for choosing the 9 point scale, including:

- The 5-level scale (Saaty 1980) of equal, weak, strong, very strong and absolute is natural for making qualitative distinctions. The compromise between adjacent values for greater precision yields nine distinct qualitative comparison values.
- Miller (1956) found a psychological limit of  $7 \pm 2$  for simultaneous comparisons. Taking the upper limit as a distinguishable scale of maximum precision yields the 9 point scale.

The ratio values representing the descriptive valuations are presented in Table 3.1.

Ratio Values	Definition	Explanation
1	Equal importance of both elements	Both elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgment slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgment strongly favor one element over another
7	Demonstrated importance of one element	A element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments
Reciprocals	if A compared with B equals X then B compared with A equals 1/X	

Table 3.1 - Ratio value comparative definitions (Adapted from Saaty 1980, p.54)

### 3.5 Pairwise Comparisons

A fundamental part of the AHP is the *pairwise comparisons* of one level of the hierarchy with respect to the next higher hierarchy level. In this manner the comparisons are as simple as possible: a pair of criteria are compared with respect to a third. Using this form of deconstruction, complex decision systems are reduced to a hierarchy of pairwise comparisons that can be individually considered. The cumulative priorities of the decision alternatives are calculated from these comparisons.

Given  $n$  elements of the  $\mu$ th level of the hierarchy and one element of the next higher level ( $\mu - 1$ ), a decision maker compares elements of the  $\mu$ th level *pairwise* with respect to the element of level  $\mu - 1$ . The scores (positive ratios) for the pairwise comparisons of each group of  $n$  elements form the  $n \times n$  matrix  $\mathbf{A}$  which is positive (all elements are greater than zero) and reciprocal ( $\forall a_{ij} \ni A : a_{ij} = 1/a_{ji}, i, j = 1, 2, \dots, n$ ) with the diagonal elements of the matrix  $\mathbf{A}$  equaling 1. The total number of values necessary to complete the matrix  $\mathbf{A}$  of size  $N$  is  $N(N-1)/2$ .

Considering Example 3.1 there are a total of 11 pairwise comparisons:

1. With respect to 'Best Car' how much more important is 'Comfort' than 'Style'?
2. With respect to 'Style' how much more important is 'Colour' than 'Form'?

3. With respect to 'Comfort' how much more preferred is a 'Prelude' than a 'Miata'?
4. With respect to 'Comfort' how much more preferred is a 'Prelude' than a 'Mustang'?
5. With respect to 'Comfort' how much more preferred is a 'Miata' than a 'Mustang'?
6. With respect to 'Colour' how much more preferred is a 'Prelude' than a 'Miata'?
7. With respect to 'Colour' how much more preferred is a 'Prelude' than a 'Mustang'?
8. With respect to 'Colour' how much more preferred is a 'Miata' than a 'Mustang'?
9. With respect to 'Form' how much more preferred is a 'Prelude' than a 'Miata'?
10. With respect to 'Form' how much more preferred is a 'Prelude' than a 'Mustang'?
11. With respect to 'Form' how much more preferred is a 'Miata' than a 'Mustang'?

These examples illustrate how the comparison adjective 'important' [ importance scale ] may be replaced with more appropriate comparison adjective such as 'preferred' [ preference scale ], 'likely' [ likelihood scale ] or 'strong(er)' [ strength scale ] to facilitate the creation of clear comparison questions.

If  $E_i$  and  $E_j$  are elements to be compared with respect to an element  $E_c$  of the next higher level then:  $[E_i \text{ compared to } E_j] = a_{ij} = 1/a_{ji} = 1/[E_j \text{ compared to } E_i]$ . We note that the numbers in  $\mathbf{A}$  represent the pairwise ratios of the elements being compared, not the actual priority of the elements. If  $w_m$  is the actual priority of element  $m$  then the general form of the decision maker's preference structure is represented by the matrix  $\mathbf{A}$ :

$$\mathbf{A} = (a_{ij}) = \left( \frac{w_i}{w_j} \right) \text{ with } i, j = 1, 2, 3, \dots, n. \quad (3.1)$$

For Example 3.1 the 5 matrices produced will have the form:

'Best Car' matrix

	Comfort	Style
Comfort	1	
Style		1

'Style' matrix

	Colour	Form
Colour	1	
Form		1

'Comfort' matrix

	Prelude	Miata	Mustang
Prelude	1		
Miata		1	
Mustang			1

'Colour' matrix

	Prelude	Miata	Mustang
Prelude	1		
Miata		1	
Mustang			1

'Form' matrix

	Prelude	Miata	Mustang
Prelude	1		
Miata		1	
Mustang			1

### 3.6 Priority Calculation

The matrix preference structure  $\mathbf{A}$  provides the information for deriving the decision maker's priorities. There are a number of different methods which have been considered for the extraction of priorities from  $\mathbf{A}$ : arithmetic mean (Saaty, 1980), geometric mean (Saaty, 1980), log least squares (Crawford and Williams, 1985; Saaty, 1980), least squares (Jensen, 1984), left eigenvector (Saaty, 1980) and right eigenvector (Saaty, 1980). The method using the right eigenvector was developed for AHP by Saaty since it handles effectively preference structures which are inconsistent (Harker and Vargas, 1987; Saaty and Vargas, 1984).

The eigenvalue problem can be stated as:

For the  $(n \times n)$  matrix  $A$ , find all scalars  $\lambda$ , such that the equation

$$A\mathbf{x} = \lambda\mathbf{x} \quad (3.2)$$

has a non-zero solution,  $\mathbf{x}$ . Such a scalar is called an **eigenvalue** of  $A$ , and any non-zero  $(n \times 1)$  vector  $\mathbf{x}$  satisfying Eq. (3.2) is called an **eigenvector** corresponding to  $\lambda$ .

Saaty (1977,1980) noted the normalized principle right eigenvector,  $\mathbf{W}$ , is the vector of the priorities for the elements compared in a preference structure and corresponds to the largest eigenvalue of  $\mathbf{A}$ ,  $\lambda_{\max}$ .

### 3.7 Consistency of Preference Structures

The  $(n \times n)$  matrix preference structure  $\mathbf{A}$  is said to be *consistent* if and only if

$$a_{ik} = a_{ij} * a_{jk} \quad \forall i,j,k = 1,2,\dots,n \quad (3.3)$$

It can be shown that if the preference structure is consistent the scale of the preference structure  $(n)$  is equal to the principle eigenvalue,  $\lambda_{\max}$  (Xiang and Whitley, 1994). However, the preference structure is rarely consistent (Saaty 1980, 1982; Yager 1979) since the decision maker is usually unable to describe  $\mathbf{W}$  precisely and may not complete the pairwise comparisons with perfect accuracy. The preference structure would not, in that case, be consistent and leads to an *estimate* for the priority vector  $\mathbf{W}$  (Xiang and Whitley 1994). Saaty and Vargas (1984) have proved that the only way to obtain a measure of both the cardinal and ordinal inconsistencies in the preference structure is by using the eigenvalue method developed by Saaty (1980) for AHP. This is a key advantage over the other methods of deriving the decision maker's priorities listed in the previous section which demand a consistent preference structure (Saaty 1987, Xiang and Whitley 1994).

Once the pairwise comparisons are gathered and the priority vector is calculated the consistency is found as follows (Saaty 1980, 1982):

Equation 3.1 is *estimated* as  $\mathbf{A}' = (a'_{ij})' = \left( \frac{w_i}{w_j} \right)'$  with  $i,j = 1,2,3, \dots, n$ . (3.4)

Using Eq. 3.4 with Eq. 3.2 gives:  $\mathbf{A}'\mathbf{W}' = \lambda_{\max}\mathbf{W}'$ . (3.5)

If the estimate of  $\mathbf{A}$ ,  $\mathbf{A}'$ , is not too far from consistency then the estimate for the priority vector,  $\mathbf{W}'$ , will be reasonably close to the true consistent preferences (Yager, 1979).

The need to quantify the amount that  $\mathbf{A}$  differs from  $\mathbf{A}'$  was addressed by Saaty (1980, 1982) with the development of the *consistency index*,  $CI$ :

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3.6)$$

where  $n$  is the size of the preference structure matrix, and  $\lambda_{\max}$  is the principle eigenvalue. We have  $\lambda_{\max} = n$  for consistent matrices and  $\lambda_{\max} > n$  for inconsistent matrices so  $CI = 0$  for consistent matrices and  $CI > 0$  for inconsistent matrices. Since the magnitude of  $\lambda_{\max}$  is related to the size of the matrix a relative measure of the inconsistency is provided by Saaty (1980) as:

$$CR = \frac{CI}{RI} \quad (3.7)$$

with:  $CR$  = consistency ratio of  $\mathbf{A}'$

$CI$  = consistency index of  $\mathbf{A}'$

$RI$  = consistency index of a randomly filled reciprocal matrix the same size as  $\mathbf{A}'$ .

matrix size (n)	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3.2 : RI values for  $n = 1, 2, \dots, 10$

$CR$  is a measure of *inconsistency*, so low values indicate a *consistent* matrix  $\mathbf{A}$ . It is recommended by Saaty (1980, p.21) to keep the  $CR$  value to less than 10% or 0.1. If this threshold is surpassed then it is suggested that preference structure  $\mathbf{A}$  be reviewed. Though the minimization of  $CR$  is encouraged, the blind pursuit of consistency may lead to unreasonable priorities (Saaty 1980, p.66). This concept of *reasonableness* refers to the retention of the decision maker's strongly held feelings by the priorities obtained from the preference structure (Saaty 1980, pp.28-34). A balance of *consistency* and *reasonableness* is necessary when validating priorities (Xiang and Whitley, 1994).

### 3.8 Cumulative Priorities

Considering the hierarchy as a whole, we can generate a list of all the contributing elements by starting with the goal-element and listing recursively an element followed by its independent sub-elements. Hierarchy elements with no sub-elements use the decision alternatives as sub-elements while the decision alternatives have no sub-elements. An element is said to be *dependent* upon its sub-elements.

Let:

$E_0, E_1, \dots, E_m$      $m < \infty$     be the list of elements including include repetitions (starting with: *goal-element* =  $E_0$ ),

$D_1, D_2, \dots, D_m$      $m < \infty$     be the associated list of *directly* dependent elements,

$P_0, P_1, \dots, P_m$      $m < \infty$     be the priorities derived for each element relative to its dependent element, with  $P_0 = 1$

and

$L_0, L_1, \dots, L_u$      $u \leq m$ ,    be the list of unique (non-repeating) elements.

The accumulated priority of any element,  $AP(L_j)$ , within the decision hierarchy is given by:

$$AP(L_j) = \sum_{i=1}^m V(E_i)$$

$$\text{where: } V(E_i) = \begin{cases} P_i * V(D_i) & \text{if } L_j = E_i \\ 1 & \text{if } i = 0 \\ 0 & \text{if } L_j \neq E_i \text{ and } i \neq 0 \end{cases} \quad (3.8)$$

with:  $AP(L_0) = 1$  and  $P_0 = 1$ .

Eq. (3.8) provides the method for calculating the total priority for each decision alternative.

### 3.9 AHP Critiques

As a recent addition to the field of decision analysis AHP has endured close scrutiny by practitioners and theoreticians alike. The former group found AHP to be understandable, versatile and flexible. The commercially available software First Choice<sup>®</sup> provides a Windows<sup>®</sup> based interface for hierarchy development and output visualization after automated calculation. Amongst the theoreticians an intense debate has generated many thoughtful papers on the various aspects of AHP. The critics have centered their concerns around the following areas of AHP.

- 1 the founding axioms of AHP (Dyer 1990)
- 2 the form of the questions used in the pairwise comparisons (Watson and Freeling, 1982)
3. the 1-9 preference measurement scale (Dyer and Wendell, 1985, Holder, 1990)
4. the eigenvalue priority calculation method (Crawford and Williams, 1985; Dyer, 1990)
5. rank reversal of relative priorities when choice alternatives are added or removed (Dyer, 1990; Shoner and Wedley, 1989)

Xiang and Whitley (1994) noted that the majority, if not all, the critics of AHP are practitioners of the standard decision analysis methods called *Multi Attribute Utility Theory (MAUT)*. MAUT practitioners are known to base their arguments on MAUT axioms and procedures which has lead to a deadlock in the literature due to the inability of the two sides to agree on a common theoretical framework. No consensus has been reached for the five criticized areas listed though the first and fifth are considered to be the most important (Dyer 1990).

Each of these five areas is considered in turn.

#### 3.9.1 Axioms

The 4 axioms of AHP are briefly presented here along with the 6 axioms of Utility Theory:

AHP Axioms: (Adapted from Saaty 1987)

##### Reciprocal Axiom

This axiom establishes the inverse relationship between directional comparisons. That is, if  $P_C(A,B)$  is the pairwise comparison of element A with element B with respect to a criteria C then  $P_C(A,B) = 1 / P_C(B,A)$ .

So, since  $P_C(A,A) = 1 / P_C(A,A)$  therefore  $P_C(A,A) = \pm 1$ .

Since all comparisons are positive we obtain the diagonal identity:  $P_C(A,A) = 1$

### Homogeneity Axiom

This axiom states that with respect to the comparison criteria  $C$ , the elements to be pairwise compared are, in fact, comparable. For example: a grain of sand and an orange are comparable with respect of sphericity even though they have very different weight, texture, density, hardness and water content.

### Hierarchy Axiom

This axiom states that the decision structure under consideration is a directionally connected hierarchy. That is, the decision structure is constructed by starting with the focus, and working down through the hierarchy, with each level supporting the previous one, so there is single path through the connected hierarchy from any element up to the goal.

### Expectations Axiom

This axiom states there is an expectation that the individuals designing the decision hierarchy will ensure their ideas are represented in the model. It is possible, and desirable, for all alternatives to be represented in the hierarchy. Rationality of the individuals is not assumed and such expectations can be accommodated.

Utility theory can be broken into Ordinal and Cardinal forms. The former is concerned with individuals ranking preferences while the latter put values on those preferences. Cardinal Utility Theory is the form most comparable with AHP since AHP both ranks and gives priorities for each alternative.

In the axioms below the term *lottery* refers to a chance mechanism which yields prizes  $A_1, A_2, \dots, A_n$  with certain probabilities  $p_1, p_2, \dots, p_n$  where each  $p_i \geq 0$  and  $\sum p_i = 1$ .

Utility Theory Axioms (Adapted from Luce and Raiffa, 1957)

### Alternative Ordering

This axiom states that pairwise rankings can be made between any two alternatives and that these rankings are transitive. That is, if  $A \geq B$  and  $B \geq C$  then  $A \geq C$ .

### Reduction of Compound Lotteries

This axiom states that using probability calculus, any lottery with a payoff of another lottery can be decomposed into simple lotteries with the same final outcomes.

### Continuity

This states that any alternative is equivalent to a combination of worst and best alternatives.

### Substitutability

This states that in any lottery, a lottery containing the worst and best alternatives can be substituted for any other alternative.

### Transitivity

This extends the first axiom to encompass lotteries as well.

### Monotonicity

This states that if presented with two lotteries involving the best and worst alternatives you would choose the one with the least chance of the worst alternative.

From these axioms one can see that:

- Utility Theory (UT) presupposes explicitly knowledge of the probability of certain alternatives while AHP provides a method for deriving these probabilities based on pairwise comparisons.
- UT preferences are scaled to the  $[0,1]$  interval while AHP produces priorities summing to unity (1).
- The repeated use of the UT *Substitutability* axiom will produce a binary hierarchy (each alternative becomes the linear combination of the two extreme alternatives).
- AHP axioms allow the translation of qualitative valuations into ratio priorities.
- AHP uses hierarchical structure to represent the decision.
- UT axioms control the manipulation of pairwise rankings of alternatives.

Saaty (1990, p. 259) presented AHP as a fundamentally different method than Utility Theory so questions of the theoretic basis of AHP were expected.

### 3.9.2 Comparison Questions

The comparison questions used by AHP have the general form (after Harker and Vargas 1990):

“ With respect to {Element A} how much [more/less] <important> is (Sub-Element B) than (Sub-Element C) ? ”

{Element A}	can be any one of the elements of the decision hierarchy except the choice alternatives (which have no sub-elements)
(Sub-Elements B & C)	are a pair of contributing elements of {Element A}
[more/less]	are the comparison direction indicators (only one is used at a time)
<important>	is the comparative adjective used and can be replaced with without changing the method to any other <i>positive</i> adjectives such as: likely, preferred, desirable, strong(er)

See Table 3.1 for details of the comparison scale using ‘importance’.

Dyer (1990, p.249) notes classical utility theory poses ‘well defined questions and depend on a choice among alternatives rather than on a subjective response on a ratio scale’. The difficulty of developing a preference theory based on the strength of preference has been noted before (Fishburn, 1970; Dyer and Sarin, 1981).

Harker and Vargas (1990) respond by clarifying the question as the form detailed above. They point out the second axiom of AHP, homogeneity, assures the comparisons are made on a homogeneous scale. They argue the fact that AHP does not use a fixed reference point (as does Utility Theory) instead using all the compared elements as reference points in turn. This is an advantage since it minimizes bias that may result from using a fixed comparison point.

### 3.9.3 The 1-9 measurement scale

When using the 9 point scale, it is possible that a series of comparisons may lead a decision maker to the point where the most consistent response to a final question lies between two of the ‘allowed’ comparison values. Saaty (1980) mentions there is no need to pursue *consistency* at all

costs and the existence of a small amount of inconsistency is expected. Dyer (1990) himself concedes that the scale has been shown to be accurate in many empirical tests.

### 3.9.4 Eigenvalue priority calculation

Consider an example preference structure comparing 4 elements A, B, C & D with respect to some criteria which looks like:

	A	B	C	D
A	1	5	6	7
B	1/5	1	4	6
C	1/6	1/4	1	4
D	1/7	1/6	1/4	1

Saaty (1980) introduces 5 methods of calculating an estimate of the eigenvalue, presented here from poorest to most exact:

#### Arithmetic mean : crude estimate

Sum the rows (gives 19, 11.2, 5.42, 1.56) and  
normalize the sums by dividing by their total (gives 0.51, 0.3, 0.15, 0.04).

#### Normalized reciprocals : better estimate

Sum the columns (gives 1.51, 6.43, 11.25, 18.00),  
take the reciprocals of these sums (gives 0.66, 0.16, 0.09, 0.06) and  
normalize these reciprocals (gives 0.69, 0.16, 0.09, 0.06).

#### Normalize sum : good estimate

Sum the columns (gives 1.51, 6.43, 11.25, 18.00),  
normalize each column by dividing by its sum,  
sum each row of the normalized matrix (gives 2.36, 0.98, 0.46, 0.20) and  
normalize these last values (gives 0.595, 0.245, 0.115, 0.050).

#### Geometric mean : good estimate

Compute the product of the rows (gives 210, 4.8, 0.167, 0.006),  
compute the geometric mean of the row (gives 3.807, 1.480, 0.639, 0.278) and  
normalize the means (gives 0.614, 0.239, 0.103, 0.045)

Crawford and Williams (1985) show that the geometric mean procedure is optimal when the decision maker's errors are multiplicative with a log normal distribution.

These estimates are all numerically simple methods of estimating exact eigenvector values. To obtain eigenvector values precise to an arbitrarily small error value the following method is used.

$N^{\text{th}}$  power of matrix : exact (to within an arbitrarily small error value)

Square the preference structure matrix to yield the 4x4 matrix below. The column on the right is the eigenvector estimate obtained by summing the rows and dividing by the sum of all the rows. This is the  $N=2$  result:

	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	
<b>A</b>	4	12.7	33.8	68	0.6247
<b>B</b>	1.924	4	10.7	29.4	0.2428
<b>C</b>	0.955	2	4	10.7	0.0930
<b>D</b>	0.361	1.11	2.02	4	0.0395

Re-squaring each time the eigenvector estimate converges as is shown the following table, with the lowest row of the table showing the sum of absolute priority changes between iterations.

<b>N =</b>	<b>1</b>	<b>2</b>	<b>4</b>	<b>8</b>	<b>16</b>	<b>32</b>
<b>A</b>	0.5111	0.6247	0.6180	0.6187	0.61867	0.6186688
<b>B</b>	0.3013	0.2428	0.2347	0.2353	0.23532	0.2353222
<b>C</b>	0.1457	0.0930	0.1017	0.1009	0.10093	0.1009340
<b>D</b>	0.0419	0.0395	0.0456	0.0451	0.04507	0.0450744

$\Sigma$    change		0.2271	0.0295	0.0025	0.0002	1.31 E -9
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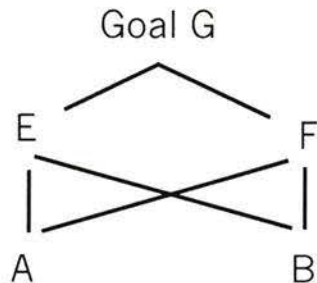
Saaty (1980, pp 167-179) presents a proof that this is the correct way to derive the principle eigenvector.

Bryson (1995) has proposed another method of deriving the eigenvector called 'a goal programming method' that considers the logarithms of the comparison matrix values and leads to different method of calculating the priority and consistencies.

### 3.9.5 Rank reversal

The phenomenon of rank reversal has generated a vigorous debate in the literature with no consensus. Some MAUT practitioners have called for the “correction” of AHP by “incorporating” some of the axioms and procedures of MAUT (Dyer 1990) while Saaty (1990) and others have dismissed the idea of diluting AHP with other theories.

The problem of rank reversal can be demonstrated with a simple hierarchy with only two hierarchy elements and two choice alternatives:



We will assume the following preference structures to start with:

‘G’ matrix

	E	F	Priority
E	1	1	0.5
F	1	1	0.5

‘E’ matrix

	A	B	Priority
A	1	9	0.9
B	1/9	1	0.1

‘F’ matrix

	A	B	Priority
A	1	1/8	0.111
B	8	1	0.889

The elements (E & F) are equally important (with respect) to the Goal (G) while A dominates B with respect to E and B is much more important than A with respect to F.

