1990

Toward an Expert System for Terrain Analysis.

Ravi Narasimhan

Louisiana State University and Agricultural & Mechanical College

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Toward an expert system for terrain analysis

Narasimhan, Ravi, Ph.D.

The Louisiana State University and Agricultural and Mechanical Col., 1990
Toward an Expert System for
Terrain Analysis

A Dissertation

Submitted to the Graduate Faculty of the
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Doctor of Philosophy

in
The Department of Civil Engineering

by
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May 1990
To my parents.
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Abstract

Terrain analysis is the systematic study of image patterns relating to the origin, and composition of distinct terrain units called landforms. It takes into account and provides information about physical site factors which are used by civil engineers for evaluating the suitability of a site for a terrain related engineering application. Terrain analysis is a time consuming labor intensive process and requires a significant degree of expertise. In this dissertation, an expert system paradigm has been adopted, for developing a computational approach to terrain analysis problem solving. A methodology was developed for the representation and management of uncertain terrain knowledge. The "vagueness" that is inherent in the descriptions of terrain analysis terms was represented using fuzzy models. The Dempster-Shafer theory of evidence was adopted to establish hypotheses about the type of terrain based on observed evidences. A goal directed backward form of reasoning was employed for evaluating the suitability of a site for a terrain related engineering application. The reasoning strategy was formalized in production rules, and the fuzzy models of terrain terms were formalized in frames. Procedural computations were formalized in LISP code. The methodology was implemented in the the Terrain Analysis eXpert (TAX) system. TAX was developed by employing the expert system shell KEE (Knowledge Engineering Environment) and the image processing package ELAS (Earth resources Laboratory Application Software). TAX was tested with a real data set consisting of a digitized color infra-red photograph and digital elevation data. The conclusions arrived at by TAX compared favorably to those reached by an expert who analyzed the same site using traditional photointerpretation techniques.
1. INTRODUCTION

Any plan for engineering site development must be compatible with the resources and constraints imposed on it by the natural environment. Reconnaissance studies of the site must therefore provide the necessary information about physical site factors. It must also take into account the interactions of surface and subsurface terrain conditions upon which design concepts and forms can evolve. Terrain analysis is the field of engineering that deals with such an analysis of the site. It takes into account and provides information about physical site factors such as geologic type and structure, soil types and associated properties, vegetation type, drainage pattern type and others. Terrain analysis involves the identification of the landform of a site, by observing pattern elements on an aerial photograph. Once the landform of the site is identified, the engineering properties of the site are inferred by association with the default properties of the prototype landform. These properties are then used to evaluate the suitability of the site for a terrain related engineering application.

Terrain analysis is a time consuming labor intensive process that requires a significant degree of expertise. The manual procedure to delineate the pattern elements from an aerial image is tedious and the procedure to synthesize these patterns in order to infer the type of terrain and its engineering properties takes years of experience. There is, therefore, a pressing need for an automated approach for analyzing terrain related information.

Terrain analysis is both an art and a science. While some researchers have laid down procedures for identifying landforms and their composition, the complexity of the problem is such that there are few instances where clear-cut rules and procedures can be formulated. Consequently, a traditional procedural
formulation of the problem and its implementation in a computer system using procedural languages becomes a very difficult task. Advancements in artificial intelligence research and the subsequent emergence of expert systems have provided a new powerful tool for the development of computer programs that can capture expertise in many fields and tasks. Knowledge-based expert systems are a field of artificial intelligence that emphasize specific, but difficult problem solving requiring expertise. In this research effort, an expert system approach has been adopted for modeling terrain analysis problem solving.

The overall objective of this research effort, was the development of a methodology, for a computational approach to terrain analysis problem solving and its implementation in a computer system. This entailed the following specific objectives:

1) Development of a methodology for a declarative representation of uncertain terrain knowledge. This involved the development of models of pattern elements, landforms, engineering properties and engineering applications.

2) Development of an inferencing mechanism for the identification of landforms and for the evaluation of the suitability of a site for a terrain related engineering application.

3) Implementation of the above in an expert system. This involved the construction of a knowledge base consisting of models of terrain objects, and the formalization of the inference mechanism using rules, and procedures.

4) Testing the developed expert system with real data.

The following data were utilized for performing terrain analysis, using the expert system developed in this research:
• A color infrared aerial photograph of the test site, at a scale of 1:60,000, was acquired from USGS. The photograph was scanned, and converted into digital multi-spectral data, in the green, red and near infrared wavelengths. The digital data was then georeferenced using a topographic map of the area. (Black and white panchromatic photographs are also necessary for some of the analysis. However, such photographs could not be obtained for the test site.)

• Digital elevation data of the test site, was obtained from the USGS. The elevation data had a ground cell size of 30 m.

It was assumed that the person using the expert system had a basic knowledge of terrain analysis, so that (s)he could identify the landcover type, drainage type, etc. of the site. While a novice photointerpreter could also use the system, the results generated by the system would be less reliable.

The expert system methodology developed in this research effort, required medium resolution digital data (scale of 1:60,000 or larger). This is because, many of the image patterns used for terrain analysis, are not visible at smaller scales. While some of the image patterns, for performing terrain analysis, were extracted automatically from the digital data of the site, others, such as the landcover, drainage type, gully type and soil tone, were obtained from the user of the system.
2. BACKGROUND

2.1 Terrain Analysis

Terrain analysis is the systematic study of image patterns relating to the origin, morphologic history and composition of distinct terrain units called landforms. Through the analysis of the image patterns visually apparent on an aerial image, the composition or parent material of the landform of a site is inferred. Among the various approaches to terrain analysis, the landform-pattern element approach has been more prominent in USA (Way, 1978; Mintzer and Messmore, 1984). Landforms are defined in this approach as land units that have resulted from constructional or destructional processes that when found under similar conditions will exhibit a definable range of visual and physical characteristics.

The pattern elements examined in the landform-pattern element approach include topographic form, drainage pattern type and texture, gully characteristics, soil tone and texture, landuse / landcover type and other special features that may be present. Taken together, descriptions of these features provide valuable clues about the identity of the landform.

Topographic form is the expression of physical relief of the land surface as developed by erosional or depositional processes under given climatic and geologic conditions. The topographic form is described in terms of relief, shape and slope. Typical topographic descriptions include gentle relief, steep slopes, "A" shaped hills and so on. Drainage patterns are formed by the aggregation of natural drainage ways in a given area (Howard, 1967). Drainage patterns result from conditions of topography, porosity, permeability and erosion of landforms.
Therefore, their identification provides a valuable insight into the conditions that generated these patterns and also provides clues about the identity of the landform. Gully characteristics are often used to infer surface materials and soil profiles. However, natural features such as forests can obscure gully characteristics and, thereby, reduce the usefulness of this landform indicator. Soil tones indicate surface and near-surface ground conditions, such as relative moisture and texture. The distribution of tones over a photograph indicates the relative homogeneity or uniformity of soil and rock materials. The pattern of vegetation, as distributed across landforms, is very useful as an indicator of soil conditions. The presence or absence of vegetative cover helps in distinguishing the texture, permeability and moisture retention capacity of soils. The way in which humans influence the land can be correlated with a landform or soil type. Landuse patterns often provide a valuable clue to the soil conditions. Most development tends to be located on the best, least expensive, least maintenance-prone sites available within a given region.

The terrain analyst examines the pattern elements individually, in relation to one another and in relation to the landform in order to make an inference about the terrain. There are basically three approaches for the manual identification of landforms from aerial photographs (Mintzer and Messmore, 1984). In the first method, the analyst observes the landforms on the aerial photographs and prepares a set of pattern element descriptions. The analyst then compares the set of descriptors of the site with the typical descriptors of landforms, found in books and manuals (Way, 1978). Once a sufficient degree of match is found between the descriptors of the site and those of a landform, the landform of the site is identified. In the second method, the analyst, generally a more experienced one, applies hypothesis testing in a different manner. The analyst first hypothesizes the identity of the landform, based on background information and experience. Then,
(s)he checks to see if the pattern elements of the hypothesized landform are manifested on the aerial photographs. If five or more of the typical set of descriptors match the site's physical expression, then the landform's identity matches the hypothesis. On the other hand, if a majority of the descriptors do not match, then the hypothesis is rejected and another landform identity hypothesis is tested. This procedure is continued until the correct hypothesis is made. The third method, the experienced analyst's approach, requires recognition of the landform's identity because the analyst has observed the same or a similar landform pattern on the ground or on aerial photographs previously (Mintzer and Messmore, 1984).

2.2 Uncertainty Management

Management of uncertainties in knowledge, is an important issue to be considered when an attempt is made to automate tasks which are commonly performed by human experts (Zadeh, 1983).

2.2.1 Bayesian Approach

One of the classical approaches for modelling uncertainties involves the treatment of certainties associated with knowledge as conditional probabilities. For example, an uncertain fact like:

(If a man is DRUNK, then he USUALLY DOES-NOT-WALK-STRAIGHT)

can be represented as the conditional probability of a man "not walking straight" given that he is drunk. That is,

\[ P(\text{DOES-NOT-WALK-STRAIGHT} / \text{DRUNK}) = 0.66 \]

where USUALLY is converted to a numerical measure of likelihood (0.66).

Now, if one were to observe a man who DOES-NOT-WALK-STRAIGHT, the probability that he may be DRUNK is given by Bayes' theorem:
\[ P(\text{DRUNK} | \text{DOES-NOT-WALK-STRAIGHT}) = \frac{P(\text{DRUNK}) \times P(\text{DOES-NOT-WALK-STRAIGHT} | \text{DRUNK})}{P(\text{DOES-NOT-WALK-STRAIGHT})} \]

where

P(\text{DRUNK}) is the \textit{a priori} probability or likelihood of a man being DRUNK

P(\text{DOES-NOT-WALK-STRAIGHT})

is the \textit{a priori} probability or likelihood of a man who DOES-NOT-WALK-STRAIGHT

P(\text{DRUNK} / \text{DOES-NOT-WALK-STRAIGHT})

is the \textit{a posteriori} probability of a man being DRUNK given that he DOES-NOT-WALK-STRAIGHT

However, the cause for DOES-NOT-WALK-STRAIGHT could also be that he is GROGGY (having just "enjoyed" a roller-coaster ride), or that he is weak and ILL. In the Bayesian formalism, the different causes \{DRUNK, GROGGY, ILL\} are considered to be the hypotheses \{H\}, and the observation DOES-NOT-WALK-STRAIGHT is considered to be the evidence, which supports each of the hypotheses (to a different degree). For example, consider a set of competing hypotheses \(H_1, H_2, \ldots, H_m\), and an evidence \(e\), which bears on the hypotheses. Bayes' theorem is then employed, to calculate the \textit{a posteriori} probabilities of competing hypotheses. Bayes' theorem states that:

\[ P(H_i | e) = \frac{P(H_i) \times P(e | H_i)}{\sum_{j=1}^{m} P(H_j) \times P(e | H_j)} \quad (2.1) \]

where

\(H_i\) is one of \(m\) competing hypotheses

\(e\) is the observed evidence
\[ P(H_i) \] is the \textit{a priori} probability of the hypothesis \( H_i \)

\[ P(e/H_i) \] is the conditional probability of observing the evidence \( e \) given the hypothesis \( H_i \)

\[ P(H_i/e) \] is the \textit{a posteriori} probability of the hypothesis \( H_i \) given the evidence \( e \) (Buchanan and Shortliffe, 1984).