Calculating the accumulated priority for each alternative we have:

$$A: 0.5 \cdot 0.9 + 0.5 \cdot 0.111 = 0.5054$$

$$B: 0.5 \cdot 0.1 + 0.5 \cdot 0.889 = 0.4946$$

so A is preferred to B.

Now we will add another alternative, C, which is an exact replica of A. The changed preference structures become:

‘E’ matrix

	A	B	C	Priority
A	1	9	1	0.4737
B	1/9	1	1/9	0.0526
C	1	9	1	0.4737

‘F’ matrix

	A	B	C	Priority
A	1	1/8	1	0.1
B	8	1	8	0.8
C	1	1/8	1	0.1

Recalculating the accumulated priority for the three alternatives:

$$A: 0.5 * 0.4737 + 0.5 * 0.1 = 0.287$$

$$B: 0.5 * 0.0526 + 0.5 * 0.8 = 0.426$$

$$C: 0.5 * 0.4737 + 0.5 * 0.1 = 0.287$$

and B is now preferred to A (and C).

This characteristic of the AHP has sparked a lively discussion between various contributors (Belton and Gear 1983, Kamenetzky 1982, Saaty and Vargas 1984; Saaty et. al. 1983; Watson and Freeling 1982,1983; Saaty 1987; Dyer and Wendell, 1985).

Dyer (1990, p.252) points to this characteristic of AHP as “symptom of a much more profound problem with the AHP : *the rankings provided by the method are arbitrary*”. The explanatory example Dyer (1990) provided to illustrate this point was not, in fact, a hierarchy (Harker and Vargas 1990). They point out that the technique for the more general systems with feedback (Saaty 1980, p.204-214) is the appropriate method for his example.

Saaty (1990) also responded to Dyer’s comments (1990) with a reminder that it is an underlying truth of the AHP that it uses all the available information within a preference structure to calculate its priority distribution. Adding or subtracting elements from the process of comparison fundamentally changes the hierarchy, and it is expected that the priority distribution will change as a consequence. There is no parallel method within Utility Theory to accommodate this possibility. The changed priorities are new and the process is logical, not “arbitrary” as Dyer (1990) thinks. Saaty (1990) also drew a parallel between Utility Theory and the use of AHP as a scoring mechanism.

To understand why rank reversal occurs for relative priorities we recall that it is *relative* priorities that are sought. Saaty (1990) discusses the effect of including copies of elements into the preference structure. He notes that with some finite number n of copies of the leading (in the original structure) element the ranking of the elements (in the original structure) will switch. As

more copies are included the *relative* importance of the dominance of the leading element (and its copies) is reduced as the dominance is effectively spread between the copies. Likewise any element which dominates the copies (and the original element) with respect to some criteria will be positively affected. Saaty (1990) draws an interesting parallel to a woman shopping for a hat. In the first store she finds a hat (A) which is slightly more desirable than another (B). But after seeing an abundance of the A-type hat in another store she returns to buy the B-type hat.

We note at this time that the rank reversal phenomenon *only* occurs with *relative* priorities.

Using AHP as a method of scoring with absolute measurement does not exhibit this characteristic (Dyer 1990; Saaty 1990).

### **3.10 Conclusion**

AHP has been shown to be an effective method for the evaluation of problems involving multiple criteria, quantification of tradeoffs and limited data. By providing a hierarchical structure for the organization of the decision criteria AHP helps decision makers to evaluate their particular problem consistently with a mind that all the contributing factors can be incorporated. Since the baseline comparisons made by the decision maker are pairwise they can be clearly considered without the interfering influences of other encroaching factors. Decisions of overwhelming complexity can be approached with greater confidence since the decision maker needs only to establish the criteria hierarchy and to make comparisons within each hierarchical level.

Inconsistencies in the pairwise comparisons can be discovered using consistency ratios. By feeding the resulting priorities back to the decision maker the levels can be validated individually and in sum. The sensitivity of the final decision option ranking upon criteria comparisons can be investigated in a clear and understandable manner. In addition, new criteria can be incorporated into the analysis with minimal reworking.

AHP has the flexibility to handle both quantitative and qualitative measures and consequently is adaptable to a wide variety of problem forms. Properly organized, AHP structures can be used to rank all forms of decisions, estimate influences and guide planning through option ranking.

In summary, AHP has the capabilities to: (from Xiang and Whitley, 1994)

1. analyze a prioritization problem in a hierarchical structure;
2. extract and represent decision makers' preference structures through pairwise comparisons;
3. recover priorities by the eigenvalue method from preference structures with cardinal or ordinal inconsistencies;
4. diagnose the inconsistencies via consistency ratios;
5. validate the priorities based on the decision makers' level of satisfaction; and
6. improve the reasonableness of the priority scores through a feedback loop.

Since its introduction in the early 1970s, that AHP method has been used in many applications. It has proven to be efficient, effective and trustworthy when handling problems involving multiple and diverse criteria and the measurement of tradeoffs (Banai-Kashani 1989; Harker 1986; Schmoldt et al. 1995; Reynolds and Holstien 1994; Mollaghasemi et al. 1995).

The website <http://www.ahp.net/hierarchon/hierarchon.htm> acts as a showroom for the First Choice AHP software and there are literally hundreds of abstracts attesting the to utility of AHP in a wide variety of research areas.

The key weakness of this method, with regard to land suitability analysis, is the number of pairwise comparisons necessitated when comparing between sites. Banai-Kashani (1989) uses a 3-site example but in general one is comparing up to many thousand homogeneous areas. Since the number of comparisons required by AHP is  $N*(N-1)/2$  comparisons between  $N$  elements, the number of comparisons demanded quickly becomes unmanageable. A method to accommodate this scenario is presented in Chapter 4.

## 4 The Roll of AHP in GIS

### 4.1 Introduction

Geographic Information Systems (GIS) have been developed to the point where complex calculations may be made quickly and easily and based on these systems many tools for the calculation of various statistics and indices for points, line and areas are available. The increasing interest in land and resource management has driven GIS system and data collection to the point where there are more data and tools available to decision and policy makers than ever before. The continuing challenge to GIS application developers and specialists is the distillation of varied data layers into a form that can be used by the decision makers. Since AHP was specifically developed to address the problem of combining and analyzing non-commensurable data (Saaty 1977-1990), it represents a potential solution to part of this dilemma.

The AHP has been accepted within the decision making community (Barzilai 1996; Bryson 1994) and the extension of AHP into spatial decision making has been investigated by several researchers (Banai-Kashani 1989, Periera and Duckstein 1993, Xiang and Whitley 1994, Keller et al. 1996, Eastman 1997).

There are a number of aspects of the AHP which will be of particularly interest to land managers and decision makers:

- Land based decisions can involve many stakeholders and concerns. The AHP can organize the analysis, combination and weighing of the various concerns for individual stakeholders and the group.
- The flexibility of the AHP allows for multi-criteria, multi-scale, multi-measurement and multi-temporal data forms to be combined in a structured manner.
- The AHP is structured and transparent. That is, the entire evaluation structure is stored in a well defined manner along with all comparisons made by the users. The structure and the comparisons can be individually or collectively re-examined at a later date.
- The AHP is transferable. Once the general form of a land evaluation hierarchy is constructed, the structure can be applied to new regions. Any changes made to the hierarchy can be tracked and understood.
- The AHP is flexible. New factors that influence the evaluation can be added and unnecessary elements can be eliminated.

- The AHP is responsive to changes in the comparisons.
- The AHP provides a method of evaluating the consistency of the user's input.
- The AHP presents a manner of encapsulating expert knowledge in a form which decision makers can understand.

Though suggested over a decade ago (Banai-Kashani 1989), the technique has only recently been incorporated into GIS systems (Idrisi 1997). With the continuing discussion of AHP for land suitability analysis (Pereira and Duckstein 1993; Xiang and Whitley 1994; Keller et al. 1996) there is sufficient interest to warrant the development of a general land evaluation tool based on the AHP. A readily available tool could generate sufficient interest and foster discussion of the technique for GIS.

This chapter discusses how specific research papers and software developments have supported the use of AHP for suitability analysis from a GIS perspective.

## 4.2 Site Evaluation

Banai-Kashani (1989) suggested AHP could be used for site evaluation. Site evaluation is the evaluation of a finite set of land areas with respect to their suitability for a specific activity or use. The selection set is a small number of land areas and the desired output is some form of ranking or relative suitability index for the sites.

The AHP can immediately be applied to this problem. The *focus* or *goal* question is: "What is the best site (for some activity)?" The decision hierarchy is developed from the *focus* question to form a representation of the structure of the decision. The choices for the decision are the specific sites under consideration and as each site is considered to have homogeneous land characteristics (Banai-Kashani 1989) they represent unique choice options. Using the techniques detailed in Chapter 3 the AHP produces a relative priority for each site and a measure of the reliability of the priorities. Ordering the sites by priority gives the ranking of each site.

### 4.3 MCDM Land Evaluation

Pereira and Duckstein (1993) suggested the use of Multi Criteria Decision Making (MCDM) techniques for the purpose of land suitability evaluation. They recognized the utility of using a general assessment method to address a question as broad as land suitability analysis. They proposed using AHP techniques to organize and analyze the suitability question. In addition they developed Saaty's (1980) idea of a general scoring system by developing normalized value functions for individual base data layers as suggested by Kamenetsky (1982). Specifically, they used the bisection method (von Sinterfeldt and Edwards 1986, p236) to produce the interval scale for the individual criteria. These calculations were implemented using the Multi-Attribute Tradeoff System (MATS) software.

Pereira and Duckstein (1993) used the technique to derive habitat suitability indices for Red Squirrel on Mt. Graham (Arizona). They conclude that factors measured at various scales and units can be combined effectively into a single index.

### 4.4 Decision Making Assistance

The Idrisi<sup>®</sup> (1998) GIS has recognized the usefulness of the AHP and has implemented a module that allows the user to derive the relative priorities between options using the technique. The user is directed to list the comparison elements and then fills in a comparison matrix with numerical values corresponding to qualitative comparison valuations similar to those listed in Table 3.1. The software calculates the priority indices for the elements and the consistency of the comparisons.

Though allowing the user to derive the relative priority of different data layers this module has serious shortcomings with respect to land evaluation:

1. There is no facility for the development of multi-level hierarchies. The module only calculates the priorities for a single level hierarchy that removes one of the strongest features of the AHP: the ability to organize the question in a structured hierarchy.
2. The user must enter the numeric value associated with each comparison and that assumes some knowledge of the mathematics of the technique.
3. The input values may lead users to think that they are entering weightings, which is false. The input values are representations of qualitative comparison valuations, priorities are calculated from the complete set of input values.

4. The comparisons are not stored in a structured manner so later analysis of the users logic and how the AHP module was used is difficult. It is left to the user to fully document all steps taken.
5. Priorities are only displayed and there is no facility to apply these priorities to actual data layers. The user must record these priorities and then re-enter them when doing data layer arithmetic.
6. Though consistencies are calculated for each matrix completed by the user, there is no method of tracking the overall consistency of the user's analysis.
7. Before calculated priorities can be applied to any data layer some further data manipulation, such as normalization or reclassification would be needed. No mention of these steps is made in the provided documentation.
8. Idrisi is primarily a numeric raster GIS. A method of deriving normalized value functions like Kamenetsky (1982), or a standardized reclassification of the data layers would be needed before the priority values can be applied to whole data layers.
9. No mention of the pitfalls of comparing non-commensurable data forms is made in the documentation.

Though potentially a powerful tool, the simplistic AHP module used by Idrisi lacks key components of Saaty's method. It is possible that Idrisi recognized the difficulties of creating a general land evaluation tool and elected only to implement the simplest module for testing. Potential users of the technique may experiment with the module though using it for complex land evaluation would be difficult.

A similar module has been created using ArcInfo's AMLs [ESRI 1998]. But this module has many of the same shortcomings (all except #8 of the list above) noted for Idrisi above.

#### **4.5 Extending Saaty's AHP for land evaluation**

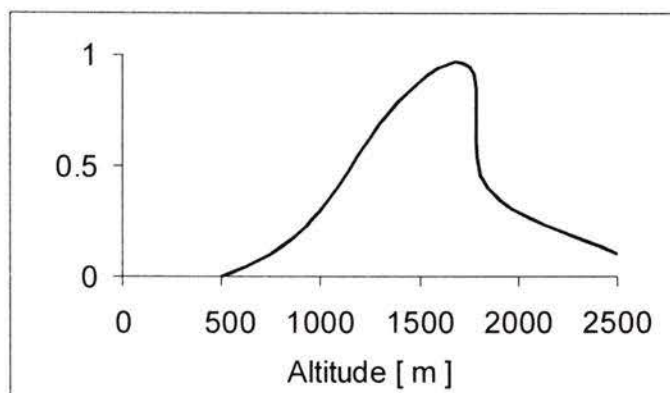
Saaty (1980) describes how the AHP can be used as a general scoring method to give relative values to a large number of options. The essential difference is that the comparisons are made between the options and a single *standard* option. In practice this *standard* is a scale measuring some option characteristic influencing the evaluation.

Pierera and Duckstein (1993) reformulated Saaty's scoring method for the purpose of land evaluation. Their method involves the construction of an evaluation hierarchy representing the dependence of evaluation concepts on land characteristics. Using AHP pairwise comparisons the relative priorities of these evaluation concepts and data layers are calculated. Their extension to the AHP is the creation of priority response functions that represent the varying contribution of the data layers with changing data values.

As an example consider a data layer containing elevation values ranging from 0-2500 meters. If the land evaluation question is "What are the best areas for down hill skiing?" then we would expect there to be some variation across the range of elevations. A graph representing this variation could look like the one shown in Figure 4.1. The vertical scale is normalized to represent strength of preference as suggested by Kamenetzky (1982). A value of one (1) can be interpreted as optimal. This graph shows the *preference strength* or *priority response* function of altitude and indicates there is an optimal elevation level around 1650m and that altitude below 500m is unsuitable for skiing.

The method used to derive a response function such as shown in Figure 4.1 is:

Select a finite number of values for the data set which represent local and global maxima, local and global minima and inflection points. These values are selected by the decision maker, an expert consultant or could be based on instrument measurement. These values will be referred to as the *key* values. Using pairwise comparisons the *relative* priorities of the *key* values, with respect to the *specific* land characteristic is obtained. Normalizing the priorities as suggested by



**Fig. 4.1 Response function example**

Kamenetzky (1982) converts the ratio scale priorities generated by the AHP into 'strength of preference' valuations. Finally, interpolating between those valuations produces Figure 4.1.

Clearly 'good skiing' depends upon more than just altitude. Appendix B details a more complex application of the generalized land evaluation method for 'good skiing' and includes sample calculations.

This method provides a systematic means of organizing and calculating general land evaluations. Based on Saaty's AHP the mathematics have been well scrutinized and accepted by the decision management research community. The extension to the process as suggested by Pierera and Duckstein (1993) based on Kamenetzky's (1982) suggestion allows the standardization of all data forms into strength of preference valuations. Once standardized, the data layers can be combined into a single land evaluation representation using the AHP generated priorities as weighting factors.

There is a clear need for a program which uses Saaty's AHP for the purpose of land evaluation. Appendix C details the logic used to select a coding method.

## 5 Implementation of AHP and GIS-AHP

### 5.1 Outline

This chapter presents the implementation techniques used to create the applications. Specific features of the application are introduced. The data structures used are detailed in Appendix D.

### 5.2 Methodologies: AHP vs GIS-AHP

Though both these methods use the calculation methods proposed by Saaty (1977) there are key differences in the user input, calculation and analysis output.

*AHP User Input* consists of the hierarchy development, element comparisons and choice list specification. The choice list is operationally limited to seven (7) or eight (8) entries (Saaty 1977, Miller 1956).

*GIS-AHP User Input* consists of the hierarchy development and element comparisons. In addition, the user selects a set of *key* values from the range of each data layer to represent that data layer. These *key* values are also inter-compared and resulting relative priorities are used to interpolate the priorities of intermediate data layer values

The *AHP priority calculation* follows the method detailed in Chapter 3, with the priorities of each of the choice options calculated from the hierarchy inter-element priorities.

The *GIS-AHP calculation* uses the AHP eigenvector methods to calculate inter-element as well as inter-*key* data layer value' priorities. This creates a functional relationship between data layer values and their priorities, allowing the inclusion of spatially variant data layers in the land evaluation (Peirera and Duckstein 1993, Kamenetzky, 1982). Summing the priority contributions across the data sets produces a 'suitability index' surface.

*AHP output* consists of a specific priority value for each of the choice options. These priorities sum to unity (1.0) and represent the *relative* priority of each of choice options.

*GIS-AHP output* consists of a priority contribution factor for each *key* value in each base data layer. These values are then used to interpolate intermediate data layer value priority contributions. Summing the contributions across the data layers produces the aggregate index that represents the *relative* suitability of the land to the particular activity for which the hierarchy was developed.

### **5.3 Development Overview**

The application appears as a website (<http://viking.geog.uvic.ca/ahp/>) and resides at the University of Victoria. The site is broken into two main areas. The first is a functional interactive site implementing Saaty's (1980) AHP. The purpose of the first site is to implement the AHP decision support method which is a useful decision making tool. The AHP-application also acts as a benchmark against which the second site area can be compared. The second site area implements the AHP for situations where a generalized evaluation or scoring is desired, such as for land evaluations.

### **5.4 Dynamic Pages**

The website is made up of two types of webpages. The first are text files on the server. These pages never change and include the 'sign-in' form page and help pages. These standard pages act as the anchor point for the application/website.

All other pages are created on demand by Perl programs. The programs interpret the inputs from the user and generate the appropriate page for display to the user. The dynamic nature of these pages allows the customization of the pages in response to the user input, decision hierarchy state and analysis results.

### **5.5 Methods**

The method used is a combination of readily available software. The programming language chosen was Perl 5.0, a run-time compiled language widely used by developers whose selection was justified in Appendix C. The mouse driven interfaces are formed with web pages, written in real time by the Perl programs and appear to the user as a series of linked pages. The user's web browser interprets the web pages and handles all the interrupt and event handling associated with a mouse driven windowed interface. Using a web browser as an interface simplifies the

programming task as the Perl programs need only interpret the state of a webpage and then generate the HTML coding for the next webpage. Perl has powerful tools for the manipulation of text which make the writing of the dynamic webpages relatively straightforward.

Hyperlinks linking web pages are fundamental to the web and are used as a quick way to get around the website. The program home page resembles a standard menu driven program (Figure 5.1).

<b>File</b>	<b>Hierarchy</b>	<b>View &amp; Edit</b>	<b>References</b>
<a href="#">Import</a>	<a href="#">New</a>	<a href="#">Structure</a>	<a href="#">AHP Theory</a>
<a href="#">Export</a>	<a href="#">Rename</a>	<a href="#">Comparisons</a>	<a href="#">Bibliography</a>
	<a href="#">Save</a>	<a href="#">Meta Data</a>	<a href="#">Credits</a>
	<a href="#">Copy</a>		
	<a href="#">Delete</a>		

<b>Help</b>
<a href="#">Getting Started</a>
<a href="#">Tutorial</a>

**Figure 5.1 Application Main Menu**

Mouse clicking any of the above 'menu' hyper-links moves the user to form pages which gather input for the specific application action desired. For example, the 'Copy' hyperlink under 'Hierarchy' links to a webpage where the user is directed to select the hierarchy to copy and enter a new name for the copy. Once this action is completed the program returns to the main menu (Figure 5.1) and the user can choose another action.

Hyper-links also appear throughout the website as 'Help' links to directly access topical information written to clarify the website components.

Standard web form elements provide a mouse driven interface with minimal programming. Selection lists and entry boxes are used to gather information from the user. Action buttons prompt Perl programs to use the state of the current webpage to determine the flow of the program as well as to generate the next webpage. For example, the 'New' link under 'Hierarchy' (Figure 5.1) leads to a page containing the form elements: one list box, two input boxes and two action buttons (Figure 5.2).

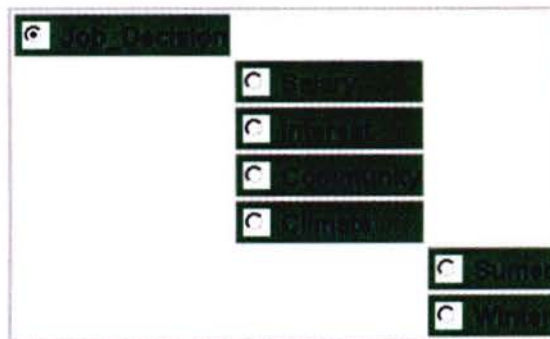
The screenshot shows a window titled 'New Hierarchy Creation Interface'. On the left, under the heading 'Data Files', there is a list box containing the following items: home.ahp, paula.ahp, sample.ahp, soft1.ahp, and software.ahp. To the right of the list box are two text input fields: the top one is labeled 'Name' and the bottom one is labeled 'Goal'. Below these input fields are two buttons: 'Create it' and 'Cancel'.

**Figure 5.2** New Hierarchy Creation Interface

'Data Files' are the currently existing hierarchies on the system. This list is provided so the user does not inadvertently enter a duplicate name in the 'Name' text input box. The 'Goal' refers to the name given to the top level of the hierarchy. When the button 'Create it' is pressed the state of the page is tested and if the inputs are valid a default hierarchy file is created. If there are errors then an error message is generated and the page is re-displayed. Pressing the 'Cancel' button returns to the main menu directly.