Equation 2.1, however, cannot handle the case where a number of evidences are acquired one at a time, and probabilities for the various hypotheses have to be analyzed sequentially. In such a case, equation (2.1) is modified to

\[
P(H_i/e) = \frac{P(o_1/H_i & e_1) \ast P(H_i/e_1)}{\sum P(o_1/H_j & e_1) \ast P(H_j/e_1)}
\] (2.2)

where

- \( e_1 \) is the set of all evidences that have been accounted for up to a given time
- \( o_1 \) is the newly acquired observation or evidence
- \( e \) is the new set of evidences after \( o_1 \) has been added to \( e_1 \)
- \( P(o_1/H_i & e_1) \) is the conditional probability of observing \( o_1 \) given \( H_i \) and \( e_1 \) (Buchanan and Shortliffe, 1984).

The Bayesian method for uncertainty management requires a large amount of data, namely, the prior probability of observing an evidence given a particular hypothesis and a particular set of evidences \( P(o_1/H_i & e_1) \). This kind of data is very difficult to acquire or estimate. Usually, an approximation of this technique is used to quantify uncertainties. The approach designed by Duda (1980) for the expert system PROSPECTOR, employed approximations of the Bayes' theorem to handle uncertainties. In this approach, each evidence had associated with it two numbers (LS, LN) which were a measure of how strongly the evidence affected the confidence in the hypothesis. LS was a measure of the sufficiency of the
evidence to confirm the hypothesis, whereas LN was a measure of the necessity of the evidence, a measure of how strongly the absence of the evidence would cause the rejection of the hypothesis. LS and LN were computed as:

\[
LS = \frac{P(E|H)}{P(E|-H)} \quad (2.3)
\]

\[
LN = \frac{1 - P(E|H)}{1 - P(E|-H)} \quad (2.4)
\]

where

\[P(E|H)\] is the probability of observing the evidence E given the hypothesis H

\[P(E|-H)\] is the probability of observing the evidence E given that the hypothesis H is false.

To compute the effect of evidences in confirming a hypothesis, the \textit{a priori} certainties associated with the hypotheses were first converted to certainty ratios CR(H) using

\[
CR(H) = \frac{C(H)}{1 - C(H)} \quad (2.5)
\]

where C(H) is the certainty associated with hypothesis H.

Next, the \textit{a posteriori} certainty ratio [CR(H/E)] of the hypothesis H given that the evidence E was observed, was computed as

\[
CR(H/E) = CR(H) * LS \quad (2.6)
\]

If the evidence was absent, the certainty ratio was modified as

\[
CR(H/-E) = CR(H) * LN \quad (2.7)
\]

It was also possible to account for the uncertainties present in the assertion of the evidence itself. Uncertainty in the evidence was specified by a number in the range -3 to +3. Negative numbers indicated absence of the evidence, while positive numbers indicated that the evidence was present. Let E' represent the observation of the uncertain evidence E, and C(E) represent the uncertainty in the
evidence (given on a scale of -3 to +3). The resulting \textit{a posteriori} certainty associated with the hypotheses was interpolated between the two cases of perfect certainty using a piecewise linear function, given by equations 2.8 and 2.9.

\begin{equation}
C(H/E') = C(H/\neg E) + \frac{C(H) - C(H/\neg E)}{3} \cdot C(E) \text{ if } C(E) < 0 \quad (2.8)
\end{equation}

\begin{equation}
C(H/E') = C(H) + \frac{C(H/E) - C(H)}{3} \cdot C(E) \text{ if } C(E) \geq 0 \quad (2.9)
\end{equation}

where

\begin{itemize}
  \item $C(H/E')$ is the \textit{a posteriori} certainty of the hypothesis $H$ given an evidence $E$ with certainty $C(E)$
  \item $C(H/E)$ is the \textit{a posteriori} certainty of the hypothesis $H$ given the definite presence of evidence $E$
  \item $C(H/\neg E)$ is the \textit{a posteriori} certainty of the hypothesis $H$ given the definite absence of evidence $E$
\end{itemize}

(Duda, 1980; Reboh, 1981).

There are two major drawbacks of the Bayesian approach. First of all, there is no formal mechanism for handling evidences which are fuzzy in nature. Evidences which employ terms used in natural language, such as "large", "moderate", "middle-aged", etc. cannot be satisfactorily represented by this approach. Secondly, it is not possible to express ignorance or lack of belief about hypotheses. If an evidence cannot lend support to a particular hypothesis, it automatically implies that the evidence lends full support to the rest of the hypotheses.

2.2.2 Fuzzy Techniques

Some facets of uncertainty such as the imprecision in natural language words like "large", "very small", "middle-aged" etc. do not lend themselves to analysis
using classical probabilistic methods. Fuzzy sets provide a way of dealing with such imprecision. A set in the regular sense of the word (also called a crisp set) is one where the objects in the universe either belong to the set or they do not. The membership of each object in the crisp set is either 0 or 1. Examples of such sets are, the set of "men", the set of "books" etc. In contrast, there are fuzzy sets where it is difficult to assign such a binary membership to objects. Examples of fuzzy sets are, the set of "tall" men, the set of "beautiful" women etc. In these instances, the constraints that need to be satisfied by an object in order to be a member of the fuzzy set are elastic and flexible. Different objects satisfy these constraints to different degrees and consequently have different degrees of membership in the set. The membership of objects in such a fuzzy set can range from 0 - indicating complete incompatibility with the constraints, to 1 - indicating total satisfaction of the constraints. For instance, a man whose height is 5 ft. would certainly not belong in the set of "tall" men, that is, the membership of 5 ft. in "tall" is 0. A man who is 7 ft. tall is certainly "tall", that is, the membership of 7 ft. in the fuzzy set "tall" is 1.

Definition: Let $X$ denote the universal set of objects, whose generic elements are denoted by $x$. A fuzzy set $A$ in $X$ is a set of ordered pairs:

$$A = \{ x, \mu_A(x) / x \in X \}$$

(2.10)

where $\mu_A(x)$ is the membership function which associates with each object $x$ in $X$ a real number in the interval $[0,1]$ (Dubois and Prade, 1980). The value $\mu_A(x)$ represents the grade of membership of the object $x$ in $A$. In the example of "tall" men, $X$ is the set of all possible heights of men, and "tall" is the fuzzy set defined in the set of heights of men. The membership of a height value in the fuzzy set "tall" is given as $\mu_{\text{tall}}(\text{height})$. For example, let $\mu_{\text{tall}}(5) = 0$, $\mu_{\text{tall}}(5.5) = 0.25$, $\mu_{\text{tall}}(6) = 0.5$, $\mu_{\text{tall}}(6.5) = 0.75$, etc. The fuzzy set "tall" is then given by:
A label such as "tall" may be construed as a fuzzy restriction, on the values of the underlying numerical variable, in this case the height in feet of a person. The numerical variable is also called the base variable of the fuzzy set. A fuzzy restriction on the values of the base variable is characterized by a compatibility function (or membership function), which associates with each value of the base variable a number in the interval [0,1], which represents its compatibility with the fuzzy restriction.

The support of a fuzzy set $A$ in $X$ is the set of all elements which are at least slightly compatible with the constraints imposed on the members by the fuzzy set. The support of $A$ is defined as

$$S(A) = \{x \in X \mid \mu_A > 0\}.$$  

The support of "tall" men is $S(\text{tall}) = \{5.5, 6, 6.5, 7, \ldots\}$. The core of a fuzzy set $A$ in $X$ is the set of all elements which are completely compatible with the constraints imposed on the members by a fuzzy set. The core of $A$ is defined as

$$C(A) = \{x \in X \mid \mu_A = 1\}.$$  

The core of "tall" men is $C(\text{tall}) = \{7, 8, \ldots\}$.

The determination of membership functions plays a key role in quantifying the fuzziness in the description of terms. There are different approaches for estimating the membership functions depending on the type of attributes to be described (Chaudhari and Majumdar, 1982). Psychometric techniques have been used by Zimmermann and Zysno (1983) to determine membership functions based on interviews with experts. In this technique, a questionnaire is used to obtain an ordering on the objects of the universe $X$, according to the subjective evaluation of the object's membership in a fuzzy set $(x_1 \geq x_2 \geq x_3 \ldots)$. In order to have a more precise membership function, an ordering defined on $X^2$ is obtained. A comparison
is made on pairs, (x1, x1') and (x2, x2') with respect to the fuzzy set, say F: 
(x1, x1') ≥ (x2, x2') means that "x1 is more compatible with F compared to x1',
than x2 is compatible with F compared with x2'." This information is then used
to come up with a mapping between members of the universe X and the real
interval [0,1]. In practice one can get a rough idea of the form of μ which will be
adequate for applications (Dubois and Prade, 1988). If X is the specific reference
set, it is easy to elicit from an expert, the core C(A) of the fuzzy set and the
support S(A). C(A) contains all the prototypes of the fuzzy set, while S(A) is
obtained by eliminating all objects that do not belong to the set at all. For simple
cases where the base variables are ordinal and the fuzzy sets are defined on an
objective linear reference scale, standardized functions could be used to capture
the form of the variations in membership. The parameters for these functions are
decided upon to reflect the different levels of membership in the fuzzy sets.
Typical membership functions are the standardized S, S' and Π functions with
adjustable parameters α, β and γ as given by Zadeh (1976):

\[ S(v; \alpha, \beta, \gamma) = \begin{cases} 
0 & \text{for } v \leq \alpha \\
2 \times \left[ \frac{v - \alpha}{\gamma - \alpha} \right]^2 & \text{for } \alpha \leq v \leq \beta \\
1 - 2 \times \left[ \frac{v - \gamma}{\gamma - \alpha} \right]^2 & \text{for } \beta \leq v \leq \gamma \\
1 & \text{for } v \geq \gamma 
\end{cases} \]  

\[ S'(v; \alpha, \beta, \gamma) = 1 - S(v; \alpha, \beta, \gamma) \]  

\[ \Pi(v; \beta, \gamma) = S(v; \gamma - \beta, \gamma - \frac{\beta}{2}, \gamma) \text{ for } v \leq \gamma \]  

\[ = 1 - S(v; \gamma, \gamma + \frac{\beta}{2}, \gamma + \beta) \text{ for } v \geq \gamma \]
For example, an S type function could be used to characterize the fuzzy set "tall" (Figure 2.1). In $S(v; \alpha, \beta, \gamma)$, the parameter $\beta = (\alpha + \gamma) / 2$ is the crossover point, that is the value of $v$ at which $S$ takes the value 0.5. All values greater than or equal to $\gamma$ form the core of the fuzzy set and values greater than $\alpha$ form the support of the fuzzy set. To characterize the fuzzy set "short", one could use a S' function (Figure 2.2). The S' function is the complement of the S function, all values less than or equal to $\gamma$ form the support of the fuzzy set, and values less than $\alpha$ form the core of the fuzzy set. A fuzzy set such as "medium", however, requires a function like $\Pi$, to characterize it (Figure 2.3). In $\Pi(v; P, \gamma)$, $P$ is the bandwidth, that is the distance between the crossover points of $\Pi$, and $\gamma$ is the point at which $\Pi$ is 1. The core of a fuzzy set represented by a $\Pi$ function is $\gamma$ and the support of such a set is the set of values in the interval $\left[\gamma - \frac{P}{2}, \gamma + \frac{P}{2}\right]$.