### 5.6 Hierarchy Construction - AHP

The developed application displays hierarchies using a tabular format. The job-decision hierarchy shown in Appendix C.7 appears in the hierarchy construction application webpage as: Only the hierarchy elements appear in the tabular display, the decision options are listed



**Figure 5.3** Tabular hierarchy example

separately. The buttons beside each element are used to 'select' a particular element for deletion or subdivision. Since there is no limit on the size of tables displayed in a webpage, hierarchies of arbitrary size and complexity can be developed. *Concept* hierarchy elements appear in green table cells. These elements are typically grouping concepts for other conceptual elements or

baseline data elements. For example the *concept* 'climate' could be used to group seasonal climatic subdivisions of winter, summer, autumn and spring.

### 5.7 Hierarchy Construction – AHP for GIS

Figure 5.3 is an example of a using the AHP for a 'decision' between a small set of decision options. Figure 5.4 shows an example of a simple land evaluation hierarchy representing the flammability of a patch of forest. The contributing elements to flammability are set to be the local **slope** of the terrain, the **distance** to already burning forest patches, the **wetness** of the patch of forest and the dominant forest **species** of the forest patch. Wetness, in turn, is dependent upon the patch Catenary Index (CI) which is calculated from upslope contributing area and the local slope using the formula (Beven and Kirkby 1979):

$$WI = \ln(A / \tan(\text{slope}))$$

with 'A' as the specific catchment area defined as the 'upslope area draining across a unit width of contour' (Speight 1980).

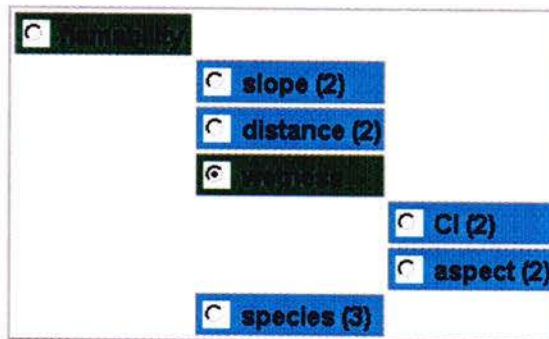


Figure 5.4 GIS-AHP Tabular hierarchy example

Note how Figure 5.4 differs from Figure 5.3:

- Baseline hierarchy elements appear in blue table cells. These elements are fundamental data sets for the analysis. Slope, Catenary Index (CI), dominant forest species and aspect are examples of baseline data.
- Only concept hierarchy elements have 'sub-elements'.
- Within baseline hierarchy elements *key* element values are chosen by the user to represent the *priority response function* of the baseline element to the evaluation question. The bracketed number to the right of each baseline element indicates the number of *key* values in the current hierarchy structure.

- d) A GIS-AHP hierarchy is considered *incomplete* when there is at least one *concept* element without direct or indirect baseline element sub-elements.

The user may edit the *key* values used for each base element. The interface allows up to 8 *key* values to be specified. If a baseline element appears more than once in the hierarchy the *key* values can be different for each.

Once the hierarchy is completed the pairwise comparisons can be gathered.

<input checked="" type="radio"/>		CR=91	
	55	<input type="radio"/>	(22,67,11) CR=100
	9	<input type="radio"/>	(69,14,17) CR=100
	22	<input type="radio"/>	(33,33,33) CR=100
	14	<input type="radio"/>	CR=100
		75	<input type="radio"/> (69,14,17) CR=100
		25	<input type="radio"/> (69,17,14) CR=100

**Overall Consistency Ratio= 93 %**

Do Comparisons    Edit Structure    Finished

**Figure 5.5 Comparison Summary Hierarchy Display**

### 5.8 Comparison Summary Interface

This interface displays the complete hierarchy with all associated priorities calculated from the entered pairwise comparisons. All comparisons are initialed to 'equal importance' so when first viewed the hierarchy shows equal priorities for each sub-hierarchy. Consider the example hierarchy shown in Figure 5.5:

Note:

- The hierarchy elements are indicated with **bolded text** in green table cells, each with a radio button.
- The radio buttons are used to select a particular hierarchy element before choosing to 'Do Comparisons'. In this way the user can select an element and immediately go to the interface where the pairwise comparisons are entered.

- The number to the left of each element is the relative priority (%) of the element to the other elements at that level. In Figure 5.5 we see that the sub-elements of **Job\_Decision** (Salary, Community, Interest and Climate) have relative priorities of 55, 9, 22 and 14 respectively.
- To the right of each element, the consistency of the comparisons made ‘with respect to’ that particular element is displayed as “CR = nn%”. Values less than 90% are considered to be overly inconsistent and the comparisons should be reviewed (Saaty 1980). In Figure 5.5 we see that the comparisons made with respect to **Job\_Decision** had a consistency of **91%**.
- The bracketed numbers to the right of elements without sub-elements indicate the relative priorities (%) of the choice options (AHP application) or the base-element key values (GIS-AHP application). In Figure 5.5 we see that the relative priorities given to the three cities with respect to **Salary** are 22, 67 and 11.
- The overall consistency of the hierarchy is **93%**.

### 5.9 Entering Pairwise Comparison Interface

The comparison values stored are gathered using a standard list selection widget. This allows the comparisons to be presented as a phrase, the ideal format for soliciting pairwise valuations (Saaty 1980). The user selects the appropriate comparison phrase from the list provided. The current state of each comparison appears as a single phrase and the user can review the state of comparisons by reading the phrases. If a phrase seems inappropriate, too strong or too weak in its declaration, the user can immediately make the necessary modification. Figure 6.6 shows an example of a single pairwise comparison.

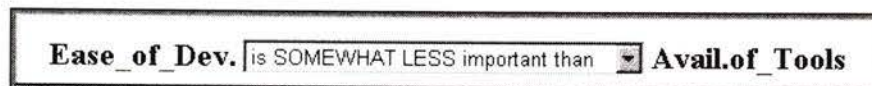


Figure 5.6 Single Comparison, inactive state

When the current ‘comparison phrase’ is mouse-clicked the other possible comparison phrases are displayed (Figure 5.7).

<b>Ease_of_Dev.</b>	is SOMEWHAT LESS important than	<b>Avail.of_Tools</b>
COMPLETELY dominates DOMINATES is FAR MORE important than is MUCH MORE important than is MORE important than is SOMEWHAT MORE important than is SLIGHTLY MORE important than is A LITTLE MORE important than is EQUALLY IMPORTANT as is a LITTLE LESS important than is SLIGHTLY LESS important than <b>is SOMEWHAT LESS important than</b> is LESS important than is MUCH LESS important than is FAR LESS important than is DOMINATED by is COMPLETELY dominated by		

Figure 5.7 Single Comparison, active state

As detailed in Chapter 3, the total number of pairwise comparisons made for a single sub-hierarchy between a set of  $N$  elements with respect to their dependent element is  $N*(N-1)/2$ . The comparison entry interface displays the pairwise comparisons in sets. Each set

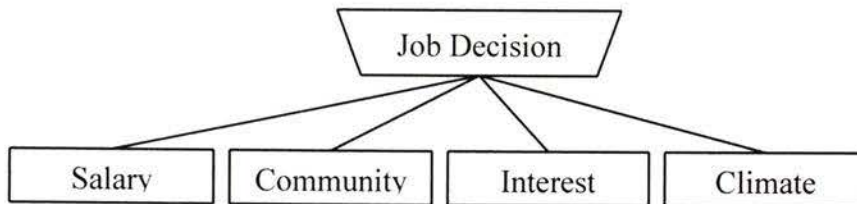


Figure 5.8 Job decision sub-hierarchy

contains all the comparisons for a particular sub-hierarchy. For the sub-hierarchy shown in Figure 5.8 the set of comparisons is shown in Figure 5.9.

<b>Salary</b>	is EQUALLY IMPORTANT as	<b>Community</b>
<b>Salary</b>	is EQUALLY IMPORTANT as	<b>Interest</b>
<b>Salary</b>	is EQUALLY IMPORTANT as	<b>Climate</b>
<input type="checkbox"/> <b>Maximize Consistency ?</b>		
<b>Community</b>	is EQUALLY IMPORTANT as	<b>Interest</b>
<b>Community</b>	is EQUALLY IMPORTANT as	<b>Climate</b>
* * * * *		
<b>Interest</b>	is EQUALLY IMPORTANT as	<b>Climate</b>

Figure 5.9 Pairwise comparisons for example sub-hierarchy

The  Maximize consistency? checkbox is provided (Figure 5.9) to allow the user the opportunity to speed up the comparison process when the number of comparisons is large, following a suggestion made by Millet (1990). Checking this box prompts the program to calculate the priority based on the first N-1 comparisons (above the checkbox). The rest of the comparisons, below the checkbox, are calculated to maximize *consistency* with the first N-1 comparisons. Ignoring the checkbox disables this feature. The website provides information to the user on the consequences of using this feature and describes what ‘consistency’ means.

Along with the set of comparisons is a schematic of the entire hierarchy with the current sub-hierarchy highlighted. The user can use this schematic for orientation within the hierarchy during the pairwise comparison process.

The three main forms of comparison phrases are importance, preference and probability. To accommodate a broad spectrum of land evaluation questions the, phrasing may be changed between phrasing sets with a single button press.

At the bottom of the comparison page a set of buttons (Figure 5.10) are used to navigate through the comparisons.



**Figure 5.10 Comparison Navigation Buttons**

- ‘Next’ moves to the next set of comparisons;
- ‘Previous’ moves to the previous set of comparisons;
- ‘Reset’ resets the comparisons to what they were when the current comparison page appeared. It does not reset all the value to ‘equally important’.
- ‘Finished’ returns to the main comparison page where the tabular hierarchy schematic is shown with the calculated priorities and consistency indices.

### 5.10 Graphs

Accessed from the main comparison interface, graphs are provided to give a visual indication of the relative priority of the elements (AHP application) or the cumulative response function of base elements (GIS-AHP application). The graphs are regenerated each time any changes are made to the hierarchy pairwise comparisons.

Graphs are generated using JavaGraph (Rugge, 1998). Figure 5.11 shows an example output showing relative contributions.

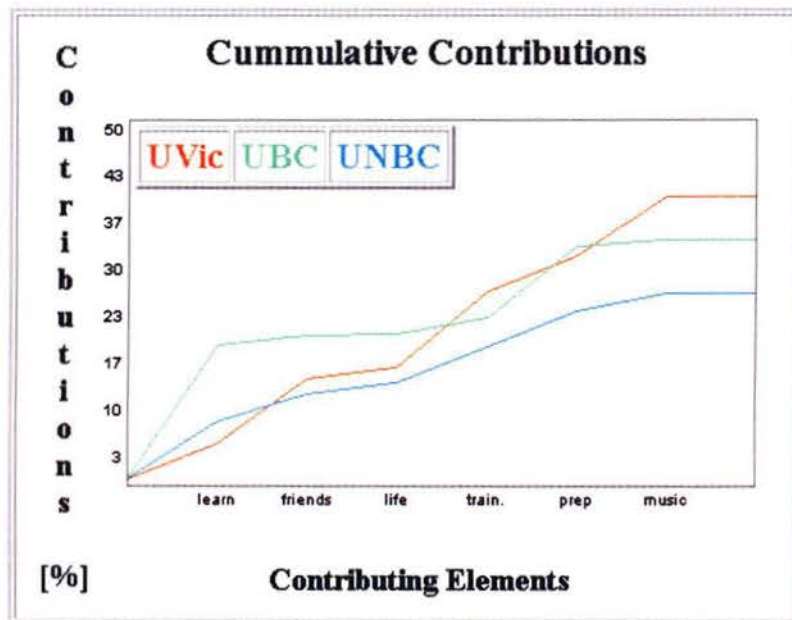


Figure 5.11 Cumulative Contributions

For the AHP application a second graph is also displayed showing the cumulative contributions of the base elements towards each choice option.

### 5.11 Output

The AHP application output is the relative priorities of the choice options and the relative priorities for each element within the hierarchy. These can be stored by saving the 'main comparison page' onto the user's system. To save the actual comparisons which were entered by the user the storage file can be *exported* using the 'export' page accessible from the main AHP application menu. Appendix D details the format of import and export files.

The GIS-AHP application output is the cumulative response function for each base element. This is given as a set of value-to-priority pairings for each base element. Priority values for intermediate base element values can be interpolated from the given pairings. An ArcInfo AML is provided in Appendix D as an example of implementation code to either vector or raster data layers using linear interpolation. This AML can also be available from the GIS-AHP application site.

### 5.12 Storing data

Developed hierarchies are stored in a text form. The storage files store the name, meta data, choice list, hierarchy and comparison data. Text files were chosen for data transfer since text files are the most universal of data forms. Appendix D contains a detailed look at the organization of the data files developed to store decision hierarchies (AHP) and land evaluation hierarchies (GIS-AHP).

### 5.13 Importing/Exporting Data

Since the application/website exists only on a single server, a means of accommodating global users is necessary. This is accomplished by providing the structure of baseline data files and allowing files to be copied to and from the site. Users, wherever they may be seated, can create a text data description file, upload it to the site, develop and modify hierarchies based on their uploaded file and then download the resulting storage and output files to their system for inclusion in their analysis.

Since the website actively facilitates the importation of foreign files onto the host server it is important to control the form of these files to basic text files with the correct structure. For

system security, all imported files are screened before use. Those not conforming to the strict text structure detailed in Appendix D are immediately deleted.

#### **5.14 Tutorials**

There are two tutorials included on the website. One introduces the AHP application site. The other introduces the GIS-AHP application site. The tutorials guide the user through the creation of an example hierarchy. They introduce all the major features of the application/site, giving interpretive explanations of the webpages as they appear.

Each tutorial is, itself, a webpage and contains example of the form widgets and graphics that appear the application pages. These examples appear in the tutorial exactly as they will to the user when the application/site is used since the user's Internet browser interprets both.

The most effective way to use the tutorials is to open a second Web Browser and access the main site with one window and view the tutorial with the other. Then the user views the tutorial instructions while performing the tasks within the application/site.

## 5.15 Summary of Application Features

### AHP Application

- full function AHP application for priority calculation between finite options;
- on line tutorial introduces all the steps necessary to create a hierarchy;
- detailed help pages available for all pages within the site;
- no limit to size/complexity of decision hierarchy;
- hierarchies can be edited after construction;
- choice options can be added or deleted whenever warranted;
- automated pairwise comparison question generation;
- automated priority/ consistency calculation;
- automated generation of relative and cumulative priority graphs
- concise display of hierarchy, priorities and consistency indices;
- comparisons can be reviewed and edited without restriction;
- generated comparison data files can be downloaded to user's file system ;
- file management utilities (rename, delete, copy) are available; and

### GIS-AHP Application

- GIS-AHP application for priority calculation between infinite options;
- on line tutorial introduces all the steps necessary to create a hierarchy;
- detailed help pages available for all pages within the site;
- no limit to size/complexity of decision hierarchy;
- hierarchies can be edited after construction;
- automated pairwise comparison question generation;
- automated priority/ consistency calculation;
- automated generation of cumulative baseline data response functions;
- comparisons can be reviewed and edited without restriction;
- concise display of hierarchy, priorities and consistency indices;
- generated comparison data files can be downloaded to user's file system;
- file management utilities (rename, delete, copy) are available; and

## 6 Using Expert Knowledge

### 6.1 Introduction

A basic assumption of the AHP is an availability of at least one expert or stakeholder whose knowledge and considerations can be incorporated into a hierarchical preference structure. There are a number of challenges associated with gathering and using information from individual experts or groups of experts (Saaty 1980, Harker 1986, Schmoldt et. al. 1994, Sutherland and Crosslin 1989, Shen et al. 1990). This chapter discusses the forms of hierarchy development that can be used to consolidate the knowledge of one or more experts and stakeholders.

The process of constructing a hierarchy preference structure is described abstractly in Chapter 3.

The explicit steps are listed here:

- 1 Choose expert(s)  
These are persons who, through years of training and experience, have developed a high level of understanding of the needs of the activity in question.
- 2 Gather factors  
Through interviews with the expert(s) compile a list of site characteristics which are influential in the site evaluation.
- 3 Group elements into categories  
Put the characteristics into groups which have a common form (e.g. topography, scenery, zoning, access, infrastructure)
- 4 Reword the characteristics so they are all 'positive' influences.
- 5 Construct hierarchy  
Build hierarchy using interactive software.  
Fill in pairwise comparisons.
- 6 Calculate element influence and expert consistency
- 7 Re-assess comparisons  
Review the results of the analysis.  
Select comparisons to be reviewed.
- 8 Finalize priorities

This chapter discusses this process for the both the single and multiple expert scenarios.

## **6.2 Single Expert / Stakeholder**

Following the steps listed in Section 6.1 a representation of the decision structure can be constructed. In this section the specific concerns of the single decision maker / expert / stakeholder are discussed.

### **6.2.1 Element Definitions**

Defining the elements properly is perhaps the most fundamental challenge to the expert.

Individual concepts of terminology need to be clarified explicitly. Small variations in naming and description may lead to confusion later in the process. These definitions must be clear in the expert's mind and the perceived meaning of each concept should be well documented. This will provide the background which will guide the reporting of any results created and aid in later analysis by future experts.

### **6.2.2 Hierarchy Completeness**

The completeness of a developed hierarchy by a single expert may be called into question. This is a primary reason for developing the hierarchy as carefully and completely as possible at the outset. Structures can always be simplified later.

The lack of a particular data layer is not sufficient reason to exclude it in the preference structure. A complete hierarchy will contain references to all influential data layers, whether or not they are available at the time of the analysis. The benefits of this are twofold: 1) the data can be included in the analysis as it becomes available and 2) the hierarchy is constructed in a complete form at the outset.

### **6.2.3 Comparison Uncertainty**

The 'expert' may be uncertain about some of the pairwise comparisons made. It is, however, easy to track the influences of such an uncertainty through a hierarchy to give a measure of the finalized priority uncertainties.

Inconsistencies in the pairwise comparisons of the expert are an expected part of the process. Saaty (1982 p.82) suggests it is normal to have some inconsistencies within a set of pairwise comparisons and these inconsistencies may be reduced with time as we integrate new experiences into our knowledge base.

### 6.3 Single Expert / Stakeholder

Making group decisions or coming to a consensus are effectively the same process when considered along with the methodologies presented in this thesis. The opinions and considerations of these people (or groups) need to be consolidated into representative priorities for the finalized hierarchy (Saaty 1982). There are a number of different ways to construct the representative hierarchies and gather the pairwise comparisons from multiple participants (Schmoldt et al. 1994, Malczewski et al. 1997) and in this section the application of those methods is discussed.

There are three basic assumptions made concerning the stakeholders (Schmoldt et al. 1994):

- The number of individuals or groups of individuals is manageably small.
- The assembly of these representatives of each group as spokespersons is feasible.
- The representatives will contribute to the process in a rational manner.

These representatives will be referred to as ‘stakeholders’ who represent individuals or groups of individuals. Examples of such groups are conservation groups, landowners, local developers and local residents.

There are a number of ways to construct a hierarchy when dealing with stakeholders. Each method has functional pros and cons. The following section presents these methods (Schmoldt et al. 1994) in turn and discusses their functional limitations. Since the AHP is probably new to stakeholders, a facilitator will be needed to instruct the stakeholders on the AHP method and their task as participants. This facilitator may be the land manager or an AHP expert but will fill the roll of instructor and guide for the stakeholders. The facilitator should work at all times to minimize influencing the stakeholders in their hierarchy constructions or comparisons.

#### 6.3.1 Composite Hierarchies

For this method the land manager constructs a hierarchy that includes the various stakeholders as intermediary elements between the goal element “land stewardship” and the baseline data layers. Each of the stakeholders completes their own sub-hierarchy. The land manager provides professional opinion regarding the relative importance of the opinions of the various stakeholders and completes the top portion of the hierarchy. In this manner the stakeholders may contribute

their own viewpoint without alteration or compromise though the stakeholders may not have direct influence upon the structure of the hierarchy.

This method separates the stakeholders, which allows each to complete their individual hierarchies without being influenced by other stakeholders. Since each stakeholder works independently scheduling meetings is easier to organize and each stakeholder can take the time they feel is necessary and ask individual questions of the facilitator which address their concerns. The relatively simple task of filling out a hierarchy can be completed quickly, reducing the time demanded of the individual stakeholders.

The facilitator will serve to keep the stakeholders 'on track' and so reduce the overall time necessary to complete the hierarchy. Since the facilitator is present at all the meetings he/she will be making a sizable time commitment to the overall process.

Since the land manager's comparisons will have paramount influence on the final results of the hierarchy all comparisons made at that will have to be well documented. The land manager can, however, choose to make no comparisons. In this situation, the sub-hierarchy of each stakeholder would have equal weight in the final hierarchy aggregation.

### **6.3.2 Disjoint Hierarchies**

With this method the land manager allows each stakeholder to construct the representative hierarchy before filling the pairwise comparisons. This allows the stakeholders the freedom to design a hierarchy structure which they feel best represents the evaluation problem under consideration. This may include layers not originally included by the land manager. Once the individual hierarchies are completed the land manager can weight the importance of each stakeholder as with composite hierarchies.

As with the 'Composite Hierarchies' the separation of the stakeholders makes scheduling easier and allows the facilitator to instruct individual stakeholders and guide the process. Here too, the land manager has an over-riding influence on the final land evaluation so all of his/her comparisons will need to be documented in full.

### **6.3.3 Single Hierarchy**

With this method the collection of stakeholders would work together to design a single hierarchy. This is likely to be a difficult task (Schmoldt et al. 1994) but there are some distinct advantages:

- The land manager will not have to integrate the resulting hierarchical priorities since the stakeholders create a complete hierarchy.
- There process of discussing the design of the hierarchy may encourage some softening of lines by stakeholders with extreme views. These more moderate views would better reflect the opinions of a reasonable and well-informed individual.
- In addition, the dynamic nature of the design process allows the inclusion of data layers not envisioned by the land manager.
- The facilitator will only have to instruct the group on the AHP once, and then can address individual questions as they arise.

### **6.3.4 Static Hierarchy**

For this method the land manager creates a single hierarchy which is completed by each of the stakeholders individually. The time commitment of each stakeholder is reduced since only the actual comparisons need to be contemplated. A large number of individuals can be 'surveyed' in this manner and the result statistically compared. This method is not effective when stakeholders have divergent opinions on which base data layers should be considered. Also, some stakeholders may feel too restricted by the single hierarchical structure enforced with this method.

### **6.3.5 Dynamic Hierarchy**

This method allows stakeholders to adjust the structure of a hierarchy provided by the land manager. The changes will bring the hierarchy more in line with the method of thinking the stakeholder is used to, which may facilitate comparison valuations and even improve the accuracy of the results (Schmoldt et al. 1994).

### **6.3.6 Gaining Consensus**

Methods used to bring consensus to a group of individuals may be used for the creation of hierarchies. Face to face discussions (brainstorming), Delphi elicitation (Dalkey and Helmer 1963) and Crawford Slip Method (Crawford and Demidovich 1981) are all examples of these techniques.

Group thinking methods are appropriate for assigning judgements within individual groups but become less effective when participant differences lead to direct confrontations. More anonymous methods are preferable in those situations (Schmoldt et al. 1994).

Saaty (1980) suggests using the geometric mean of the ratio scale comparison judgments as a method of combining comparisons from different stakeholders. The land manager can then weight the opinions of stakeholders by using the formula:

$$A_w = \sqrt[k]{\prod_{i=1}^n X_i^{j_i}}$$

where  $k = \sum_i j_i$

n = number of stakeholder groups  
 $A_w$  = weighted geometric average  
 $j_i$  = weight value for each group

#### 6.4 Summary

Following the steps listed in the opening section of this chapter a hierarchy may be created for general decision and land evaluation problems. This method may equally be applied to an individual stakeholder or a collection of stakeholders.

When the opinions of a group of stakeholders need to be consolidated then there are a number of techniques that can be applied. The selection of the most appropriate technique will depend upon a number of criteria and include: time and resources available, number of stakeholders, physical location of the stakeholders, communication skills of the stakeholders and the degree of divergence of the stakeholder opinions.

Once collected, the input from an individual or individuals can be consolidated into a single decision priority (for decision making) or scoring parameter priorities (for land evaluation).

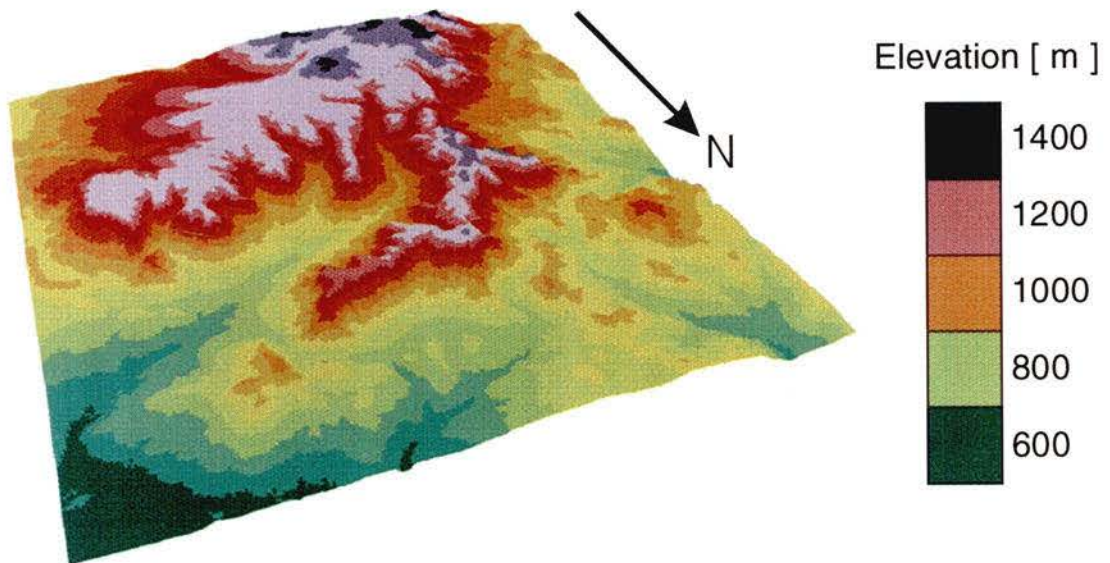
## 7 Implementation Testing

### 7.1 Introduction

Though the primary goal of this thesis was to research and develop a general method for land evaluation, it is instructional to view how the application can be used in more practical terms. This chapter describes two hypothetical land evaluation scenarios.

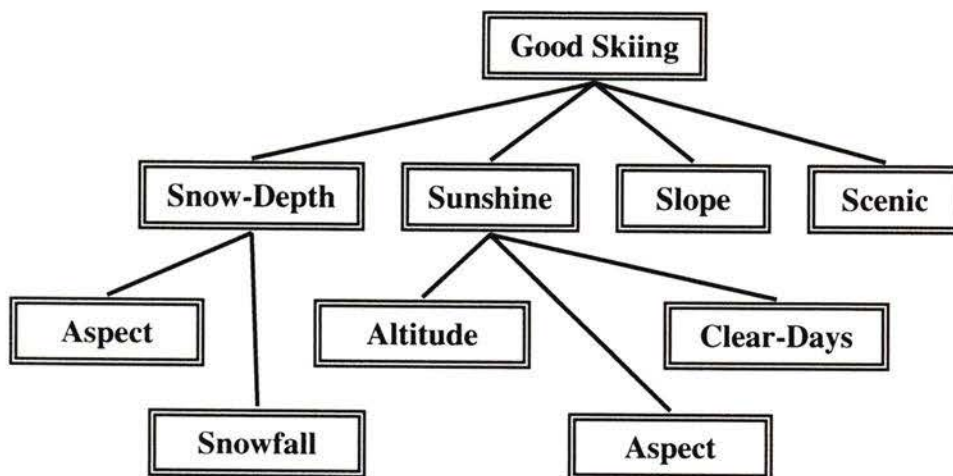
### 7.2 Scenario 1: Skiing Potential

As an example of a general land evaluation problem we will consider the question “Where are the prime skiing areas?” and will assume (naively) that the optimal ski experience is a function of snow, sun and scenic beauty. The digital elevation model (DEM) shown in Figure 7.1 shows the area of interest. Situated in northern Alberta near Lesser Slave Lake, the area is undeveloped at this time.



**Figure 7.1** Digital Elevation model for ski potential evaluation

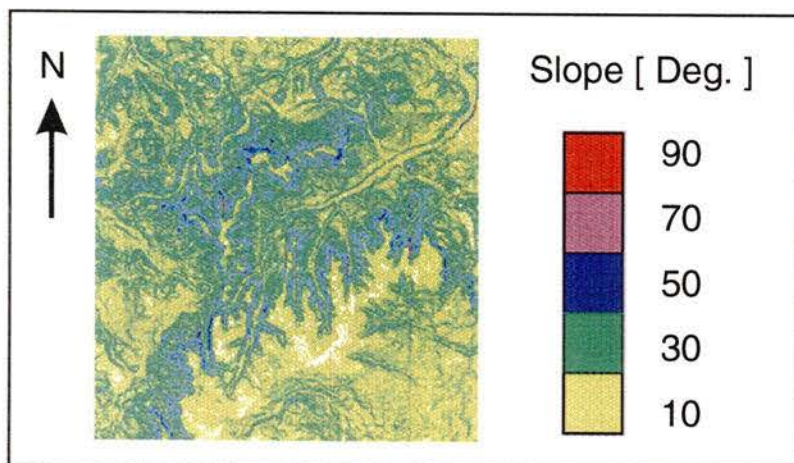
With this researcher's direction, a group of five graduate students from the University of Western Ontario developed the land evaluation hierarchy shown in Figure 7.2.



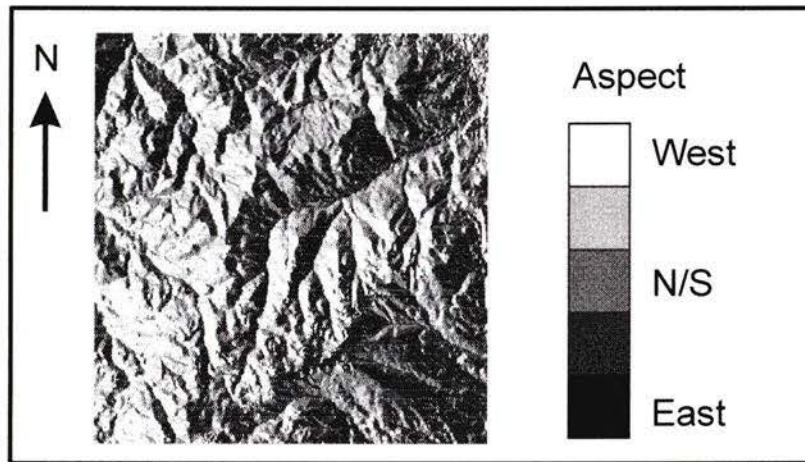
**Figure 7.2 Skiing Potential Land Evaluation Hierarchy**

The logic of the hierarchy and priority response function development is detailed in Appendix B. Of the seven data layers required by the developed hierarchy four were derived using the elevation model (elevation, slope, aspect and sunshine).

Slope and aspect base data layers are directly obtained from the elevation model.

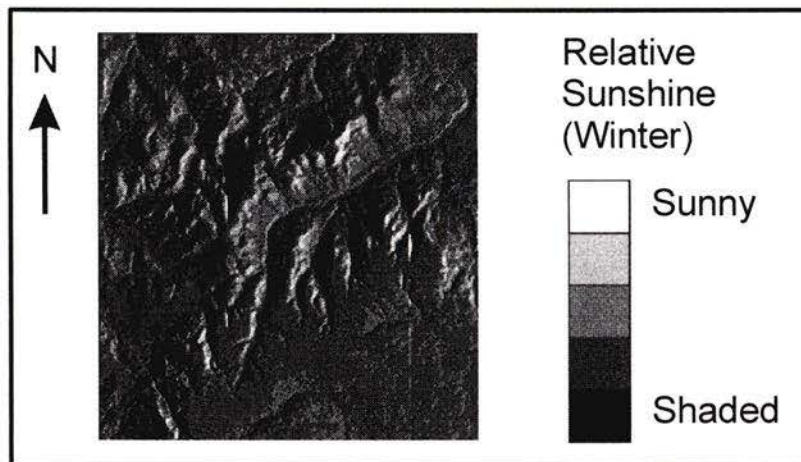


**Figure 7.3 Topographic Slope [degrees]**



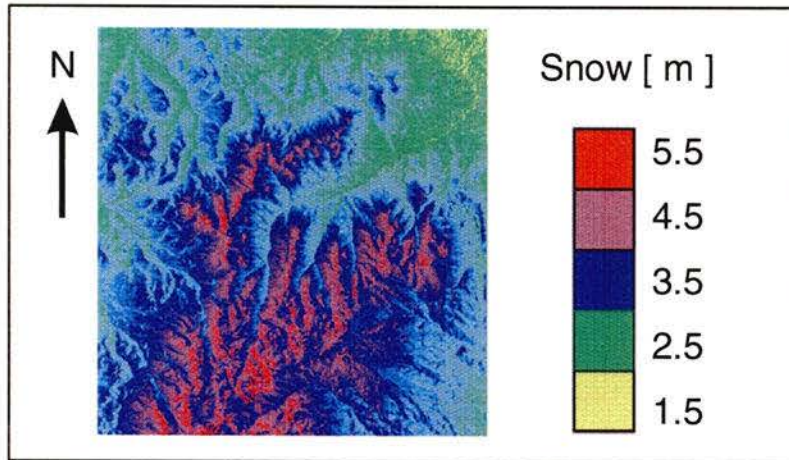
**Figure 7.4 Aspect base data layer**

Due to its relatively small geographic area ( $10 \text{ km}^2$ ) the number of sunny days is constant across the test region. There is however, some variation in amount of sunlight that actually reaches the ground due to topographic shading. A hillshade model was used to estimate an average hillshading for the region over the course of the winter season and is shown in Figure 7.5.



**Figure 7.5 Relative Sunshine**

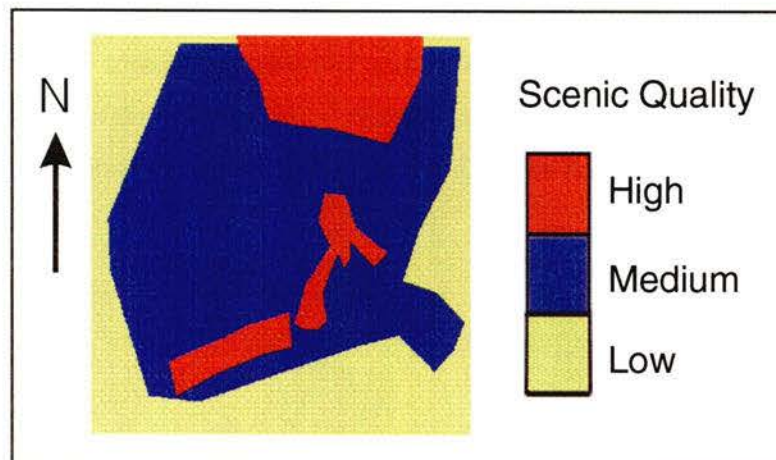
Since prevailing winds are from the west (Environment Canada, 1998), greater snow accumulation due to drifting can be expected on the eastern slopes. Some altitude influence upon the accumulation with assumed accumulations from two to five meters between low and high alpine elevations (Figure 7.6).



**Figure 7.6 Snow accumulation estimate**

As for scenic quality, Slave Lake and lowland are to the north of the study so those areas that have a generally northerly outlook of sufficient elevation were given a 'high' scenic value. Low land areas were given low scenic value and the remainder was considered as 'medium' value. This is definitely an arbitrary valuation, though it is probably still better than assuming a uniform scenic outlook for the whole region. Figure 7.7 shows the scenic value boundaries.

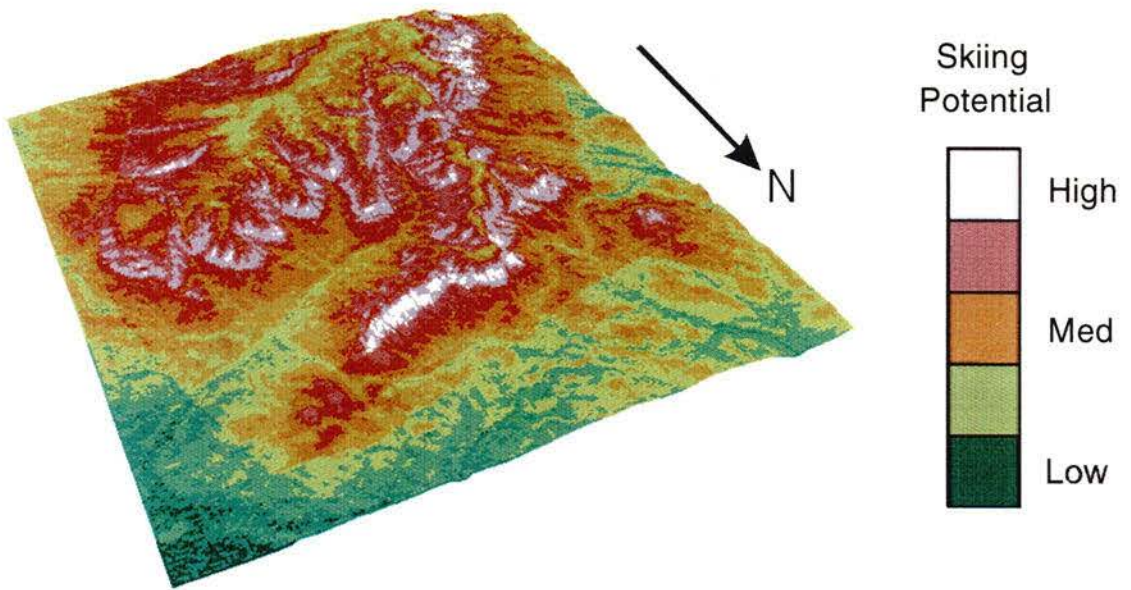
Applying the developed priority response functions (Figure B.2 in Appendix B) for each base



**Figure 7.7 Scenic Quality**

data layer to data obtained for the test area produces the composite map:

Figure 7.8 shows the resulting Skiing Potential.



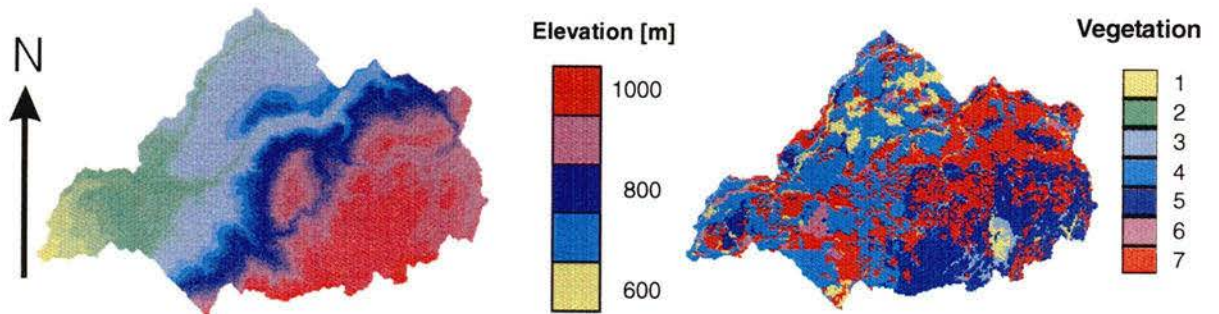
**Figure 7.8** Aggregate Skiing Potential draped over the DEM

A few observations

- The importance of an optimal snow depth is apparent as a elevation band is apparent as a desirable zone.
- The contribution of the zone of 'high scenic quality' makes the most northerly ridge the most desirable contiguous area.
- There is a large zone of high potential near the southwest corner of the study area.
- The boundary of the 'scenic quality' areas is just visible between the 'low' and 'medium' scenic quality areas along the northwestern and eastern boundaries.

The large influence of the ‘count’ variable reflects the initial assumption that the fire can only spread to neighbouring pixels.

The Marten River Watershed that flows into Slave Lake in Alberta, Canada was used for this example. The shape of the graphics reflects the watershed boundary. Two of the baseline data layers for the Marten Creek watershed are shown in Figure 7.11.



**Figure 7.11** Baseline data for wildfire model

**Vegetation Legend:** grass (1), shrub (2), bog (3), aspen (4, *aspen*, *trembling aspen*), fen (5, *black spruce*, *tamarack*), deciduous (6, *balsam poplar*, *paper birch*), and coniferous (7, *white spruce*, *lodgepole pine*, *balsam fir*).

The relative volatility of the site species shown in Figure 7.9 was taken as:

non-volatile: *wetlands*

weakly volatile: *shrubs*, *grassland*, *forbs*, *mosses*

less volatile: *aspen*, *trembling aspen*

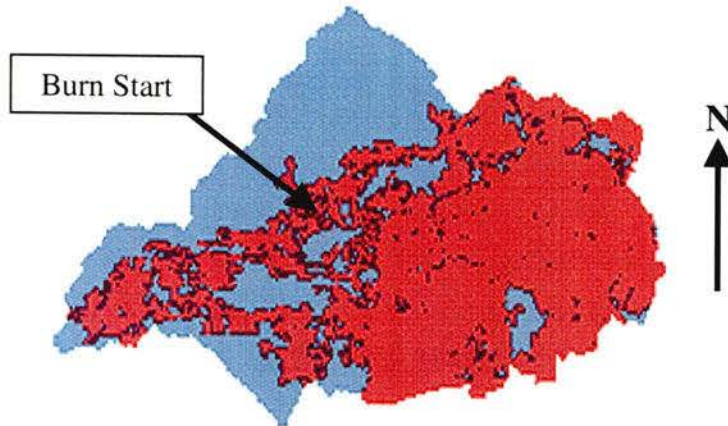
moderately volatile: *white birch*, *balsam poplar*

more volatile: *white spruce*

strongly volatile: *black spruce*, *tamarack*, *lodgepole pine*, *balsam fir*

The priority response functions for each of the baseline data layers was calculated and the generated weightings for each of those functions are obtained from Table 7.1. For example, the weighting applied to the catenary index function for site wetness is  $30\% * 33\% * 50\% = 0.0495$  and the weighting applied to the ‘aspect’ element of ‘fire-spread’ is  $70\% * 57\% * 33\% * 50\% = 0.0658$

The model assumed a fire start at the point indicated by the arrow in Figure 7.12. At each iteration, all the cells were checked to see if the “site ignition index” was greater than a threshold. If so, the site was set to burn for the next iteration. The extent of the burn is indicated in Figure 7.11 by the red shading.



**Figure 7.12 Burn Model result**

### **Conclusions**

This example demonstrates how the more general use of the concept ‘suitability’ leads to the development of a dynamic land evaluation model. The model evolves since each calculation of the ‘wild fire spread’ suitability leads to changes in one of the contributing data layers, which influence future iterations. The model continues until there is no change detected between two consecutive iterations.

This wildfire model is not presented as serious alternative to available fire models that incorporate such essential factors as wind direction and velocity, precipitation and fire breaks. It is presented as a demonstration of the utility of the AHP process for land evaluation by showing that a land evaluation hierarchy can represent the knowledge and opinions of an ‘expert’. Further, these expert opinions are available and interpretable as they stand in the hierarchy and calculated priorities. There is no need to discuss how the expert arrived at their final evaluations since their comparisons are implied by the calculated priorities. It is less important that one agrees with every valuations made by the expert and more important that one is able to interpret and understand what comparisons the expert has made so that well informed suggestions may be contributed to the evaluation process.