Standardized functions like $S$, $S'$ and $\Pi$ are adequate for characterizing the membership functions of fuzzy sets such as "young", "tall", etc. which have a well-defined numerical base variable. The base variable for the fuzzy set "young" is "age in years", and the base variable for "tall" is "height in feet". However, in the case of more complex categories where several reference scales play a part ("stocky") or where the reference scales may be hard to identify ("beautiful") other approaches have to be adopted. In such cases prototypes in the universe are identified and all other objects are described based on their compatibility with these standard prototypes. Bremermann (1976) devised this technique, for recognition of handwritten characters. He estimated the compatibilities between prototypical characters and the sample to be identified, as a measure of the energy required to deform the prototypes so as to match the object. He considered the constraints that define the prototypes as elastic springs, which may need to be
Figure 2.1. Plot of S function for "tall".
Figure 2.2. Plot of S' function for "short".
Figure 2.3. Plot of $\Pi$ function for "medium"
stretched or compressed in order to match a given object. Carrying the analogy further, he suggested that the different springs (constraints) could have different stiffnesses so that deformation of the prototype with respect to one constraint may involve much more energy than with respect to another.

2.2.3 Dempster-Shafer Theory of Evidence

The use of fuzzy sets and membership functions, makes it possible to deal with imprecise linguistic terms, commonly used by experts, and thus overcomes a fundamental drawback of Bayesian approach. Another drawback of the Bayesian formalism is that it is not possible to express lack of belief or ignorance about hypotheses. Evidence for a hypothesis to a degree P, automatically implies that there is evidence to a degree (1 - P) for the negation of the hypothesis. This is because of the requirement that the probabilities of competing hypotheses must sum to 1. The case of total ignorance is very poorly handled by the probabilistic model. The probabilistic model presupposes that a set of mutually exclusive possible events have been identified which are assigned equal probabilities. For instance, let us consider, the results of a student’s exam. Let the likely outcome of the exam be PASS or FAIL. In case of total ignorance about the student and the exam, the \emph{a priori} probability assigned to PASS and FAIL will be equal.

\[ P(\text{PASS}) = 1/2 = 0.5 \]

However, if the outcome of the exam is considered to be one of the letter grades, A, B, C, D or F, the \emph{a priori} probability assigned to each of the grades in case of total ignorance, will be equal (0.2). The probability of passing is then equal to the probability of getting one of the grades A, B, C or D.

\[ P(\text{PASS}) = P(A \text{ or } B \text{ or } C \text{ or } D) = P(A) + P(B) + P(C) + P(D) = 0.8. \]

The \emph{a priori} probability assigned to an event therefore becomes dependent on the
number of events identified, rather than on the likelihood of the occurrence of the event. This problem is effectively handled in the Dempster-Shafer model.

In the Dempster-Shafer model, the set of competing hypotheses is called the frame of discernment \( \Theta \). The hypotheses in \( \Theta \) are assumed mutually exclusive and exhaustive. A subset of the hypothesis in \( \Theta \) gives rise to a new hypothesis, which is equivalent to the disjunction of the hypotheses in the subset. A piece of evidence could lend support to any single element in \( \Theta \), or to any of the possible subsets of \( \Theta \). The set of all possible subsets of \( \Theta \) is called the power set of \( \Theta \) and is denoted by \( 2^\Theta \). For example, let the hypotheses in the frame of discernment be,

\[ \Theta = \{H_1, H_2, H_3\}. \]

The power set of \( \Theta \) is,

\[ 2^\Theta = \{H_1, H_2, H_3, H_1 \lor H_2, H_2 \lor H_3, H_3 \lor H_1, H_1 \lor H_2 \lor H_3, \text{null}\}. \]

\((H_m \lor H_n \text{ stands for } H_m \text{ OR } H_n)\)

In the Dempster-Shafer theory, the impact of each piece of evidence on the subsets of \( \Theta \) is represented by a function \( (m) \), called a basic probability assignment (bpa). A bpa assigns a number in the interval \([0,1]\), called a measure of belief, to every subset of \( \Theta \) such that \( \sum_{H_i \in \Theta} m(H_i) = 1 \) (Dempster, 1967). Another feature of a bpa is that the measure of belief assigned to null is 0.

The quantity \( m(H_i) \) is also called \( H_i \)'s basic probability number, and it is the measure of belief that is committed exactly to \( H_i \). To obtain the total belief that is committed to \( H_i \), denoted by \( \text{Bel}(H_i) \), one must add to \( m(H_i) \) the quantities \( m(H_j) \) for all proper subsets \( H_j \) of \( H_i \).

\[
\text{Bel}(H_i) = m(H_i) + \sum_{H_j \subsetneq H_i} m(H_j)
\]

For example, the total belief that is committed to the hypothesis \( (H_1 \lor H_2) \) in \( \Theta \) is

\[
\text{Bel}(H_1 \lor H_2) = m(H_1 \lor H_2) + (m(H_1) + m(H_2))
\]
The function Bel is called the belief function over \( \Theta \). An hypothesis \( H_i \) is called a focal element of the belief function Bel if \( \text{Bel}(H_i) > 0 \).

Given several belief functions over the same frame of discernment but based on distinct bodies of evidence, Dempster's rule of combination provides a method for computing their orthogonal sum, that is, a new belief function based on the combined evidence. Let \( m_1 \) be the basic probability assignment for a belief function \( \text{Bel}_1 \) over a frame \( \Theta \). Let the focal elements of \( \text{Bel}_1 \) be \( A_1, A_2, \ldots, A_k \).

Similarly, let \( m_2 \) be the basic probability assignment of another belief function \( \text{Bel}_2 \) with focal elements \( B_1, B_2, \ldots, B_l \). Consider a measure of belief \( m_1(A_i) \) exactly committed to \( A_i \), by \( \text{Bel}_1 \) and \( m_2(B_j) \) exactly committed to \( B_j \), by \( \text{Bel}_2 \). The joint effect of \( \text{Bel}_1 \) and \( \text{Bel}_2 \), given by the bpa \( m_1 \otimes m_2 \) is to commit a measure of belief \( m_1(A_i) * m_2(B_j) \) to the intersection of \( A_i \) and \( B_j \). A given subset \( H_i \) of \( \Theta \) may have more than one such intersection committed exactly to it. The measure of belief (bpm), exactly committed to \( H_i \) is therefore equal to

\[
m_1 \otimes m_2(H_i) = \sum_{A_i \cap B_j = H_i} m_1(A_i) \cdot m_2(B_j)
\]

(2.17)

where \( A_i \) and \( B_j \) are the focal elements of \( \text{Bel}_1 \) and \( \text{Bel}_2 \) (Shafer, 1976).

For instance, let

\[
\begin{align*}
m_1(H_1) &= 0.2 \\
m_1(H_1 \lor H_2) &= 0.3 \\
m_1(H_1 \lor H_2 \lor H_3) &= 0.5 \\
m_2(H_2) &= 0.2 \\
m_2(H_1 \lor H_3) &= 0.4 \\
m_2(H_1 \lor H_2 \lor H_3) &= 0.4
\end{align*}
\]
The measure of belief committed to $H_1$ by $m_1 \bigodot m_2$ is

$$m_1 \bigodot m_2(H_1) = \sum (m_1(H_1) \times m_2(H_1 \vee H_2 \vee H_3))$$

$$+ m_1(H_1) \times m_2(H_1 \vee H_2 \vee H_3)$$

$$+ m_1(H_1 \vee H_2) \times m_2(H_2)$$

$$+ m_1(H_1 \vee H_2) \times m_2(H_1 \vee H_3)$$

$$= 0.1 \times 0.4 + 0.1 \times 0.4 + 0.3 \times 0.2 + 0.3 \times 0.4$$

$$= 0.26$$

However, it is possible that the intersection of two focal elements in the two belief functions may be null. The total measure of belief assigned to null is given by

$$m_1 \bigodot m_2(null) = \sum_{A_i \cap B_j = null} m_1(A_i) \times m_2(B_j)$$

In the example given above the belief assigned to null is

$$m_1 \bigodot m_2(null) = m_1(H_1) \times m_2(H_2)$$

$$= 0.2 \times 0.2 = 0.04$$

This violates the requirement for a bpa, which states that the belief assigned to null is 0. In order to overcome this problem, the measure of belief assigned to null is set to 0, and the measure of belief assigned to all other elements is adjusted by dividing them by $[1 - m(null)]$, so as to bring

$$\sum m_1 \bigodot m_2(A) = 1$$

The adjusted measure of belief for $H_1$ is

$$m_1 \bigodot m_2(H_1) = \frac{0.26}{1 - 0.04} = 0.27$$

2.3 Expert Systems

Knowledge-based expert systems are a field of artificial intelligence that emphasize specific, but difficult problem solving requiring expertise (Hayes-Roth et al., 1983). The success of these expert systems is largely determined by the effective representation of domain knowledge (Harmon and King, 1985).
2.3.1 Rule-based Systems

The most widely used knowledge-representation scheme is the one of rule-based systems (Harmon and King, 1985; Hayes-Roth et al., 1983). In such a system, the problem solving strategy is represented as sets of rules that will be checked against a collection of facts or knowledge about the current situation. Rule-based knowledge representation centers on the use of IF ("condition statements") THEN ("action statements") constructs. Rules can be employed in a forward or backward chaining mode. In forward chaining, if the current set of facts matches the IF part of a rule the action specified by the THEN part is performed. It is common for the execution of a set of rules to result in a new set of facts which is added to the current set of facts, which trigger other rules until no more rules are triggered. In backward chaining on the other hand, the system starts with a goal that it wants to prove and tries to establish the facts it needs to prove it. This is accomplished by repeatedly matching the goal with the THEN part of a rule and replacing it with the IF part of the rule. This process continues till all the goals to be proved are the currently known facts.