## 8 Conclusions

This chapter summarizes the thesis, highlighting the research justification, solution selection and software development. The chapter concludes with an emphasis on the research contributions of the thesis and avenues of further research.

### 8.1 Summary

The problem of land evaluation has been a constant companion of humankind, dating from the earliest choices of hunting grounds. Through the original settling of prime agriculture deltas and the settling of North America, humankind has long sought to optimize its use of the land and thereby its quality of life. These drives are still with us. Contemporary land managers still seek to optimize profit, advantage or the quality of life for individuals, groups or society as a whole. The relative abundance of qualitative and quantitative data for land areas has supported the desire of contemporary land managers to consider a wide spectrum of issues and concerns when planning land utilization, but the wealth of information provides challenges. In particular, a method of combining the various data layers into a single land evaluation index has remained elusive. Land managers know their decisions will continue to be scrutinized long after they have been made and consequently they have a real interest in formalizing the hitherto qualitative analysis of land evaluation.

The advent to geographic information systems and the development of inexpensive computers offers opportunity to address the desire of land managers to have a defensible method for combining data forms.

GIS has provided a computational tool for analysis of spatial data. Ranging from simple visual overlays to complex computer inference calculations, there are many techniques that have been turned to the problem of land evaluation.

Building on research from the field of decision making, a general method for the organization, consolidation and analysis of land data layers taking advantage of GIS and computing has been recognized. The essential features of the technique are:

1. Problems are deconstructed into a hierarchical form.
2. Expert input is elicited using pairwise comparisons.

3. A measure of the consistency of the expert input is calculated based upon the pairwise comparisons.
4. Formal mathematical procedures derive the relative influence of hierarchy elements from the pairwise comparisons.
5. A functional dependency of the 'strength of preference' of data layer values is derived from further pairwise comparisons between selected values.
6. An aggregate linear equation is generated as the sum of the data layers functions with the functions weighted based on the hierarchical priorities of the data layers.

With a workable method in hand, the coding of an application was the logical continuation of the research. A listing of all the factors that influence the coding method selection suggested using a decision making technique to make and justify the selection of a coding method. With an emphasis on functionality and accessibility, a composite coding method using available free software was selected. The application code was written using Perl with the mouse functionality provided by the user's web browser. The application appears as a website and interprets the mouse selections and text entries of the user to design, develop, analysis and manipulate the hierarchies. The application interprets the user's web form inputs and generates the next web page as needed. The resulting application can be run by anyone with Internet access and provides the functions for the development, analysis, management and manipulation of both general decisions between finite options and general land evaluation based on spatial data layers.

The breadth of application potential was demonstrated using two land evaluation scenarios. The first used static data layers and demonstrated a generic data layer weight derivation for indicating the suitability of land for a particular activity, skiing. The form of other land suitability analyses would be similar, though the hierarchy usable for any particular activity will depend upon the activity expert, available data and other constraints. The second example considers the incorporation of a temporal component to the land, and modeling the spreading of wildfires in a simple manner. Other examples of temporal and spatial modeling feasible using the developed method include settlement expansion, pest proliferation and seedling establishment.

## 8.2 Research Contributions and Future Research

This thesis has contributed to geographical field in two ways. It has compared the spectrum of analytic methods for the purpose of land evaluation and used an innovative coding technique to produce a general-purpose application.

The primary focus of this research has been the development of a general method for combining arbitrary data layers in a logical, understandable and defensible manner. The method, as developed, represents an advance in the general utility of GIS analysis and its contribution to land management decisions. In addition, the method development did not assume any spatial organization of data layers so can be transferred to non-geographic fields with no modification. The method encourages users to think carefully about the problem at hand by forcing them to deconstruct the process of land evaluation into a hierarchy of contributing elements. That alone may lead to insights into complex systems.

The application development using simple, free and robust programming elements represents a change in coding philosophy and some significant programming savings. Until recently, programs were usually installed and run on an individual's computer or at a central network hub. With a web style application, programs can be written for the internet world at large, freeing the developer from the chore of writing new code for different hardware platforms. In addition, since the programmer no longer has to struggle with the challenges of developing event driven interfaces from scratch, more scientists will be able to write useful programs for general consumption. Using these coding techniques the development of graphic interfaces for existing command-line programs is straightforward and can be tackled after the analytical part of the programs has been fully tested.

The general data combination method detailed in this thesis can be applied in almost any setting where factors are recognized to interact, but an empirical formula describing the interaction is lacking. Once completed, the hierarchy may be interpreted as a guide for the investigation of how specific elements contribute to the goal. The researcher can then focus their attention on a specific sub-hierarchy interaction with the knowledge their efforts have a place in the larger research agenda and will act as a logical contribution to that agenda. If an exact empirical or theoretic relationship is found for one of the sub-hierarchies, it may be introduced into the overall hierarchy with little modification. In this way, researchers may build up their understanding of a

process or question piece by piece, adding formulae where available, and relying on expert knowledge otherwise.

The application interface, as developed, can act as a template for future web-interface development. The web-interfaces for collection of surveys, program parameter entry and student testing are just some of the potential developments. Already, there are newer and more expressive tools readily available to add functionality to web-application-interfaces with great potential for research and application development.

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## Appendix A

## Decision Hierarchy Calculation

The following worked example details the steps, assumptions and organization of Saaty's Analytic Hierarchy Process (AHP). The on-line implementation of this methodology can be reached at <http://viking.geog.uvic.ca/ahp/>

The steps of the process are:

1. Formulation of the decision question.
2. Establishing the decision options.
3. Designing the decision hierarchy.
4. Gathering of pairwise comparisons.
5. Calculation of hierarchy element priorities.
6. Calculation of comparison consistencies.
7. Calculation of decision option priorities.
8. Calculation of hierarchy consistency index.

Consider the situation where you need to decide on one of three summer jobs offered in Victoria, Bella-Bella and Prince George. The AHP analysis could proceed as follows:

### 1. Formulation of the decision question:

“Which job should I choose?”

### 2. Establishing the decision options:

The options are the three jobs: Victoria, Bella-Bella and Prince George.

### 3. Designing the decision hierarchy:

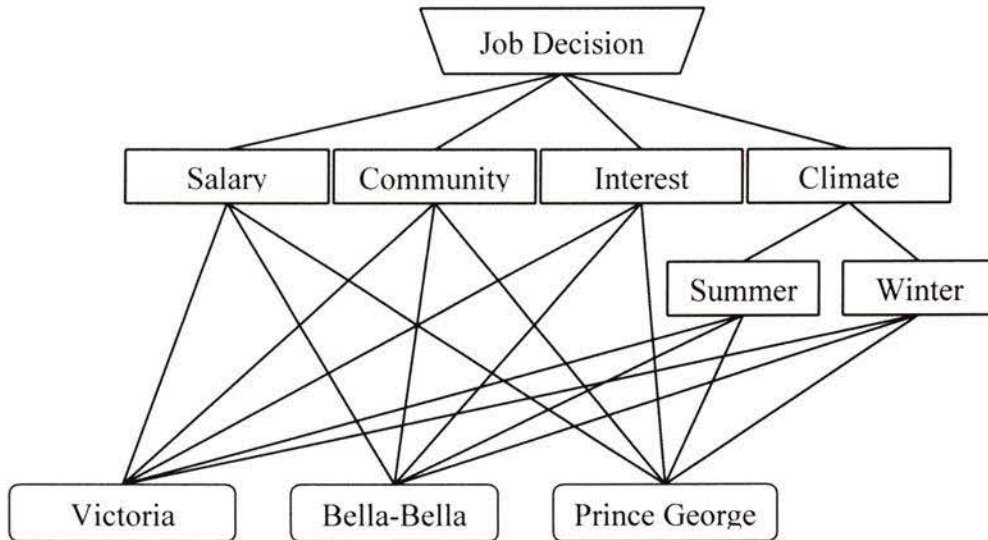
The criteria considered for this decision could be:

Salary	
Community	(sense of)
Interest	(in the work)
Climate	(of the region) [ Summer and Winter ]

There are many other criteria applicable to this decision but for the purposes of this example these are sufficient to demonstrate the essential methodological steps.

Note that all the criteria are considered in a positive sense, making pairwise comparison phrasing logical. As a counter example we could have used ‘boredom’ instead of ‘interest’ but that would have lead to illogical comparisons such as: “What is more important to the attractiveness of the job: salary or boredom?”

In graphic form this decision hierarchy looks like:



#### 4. Gathering of pairwise comparisons.

The hierarchy has a recursive structure with sub-hierarchies of elements supported by their sub-elements. Each of these sub-hierarchies is considered individually. In this example there are seven (7) sub-hierarchies.

We can start with any of the sub-hierarchies but for this example we will start with the hierarchy formed by the hierarchy *focus* (Job Decision) and the primary *elements* (Salary, Community, Interest, Climate). We will construct a 4x4 priority matrix which contains the pairwise comparisons between the elements.

Recalling Table 4.1:

Ratio Values	Definition	Explanation
1	Equal importance of both elements	Both elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgment slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgment strongly favor one element over another
7	Demonstrated importance of one element	A element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments
Reciprocals	if A compared with B equals X then B compared with A equals 1/X	

The first pairwise comparison question is: “How important, with respect to the ‘Job Decision’, are ‘Salary’ and ‘Sense of Community’?” If our response to this comparison question is “Salary is weakly more important than Sense of Community” then we put a “3” across from Salary and below Community. Since comparisons are reflexive we could equally have responded to the comparison question with: “Sense of Community is weakly less important Salary” and so we put the **0.33** (=1/3) across from Community and below Salary. In practice we fill in one half of the matrix cell and use the reflexive symmetry of the comparison matrix to complete the matrix.

Considering each pairwise comparison in turn we construct and fill the preference matrix (M1) as:

<b>Job Decision</b>	Salary	Community	Job-Interest	Climate
Salary	1	<b>3</b>	0.20	0.33
Community	<b>0.33</b>	1	0.20	0.20
Job-Interest	5	5	1	1
Climate	3	5	1	1

## 5. Calculation of hierarchy element priorities:

Calculating the Geometric Mean (GM) of the rows of M1 then normalizing gives the relative priority of the elements:

	Geometric Mean (GM)	GM	Normalize	Priority
Salary	$(1*3*0.2*0.33)^{0.25}$	0.67	= 0.67/5.21	0.13
Community	$(0.33*1*0.2*0.2)^{0.25}$	0.34	= 0.34/5.21	0.07
Job-Interest	$(5*5*1*1)^{0.25}$	2.24	=2.24/5.21	0.43
Climate	$(3*5*1*1)^{0.25}$	1.97	=1.97/5.21	0.38
	Sum of GM	<b>5.21</b>		

It should be noted that this method produces an approximation for the dominant eigenvector. Though it is a good approximation and is used by Saaty throughout his 1982 book "Decision-making of Leaders" the exact method is worth viewing. An algorithm describing the steps is:

1. raise the preference matrix, A, to powers that are successively squared each time (ie.  $A^2$   $A^4$   $A^6$   $A^8$  ...)
2. sum the rows and normalize the resulting 'column of sums' to produce a priority vector for the matrix
3. if the total absolute difference between two successive priority vectors is greater than a predetermined small error level then return to step 1 and consider the next square power of the matrix, else stop. (a typical error threshold is 0.0001)

## 6. Calculation of comparison consistencies

The reliability of the priorities calculated is related to the consistency of the pairwise comparisons entered by the user. Clearly a matrix containing highly inconsistent pairwise comparisons will lead to unreliable priorities. Though the overall consistency of a matrix is desirable, it is almost inevitable some inconsistencies will exist in larger matrices as the subjective comparisons are made (Saaty 1982, Harker and Vargas 1987).

If the pairwise comparisons are not completely consistent then some measure of the *inconsistency* is needed. Saaty's (1982) method is:

1. multiply each column of the original matrix by the average of the corresponding normalized matrix row.
2. total the rows of the resulting matrix
3. divide these row totals by the average of the normalized matrix rows
4. calculate the average of the result (=  $\lambda_{\max}$ .)
5. calculate the consistency index, CI, using the formula

$$CI = \frac{\lambda_{\max} - n}{(n-1)}$$

6. divide the result by RC (see TABLE A.1) for a matrix of similar size (n) filled at random

with values from the scale 1/9,1/8,...,1,2,..8,9. The resulting ratio is a measure of the similarity of the comparisons to a randomly filled decision matrix. A result greater than 0.1 indicates too much inconsistency in the matrix. The random consistency of matrices of size 1-10 are:

matrix size (n)	1	2	3	4	5	6	7	8	9	10
Random consistency (RC)	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

**TABLE A.1 (from Saaty 1982)**

Following these steps for the *original* matrix (M1):

<b>Job Decision</b>	Salary	Community	Job-Interest	Climate
Salary	<b>1</b>	<b>3</b>	<b>0.20</b>	<b>0.33</b>
Community	<b>0.33</b>	<b>1</b>	<b>0.20</b>	<b>0.20</b>
Job-Interest	<b>5</b>	<b>5</b>	<b>1</b>	<b>1</b>
Climate	<b>3</b>	<b>5</b>	<b>1</b>	<b>1</b>

M1 = original pairwise comparison matrix (matrix dimension = n = 4)

Normalizing the columns gives the *normalized* matrix (M2). Next, averaging the rows of M2 yields the RA values:

<b>Job Decision</b>	Salary	Community	Job-Interest	Climate	<b>Row-Average (RA)</b>
Salary	0.107	0.214	0.083	0.132	<b>0.134</b>
Community	0.036	0.071	0.083	0.079	<b>0.067</b>
Job-Interest	0.536	0.357	0.417	0.395	<b>0.426</b>
Climate	0.321	0.357	0.417	0.395	<b>0.372</b>

M2 = normalized M1

Multiplying each column of the *original* matrix (M1) by the respective row average of the *normalized* matrix (M2) produces M3. The row sums (RS) of M3 are then calculated:

	Salary	Community	Job-Interest	Climate	<b>Row-Sum (RS)</b>
Salary	0.134	0.202	0.085	0.124	<b>0.546</b>
Community	0.045	0.067	0.085	0.074	<b>0.272</b>
Job-Interest	0.670	0.337	0.426	0.372	<b>1.806</b>
Climate	0.402	0.337	0.426	0.372	<b>1.538</b>

M3 = M1 \* [ M2 row average ]

Calculating the quotient of the **RS** and **RA**:

	<b>RS</b>	<b>RA</b>	<b>RS / RA</b>
Salary	0.546	0.134	4.07
Community	0.272	0.067	4.03
Job-Interest	1.806	0.426	4.24
Climate	1.538	0.372	4.13

Averaging the RS/RA column gives  $\lambda_{\max} = 4.12$

Using the *CI* formula:  $CI = \frac{\lambda_{\max} - n}{(n-1)}$   $CI = (4.12 - 4)/3 = 0.039$

From the TABLE A.1 we have  $RC = 0.90$  so  $CR = 0.03 / 0.9 = 0.043$ .

*CR* is a measure of *inconsistency* so low values are desirable. Saaty (1986) uses the value of 0.10 as a threshold between acceptable (*RC* less than 0.10) and unacceptable (*RC* greater than 0.10) inconsistency.

Repeating the above process for the other pairwise comparison matrices of the decision hierarchy produces the following results:

Salary	V	BB	PG	Priority	CR
Victoria	1	0.25	0.5	0.14	0.013
Bella-Bella	4	1	3	0.63	
Prince George	2	0.33	1	0.24	

Community	V	BB	PG	Priority	CR
Victoria	1	4	6	0.70	0.009
Bella-Bella	0.25	1	2	0.19	
Prince George	0.167	0.5	1	0.11	

Job Interest	V	BB	PG	Priority	CR
Victoria	1	1	0.25	0.18	0.046
Bella-Bella	1	1	0.5	0.23	
Prince George	4	2	1	0.58	

Climate	S	W		Priority	CR
Summer	1	2		0.67	0.0
Winter	0.5	1		0.33	
Summer	V	BB	PG	Priority	CR
Victoria	1	5	6	0.72	0.081
Bella-Bella	0.2	1	3	0.19	
Prince George	0.167	0.33	1	0.09	
Winter	V	BB	PG	Priority	CR
Victoria	1	4	0.25	0.22	0.032
Bella-Bella	0.25	1	0.11	0.07	
Prince George	4	9	1	0.72	

### 7. Calculation of decision option priorities.

Now that all the comparisons are completed we can compute the overall priority of the three city choices and estimate the aggregate consistency of all the comparisons.

Rewriting the results in a concise tabular hierarchy form gives:

Job Decision		(V, BB, PG)	(V, BB, PG)
0.13	<b>Salary</b>	(0.14, 0.63, 0.24)	
0.07	<b>Community</b>	(0.70, 0.19, 0.11)	
0.43	<b>Job-Interest</b>	(0.18, 0.23, 0.58)	
0.38	<b>Climate</b>		
	0.67	<b>Summer</b>	(0.72, 0.19, 0.09)
	0.33	<b>Winter</b>	(0.22, 0.07, 0.72)

Values to the left of hierarchy elements show the priority of the elements with respect to their dependent element. The values in brackets show the calculated priorities for each of the choice options with respect to the base hierarchy elements, which appear to the left of the bracketed values.

The aggregate priority for each of the choice options is calculated as the sum of the contributing priorities. For **Victoria** the contribution from the **Salary** element is equal to the ‘priority of **Victoria** with respect to **Salary**’ times the ‘priority of **Salary** with respect to the **Job Decision**’:  $0.14 * 0.13 = 0.0172$ . Similarly, the priority contributions of community and job-interest are calculated. For **Victoria**, the contribution from the **Summer** element is equal to the ‘priority of **Victoria** with respect to **Summer**’ times the ‘priority of **Summer** with respect to **Climate**’ times the ‘priority of **Climate** with respect to the **Job Decision**’:  $0.72 * 0.67 * 0.38 = 0.1833$ .

The total priorities for the three choices are calculated as:

$$P_{Vic} = 0.14 * 0.13 + 0.70 * 0.07 + 0.18 * 0.43 + 0.72 * 0.67 * 0.38 + 0.22 * 0.33 * 0.38 \approx 0.35$$

$$P_{BB} = 0.63 * 0.13 + 0.19 * 0.07 + 0.23 * 0.43 + 0.19 * 0.67 * 0.38 + 0.07 * 0.33 * 0.38 \approx 0.25$$

$$P_{PG} = 0.24 * 0.13 + 0.11 * 0.07 + 0.58 * 0.43 + 0.09 * 0.67 * 0.38 + 0.72 * 0.33 * 0.38 \approx 0.40$$

These priorities indicate the *relative* priority of each of the choice options with respect to our decision objective. We can conclude at this point that the job in Prince George is the most desirable.

## 8. Calculation of hierarchy consistency index.

A measure of the overall consistency for the pairwise comparisons gives a method of evaluating the reliability of the final calculated choice priorities. To calculate the aggregate consistency of all the comparisons it is easier to first subtract all the *inconsistency* values (CR) from one (1). This transformation produces a measure of *consistency* ranging from zero (0.0) for completely inconsistent comparisons to one (1.0) for completely consistent comparisons. The overall hierarchy consistency is then calculated as the aggregate sum of all consistencies weighted by their respective hierarchy priority.

For the example hierarchy the calculation is as follows:

$$CH \approx 0.13 * 0.987 + 0.07 * 0.991 + 0.43 * 0.954 + 0.38 * 1.0 * (0.67 * 0.919 + 0.33 * 0.968)$$

$$CH \approx 0.96$$

Since 0.96 is greater than 0.9 we can say that the hierarchy has an acceptable level of *inconsistency* (ie.  $0.04 < 0.1$ ).

## Appendix B

## AHP for Land Evaluation Example

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The following worked example details the steps, assumptions and organization of the developed general land evaluation methodology. The on-line implementation of this methodology can be reached at <http://viking.geog.uvic.ca/ahp/>

There are many computational similarities between the general land evaluation methodology and Saaty's original AHP. Only the differences between the two methodologies are detailed in this appendix. See appendix A for a detailed example of the AHP as developed by Saaty.

The steps are:

1. Specification of evaluation objective.
2. Establishing the contributing data layers.
3. Designing the decision hierarchy.
4. Gathering of pairwise comparisons.
5. Calculation of hierarchy element priorities.
6. Calculation of data layer priority functions.
7. Calculation of consistencies.
8. Formulation of evaluation function.

Consider the situation where you are asked to evaluate the land for the purpose of a skiing. The resulting graphic will show the *relative* suitability of the land for skiing. The implementation could proceed as follows:

### 1. Specification of evaluation objective

The goal of this example evaluation is an indication of the "suitability for skiing" so the goal of the hierarchy evaluation could be labeled 'Best Skiing'. In general, short, descriptive hierarchy element labels work well.

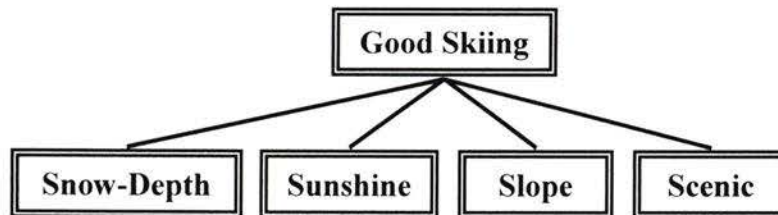
### 2. Establishing the contributing data layers

We will assume we have basic topographic, climatic information and some scenic valuation for the area under consideration: a digital elevation model (DEM), precipitation records and the results of tourist survey on the scenic outlook beauty within the region. From the DEM the slope, aspect, and altitude can be directly obtained. The climatic data will be assumed to contain the

snowfall for the area of interest and some indication of the number of clear days across the region. The scenic survey delineates areas with 'high', 'medium' and 'low' scenic outlooks.

### 3. Designing the decision hierarchy

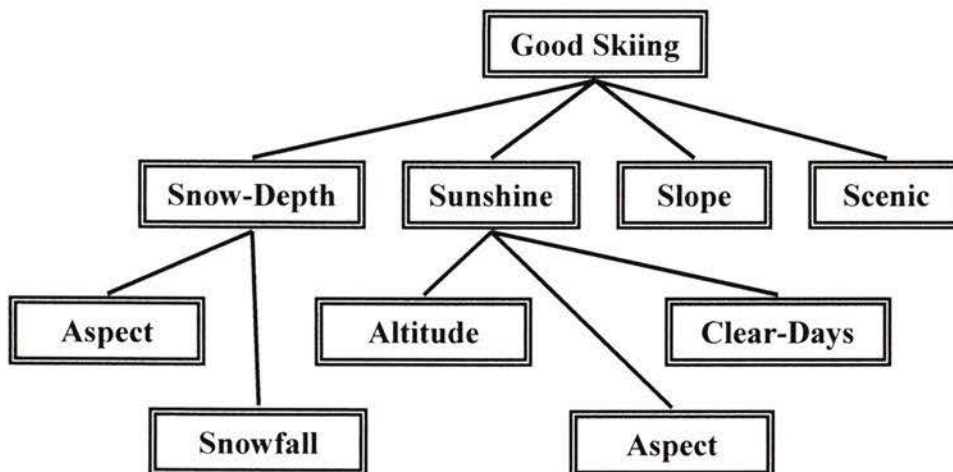
Three basic influences on the suitability of an area for skiing are snow, sunshine and scenic beauty. There are other influences such as proximity to skiers, transportation facilities and support infrastructure but for this example we will focus on the suitability of the land and leave the question of "where is best the place to build a ski-resort?" for others. The basic hierarchy with the three influences would look like:



'Snow Depth' is dependent on the balance between snowfall and how quickly the snow pack melts. The aspect and snowfall base layers contribute to these factors.

'Sunshine' is dependent upon actual sunlight hours, aspect of individual areas within the region and whether the area is shaded by nearby mountain peaks. The base layers 'clear-days', 'aspect' and 'altitude' contribute to these factors.

The base layers 'slope' and 'scenic' can be used directly. The completed hierarchy looks like:



#### 4. Gathering of pairwise comparisons

Using the AHP methodology the priorities of the elements for each sub-hierarchy within the hierarchy is obtained by pairwise comparing the sub-elements:

Snow Depth, Sunshine & Slope are pairwise compared with respect to 'Good Skiing'.

Aspect & Snowfall are pairwise compared with respect to 'Snow Depth'.

Altitude, Aspect and Clear-Days are pairwise compared with respect to 'Sunshine'.

For each of the hierarchy elements which is base data layer (aspect, snowfall, altitude, clear-days, slope and scenic) we need to select *key* values which will be used to derive the *priority response function* for each of the elements. Some guidelines for the selection of the *key* values are given below for ordinal, interval and ratio data forms.

##### Ordinal data

Select one key element for each unique data value.

##### Interval or Ratio data

1. select the minimum of the data range
2. select the maximum of the data range
3. select the data value which has the minimum priority
4. select the data value which has the maximum priority
5. select data values which mark discontinuities in the response function
6. select data values which mark changes in the slope of the response function

Considering each base data layer in turn:

'Aspect' is an interval data layer and appears twice in the hierarchy. As a contributor to 'Snow Depth', 'Aspect' has key values of 0, 90, 160, 235 and 360 [degrees]. These are chosen using guidelines 1, 6, 6, 4 & 2 respectively. As a contributor to 'Sunshine', 'Aspect' has key values of 0, 90, 180, 270 & 360 [degrees] chosen using guidelines 1, 6, 4, 6 & 2 respectively.

'Snowfall' contributes to 'Snow Depth' and has key values of 0, 1, 2, 3, 3.5 & 5 [meters] chosen using guidelines 1, 5, 6, 5, 4 & 2 respectively.

'Altitude' contributes to 'Sunshine' and has key values of 1000, 1999, 2000, 2500, 2501 & 4000 [m] chosen using guidelines 1, 5, 5, 5, 5 & 2 respectively.

'Clear Days' contributes to 'Sunshine' and has key values of 0 & 150 chosen using guidelines 1 & 2 respectively.

'Slope' has key values of 0, 5, 25, 45, 70 & 90 chosen using guidelines 1, 5, 6, 4, 5, 2 respectively.

'Scenic' is an ordinal data type so we choose 'high', 'medium' and 'low' as its key values.

With the key values chosen for each base element we can pairwise compare the *key* values with respect to the *element immediately superior* to the base element.

One of the 'Snowfall' pairwise comparisons would be:

'With respect to *Snow Depth* how much more preferred is a *snowfall of 2m* than a *snowfall of 4m*?'

One of the pairwise comparisons for 'Slope' would be:

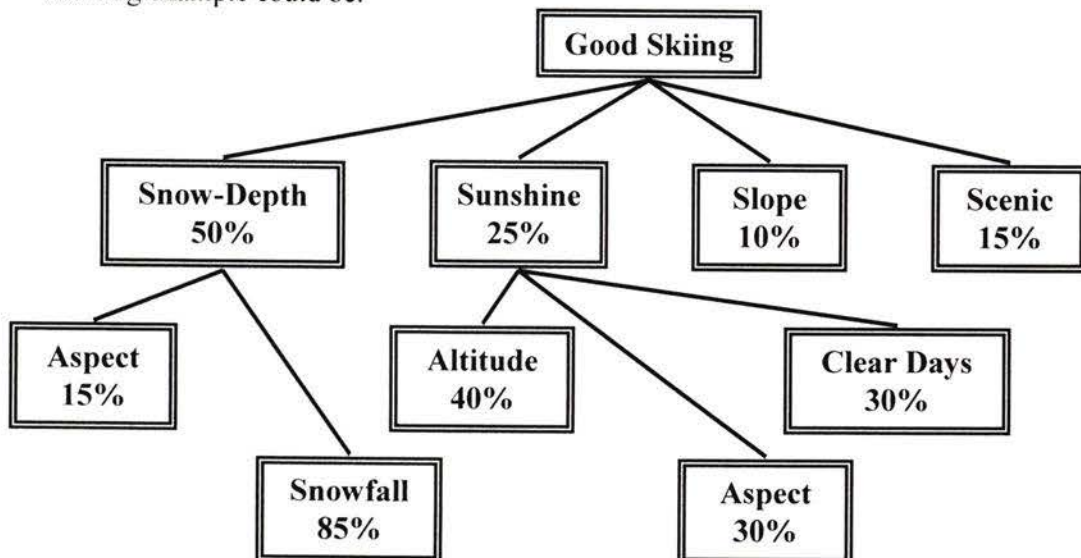
'With respect to *Good Skiing* how much more preferred is a *slope of 25 degrees* than a *slope of 45 degrees*?'

One of the pairwise comparisons for 'Scenic' would be:

'With respect to *Good Skiing* how much more preferred is *medium scene quality* than *low scene quality*?'

## 5. Calculation of hierarchy element priorities

The priorities and consistency indices for each sub-hierarchy above the base elements is calculated using the methodology detailed in Step 5 of Appendix A. The priority results for the working example could be:



The priority weighting of each of the base elements,  $W_i$ , is obtained as the product of its' dependent elements and its own priority weighting. For the example:

$$\begin{aligned} W_1 &= W_{\text{aspect.1}} \\ &= (\text{Priority of Aspect with respect to Snow Depth}) * (\text{Priority of Snow-Depth with respect to Good Skiing}) \\ &= 15\% * 50\% \\ &= 7.5\% \end{aligned}$$

Similarly :

$$\begin{aligned} W_2 &= W_{\text{snowfall}} = 85\% * 50\% = 42.5\% \\ W_3 &= W_{\text{altitude}} = 40\% * 25\% = 10\% \\ W_4 &= W_{\text{aspect.2}} = 30\% * 25\% = 7.5\% \\ W_5 &= W_{\text{clear\_days}} = 30\% * 25\% = 7.5\% \\ W_6 &= W_{\text{slope}} = 10\% \\ W_7 &= W_{\text{scenic}} = 15\% \end{aligned}$$

The sum of these weights,  $W_{1,7}$ , is 100%. These relative priorities of the base elements will be used as weighting factors when the elements are combined.

## 6. Calculation of data layer priority functions

The selection of *key* values for each of the base elements provides a means of estimating a priority response function which will represent the manner the suitability varies with changing base element values. This is accomplished for each element by making pairwise comparisons between the chosen *key* values with respect to the *element immediately superior* to the base element.

Two of the fifteen (15) 'Snowfall' pairwise comparisons are:

'With respect to *Snow Depth* how much more preferred is a *snowfall of 1m* than a *snowfall of 3.5m*?'

and

'With respect to *Snow Depth* how much more preferred is a *snowfall of 2m* than a *snowfall of 5m*?'

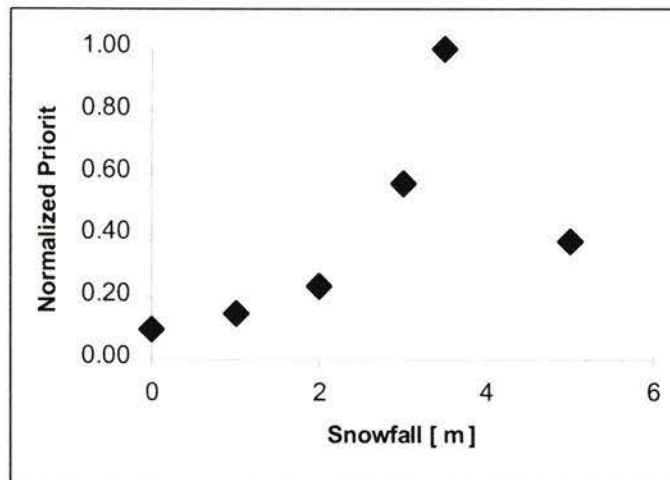
Completing the pairwise comparison matrix for 'Snowfall' we have (for example):

### Snowfall

	0m	1m	2m	3m	3.5m	5m	Priority	RC
0m	1	0.50	0.33	0.20	0.14	0.25	0.04	0.02
1m	2	1	0.50	0.33	0.17	0.25	0.06	
2m	3	2	1	0.33	0.25	0.50	0.10	
3m	5	3	3	1	0.50	2	0.23	
3.5m	7	6	4	2	1	4	0.41	
5m	4	4	2	0.50	0.25	1	0.16	

Since the magnitude of the maximum priority is dependent on the number of comparison elements we normalize the priorities of the key values so that the maximum is always 1.0. This ensures proper priority contribution scaling between base element irrespective of the number of key values chosen for each base element.

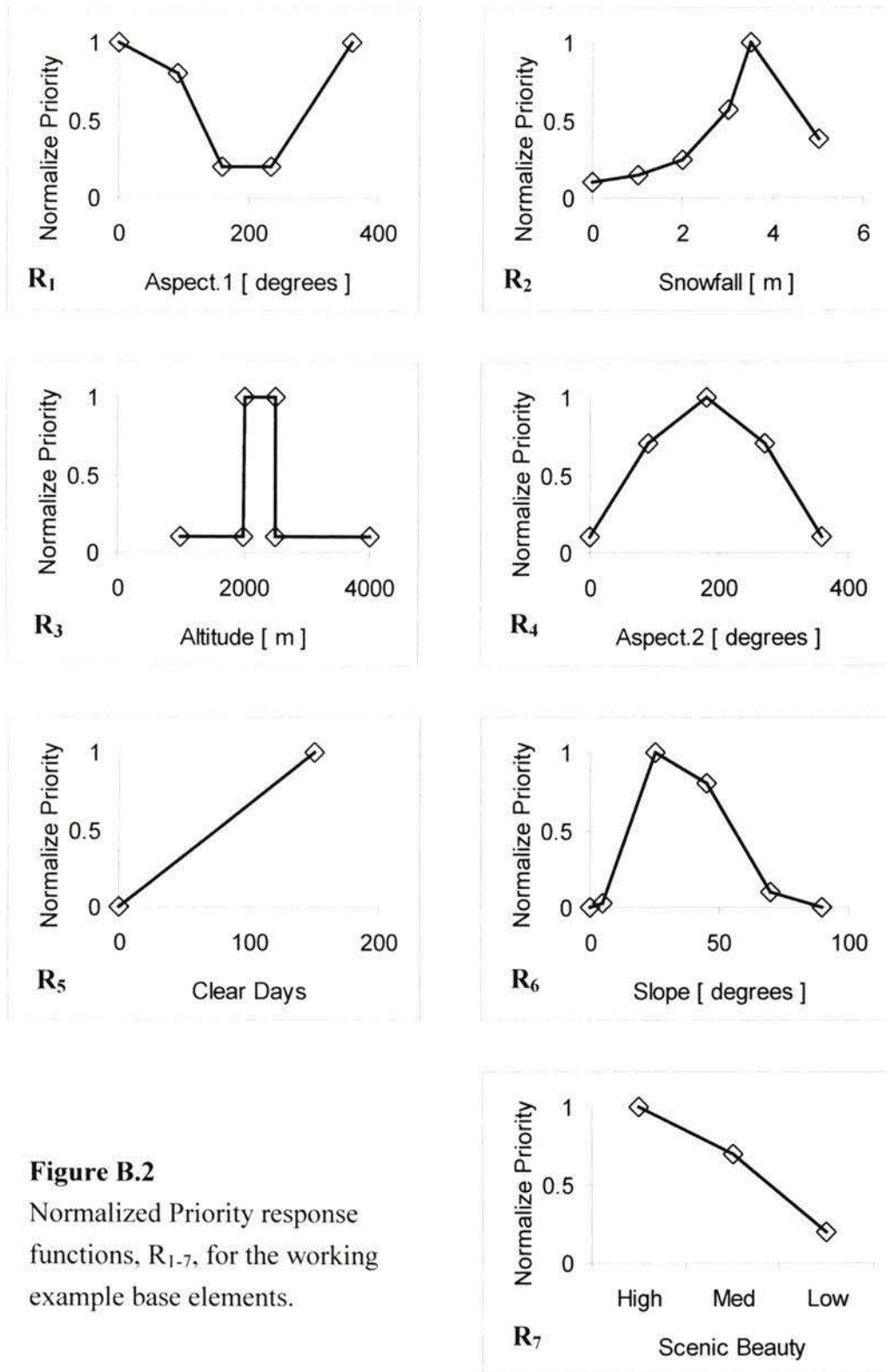
The normalized priority values for the 'Snowfall' key values above are then 0.10, 0.15, 0.24, 0.57, 1.0 & 0.38 and a graph of these data points is:



**Figure B.1** Normalized Priorities of Snowfall with respect to Snow Depth

Joining the priority response data points in Figure B.1 creates an estimate of the *priority response function* that can be used to estimate the priority contribution for arbitrary snowfall values.

Repeating this process for the other base elements produces the graphs in Figure B.2. These response functions,  $R_{1-7}$ , are used to interpolate an appropriate response for values between the



**Figure B.2**

Normalized Priority response functions,  $R_{1-7}$ , for the working example base elements.

*key* values used to form the functions. Linear interpolation lines are shown in Figure B.2 to indicate the interpolation method to be used in this example.

With the response functions completed the final step is to combine the response functions into a single function,  $F$ , which will be used to calculate the suitability score for our example question.

### 7. Calculation of consistencies.

Consistency calculations are detailed in Step 6 of Appendix A.

### 8. Formulation of evaluation function.

The aggregate function,  $F$ , has the form:

$$F(p) = \sum_{i=1}^n W_i [R_i(p)]$$

$F(p)$  : the value of the function at position  $P$

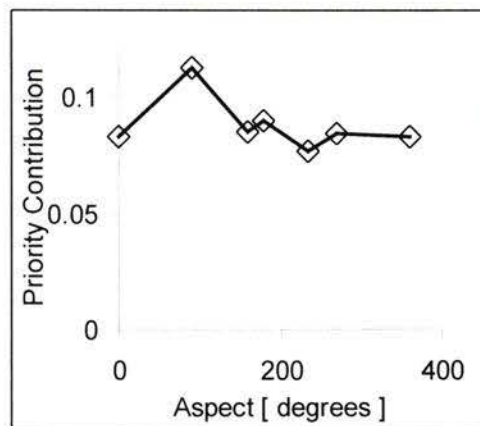
$n$  : the number of base elements

$W_i$  : the priority weighting of the  $i^{\text{th}}$  base element

$R_i(p)$  : the value of the  $i^{\text{th}}$  base element response function evaluated at position  $P$

Since aspect appears twice in the hierarchy there are two response functions calculated for it,  $R_1$  and  $R_4$ . We can combine these two functions to find the total effective response function for aspect:

$$F_{\text{aspect}} = W_1 R_1 + W_4 R_4 = 0.075 * R_1 + 0.075 * R_4$$



**Figure B.3** Aggregate Priority Contribution for Aspect

Figure B.3 shows the aggregate response function as more complex in form than its contributing functions and illustrates how the methodology can ‘model’ subtle element contribute variations. Note the vertical scale for this graph is 0-0.12. The effective priority contribution for aspect is approximately 10%.

This appendix discusses the reasons for computerization of the AHP method, the general avenues of implementation, the specific criteria used to choose implementation methods, and the method selection.

### **C.1 Automation Suitability**

Analysis of the structure of the process is the first step of automation. Breaking a process down into its component steps (or routines) is called the 'top-down' design method (Dahl 1972). With this in mind an AHP application will need the following steps and sub-steps:

- A. Hierarchy Design
  - Goal designation
  - Sub-element placement
- B. Gathering of Pairwise Comparisons
  - Organizing the comparisons
  - Comparison entry
- C. Calculation of Priorities & Consistencies
  - Matrix manipulation
  - Calculations
- D. Display of Results
  - Priority listings
  - Consistency statistics
  - Graphics of relative contributions
- E. Utilization of Results
  - Interpretation
  - Refinement of comparisons

The AHP requires the organization, display and manipulation of hierarchical structures. Computers are well suited for handling data structures containing clearly defined objects, performing repetitive tasks and displaying visual representations of numerical entities. It makes intuitive and logical sense, therefore, to automate the AHP, taking advantage of the digital computing.

The computer can be programmed to:

- facilitate the design of hierarchies through clear hierarchy schematics;
- automate the data entry form generation;
- calculate all element priorities and consistency coefficients;
- and generate descriptive graphics.

Freed from these numerical, clerical and graphic creation tasks the user will be able to concentrate on the more imaginative and expert tasks:

- conceptualizing the hierarchical structure;
- contemplating the individual pairwise comparisons;
- reviewing the resulting priorities and
- fine tuning the hierarchy as a whole.

## C.2 AHP Software

A software version of the AHP is available from [www.expertchoice.com](http://www.expertchoice.com) and is called First Choice™. Developed and marketed to the business community this software allows for the development of general decision hierarchies, collection of pairwise comparisons, and calculates the resulting priorities. First Choice™ provides a good example of an interface allowing the user to see the developing hierarchy as it forms.

Another PC application of the AHP is the Aliah™ Decision Modeling System by Flagship Products™. A search of the web revealed a Java applet AHP site (<http://summer.ics.nitech.ac.jp/~itota/research/AHP/AHP.html>) under construction.

Hoffman (1984) demonstrated how to do the AHP using a spreadsheet.

As mentioned in Chapter 4, the GIS software *Idrisi* developed at Clark University also has incorporated a decision support module that uses the AHP method to generate the relative priorities of decision options. It does not, however, allow the construction of anything but simple comparison matrices. Using their software the user can calculate the relative priorities between a finite set of options and perhaps could be used to inter-compare a set sites using the method described by Banai-Kashani (1989). Further, the method of data input is the simple matrix format, which does not allow the user to easily use natural language when defining the comparisons between elements as Saaty (1977) method prescribes.

### C.3 Development Software Options

The extension of AHP for GIS applications demands certain modifications to the AHP method, specifically to accommodate the combination of different data types. A specialized interface was envisioned to bridge the gap between the user and an arbitrary GIS. The conceptual design of the interface is a mostly mouse driven windowed environment which could be used in conjunction or simultaneously with the GIS.

The criteria considered important in this development are listed in Table C.1.

1	ease of coding development
2	availability of flexible interactive tools for basic user input
3	processing speed
4	intuitive pairwise comparison input method
5	dynamic hierarchy development
6	visualization of results
7	availability to prospective users

Table C.1 Development criteria

There are literally hundreds of possible languages and environments where development would be possible. The special needs of this development focus the programming needs on two forms of coding: Scripting within a GIS application and coding a stand alone application.

Three representative coding methods readily available at the University of Victoria's Spatial Sciences Laboratory are:

- AML - ArcInfo's macro language (AML)
- Visual C - a general purpose windows based programming language
- Perl 5.0 - a general purpose reporting language

These three programming methods will be considered individually with respect to the listed development criteria (Table 5.1). References for this section are: ArcInfo Help (ESRI 1998), Visual C++ (MicroSoft 1998) and Perl Programming (Wall et al. 1996).

### C.4 Ease of Development

The three programming methods considered allow the fundamental programming constructs of looping, branching and subroutines that were essential in the development of the application. AMLs and Perl programs are written using any text editor. AMLs are scripts, each line of the

AML is considered in sequence and acted upon, and no pre-compile checks for syntax errors within scripts are made. Each line is considered separately and all syntax errors are found as the script is processed. GIS commands can be seamlessly inserted within the program as the AML interpreter reads in the script line, decides whether the line of code is a programming construct or a GIS command and then executes the appropriate action. This combination of scripting versatility and linkage with a powerful GIS make scripts such as AMLs very useful for automating repetitive GIS tasks.