2.3.2 Frame-based Systems

A frame is another very popular knowledge representation scheme. A frame is a structure that collects together knowledge about a particular object and provides expectations and default knowledge about that object (Minsky, 1975). Frames provide a structured representation of an object or class of objects. Frames can be linked together to form a taxonomical structure. This facility allows classes to be represented as subclasses of other more generic superclasses and individuals to be represented as members of classes (Fikes and Kehler, 1985). For example, a taxonomical organization of Automobiles is shown in Figure 2.4. The subclasses
Figure 2.4. Taxonomical organization of Automobiles.
of Automobiles are the classes Cars, Trucks, and Vans. The members of the class Cars are the individual cars such as Mycar, Yourcar etc. Subclasses are linked to their superclass frame by means of Subclass links, and members of a class are connected to a parent by Member links.

Frames contain sets of attribute descriptions called slots. These slots describe various aspects of the object. A frame for a class of objects can contain prototype descriptions for the members of the class as well as descriptions which pertain to the class alone. Prototype descriptions are contained in Member slots, other descriptions of an object are contained in Own slots. The frame for Cars is shown in Figure 2.5. The attributes which are common to the individual cars such as Mycar, could be represented in the frame Cars as Member slots. While attributes of frames are described by slots, attributes of slots are described by facets. The value of a slot is stored in a special facet of the slot called Values. The value of a slot usually refers to the value stored in the Values facet of the slot. Member slots such as Owner, Color etc. cannot have any values associated with them, because the values for these attributes cannot be generalized. However, other Member slots such as No.of.Wheels, can describe some attributes which are common to all cars. Descriptions which pertain to the class Cars as a whole, rather than to the individual members, such as Fastest, Most.Expensive etc. are represented as Own slots of Cars. Even if it is not possible to associate values for Member slots at the parent level, it is still preferable to set up the attributes necessary for describing members as Member slots of the parent. This ensures standardization of the descriptions, and also improves efficiency since the slots do not have to be created for each member.

In addition to the facet Values of a slot, it is possible to create additional facets for a slot to describe other attributes of a slot. For instance, the slot
<table>
<thead>
<tr>
<th>Member slot: COLOR from CARS</th>
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<table>
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<td></td>
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<tr>
<td>(ONE.OF DIESEL GASOLINE)</td>
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<tr>
<td>Highway: UNKNOWN</td>
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<table>
<thead>
<tr>
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<table>
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<tr>
<th>Member slot: OWNER from CARS</th>
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<tbody>
<tr>
<td>Values: UNKNOWN</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: REGISTRATION.NO from CARS</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values: UNKNOWN</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: FASTEST from CARS</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values: LAMBORGHINI</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: MOST.EXPENSIVE from CARS</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values: ROLLS-ROYCE</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.5. Frame representing the class Cars.
Mileage in Cars has the facets City and Highway, corresponding to the two different values for mileage. It is also possible to impose constraints on the values that a slot could take, by creating a facet for the slot called Valueclass. Such constraints provide effective partial descriptions of unknown slot values. The slot Fuel in Cars has the facet Valueclass, which imposes the restriction that, the fuel for cars should be Gasoline or Diesel.

A frame based representation facility performs a set of inferences, called inheritance, based on the structural properties of frames and taxonomies. A frame inherits the Member slots of the class to which it has Member links. The inherited slots become Own slots of the Member frame. A subclass frame inherits the Member slots of it’s superclass frame as additional Member slots. The frame for Mycar is shown in Figure 2.6. The Member slots of Cars, like Owner, Color, No.of.Wheels etc. are inherited by Mycar as Own slots. The inheritance of slot values is controlled by the facet Inheritance. The default value for this facet is "Override.Values". This implies that, the value of the slot at the member level (also called local value) replaces or overrides any value that the slot may have had at the parent level. (It is possible to change the setting of the Inheritance facet from "Override.Values" to "Union". In this case, the value of the slot at the member level is taken to be the union of the local values of the slot, and the values of the slot at the parent level.)

2.3.3 Hybrid Systems

Sophisticated expert system shells such as KEE (Knowledge Engineering Environment), are hybrid systems. These systems provide a facility for representing knowledge in the form of frames, and also provide rules for encapsulating the inferencing process. Each rule is represented by a frame and the
Figure 2.6. Frame representing Mycar.
text of the rule is stored as the value of a slot in the frame. Rules are allowed to be grouped into rule-classes. This makes it possible, to perform inferencing on just a subset of the entire set of rules, relevant for a specific task. Forward chaining on a rule-class is started by invoking the rule-class with a fact. Backward chaining is started by invoking a rule-class with a goal to be proved. Hybrid systems also provide a facility for encapsulating procedural knowledge, in the form of methods. These methods are stored as values of slots in frames. Usually, methods are written in the language in which the expert system shell was written. For instance, methods in KEE are written in LISP. Methods are invoked by sending a message to the slot that contains them, along with any arguments that may be necessary for the method.

2.4 Expert Systems for Terrain Analysis

Expert systems have been successfully employed for representation of knowledge related to interpretation tasks, including interpretation of urban scenes (McKeown et al., 1985), site evaluations for mineral resources (Duda, 1980) and military intelligence (Hall and Benz, 1985). Although progress has been made toward the computational interpretation of certain terrain features (Argialas et al., 1988), limited computational approaches have been developed to model terrain analysis logic, that is the problem solving strategy of expert terrain analysis. Mark (1976) demonstrated that the pattern element approach is adaptable to a procedural representation. Leighty (1973) employed a logical approach for terrain pattern recognition and Leighty (1979) has suggested the use of rule-based systems for terrain analysis problem solving. Rinker and Corl (1984) outlined a computer assisted approach for analyzing aerial photographs in order to infer landforms. The user is expected to have enough training so that he can map landform boundaries,
delineate drainage lines and map characteristics associated with tone, vegetation etc. Mintzer (1988) developed a prototype expert system which interacts with the user and elicits values for pattern elements. If all pattern element values match a landform description in the knowledge base, the expert system returns the name of the identified landform with the highest value of certainty. If no single landform description is consistent with all the user specified observations, the system returns a ranked list of candidate landforms with different degrees of belief in the identification based on the degree of match.

Argialas and Narasimhan (1988a) described terrain knowledge with models of terrain related objects and decision rules pertaining problem solving in terrain analysis. Facts and decision rules with uncertain knowledge sources were identified and methods were developed for their representation. Models were designed to represent the association between physiographic sections, their expected landform types, and their associated probabilities, based on information derived from physiographic and geomorphologic books and maps (Lobeck, 1932; Fenneman, 1938). Models of landforms were constructed to describe the relationship between landforms and their expected pattern elements (Narasimhan and Argialas, 1988a). This description was composed of the expected value of the pattern elements, and an estimation of the degree by which these pattern element values provided evidence in support of that landform. The latter was represented with two probability values, the probability of the occurrence of the pattern element value in that landform, or the probability of the evidence given the hypothesis P(E/H), and the probability of the occurrence of the same pattern element value in all other landforms, or the probability of the evidence given the absence of the hypothesis P(E/-H). The values of P(E/H) were initially extracted from books and reports and later refined by consulting with experts. The values of
P(E/−H) were computed by taking into account the available physiographic information concerning the list of hypothesized landforms of the site, based on the relations between physiographic sections and landforms.

Argialas and Narasimhan (1988a) accounted for the uncertainties in the landform identification process by considering the landform of the site to be the hypothesis (H) and the pattern elements as evidences (E) which strengthened or weakened the hypothesis. Each evidence had associated with it two numbers (LS, LN) which were a measure of how strongly the evidence affected the confidence in the hypothesis. The number LS indicated how encouraging it was for the belief in the hypothesis to find the evidence present, while LN indicated how discouraging it was find the evidence absent. The two numbers LS and LN, specified the sufficiency and necessity measures, respectively, and were computed from the conditional probabilities [P(E/H) and P(E/−H)] provided by the expert. The PROSPECTOR approach was then followed in order to arrive at a certainty for the hypothesis.

The terrain analysis expert system was formalized in a rule-based system and implemented in OPS5 (a production system language) (Argialas and Narasimhan, 1988b). A backward form of reasoning was followed in order to arrive at the identity of the landform of the site. At first, the a priori certainty associated with the hypothesis of a landform was estimated from information related to the physiography of the site. The a priori certainty of each hypothesized landform was initialized to the probability of the occurrence of the landform in that physiographic section. The expert system then selected the hypothesized landforms, one by one, and attempted to establish each one of them by matching the pattern elements of the site with the models of the landforms.
Some of the limitations in the above version of the terrain analysis expert system were:

1) The values of the pattern elements were not defined or described, so it was not possible to represent the vagueness in the description of the pattern element values.

2) The evidence accumulation process was such that each piece of evidence had to either support a hypothesis or support the negation of the hypothesis, it was not possible to assign belief to ignorance in case of inconclusive evidence.

3) The assumption that the site was composed of just one landform, consequently, the burden of segmenting the site into homogeneous forms was left to the user.

4) The values for all the pattern elements were supplied by the user.

The present formulation of the Terrain Analysis eXpert (TAX) system overcomes the above limitations by:

1) Defining the pattern element value classes using fuzzy set theories, and providing for partial membership in classes.

2) Combining evidences according to Dempster's rule of combination, and providing a facility for an evidence to express lack of belief in hypotheses.

3) Providing a user-assisted segmentation of the site.

4) Automatically extracting some of the pattern element values from the digital data of the site.
3. METHODOLOGY

The first step in the construction of TAX (Terrain Analysis eXpert), involved
the conceptualization of models of terrain related concepts. As was seen in section
2.2.1, classical methods for modelling uncertainties using Bayesian formalisms, are
unable to deal with the intrinsic fuzziness in expert knowledge. Fuzzy set
approaches, pioneered by Zadeh (1976), have been employed in this dissertation,
for modelling the imprecise descriptions of terrain analysis terms.

Next, an inference scheme was designed, for the identification of the
landforms of the site and for the evaluation of the suitability of a site for an
application. The propagation of uncertainty in the inference procedure, and the
effect of multiple uncertain evidences in the confidence associated with
hypotheses, was modelled according to Dempster-Shafer theory of evidence. The
choice of the evidential approach (proposed by Dempster (1967)) for modelling
the inferencing procedure in terrain analysis, was based on the premise that each
piece of evidence contributes individually towards the establishment or rejection of
hypotheses, and that the effect of the sum of all the evidences can be computed by
combining the effect of the individual evidences. Other approaches for establishing
hypotheses such as the one adopted by Chandrasekaran (1982), involve the
assignment of confidence to hypotheses by considering all the evidences together.
In terrain analysis, about 8 pattern elements (evidences) are typically evaluated for
the identification of landforms (hypotheses). Each pattern element has on an
average about 5 possible values. An explicit enumeration of all possible evidence
combinations, for the assignment of confidence to hypotheses would number about
$5^8$. If one takes into account the different levels of certainties associated with the
evidences, the problem becomes one of combinatorial explosion. Proponents of
this approach counter this problem with the argument that it is not necessary to consider all possible combinations, since only a subset of these cases occur in practice. However, in automated systems where evidences are acquired automatically, errors in the evidence gathering process could produce erroneous values for some evidences. This would result in unforeseen combinations of evidences, which could not be handled by a system combining evidences based on the explicit enumeration of their combinations. In the evidential approach, erroneous evidences would certainly have a detrimental effect on the establishment of hypotheses, but this would be compensated by the observation of a number of error-free evidences. The case of missing pieces of evidences also causes problems in the explicit enumeration approach.

The conceptual models of terrain concepts and the inference strategy for the identification of landforms and for the evaluation of the suitability of a site for an engineering application were then formalized in frames. The choice of frames for the representation of terrain knowledge, was dictated by the considerable advantages of frames over simple rule-based systems (as outlined in section 2.3).

3.1 Models of Uncertain Knowledge in Terrain Analysis

The models of terrain objects were qualitative descriptions using linguistic terms to describe various attributes of the concept. Landforms, for instance, were described using terms such as "gentle" for the attribute of "Relief", and terms like "partly dendritic, partly rectangular" for the attribute of "drainage pattern". Such descriptions contain knowledge which is not precise. Fuzzy systems provide a way for dealing with such vague linguistic descriptions, and have been adopted in TAX, for building models of terrain objects.

While every effort was made to arrive at reasonable values for the parameters
in the models of terrain objects, the emphasis in this research effort was to
develop a framework for representing these models, rather than to obtain "correct"
values for these parameters.

3.1.1 Models of Pattern Elements

The primary goal of the terrain analysis process was to identify the landforms
of the site, based on the observed pattern elements of the site. This involved
matching the pattern element values of the site with those of landforms. Often an
exact match between these two sets of pattern element values could not be
obtained. It was therefore necessary to devise a scheme to compute the proximities
or compatibilities of different pattern element values with each other, so as to
arrive at a measure of match between pattern element values. The pattern
elements used for the identification of landforms in TAX were topographic
attributes such as Relief and Slope, drainage attributes like Drainage-Type and
Texture, Gully-Type, Landuse/Landcover in summits, side-Slopes and plains,
Soil-Tone and Soil-Tone-Texture. The names of these pattern elements as they
were used in TAX is given in Table 3.1.
Table 3.1. Pattern elements used in TAX

<table>
<thead>
<tr>
<th>Relief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
</tr>
<tr>
<td>Drainage-Type</td>
</tr>
<tr>
<td>Drainage-Texture</td>
</tr>
<tr>
<td>Gully-Type</td>
</tr>
<tr>
<td>Landuse-Summits</td>
</tr>
<tr>
<td>Landuse-Slopes</td>
</tr>
<tr>
<td>Landuse-Plains</td>
</tr>
<tr>
<td>Soil-Tone</td>
</tr>
<tr>
<td>Soil-Tone-Texture</td>
</tr>
</tbody>
</table>

In the traditional photointerpretation of terrain the values given to these pattern elements are all symbolic, for instance, Steep Slopes, Trellis Drainage-Type, Forested Landuse, etc. However, the characteristic of the pattern element that each of these symbolic values are attributed to, is quite different in each of the cases. Landuse is a pattern element that takes discrete values like Water, Forests, Cultivated etc. Drainage-Type, on the other hand, takes continuous values, all kinds of mixtures of ideal Drainage-Types, like Dendritic and Rectangular, are possible. The features that are used for characterizing Drainage-Types, however, are not clearly defined. Pattern elements like Relief and Slope, also take continuous values, but they have a well defined base variable for characterizing the linguistic values attributed to them. The treatment of each of these different types of pattern elements, for the computation of compatibilities, is discussed in
3.1.1.1 Pattern Elements with Well-defined Base Variables

The pattern elements which fall in this group are Relief, Slope and Drainage-Texture. For each of these pattern elements there is a well-defined continuous numeric base variable. A linguistic label such as Gentle Relief may be construed as a fuzzy restriction on the values of the base variable "Relief in feet". A fuzzy restriction on the values of the base variable is characterized by a compatibility function which associates with each value of the base variable a number in the interval [0,1] which represents its compatibility with the fuzzy restriction. Membership functions were designed to represent the compatibility of the numerical values of the base variables with the linguistic pattern element values. The models of these pattern element values, are the parameters of the compatibility function, of the fuzzy set representing them.

Relief is defined as the relative elevation or the difference in elevation between the highest and lowest points in an area. Relief of a landscape is usually expressed using terms such as Gentle, Moderate and Strong. Table 3.2 gives a typical range of values used by experts, for each of the classes of Relief (Hoffman, 1985).
Table 3.2. Descriptions of Relief classes

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle</td>
<td>~ 0 - 100 m</td>
</tr>
<tr>
<td>Moderate</td>
<td>~ 100 - 300 m</td>
</tr>
<tr>
<td>Strong</td>
<td>~ &gt; 300 m</td>
</tr>
</tbody>
</table>

From the above definitions, we can see that a flat plain or a site having a Relief of 0 m would be definitely called Gentle Relief, that is, the membership of 0 m in Gentle Relief would be 1. A Relief of 100 m could be called Gentle or Moderate, that is, the membership value in Gentle Relief would be 0.5 and the membership value in Moderate Relief would be 0.5. The membership value in Gentle Relief decreases from 1 to 0, as the Relief increases and becomes 0 when Relief equals 200 m. The core of the membership function characterizing Gentle Relief, that is the value of Relief at which μ is 1, is therefore 0.

\[ C(\mu_{Gentle}) = \{0\} \]

The support of this function is the set of values between 0 and 200 m, including 0 but excluding 200 m.

\[ S(\mu_{Gentle}) = [0,200) \]

The characteristics of the membership function are:
\[
\begin{align*}
\mu_{\text{Gentle}} (\text{Relief}) &= 1 && \text{for Relief} = 0 \text{ m} \\
0.5 < \mu_{\text{Gentle}} (\text{Relief}) &< 1 && \text{for } 0 < \text{Relief} < 100 \text{ m} \\
\mu_{\text{Gentle}} (\text{Relief}) &= 0.5 && \text{for Relief} = 100 \text{ m} \\
0 < \mu_{\text{Gentle}} (\text{Relief}) &< 0.5 && \text{for } 100 \text{ m} < \text{Relief} < 200 \text{ m} \\
\mu_{\text{Gentle}} (\text{Relief}) &= 0 && \text{for Relief} = 200 \text{ m}
\end{align*}
\]

These characteristics were represented by an S' type function with an \( \alpha = 0, \beta = 100 \) and \( \gamma = 200 \) (Figure 3.1).

The membership value in Moderate Relief is maximum, that is, 1, when Relief equals 200 m. The membership value in Moderate Relief decreases as the value of Relief goes farther from 200 m on either side. When Relief equals 100 m, the membership in Gentle Relief is 0.5 and so is the membership in Moderate Relief. A Relief of 0 m is fully compatible with the concept of Gentle Relief \( \mu_{\text{Gentle}} (0) = 1 \), it's membership in Moderate Relief is therefore 0. If the Relief is 300 m, it could be classified as Moderate or Strong Relief. Therefore \( \mu_{\text{Moderate}} (300) = 0.5 \). When the value of Relief becomes much greater than 300 m, and is equal to 400 m, the Relief is definitely classified as Strong, and the membership in Moderate is 0. From the above observations, we see that the core of the membership function,

\[ C(\mu_{\text{Moderate}}) = \{200\}. \]

The support of the function is the set of values between 0 and 400 m,

\[ S(\mu_{\text{Moderate}}) = (0,400). \]

The characteristics of the membership function are:
\[\mu_{\text{Moderate}} (\text{Relief}) = 0 \quad \text{for Relief} = 0 \text{ m}\]
\[0 < \mu_{\text{Moderate}} (\text{Relief}) < 0.5 \quad \text{for} \ 0 < \text{Relief} < 100 \text{ m}\]
\[\mu_{\text{Moderate}} (\text{Relief}) = 0.5 \quad \text{for Relief} = 100 \text{ m}\]
\[0.5 < \mu_{\text{Moderate}} (\text{Relief}) < 1 \quad \text{for} \ 100 \text{ m} < \text{Relief} < 200 \text{ m}\]
\[\mu_{\text{Moderate}} (\text{Relief}) = 1 \quad \text{for Relief} = 200 \text{ m}\]
\[0.5 < \mu_{\text{Moderate}} (\text{Relief}) < 1 \quad \text{for} \ 200 < \text{Relief} < 300 \text{ m}\]
\[\mu_{\text{Moderate}} (\text{Relief}) = 0.5 \quad \text{for Relief} = 300 \text{ m}\]
\[0.5 < \mu_{\text{Moderate}} (\text{Relief}) < 0 \quad \text{for} \ 300 \text{ m} < \text{Relief} < 400 \text{ m}\]
\[\mu_{\text{Moderate}} (\text{Relief}) = 0 \quad \text{for Relief} = 400 \text{ m}\]

These characteristics were represented by a \(\Pi\) type function with \(\gamma = 200 \text{ m}\), and \(\beta = 200 \text{ m}\) (Figure 3.1).

The characteristics of Strong Relief are the reverse of Gentle Relief. The membership value in Strong Relief is 0, when Relief is 200 m. From there onwards, the membership in Strong Relief increases as Relief increases. The membership is equal to 0.5 when Relief is 300 m and reaches a maximum value of 1, when Relief is greater than or equal to 400 m. The core of the membership function consists of all values greater than 400 m, that is,
\[C(\mu_{\text{Strong}}) = \{x / x \geq 400\}\]
The support of the membership function is the set of values greater than 200 m, that is,
\[S(\mu_{\text{Strong}}) = \{x / x > 200\}.\]
The characteristics of the membership function are:
\[ \mu_{\text{Strong}} (\text{Relief}) = 0 \quad \text{for Relief} = 200 \text{ m} \]
\[ 0 < \mu_{\text{Strong}} (\text{Relief}) < 0.5 \quad \text{for} \ 200 < \text{Relief} < 300 \text{ m} \]
\[ \mu_{\text{Strong}} (\text{Relief}) = 0.5 \quad \text{for Relief} = 300 \text{ m} \]
\[ 0.5 < \mu_{\text{Strong}} (\text{Relief}) < 1 \quad \text{for} \ 300 \text{ m} < \text{Relief} < 400 \text{ m} \]
\[ \mu_{\text{Strong}} (\text{Relief}) = 1 \quad \text{for Relief} = 400 \text{ m} \]

These characteristics were represented by an S type function with an \( \alpha = 200 \text{ m} \), \( \beta = 300 \text{ m} \) and \( \gamma = 400 \text{ m} \) (Figure 3.1).