There are a number of problems with using AMLs. They will be discussed individually in the sections below. However, one problem is worthwhile highlighting as it impacts the development ease: AML variables are tagged using bracketing percent (%) symbols so the string %A% is interpreted as the 'value of the variable A'. In form dialog files, the files that describe the appearance of user interaction dialogs, the percent symbol is also used as an interpreter flag so when an AML is written to create dynamic dialogs the % symbol must be written and used simultaneously. The resulting programming is cumbersome and difficult to write cleanly. This, in turn, will make future correction and modification of the code unnecessarily challenging.

Though all high level programs can be written using only text editors, in practice this programming technique is no longer used when writing code in visual codes, such as Visual C. A graphical interface allows the programmer to develop intuitive and familiar program interfaces more quickly as much of the difficult window management is handled automatically by the integrated development environment (IDE). This does, however, make it complex to program applications whose interface react dynamically to changing parameters. Applications need then to be constructed 'at arms length' so that appropriate changes are made automatically. All syntax errors are trapped when the program is compiled into binary (executable) form.

Perl is a pre-run compiling language and the program is compiled before each run. Syntax errors are trapped at this time. Available at no cost on the Internet, Perl 5.0 is popular with website developers because of its large array of text manipulation functions and programming ease. ([www.perl.com](http://www.perl.com))

## **C.5 Interactive Tools**

The transition from command line to mouse driven programs has resulted in a standardization of the design and 'feel' of computer programs. Object oriented programs with event handling

processes that control and monitor the actions of the mouse are the standard for development. To create a viable predominantly mouse driven interface some specific visual ‘widgets’ are useful:

- Action buttons : - causes an action or calculation to occur.
- Radio buttons : - the user can select one, and only one, of a set of these buttons at a time: no action occurs when these buttons are pressed other than they appear checked or depressed to indicate they are selected.
- Check box : - a box which can be toggled between on and off states.
- Entry box : - text entry box where the user can type in information.
- Selection list : - selection list from which the user can make a selection; only the current selection is visible; pressing the selection makes other choices appear as a list from which a new choice can be made.
- Slider : - the user can select a value (usually numeric) by dragging a indicator box along a graphic line;.
- Dropdown Menu : - a constantly visible keyword can be mouse-clicked to reveal a list of related commands which execute when selected.

The AML interpreter provides a method of creating mouse clickable widgets using a ‘form’ method. A text file containing key words and symbols defines the organization of the interface dialog window. Using this method all of the above listed widgets are available though there is little control over the font, size and orientation of the tools as they appear. Menus can be used to call up form interfaces which collect the user’s input and then execute calculations and GIS commands when an ‘action button’ is pressed (ESRI, 1997).

Visual C also provides the means of creating all of the above listed tools. In addition the programmer can completely control the organization and appearance of all tools and menus (Microsoft, 1998).

Perl 5.0 cannot directly generate a graphic interface. A version of Perl, Perl/TK, is a windows based object oriented development language that allows the creation of windows based programs much like Visual C. Perl 5.0 can, like most programming languages, write to text files and these text files can be interpreted as a graphic interface just as AMLs use text files to represent dialog forms. One of the fundamental components of Internet websites is also text files. Properly constructed, these text files are interpreted by a web browser (such as Navigator™, Explorer™ or

Mosaic™) as a webpage containing text, graphics and user input tools. All the tools listed above are available though sliders and menu selection systems require using more advanced web development tools such as a Javascripts. It is possible that the Hyper Text Markup Language (HTML) standards will grow to encompass sliders and menu selections in the future.

### **C.6 Processing Speed**

AMLs process slowly, as each line of the script is interpreted sequentially. This is particularly evident when long looping commands are executed and complex variable manipulation requires long command lines. Visual C produces very fast programs as they are run at binary speeds directly from the compiled state. Perl's pre-run compilation introduces a short delay before running at binary speeds.

The calculations demanded by the AHP involve arrays and real numbers, but are not complex. Even the AML program tested showed only minor hesitation before finishing its calculations. The execution of Perl programs is similar to the C programs, once the initial compilation is completed. Visual C programs run extremely quickly and often appear to react instantaneously to user input.

### **C.7 Pairwise comparison input method**

The most fundamental part of the AHP is the gathering of pairwise comparisons between hierarchy elements. The developed application interface should be user friendly. That is, it should be concise, easy to interpret, logical to navigate and present the comparison questions as clearly as possible. Saaty (1977-1993) puts emphasis on natural wording to describe the comparisons between hierarchy elements. He comments that since the numeric values associated to these comparison phrases are used in an exponential manner during the priority calculation it is misleading to think of the comparison scale as simply linear (Saaty 1980, p.46). An application developed around Saaty's work should therefore present the comparison phrases in a manner that is as close to 'natural language' as possible.

Using AML, a series of 'widgets' are available (action buttons, scroll bars, text input boxes and choice buttons) and provide a means of creating mouse driven dialog windows for gathering information from the user. These dialog windows are text files that use simple codes to describe the widgets and their organization within the dialog. The power of this method is the idea that since AMLs can write to text files, an AML can create a dialog in response to user input and then

call up the newly created dialog, tailored to the current state of the process, to gather more information from the user.

There are a number of ways to input pairwise comparisons using the dialog widgets listed. We will consider the matrix, questionnaire, slider and selection menus.

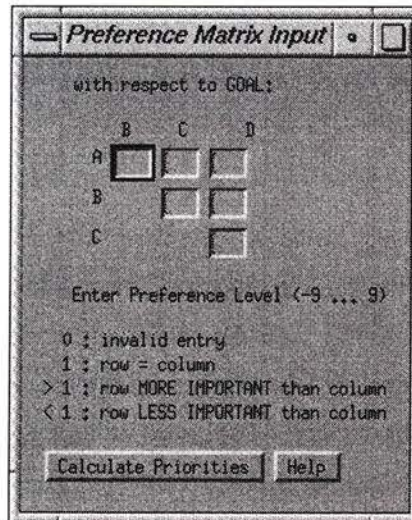


Figure C.1 Matrix Input

Figure 5.1 shows the inputs for a 4x4 matrix, using text input boxes. The 6 comparisons (A-B, A-C, A-D, B-C, B-D & C-D) complete the input since the entries are inversely related across the matrix diagonal. The interface is simple and concise but requires the user to be familiar with the significance of the values to be entered. Using this input method would require online help to guide the user in the data entry or a descriptive tutorial to introduce the user to the input method. Once familiar with the method, the user can be guided with brief instructions included on the dialog box. A help button could bring up more detailed instructions including the implied descriptive comparison statements (Table 3.1).

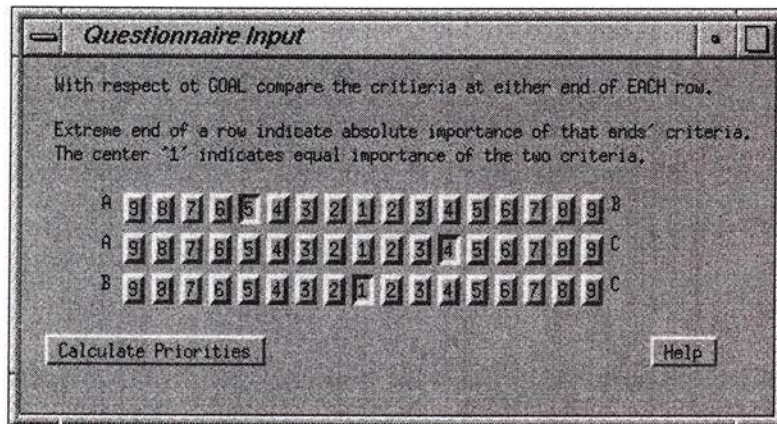


Figure C.2 Questionnaire Input

Questionnaire input (Figure 5.2) presents an array of buttons to the user. Each row of buttons is a 'choice widget' which allows only a single entry per line. Selecting any button on a line automatically deselects all the other buttons on the line. This form of data entry is common for surveys and questionnaires though usually the number of possible values is limited to 5 or so (Miller 1956). Users have been found to treat the value list as a linear continuum (Keller et al. 1996) which is an incorrect interpretation of the comparison scale of the AHP (Saaty, 1980). Further instructions can be provided to the user through the use of an automatically visible window or using a 'help' button, as shown.

The AML development of the AHP interface using questionnaire input-forms is difficult for a number of reasons.

- a) AMLs are limited to 100 entities per dialog window and since all the buttons and text words are counted separately this method is limited to 4x4 matrices as shown in Figure 5.2. This is serious shortfall as matrices of up to 8x8 are envisaged for the AHP interface. By eliminating even values, the number of buttons is reduced by approx. 50% and the dialog can handle up to 6x6 matrices. This is minimally acceptable but the reduction of choices also reduces the sensitivity of user input. Alternately the questionnaire could be split between a number of dialog boxes but this leads to multiple overlapping windows which are hard to navigate for the user and quickly complicates the programming for the developer as each dialog has to be written and referenced dynamically by the main AML.
- b) The organization of the interface dialog is defined by the placement of text within a descriptive text file. The positions of the percent "%" key symbols within the text file are

critical as the row:column position of the “%” relates directly to the visualized position of the input ‘widget’ the user sees. When the graphic dialog is displayed it does not use fixed width fonts so the careful alignment of the defined widgets and text may not be accurately translated to the dialog. There is a method of ‘tagging’ certain columns and using them to control the horizontal spacing of dialog entities, but it is not easily implemented in a dynamic manner, as the AHP interface will require.

- c) The ‘%’ symbol is used to define variables within AML scripts, tag widget positions in AML dialog files and signal widget definitions. The multiple use of a single symbol complicates the programming process and the finalized code.

Visual C does not limit the number of choice boxes. The programming environment provides the means to completely organize the appearance of interface dialogs.

Web browsers do not appear to have any limit on the number of radio buttons (equivalent to choice boxes) but the button value cannot be displayed directly on the button. One labeling method is to put the descriptive text to one side, below or above the button which works well when the number of clustered buttons is small.

Using sliders (Figure 5.3) is a concise method of gathering comparison information. The user can either drag the slider marker to the desired point or enter the comparative value in the entry box shown to the left of each slider. The interface is easily understood by users and can be expanded to up to 7x7 matrices without exceeding the 100-entity limit of AML form dialogs. Since the scale runs from -9 to +9 (the sliders are locked into a monotonic scale) some explanation must be provided that the negative values represent the reciprocals of the positive comparison values (Table 3.1). In addition, some explanation of the implied link between the linear (slider) input method and the non-linear comparison phrases. Users could find this level of abstraction confusing and unnecessarily obscure. AML sliders do not have reference markers along the slider but provide an input box for the manual typing in of a specified value.

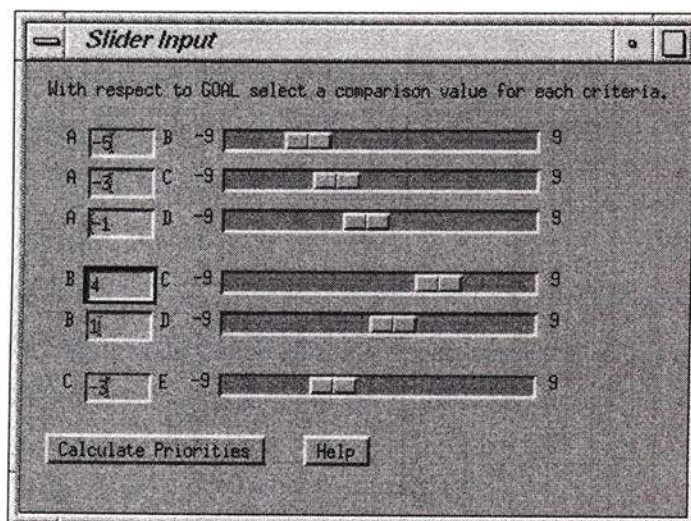


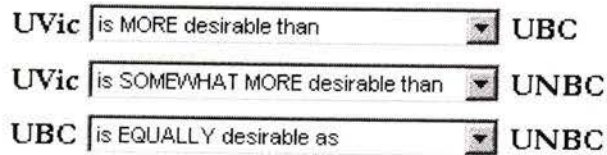
Figure C.3 Slider input

Visual C allows non-numeric sliders so the ‘comparisons phrase’ could be shown beside the slider using a vertical slider but this leads to a busy interface where the user sees far more text than is useful.

The HTML standards do not directly support sliders but they can be implemented using available Javascripts. As with Visual C the developed interface quickly becomes cluttered with text designating positions on the slider.

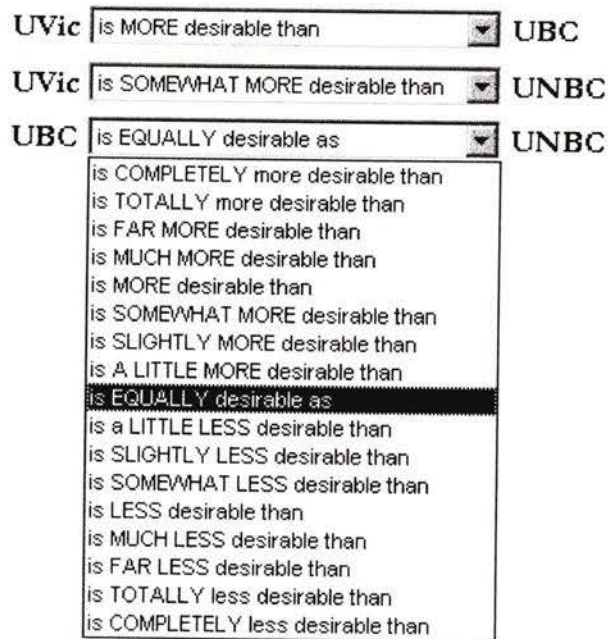
Menu selections allow the user to input comparisons in the most basic form – comparison phrases. By bracketing the two elements to be compared around a menu selection the user’s choice appears as a phrase. If the user feels that the phrase is inappropriate then it can be changed quickly with a couple of mouse-clicks. This provides an immediate quality check on the user’s inputs as the phrases can be ‘reviewed’ by the user to confirm the settings. This simple method of checking is missing from numeric input methods like the slider and matrix where the user will have to continually refer back to the table showing the numeric-to-phrase relationship. Further, the use of comparison language encourages the user to think in those terms instead of numeric values. This is important to the correct calculation of priorities since the linear numeric scale is used in a non-linear manner within the calculations (Saaty 1980).

AMLs can produce a form of menu selection using selection lists with scroll bars. Visual C and web browsers support selection menus directly.

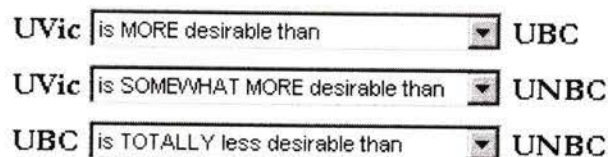


**Figure C.4 Menu Selection**

Figure C.4 shows a menu selection interface with three menu selections in a column. Only the current value of the selection is displayed. Mouse clicking anywhere within the last menu selection box causes all the menu options to be displayed as shown in Figure C.5 with the current selection highlighted in blue.



**Figure C.5 Mouse Clicked Menu Selection**



**Figure C.6 Modified Menu Selection**

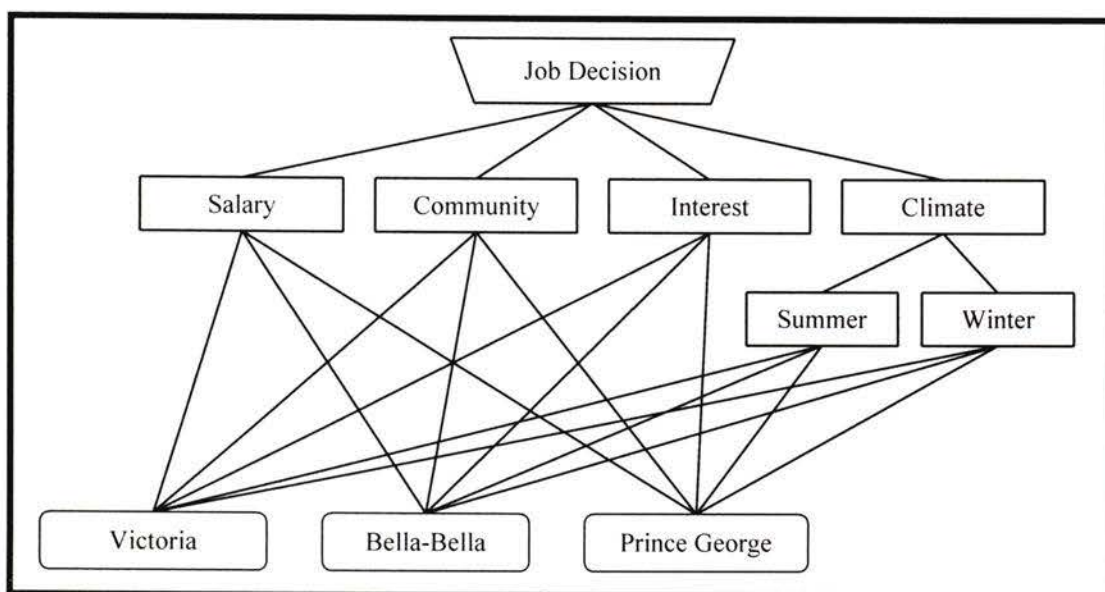
Mouse clicking on any of the selections ‘closes’ the menu widget and the new value is shown in Figure C.6.

### C.8 Dynamic hierarchy development

As the user creates a hierarchy some form of easily interpretable display is desirable to show the current state of the hierarchy and allow the user to add and delete elements from the hierarchy with a minimum of interface complexity. Developing an appropriate hierarchy can be a difficult task, and the hierarchy development environment should help, not hinder the user.

Using AMLs, a form interface can be created which shows the hierarchy using an indentation to indicate sub-elements. The 100-entity limit for AML forms becomes troublesome for hierarchies with more than 40 elements. A graphical form which is easily editable would be more visually appealing, but is extremely difficult to create dynamically using AML commands.

Visual C can produce a workable hierarchy development interface as demonstrated by First Choice<sup>®</sup> software. Another example of a graphic interface most computer users are familiar with is the directory manipulation and display program called ‘Windows Explorer<sup>®</sup>’, developed by Microsoft<sup>®</sup>. This graphic interface allows complex directory structures to be shown in full or collapsed with simple mouse clicks. Moving pieces of the hierarchical structure around is



**Figure C.7 Job Decision**

allowed so ‘pruning’ and ‘grafting’ of bits of the directory tree are quickly accomplished. Elements of the structure can be renamed directly within the display.

One of the formats supported by HTML codes is tabular. A table contains an array of ‘cells’ each containing text, graphics, form input entities or even another table. Tables are often used to organize the placement of specific objects within a webpage. The hierarchy shown in Figure C.7 can equally be represented in a tabular form as Table C.2 (below) shows.

<b>Job Decision</b>			
	<b>Salary</b>		
		Victoria	
		Bella-Bella	
		Prince George	
	<b>Community</b>		
		Victoria	
		Bella-Bella	
		Prince George	
	<b>Interest</b>		
		Victoria	
		Bella-Bella	
		Prince George	
	<b>Climate</b>		
		Summer	
			Victoria
			Bella-Bella
			Prince George
		Winter	
			Victoria
			Bella-Bella
			Prince George

**Table C.2      Tabular Hierarchy**

A more compact tabular representation is achieved by splitting the hierarchy into two sections and representing them differently. The decision hierarchy is shown as before while the decision choices are listed to the right of their dependent elements.

Job Decision		
	Salary	(Victoria, Bella-Bella, Prince George)
	Community	(Victoria, Bella-Bella, Prince George)
	Interest	(Victoria, Bella-Bella, Prince George)
	Climate	
		Summer (Victoria, Bella-Bella, Prince George)
		Winter (Victoria, Bella-Bella, Prince George)

**Table C.3 Compact Tabular Hierarchy**

Since radio buttons can be placed within table cells they can be used as method for the user to select a particular hierarchy elements for expansion, deletion or comparison. In addition adjacent cells are a convenient place to put information about the hierarchy element, such as decision choices. The result is a clean, concise and quickly modifiable hierarchy display. The relative simple syntax of tables can be programmed into Perl code so the display reacts dynamically to the user's input. In addition, HTML tables can be arbitrarily large so any hierarchy may be displayed.

### C.9 Visualization of results

The output produced by AHP for decision making is different than the output for general GIS purposes so these two options are discussed separately.

Using AHP for decision making produces a *relative priority* for each of the choice options. Two graphs that are useful for conveying these priorities are:

a) 'Base Element' Vs 'Priority Contribution' (for each choice option)

This graph shows the relative contributions of all the elements comprising the lowest level of the hierarchy. These are the elements relative to which the choice options are compared.

b) 'Base Element' Vs 'Accumulated Priority' (for each choice option)

This graphs shows the accumulated contributions of the contributions made by each of the elements which comprise the lowest level of the hierarchy.

For both of these graphs, the different options are shown as different coloured lines so the options can be compared one *relative* to the other. Here are the graphs output for a comparison of Universities with respect to some decision.