In addition to the primary Relief classes Gentle, Moderate and Strong, linguistic modifiers were used to define additional derived classes. The derived classes were Very Gentle and Very Strong. The effect of the modifier "Very" on a fuzzy set, is to make the membership in the fuzzy set more restrictive. Zadeh (1975) suggested that the membership in a fuzzy set, say "Very Tall" can be computed as
\[ \mu_{\text{Very Tall}}(A) = [\mu_{\text{Tall}}(A)]^2 \]

Following Zadeh's formalism,
\[ \mu_{\text{Very Gentle}}(\text{Relief}) = [\mu_{\text{Gentle}}(\text{Relief})]^2 \]
\[ \mu_{\text{Very Strong}}(\text{Relief}) = [\mu_{\text{Strong}}(\text{Relief})]^2 \]

The models of the primary Relief classes are given in Table 3.3, in terms of the parameters of their membership functions. The derived classes Very Gentle and Very Strong, do not have a membership function associated with them. The membership in these derived classes was computed, by calculating the membership in the primary class from which they were derived, and then applying the modifier on the calculated membership.
Table 3.3. Models of Relief classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of function</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle</td>
<td>S'</td>
<td>0</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Moderate</td>
<td>Π</td>
<td>-</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Strong</td>
<td>S</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>

Slope is the average value of the gradient in an area. In a mountainous region, Slope is computed by taking the average value of gradient, over the sideslopes instead of over the whole area. Table 3.4 gives the range of values for the typical Slope classes (Hoffman, 1985). Slope values in these classes are usually defined in terms of percent slope.

Table 3.4. Descriptions of Slope classes

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle</td>
<td>0 - 15 %</td>
</tr>
<tr>
<td>Moderate</td>
<td>15 - 45 %</td>
</tr>
<tr>
<td>Steep</td>
<td>&gt; 45 %</td>
</tr>
</tbody>
</table>

The design of the membership functions for each of the Slope classes was similar to the one outlined for Relief. The characteristics of the membership function for Gentle Slope are:
\[ \mu_{\text{Gentle}} \text{ (Slope)} = 1 \quad \text{for Slope} = 0 \% \]
\[ 0.5 < \mu_{\text{Gentle}} \text{ (Slope)} < 1 \quad \text{for} \ 0 < \text{Slope} < 15 \% \]
\[ \mu_{\text{Gentle}} \text{ (Slope)} = 0.5 \quad \text{for Slope} = 15 \% \]
\[ 0 < \mu_{\text{Gentle}} \text{ (Slope)} < 0.5 \quad \text{for} \ 15 \% < \text{Slope} < 30 \% \]
\[ \mu_{\text{Gentle}} \text{ (Slope)} = 0 \quad \text{for Slope} = 30 \% \]

These characteristics were represented by an \( S' \) type function with an \( \alpha = 0, \beta = 15 \) and \( \gamma = 27.5 \) (Figure 3.2).

The characteristics of the membership function for Moderate Slope are:

\[ \mu_{\text{Moderate}} \text{ (Slope)} = 0 \quad \text{for Slope} = 0 \% \]
\[ 0 < \mu_{\text{Moderate}} \text{ (Slope)} < 0.5 \quad \text{for} \ 0 < \text{Slope} < 15 \% \]
\[ \mu_{\text{Moderate}} \text{ (Slope)} = 0.5 \quad \text{for Slope} = 15 \% \]
\[ 0.5 < \mu_{\text{Moderate}} \text{ (Slope)} < 1 \quad \text{for} \ 15 \% < \text{Slope} < 30 \% \]
\[ \mu_{\text{Moderate}} \text{ (Slope)} = 1 \quad \text{for Slope} = 30 \% \]
\[ 0.5 < \mu_{\text{Moderate}} \text{ (Slope)} < 1 \quad \text{for} \ 30 < \text{Slope} < 45 \% \]
\[ \mu_{\text{Moderate}} \text{ (Slope)} = 0.5 \quad \text{for Slope} = 45 \% \]
\[ 0.5 < \mu_{\text{Moderate}} \text{ (Slope)} < 0 \quad \text{for} \ 45 \% < \text{Slope} < 60 \% \]
\[ \mu_{\text{Moderate}} \text{ (Slope)} = 0 \quad \text{for Slope} = 60 \% \]

These characteristics were represented by a \( \Pi \) type function with \( \gamma = 30 \), and \( \beta = 30 \) (Figure 3.2).

The characteristics of the membership function for Steep Slope are:
Figure 3.2. Membership functions for slope classes.
\[
\mu_{\text{Steep}}(\text{Slope}) = 0 \quad \text{for Slope} = 30\% \\
0 < \mu_{\text{Steep}}(\text{Slope}) < 0.5 \quad \text{for} 30 < \text{Slope} < 45\% \\
\mu_{\text{Steep}}(\text{Slope}) = 0.5 \quad \text{for Slope} = 45\% \\
0.5 < \mu_{\text{Steep}}(\text{Slope}) < 1 \quad \text{for} 45\% < \text{Slope} < 60\% \\
\mu_{\text{Steep}}(\text{Slope}) = 1 \quad \text{for Slope} = 60\% 
\]

These characteristics were represented by an S type function with an \( \alpha = 30 \), \( \beta = 45 \) and \( \gamma = 60 \) (Figure 3.2).

In addition to the primary Slope classes Gentle, Moderate and Steep, linguistic modifiers were used to define derived classes. The derived classes were Very Gentle Slope and Very Steep Slope. Following Zadeh’s formalism,

\[
\mu_{\text{VeryGentle}}(\text{Slope}) = (\mu_{\text{Gentle}}(\text{Slope}))^2 \\
\mu_{\text{VerySteep}}(\text{Slope}) = (\mu_{\text{Steep}}(\text{Slope}))^2
\]

The models of the primary Slope classes are given in Table 3.5, in terms of the parameters of their membership functions.

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of function</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle</td>
<td>( \Sigma' )</td>
<td>0</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Moderate</td>
<td>( \Pi )</td>
<td>-</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Steep</td>
<td>( \Sigma )</td>
<td>30</td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>

Drainage-Texture is often indicated in three categories, fine, medium and

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coarse, as based upon it's appearance in photographs (Way, 1978). A more quantitative approach to classification involves measurement of the distance between the drainage tributaries. The approximate ranges of values, of ground distance between tributaries, for the various classes are given in Table 3.6 (Way, 1978). Another measure of Drainage-Texture is the average length of drainage channels in an unit area. The measure of distance between tributaries has been converted to average length measures and presented in Table 3.6.

<table>
<thead>
<tr>
<th>Class</th>
<th>Ground distance between tributaries</th>
<th>Length/Unit area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>~ &lt; 120 m</td>
<td>~ &gt; 8/Km</td>
</tr>
<tr>
<td>Medium</td>
<td>~ 120 - 1000 m</td>
<td>~ 1/Km - 8/Km</td>
</tr>
<tr>
<td>Coarse</td>
<td>~ &gt; 1000 m</td>
<td>~ &lt; 1/Km</td>
</tr>
</tbody>
</table>

For measures such as Drainage-Texture, the interval between numbers does not represent the same difference in value at different regions in the scale. For instance, a change of 0.5/Km, from 1/Km to 0.5/Km causes the Drainage-Texture to be much more coarse, than a change from 8/Km to 8.5/Km. In such cases, a logarithmic transformation of the data, and a subsequent characterization, using membership functions gives a better idea of the compatibilities of these values with the texture classes. A logarithmic transformation yields the ranges for Drainage-Texture, as given in Table 3.7.
Table 3.7. Transformed Drainage-Texture ranges

<table>
<thead>
<tr>
<th>Class</th>
<th>Length/Unit area</th>
<th>ln (Length/Unit area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>&gt; 8/Km</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Medium</td>
<td>1/Km - 8/Km</td>
<td>0 - 2</td>
</tr>
<tr>
<td>Coarse</td>
<td>&lt; 1/Km</td>
<td>&lt; 0</td>
</tr>
</tbody>
</table>

The characteristics of the membership function for Fine Drainage-Texture are:

\[
\mu_{Fine} (Drng.Txtr) = 0 \quad \text{for } \ln(Drng.Txtr) = 1
\]

\[
0 < \mu_{Fine} (Drng.Txtr) < 0.5 \quad \text{for } 1 < \ln(Drng.Txtr) < 2
\]

\[
\mu_{Fine} (Drng.Txtr) = 0.5 \quad \text{for } \ln(Drng.Txtr) = 2
\]

\[
0.5 < \mu_{Fine} (Drng.Txtr) < 1 \quad \text{for } 2 < \ln(Drng.Txtr) < 3
\]

\[
\mu_{Fine} (Drng.Txtr) = 1 \quad \text{for } \ln(Drng.Txtr) = 3
\]

These characteristics were represented by an S type function with an \( \alpha = 1, \beta = 2 \) and \( \gamma = 3 \) (Figure 3.3).

The characteristics of the membership function for Medium Drainage-Texture are:
Figure 3.3. Membership functions for Drainage-Texture.
The characteristics of the membership function for Coarse Drainage-Texture are:

\[
\begin{align*}
0 < \mu_{\text{Coarse}}(\text{Drng.Txtr}) &< 0.5 & \text{for } -1 < \ln(\text{Drng.Txtr}) &< 0 \\
\mu_{\text{Coarse}}(\text{Drng.Txtr}) & = 0.5 & \text{for } \ln(\text{Drng.Txtr}) & = 0 \\
0.5 < \mu_{\text{Coarse}}(\text{Drng.Txtr}) &< 1 & \text{for } 0 < \ln(\text{Drng.Txtr}) &< 1 \\
\mu_{\text{Coarse}}(\text{Drng.Txtr}) & = 1 & \text{for } \ln(\text{Drng.Txtr}) & = 1 \\
0.5 < \mu_{\text{Coarse}}(\text{Drng.Txtr}) &< 1 & \text{for } 1 < \ln(\text{Drng.Txtr}) &< 2 \\
\mu_{\text{Coarse}}(\text{Drng.Txtr}) & = 0.5 & \text{for } \ln(\text{Drng.Txtr}) & = 2 \\
0.5 < \mu_{\text{Coarse}}(\text{Drng.Txtr}) &< 0 & \text{for } 2 < \ln(\text{Drng.Txtr}) &< 3 \\
\mu_{\text{Coarse}}(\text{Drng.Txtr}) & = 0 & \text{for } \ln(\text{Drng.Txtr}) & = 3
\end{align*}
\]

These characteristics were represented by an \( S' \) type function with \( \alpha = -1, \beta = 0 \) and \( \gamma = 1 \) (Figure 3.3).

The models of the Drainage-Texture classes are given in Table 3.8, in terms of the parameters of their membership functions.
Table 3.8. Models of Drainage-Texture classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of function</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>S</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Medium</td>
<td>Π</td>
<td>-</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Coarse</td>
<td>S'</td>
<td>-1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

3.1.1.2 Pattern Elements with Ill-defined Base Variables

The pattern elements that fall in this category are Drainage-Type, Gully-Type, Soil-Tone, and Soil-Tone-Texture. For pattern elements such as Drainage-Type, there is not a well-defined base variable, as there is in the case of Relief. Drainage patterns are described using the attributes of trunk, branches, leaves and their interrelationships (Argialas et al., 1988). Though it is possible to view the various Drainage-Types, as a fuzzy restriction on the values of these attributes, it is very difficult to design a compatibility function that would take into account all of the factors. So, it is not possible to express the membership functions of each of the Drainage-Types in terms of standardized parameters. Instead, each of the Drainage-Types was considered to be a prototype, and the compatibility between these prototypes was estimated. The compatibilities were given on a scale of 0 - 1. The linguistic terms used to describe compatibility were transformed to numerical values as given below:

Incompatible 0
Slightly compatible 0.25
Moderately compatible 0.5
Highly compatible 0.75
Completely compatible 1.0

The compatibilities between prototypes was used to arrive at a measure of compatibility between the pattern element value of the site and that of the landform. The models of these pattern element values, are the compatibilities of the pattern element values with each other.

Drainage patterns are formed from the aggregation of natural drainage ways in a region. Drainage pattern analysis gives a great deal of information concerning the parent rock and soil materials, since these influence how and to what extent water drains off a landform surface. The descriptions of some of the important Drainage-Types are given in Table 3.9 (Way, 1978).
An approach similar to the one followed by Bremermann (1976) was adopted to arrive at a measure of compatibility between different Drainage-Types. Each of the Drainage-Types was considered to be a prototype, and an estimate of the amount of the deformation energy required to transform one prototype to another.
was made. The compatibilities between prototypes is inversely proportional to the deformation energy. The deformation energy required for the transformation from one prototype to another is based on the geomorphic processes responsible for the manifestation of the shapes in the drainage patterns rather than on the geometric properties of the patterns.

From the descriptions of the Drainage-Types given in the preceding table we can see that the Dendritic pattern can be thought of as the principal pattern and the Pinnate, Trellis and Rectangular pattern as modifications of this principal pattern. The Dendritic pattern occurs on homogeneous, uniform soil and rock materials. The Rectangular pattern is a modification of the Dendritic pattern caused by bedrock jointing, foliations or fracturing. The compatibility between Dendritic and Rectangular patterns can be considered moderate. The Angular pattern is a modification of the Rectangular, where intersecting faults, fractures or jointing systems have created a mixture of acute, right and obtuse angles in the individual streams. The compatibility between Dendritic and Angular is considered slight to moderate, and that between Rectangular and Angular is considered high. The Trellis pattern is another modification of the Dendritic pattern and is characteristic of tilted interbedded sedimentary strata. The compatibility of Trellis with Dendritic pattern is considered moderate and that with Rectangular and Angular is considered slight. The Pinnate pattern is a modified form of Dendritic where the soil has a high silt content. The compatibility of this pattern with Dendritic is considered moderate. Parallel drainage systems arise because of a pronounced regional Slope, controlled by parallel topographic features or by parallel folded or faulted structures. The compatibility of this pattern with the Dendritic, Trellis, Rectangular and Angular pattern is considered moderate.
Internal drainage is associated with granular materials having high permeability or with porous rock materials. This pattern is quite different from all other patterns examined above, and is therefore considered incompatible with all the other pattern types. The Deranged pattern, like the Internal drainage, is completely different from all the other patterns, and it's compatibility with the other patterns is 0. Table 3.10 gives the models of the various drainage pattern types, in terms of their compatibilities with each other.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dendritic</td>
<td>1</td>
<td>0.5</td>
<td>0.37</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rectangular</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Angular</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Parallel</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trellis</td>
<td>1</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pinnate</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Internal</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Deranged</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gullies are formed when sheet runoff collects in channelized flow and by eroding the bottom, forms the first-order drainage system. As the gullies erode through the surface soils, they adopt characteristic cross-sectional shapes which reflect the textural composition and cohesiveness of the surrounding soils. Table 3.11 lists the different Gully-Types employed in terrain analysis (Way, 1978).
The construction of compatibility measures for Gully-Types is similar to the one employed in drainage patterns. The shapes of gullies are a manifestation of the texture of the soil (Way, 1978). The deformation energy required to bring about a change in Gully-Types can then be thought of as the change in soil texture. V-shaped gullies are formed in granular, non-cohesive materials. As the texture of the soil becomes finer and becomes silty and moderately cohesive the gully type shifts to box-shaped. Moderately cohesive sand-clay mixtures have characteristic U-shaped gullies. When the soil type becomes very fine and clayey, the gully type becomes sag-and-swale. The compatibility is considered to be slight between adjacent Gully-Types. The models of gullies in terms of the compatibilities with other Gully-Types are given in Table 3.12.

<table>
<thead>
<tr>
<th>Table 3.11. Types of Gullies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sag-and-Swale</td>
</tr>
<tr>
<td>U-shaped</td>
</tr>
<tr>
<td>Box-shaped</td>
</tr>
<tr>
<td>V-shaped</td>
</tr>
</tbody>
</table>
Table 3.12. Models of Gully-Types

<table>
<thead>
<tr>
<th></th>
<th>Sag-and-Swale</th>
<th>U-shaped</th>
<th>Box-shaped</th>
<th>V-shaped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sag-and-Swale</td>
<td>1</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U-shaped</td>
<td></td>
<td>1</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>Box-shaped</td>
<td></td>
<td>1</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>V-shaped</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Soil-Tone - Though Soil-Tone has a well-defined numeric base variable, the reflectance value in a digital image, it is difficult to construct a membership function for the various tonal classes. This is because the absolute reflectance value depends on several factors like scanner characteristics, atmospheric characteristics, film and processing characteristics etc. Soil-Tones are usually described by terms like White, Light Gray, Dull Gray, and Black. Each of these classes is considered to be slightly compatible with its immediate neighbors. The various tonal classes and their compatibilities are given in Table 3.13. The tonal classes described here refer to the reflectance characteristics of soils on black and white panchromatic photographs. Such data should be used along with color infrared photographs for analyzing soil tones, since expert knowledge about soil tones of landforms exist only for panchromatic photographs.
Table 3.13. Models of Soil-Tones

<table>
<thead>
<tr>
<th></th>
<th>White</th>
<th>Light Gray</th>
<th>Dull Gray</th>
<th>Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>1</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Light Gray</td>
<td>1</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dull Gray</td>
<td>1</td>
<td>1</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Black</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Soil-Tone-Texture - The distribution of tones over a photograph indicates the relative uniformity or homogeneity of the soil and rock materials. The texture of Soil-Tone is described as Uniform, Mottled, Banded and Scrabbled. Uniform tones indicate uniform soil texture and moisture conditions. Mottled tones indicate significant changes in soil moisture or texture within short distances, these changes result in the presence of many puffy light and dark tones. Banding occurs where there are linear-shaped differences in soil or rock texture, drainage or moisture availability. Interbedded sedimentary rocks or highly foliated rocks containing seep zones or areas of different moisture availability appear banded because of the distribution of vegetation. Banding may also represent differences in the natural rock color. Scrabbled tones are common in arid regions where alkali deposits are found on the ground surface (Way, 1978). The various texture classes are manifestations of distinct soil and rock properties. They are therefore considered distinct and incompatible with one another.

Landuse/Landcover - For the purposes of terrain analysis, a Level I United States Geological Survey (USGS) classification is considered adequate (Mintzer
The various Landuse/Landcover classes that are often employed in terrain analysis, are given in Table 3.14 (Anderson et al., 1976).

<table>
<thead>
<tr>
<th>Table 3.14. USGS Level I Landuse/Landcover classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban or Built-up land</td>
</tr>
<tr>
<td>Agricultural</td>
</tr>
<tr>
<td>Rangeland</td>
</tr>
<tr>
<td>Forest</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Wetland</td>
</tr>
<tr>
<td>Barren</td>
</tr>
<tr>
<td>Tundra</td>
</tr>
<tr>
<td>Perennial snow or ice</td>
</tr>
</tbody>
</table>

Landuse is an attribute that takes discrete values. The labels of the Landuse classes are well-defined crisp sets, rather than fuzzy sets. For such well-defined crisp sets, it is meaningless to evaluate the compatibility of one class with another. The classes are considered distinct and completely incompatible with one another.

3.1.2 Models of Engineering Properties

Landforms have associated with them a set of engineering properties that are expected of them (Way, 1978; Mintzer and Messmore, 1984). Therefore, it is assumed, that once the landform of a site is identified, the site will exhibit these properties, as default values. The properties are not uniform over the entire landform, but vary depending on site specific characteristics such as the
topographic location of the area. These site specific characteristics modify the default expectations of the engineering properties. Further, the confidence associated with the default property values of the landforms is rather low, because the same landform could exhibit slightly different properties depending on local conditions. Some of the specific values of pattern elements which are used to infer the landform of the site could also give additional information about the properties of the site.

The modification of the default values of the properties of the site, is modelled according to Dempster-Shafer theory of evidence. The modifiers are considered to be evidences, which bear upon the hypotheses about the property values. Each modifier has associated with it a basic probability assignment (bpa). The bpa assigns a measure of belief or basic probability number (bpn), to each of the property values, according to the value of the modifier observed in the site. The computations involved in the modification of the property values, are discussed in detail in section 3.2.2. This section discusses the models of engineering properties, the modifiers which affect these properties, and the models of these modifiers.

Some of the engineering properties that were represented in the present site suitability formulation were Depth-to-Water-Table, Depth-to-Bedrock, Soil-Permeability, and Bedrock-Permeability.

Depth-to-Water-Table: The Depth-to-Water-Table is difficult to map and requires local knowledge of the expected ranges of conditions. Well records and boring logs are extremely helpful in determining the location of the water table and should be used when available. However, it is possible to get an estimate of the Depth-to-Water-Table, based on the type of bedrock, the soil type, and drainage characteristics of the area. The approximate ranges of values for the
various classes of Depth-to-Water-Table have been adapted from Way (1978), and are given in Table 3.15.