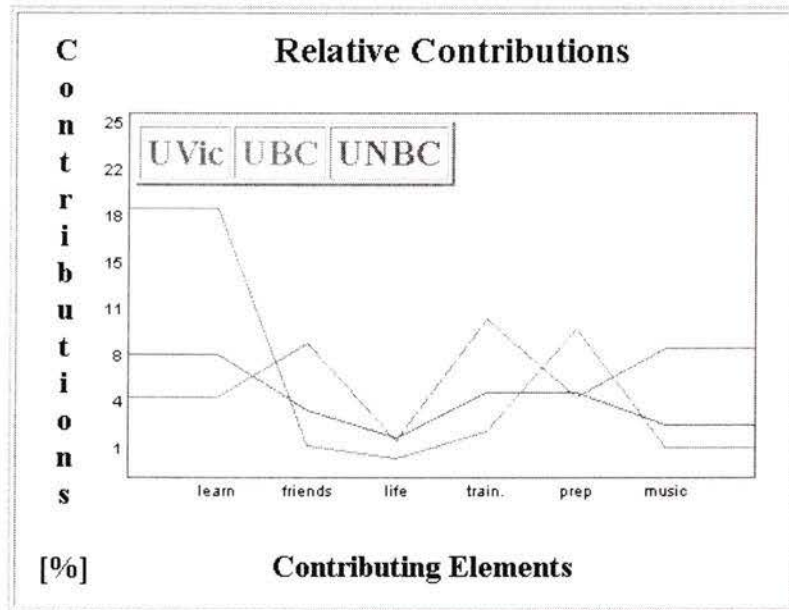


Figure C.8 Relative Contributions

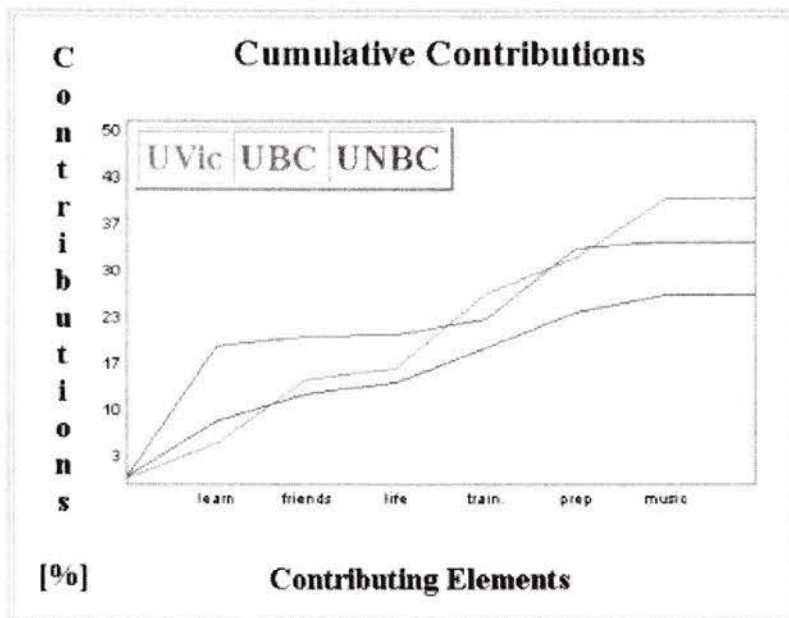


Figure C.9 Cumulative Contributions

To be useful these graphs should be available for viewing whenever the user is examining the results of entered comparisons. Equally, a user may be interested in investigating the effect of modifying a comparison. This means the graphs have to be generated within the code since they will be created, inspected and considered many times for each hierarchy. Though the graphs can be generated by exporting the priority contributions to a graphing program this may result in a slow, clumsy and unsatisfactory interface for the user.

Since AMLs run inside a GIS environment, the visualizing tools of the GIS are available to generate graphs immediately. A general AML procedure would have to be developed to draw the graphs using the basic line, symbol and text display tools of the GIS. The result would be a responsive display of the state of the hierarchy with little generation delay.

There are ample tools within the Visual C development environment to generate a general graphing routine to display these graphs. The result would be a responsive display with very little generation delay.

Using a Javascript program graphs can be generated automatically for webpages. The web program called JavaGraph is available freely from [www.infocalyptika.com](http://www.infocalyptika.com). Essentially, the graph points are included (using a specific format) within the webpage, the web browser recognises the format and runs a program sitting on the server which generates a graphic file which is inserted into the webpage. There is short delay while the graphic file is generated and loaded into the webpage.

### **C.10 Visualizing AHP for GIS applications**

Using AHP for the purpose land evaluation also requires intermediary graphs (as described above) as well as a visualization of the *relative land priorities* in a geographic manner. A choropleth map with an appropriate colour scale showing the gradation of priorities as well as the spatial distribution of those priorities over the area of interest would convey the essential information to the user.

Since AMLs work within a GIS environment, the display of such a map would be quick and easily implemented. The automated procedures to construct the map layer using the calculated land priorities, generation of a color scale, and display of the data layer are all part of the GIS.

A program written in Visual C or Perl would have to export its calculated priority values to a GIS so that a representative graphic could be generated, imposing a delay between the creation of priority values and full visualization. This is easily accomplished using simple text files that are readable by GIS systems. Most GIS systems have some form of scripting (like ArcInfo's AMLs) and these could be used to generate the map displays using the transferred priorities as input.

### **C.11 Availability to users**

The number of users who can use an application depends upon a number of factors including: the specific computer platform the program was written for; the form of the application; the language used to create it and the graphic intensity of the display.

Purpose written software tends to be platform specific. That is, programs written for the PC (Intel Chip) may not run on Mac (Motorola Chip) or Unix (various CPU chips) platforms. The new programming language, Java, claims to be compatible across platforms but relies on the presence of 'Java interpreter' software on the user's computer (Sun 1997, Microsoft 1998).

AMLs are specific to the ArcInfo<sup>®</sup> GIS package and rely on the GIS for the computational aspects of the processing. Writing the AHP application using AMLs will effectively confine the utility of the application to ArcInfo<sup>®</sup> users. Though ArcInfo<sup>®</sup> is arguably the most widely used GIS for large applications, its popularity is by no means universal. SPANS<sup>®</sup>, Intergraph<sup>®</sup>, Idrisi<sup>®</sup> and GRASS<sup>®</sup> are other well-used GISs.

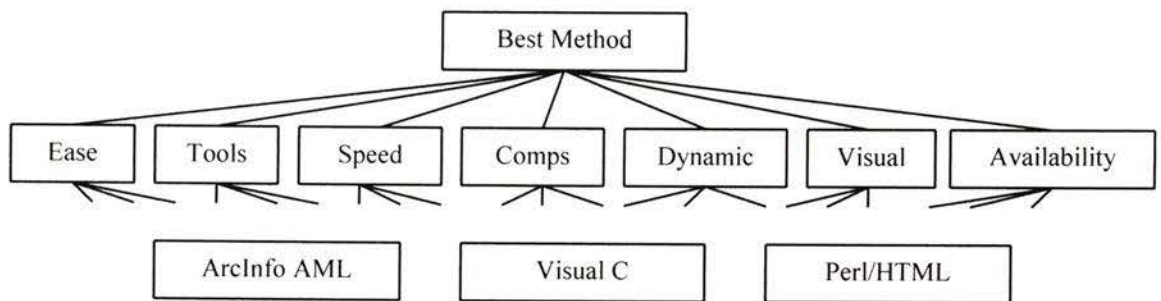
An application written in Visual C would run on many computers since the PC platform is widely used. Some GIS software is available for the PC platform (e.g. ArcInfo<sup>®</sup>, Idrisi<sup>®</sup>) and passing the output from the AHP application into these GISs can be accomplished through the use of standard text files.

A Perl based application, using web pages as an interface shell, would be available to any user with an Internet connection. The appearance of the site would change slightly depending upon the web-browser used but the functionality would not be affected by the computer platform of the user. That is, the user can use any of the major hardware platforms: MacIntosh, PC, Unix, Intergraph or NeXT with no loss of functionality. Passing input data files and calculated indices back and forth between the user and the Victoria AHP site can be accomplished with standard webpage tools. The application would not need to be distributed since it runs in Victoria and

users simply visit the application site. The AIX-Unix workstation can manage multiple user simultaneously so more than one user can utilize the site at any one time. Any modifications and software updates would be immediately available to all users, as would current documentation and notices of code/procedure changes.

### C.12 Choosing the development method

Choosing the best method of developing this application is function of a number of different criteria. The seven most important were listed earlier. The three development methods considered have relative strengths and weaknesses, and the overall best method is not completely clear. The hierarchy representing this decision looks like:



**Figure C.10** Choosing a coding method

Of the hierarchy elements, the most important is the ‘Comparison Method’ (Comps) as the original AHP development uses phrased comparison questions. Simply using a numerical input scale is a less effective manner of gathering expert comparison valuations (Saaty 1980, p23). In addition, since the numeric values which are linked to the comparison phrases are used in a non-linear manner when generating the priority eigenvector it can be misleading for the user to enter the comparisons as numeric valuations. It is a basic premise of the AHP that the comparisons should be made using phrases, and the use of a simple numeric input should be used with care (Saaty, 1980).

Following the general process detailed in Chapter 3 the relative priority ratings are produced using comparisons based on the review of the methodologies presented in this appendix.

ArcInfo AML	19.2
Visual C	27.9
Perl/HTML	52.7

So, the overall most desirable method of developing the interface is Perl/HTML. Chapter 5 details the implementation of Saaty's AHP for decision making (AHP application) and the extension of the AHP for GIS data sets (GIS-AHP application).

## Appendix D

## Data Structures

The developed data structures used by the application website to store hierarchies and output are detailed in this appendix. An example of GIS scripting code, that uses the evaluation output, appears in the final section.

### AHP-decision storage structure

The hierarchy structure and pairwise comparisons for decision between discrete options is stored in a text file within the web-site directory structure. In the listing below the complete text file for the 'sample.ahp' hierarchy is listed in the left column of Table D.1, with one line in each cell. Explanatory comments are in the right column.

Filename : Car.ahp	Top of file
Created : Wed Jun 16 06:07:20 PDT 1999	the date line is ONLY one line, wrapped here to save space
Meta-Data__TOP	top of meta-data flag
No Meta-Data yet	
Meta-Data__BOTTOM	bottom of meta-data flag
choices 3 Miata Mustang Honda	keyword 'choices', number of choices and choice listing
element_cnt 8	keyword 'element_cnt' and value
1 0 Car 2 0	element number, number of dependent element (here there is none), name of element, number of sub-elements and number of sub-choices.
1 4	The next two lines are the two rows of the comparison matrix storing the pairwise comparisons between the two sub-elements of 'Best_School'
-4 1	negatives represent reciprocals so: '-4' represents 1/4
12 1 Economy 2 0	element number, number of dependent element (=1 → 'Car' is dependent element), name, number of sub-elements, number of sub-choices.

1 1	
1 1	
122 12 gas 0 3	
1 1 1	
1 1 1	
1 1 1	
121 12 repairs 0 3	
1 1 1	
1 1 1	
1 1 1	
11 1 Style 3 0	
1 1 5	
1 1 -3	
-5 3 1	
113 11 Form 0 3	
1 1 1	
1 1 1	
1 1 1	
112 11 color 0 3	
1 1 1	
1 1 2	
1 -2 1	
111 11 Interior 0 3	
1 1 1	
1 1 1	
1 1 1	Last line of data file

**Table D.1 Example of (AHP) storage file (left column only)**

The storage file has a recursive structure to accommodate the insertion and deletion of sub-elements and choice options by the user. The *goal* element is always numbered “1” and all other element are numbered relative to it. Sub-elements of the *goal* element have two digit numbers, sub-elements of the sub-elements have three digit numbers, and so on.

The calculated priorities for the choices are NOT stored in the data file. These values appear only in the displayed web pages. The user may transcribe these values, save the webpage to a local storage drive or print out the results.

### GIS-AHP base data layer description

For the general landscape evaluation a set of baseline data layers is needed. The user supplies this information by providing a ‘data layer description’ file like the one listed in the left column (one line per cell) of table D.2. The right column of the table contains clarification comments.

Source Filename: Mountain info	Top of data file
Source GIS: gg	Meta-data
-----	spacer line
6 attributes	number of baseline data layers
1 Altitude F 6 1000,1999,2000,2500,2501,4000	layer number, layer name, data type, number of <i>key</i> elements listed, list of <i>key</i> elements
2 Aspect F 2 1,360 C 4 Alces_River,Seine_River,Danube_River,Thames_River	F = Float → some real value
3 Scenic C 3 Good,Moderate,Poor	C = Character → some ordinal value
4 Snowfall F 2 1,5	
5 Clear_Days F 2 150,0	
6 Slope F 2 0,90	last line of data file

**Table D.2 Example of baseline data storage file (left column only)**

The text parser looks for spaces (NOT tabs) between the first four values on an ‘attribute description’ line and expects commas between the listing of *key* values. Only eight *key* values are permitted for any attribute.

**GIS-AHP general**

For the developed land evaluation application, the hierarchy structure, pairwise comparisons and original attribute descriptions are stored in a text file within the web-site directory structure. In the listing below the complete text file for the 'ski.gis' hierarchy is listed in the left column of Table D.3, with one line in each cell. Explanatory comments are in the right column.

Filename : Skiing.gis	Top of data file
Created : Sat Jun 12 13:58:04 PDT 1999	base meta-data
Meta-Data__TOP	
Source Filename: Mountain info	user modifiable meta-data
Source GIS: gg	
Meta-Data__BOTTOM	
6 attributes	number of attributes
1 Altitude F 6 1000,1999,2000,2500,2501,4000	listing of original data descriptions
2 Aspect F 2 1,360	
3 Scenic C 3 Good,Moderate,Poor	
4 Snowfall F 2 1,5	
5 Clear_Days F 2 150,0	
6 Slope F 2 0,90	
Elements 9	number of hierarchy elements
1 0 Good_Skiing 3 0	Goal element : number, number of dependent element (0), name, number of sub-elements, number of key attribute values
1 4 8	The next 3 lines contain the three lines of the matrix containing the pairwise comparisons between the three sub-elements of "Good_skiing"
-4 1 2	
-8 -2 1	
13 1 Snow_Depth 2 0	Note: parent element number = 1 → Good_skiing
1 -4	2x2 comparison matrix

4 1	
132 13 Aspect 0 5	3 <sup>rd</sup> level element, parent = "snow_depth"
360 280 235 90 1	list of the 5 <i>key</i> attribute values entered by the user to represent the priority response function for the 'Aspect' attribute contributing to "snow_depth"
1 4 4 3 1	
-4 1 1 1 -4	
-4 1 1 1 -4	
-3 1 1 1 -3	
1 4 4 3 1	
131 13 Snowfall 0 5	
4 3.5 3 2 1	
1 -3 -2 2 7	
3 1 2 6 9	
2 -2 1 4 9	
-2 -6 -4 1 4	
-7 -9 -9 -4 1	
12 1 Sunshine 3 0	
1 4 -2	
-4 1 -5	
2 5 1	
123 12 Altitude 0 6	
4000 2501 2500 2000 1999 1000	
1 1 -8 -8 1 8	
1 1 -8 -8 1 8	
8 8 1 1 8 9	
8 8 1 1 8 9	
1 1 -8 -8 1 8	
-8 -8 -9 -9 -8 1	
122 12 Aspect 0 4	2 <sup>nd</sup> occurrence of 'Aspect' in hierarchy
360 260 180 80	note different <i>key</i> values this time

1 -5 -6 -4	
5 1 1 1	
6 1 1 2	
4 1 -2 1	
121 12 Clear_Days 0 4	
150 100 60 40	
1 2 3 5	
-2 1 2 3	
-3 -2 1 2	
-5 -3 -2 1	
11 1 Slope 0 5	
90 70 45 20 5	
1 1 -8 -6 -4	
1 1 -8 -6 -4	
8 8 1 1 2	
6 6 1 1 2	
4 4 -2 -2 1	last line of storage data file

**Table D.3 Land evaluation sample hierarchy storage file (left column only)**

## Land Evaluation Output

The output from the application is in the form of a simple text file which can be viewed or downloaded from the website. Table D.4 contains a sample of output.

Filename : Skiing.gis	Top of data file
Created : Sat Jun 12 13:58:04 PDT 1999	meta-data
Meta-Data__TOP	
Source Filename: Mountain info	
Source GIS: gg	
Meta-Data__BOTTOM	
---- Original Attribute information ----- ( #,name,type,key-values )	spacer with labels
6 attributes	number of attributes
1 Altitude F 6 1000,1999,2000,2500,2501,4000	original data descriptions follow
2 Aspect F 2 1,360	
3 Scenic C 3 Good,Moderate,Poor	
4 Snowfall F 2 1,5	
5 Clear_Days F 2 150,0	
6 Slope F 2 0,90	
---- Derived Weightings ----- ( name, value, weight )	spacer with labels
Aspect 1 0.145454	name of attribute, <i>key</i> value, suitability contribution associated with the <i>key</i> value
Aspect 80 0.011313	
Aspect 90 0.043214	Compare with Table C.3 to see how the different <i>key</i> values have been meshed together
Aspect 180 0.017707	
Aspect 235 0.038517	
Aspect 260 0.014226	

Aspect 280 0.038517	
Aspect 360 0.148329	
Snowfall 1 0.039043	
Snowfall 2 0.111388	
Snowfall 3 0.37492	
Snowfall 3.5 0.581818	
Snowfall 4 0.216907	
Altitude 1000 0.002523	
Altitude 1999 0.010497	
Altitude 2000 0.060558	
Altitude 2500 0.060558	
Altitude 2501 0.010497	
Altitude 4000 0.010497	
Clear_Days 40 0.018906	
Clear_Days 60 0.03362	
Clear_Days 100 0.058232	
Clear_Days 150 0.103552	
Slope 5 0.045454	
Slope 20 0.081027	
Slope 45 0.090909	
Slope 70 0.012036	
Slope 90 0.012036	last line of data file

**Table D.4 Land evaluation output**

The output lists all the unique *key* attribute values along with their calculated 'suitability' contribution. For other attribute values not appearing in the list some form of interpolation (eg. linear or spline) between these values will generate the necessary values.

### AML Example for Evaluation import into a GIS

The following AML (ArcInfo<sup>®</sup>) is a simple example of an AML which will import the output from the web-based application and use it in a GIS.

```

/* This AML implements LINEAR interpolation between the 'key'
attribute */
/* values to generate priority contributions for intermediate
values. */
/* This AML runs from within the ArcInfo GRID module and assumes
the */
/* data layers (attributes) are grid rasters. With minor
changes */
/* it can be converted to run within the ArcInfo ARCEDIT module,
and use */
/* the attributes of vector layers.
*/

/* &s file = [response 'Enter file name to use']
&echo &on
&s file = skiing.gis
&s fileunit = [open %file% openstatus -read]

&if %openstatus% = 0 &then
&do
  /* Find top of the list of attributes */

  &s line = init
  &s target = '----'
  &s str_pos = 0

  &do &until %str_pos% > 0
    &s line := [read %fileunit% readstatus]
    &s str_pos = [index %line% %target%]
  &end

  /* Check the data type of each attribute --> ordinal data has
*/
  /* to be handled differently than ratio data.
*/

  &s line := [read %fileunit% readstatus]

  &s list_atts = [before %line% ' ']

  &do i = 1 &to %list_atts%
    &s line := [read %fileunit% readstatus]

    &s line = [after %line% ' ']

```

```

    &s List_name%i% = [before %line% ' ']
    &s line = [after %line% ' ']
    &s List_type%i% = [before %line% ' ']

&end

/* Find top of the list of Derived Weightings */

&s line = init
&s target = '---- Derived Weightings ----'
&s str_pos = 0

&do &until %str_pos% > 0
    &setvar line := [read %fileunit% readstatus]
    &s str_pos = [index %line% %target%]
&end

&s atts = 0
&s last_att = ""

/* Read the Attribute, Value, Priority Contribution */
/* into arrays. */

&do &until %readstatus% = 102
    &setvar line := [read %fileunit% readstatus]

    &s current_att = [before %line% ' ']
    &s line = [after %line% ' ']

    /* Check for a new attribute */

    &if %current_att% <> %last_att% &then &do
        &s last_att = %current_att%
        &s atts = %atts% + 1

        &do i = 1 &to %list_atts%
            &if [value list_name%i%] = %current_att% &then
                &s att_type%atts% = [value list_type%i%]
            &end

            &s name%atts% = %current_att%
            &s att_cnt = 0
        &end

        &s att_cnt = %att_cnt% + 1

        &s n%atts%v%att_cnt% = [before %line% ' ']
        &s line = [after %line% ' ']

        &s n%atts%p%att_cnt% = [before %line% ' ']
        &s line = [after %line% ' ']
    &end

```

```

        &s name%atts%cnt = %att_cnt%
    &end
&end
&else
&do
    &type Error opening file : %file%
    &return
&end

/* List out the Attribute NAME,VALUE & PRORITY contribution */
/* for each attribute. This is here as simple visual check. */

&do i = 1 &to %atts%
    &do j = 1 &to [value name%i%cnt]
        &type [value name%i%] [value n%i%v%j%] [value n%i%p%j%]
    &end
&end

/* With the attributes in arrays the aggregate land evaluation
*/
/* surface may be computed.
*/

/* This AML implements LINEAR interpolation between the 'key'
attribute */
/* values to generate priority contributions for intermediate
values. */

/* This AML runs from within the ArcInfo GRID module and assumes
the */
/* data layers (attributes) are grid rasters. With minor
changes */
/* it can be converted to run within the ArcInfo ARCEDIT module,
and use */
/* the attributes of vector layers.
*/

/* Disable the verification prompts so that GRIDs are
overwritten without */
/* prompting the user every time.
verify off

Land_value = 0;

&do i = 1 &to %atts%
    &do j = 1 &to [calc [value name%i%cnt] - 1]
        &s k = %j% + 1

        &if [value att_type%i%] = C &then
            Land_value = Land_value + [value n%i%p%j%]
        &else
            &do

```

```

&s V_bottom = [value n%i%v%j%]
&s V_top = [value n%i%v%k%]
&s V_dif = %V_top% - %V_bottom%

&s P_bottom = [value n%i%p%j%]
&s P_top = [value n%i%p%k%]

Land_value = con([value name%i%] >= %V_bottom% and [value
name%i%] < %V_top%, ~
%P_bottom% ) * ~
%V_dif% , ~
( [value name%i%] - %V_bottom% ) /
Land_value )
&end
&end
&end

verify on

&return

```

---

VITA

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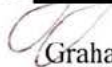
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Title of Thesis/Dissertation:

Land Evaluation using AHP

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December 9, 1999