Table 3.15. Descriptions of Depth-to-Water-Table classes

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>~ 0 - 1 m</td>
</tr>
<tr>
<td>Medium</td>
<td>~ 1 - 3 m</td>
</tr>
<tr>
<td>High</td>
<td>&gt; 3 m</td>
</tr>
</tbody>
</table>

The attribute Depth-to-Water-Table has a well defined numeric base variable (the distance from the surface to the water table in m), so it is possible to characterize the classes, using membership functions. The characteristics of the membership function for Low Depth-to-Water-Table are:

\[
\mu_{Low}(DWT) = \begin{cases} 
1 & \text{for } DWT = 0 \text{ m} \\
1 < \mu_{Low}(DWT) < 0.5 & \text{for } 0 < DWT < 1 \text{ m} \\
0.5 & \text{for } DWT = 1 \text{ m} \\
0.5 < \mu_{Low}(DWT) < 0 & \text{for } 1 \text{ m} < DWT < 2 \text{ m} \\
0 & \text{for } DWT = 2 \text{ m} 
\end{cases}
\]

These characteristics were represented by an S' type function with an \(\alpha = 0\) m, \(\beta = 1\) m, \(\gamma = 2\) m (Figure 3.4). The characteristics of the membership function for Medium Depth-to-Water-Table are:
These characteristics were represented by a \( \Pi \) type function with \( \gamma = 2 \text{ m} \), and \( \beta = 2 \text{ m} \) (Figure 3.4). The characteristics of the membership function for High Depth-to-Water-Table are:

\[
\begin{align*}
\mu_{High}(DWT) &= 0 & \text{for DWT} &= 2 \text{ m} \\
0 < \mu_{High}(DWT) < 0.5 & & \text{for} & 2 < \text{DWT} < 3 \text{ m} \\
\mu_{High}(DWT) &= 0.5 & \text{for DWT} &= 3 \text{ m} \\
0.5 < \mu_{High}(DWT) < 1 & & \text{for} & 3 < \text{DWT} < 4 \text{ m} \\
\mu_{High}(DWT) &= 1 & \text{for DWT} &= 4 \text{ m}
\end{align*}
\]

These characteristics were represented by an \( S \) type function with an \( \alpha = 2 \text{ m} \), \( \beta = 3 \text{ m} \), \( \gamma = 4 \text{ m} \) (Figure 3.4). Table 3.16 gives the models of the various Depth-to-Water-Table classes, in terms of the parameters of their membership functions.
Table 3.16. Models of Depth-to-Water-Table classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of function</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$S'$</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Medium</td>
<td>$\Pi$</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>High</td>
<td>$S$</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The effect of the Topographic-Position of the site on Depth-to-Water-Table is as follows: if the site is in a Valley, then the Depth-to-Water-Table is likely to be Low, that is near the surface, whereas if the site is on a Summit then Depth-to-Water-Table is likely to be High. The Topographic-Position of the site was considered as an evidence, which had a bearing on the hypotheses, the Depth-to-Water-Table. The hypotheses in the frame of discernment were

$$\theta = \{\text{Low.DWT, Medium.DWT, High.DWT}\}.$$  

The values of the modifier, Topographic-Position were $\{\text{Valley, Summit, Side-Slopes}\}$. The basic probability numbers assigned to the various values of Depth-to-Water-Table, by the modifiers are given in Table 3.17.
Table 3.17. Models of modifiers for Depth-to-Water-Table

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>DWT</th>
<th>bpn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valley</td>
<td>Low</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Summit</td>
<td>High</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

Depth-to-Bedrock: Mapping soil depths to bedrock can be accomplished in situations where the rock is covered by less than 10 feet of soil. The characteristics of the rock, topography, drainage and tones are still apparent and suggest a rock-controlled topography. The identification of the landform and the bedrock type provides a valuable clue about the erosion and weathering characteristics, and is useful for inferring the soil depths to bedrock. The descriptions of Depth-to-Bedrock classes have been adapted from (Way, 1978), and are given in Table 3.18.

Table 3.18. Descriptions of Depth-to-Bedrock classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>~ 0 - 1 m</td>
</tr>
<tr>
<td>Medium</td>
<td>~ 1 - 3 m</td>
</tr>
<tr>
<td>High</td>
<td>~ &gt; 3 m</td>
</tr>
</tbody>
</table>

The various Depth-to-Bedrock classes have a well defined numeric base variable,
the height of the soil layer expressed in meters. So, it is possible to characterize them using membership functions. The characteristics of the membership function for Low Depth-to-Bedrock are:

\[
\begin{align*}
\mu_{Low}(DBR) &= 1 \quad \text{for } DBR = 0 \text{ m} \\
1 < \mu_{Low}(DBR) < 0.5 &\quad \text{for } 0 < DBR < 1 \text{ m} \\
\mu_{Low}(DBR) &= 0.5 \quad \text{for } DBR = 1 \text{ m} \\
0.5 < \mu_{Low}(DBR) < 0 &\quad \text{for } 1 \text{ m} < DBR < 2 \text{ m} \\
\mu_{Low}(DBR) &= 0 \quad \text{for } DBR = 2 \text{ m}
\end{align*}
\]

These characteristics were represented by an \( S' \) type function with \( \alpha = 0 \text{ m}, \beta = 1 \text{ m}, \gamma = 2 \text{ m} \) (Figure 3.5). The characteristics of the membership function for Medium Depth-to-Bedrock are:

\[
\begin{align*}
\mu_{Medium}(DBR) &= 0 \quad \text{for } DBR = 0 \text{ m} \\
0 < \mu_{Medium}(DBR) < 0.5 &\quad \text{for } 0 < DBR < 1 \text{ m} \\
\mu_{Medium}(DBR) &= 0.5 \quad \text{for } DBR = 1 \text{ m} \\
0.5 < \mu_{Medium}(DBR) < 1 &\quad \text{for } 1 \text{ m} < DBR < 2 \text{ m} \\
\mu_{Medium}(DBR) &= 1 \quad \text{for } DBR = 2 \text{ m} \\
0.5 < \mu_{Medium}(DBR) < 1 &\quad \text{for } 2 \text{ m} < DBR < 3 \text{ m} \\
\mu_{Medium}(DBR) &= 0.5 \quad \text{for } DBR = 3 \text{ m} \\
0.5 < \mu_{Medium}(DBR) < 0 &\quad \text{for } 3 \text{ m} < DBR < 4 \text{ m} \\
\mu_{Medium}(DBR) &= 0 \quad \text{for } DBR = 4 \text{ m}
\end{align*}
\]

These characteristics were represented by a \( \Pi \) type function with \( \gamma = 2 \text{ m}, \beta = 2 \text{ m} \) (Figure 3.5). The characteristics of the membership function for High Depth-to-Bedrock are:
Figure 3.5. Membership functions for Depth-to-Bedrock.
\[ \mu_{\text{High}}(\text{DBR}) = 0 \quad \text{for } \text{DBR} = 2 \text{ m} \]
\[ 0 < \mu_{\text{High}}(\text{DBR}) < 0.5 \quad \text{for } 2 < \text{DBR} < 3 \text{ m} \]
\[ \mu_{\text{High}}(\text{DBR}) = 0.5 \quad \text{for } \text{DBR} = 3 \text{ m} \]
\[ 0.5 < \mu_{\text{High}}(\text{DBR}) < 1 \quad \text{for } 3 \text{ m} < \text{DBR} < 4 \text{ m} \]
\[ \mu_{\text{High}}(\text{DBR}) = 1 \quad \text{for } \text{DBR} = 4 \text{ m} \]

These characteristics were represented by an S type function with an \( \alpha = 2 \text{ m} \), \( \beta = 3 \text{ m} \), \( \gamma = 4 \text{ m} \) (Figure 3.5). The models of the various Depth-to-Bedrock classes are given in Table 3.19 in terms of the parameters of their membership functions.

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of function</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>( S' )</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Medium</td>
<td>( \Pi )</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>High</td>
<td>( S )</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The Topographic-Position of the site has a considerable influence on the soil depths. Rock outcrops and shallowest soils usually occur along the upper hillside Slopes in a dissected topography. Hilltops, depending upon their size, may contain relatively deep soils, and lower hillside Slopes will accumulate deeper deposits from Slope processes of creep, slumping and erosion. Major valleys contain fluvial transported landforms that can be assumed to be deep. The Topographic-Position of the site was modelled as the evidence which influenced the hypotheses about Depth-to-Bedrock. The hypotheses were

\[ \theta = \{ \text{Low.DBR}, \text{Medium.DBR}, \text{High.DBR} \} \].
The values of the modifier, Topographic-Position were \{Valley, Summit, Side-Slopes\}. The basic probability numbers assigned to the various values of Depth-to-Bedrock, by the modifiers are given in Table 3.20.

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>DBR</th>
<th>bpn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic position</td>
<td>Valley</td>
<td>High</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Side-Slope</td>
<td>Low</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Soil-Permeability: The permeability of soils ranges from 0.1 cm/sec in coarse gravels to less than $10^{-7}$ cm/sec in clays. Table 3.21 adapted from (Sowers and Sowers, 1970) gives the typical ranges for the various classes of permeability.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$&lt; 10^{-3}$ cm/sec</td>
</tr>
<tr>
<td>Medium</td>
<td>$10^{-1}$ - $10^{-3}$ cm/sec</td>
</tr>
<tr>
<td>High</td>
<td>$&gt; 0.1$ cm/sec</td>
</tr>
</tbody>
</table>

The various Soil-Permeability classes have values ranging over several orders of magnitude. A logarithmic transformation of the data and a subsequent characterization of the classes using standardized functions has been done to

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define the membership functions. The characteristics of the membership function for Low permeability are:

\[
\mu_{\text{Low}} (\text{Perm}) = 1 \quad \text{for } \log(\text{Perm}) = -4
\]

\[
1 < \mu_{\text{Low}} (\text{Perm}) < 0.5 \quad \text{for } -4 < \log(\text{Perm}) < -3
\]

\[
\mu_{\text{Low}} (\text{Perm}) = 0.5 \quad \text{for } \log(\text{Perm}) = -3
\]

\[
0.5 < \mu_{\text{Low}} (\text{Perm}) < 0 \quad \text{for } -3 < \log(\text{Perm}) < -2
\]

\[
\mu_{\text{Low}} (\text{Perm}) = 0 \quad \text{for } \log(\text{Perm}) = -2
\]

These characteristics were represented by an S' type function with an \( \alpha = -4, \beta = -3, \gamma = -2 \) (Figure 3.6). The characteristics of the membership function for Medium permeability are:

\[
\mu_{\text{Medium}} (\text{Perm}) = 0 \quad \text{for } \log(\text{Perm}) = -4
\]

\[
0 < \mu_{\text{Medium}} (\text{Perm}) < 0.5 \quad \text{for } -4 < \log(\text{Perm}) < -3
\]

\[
\mu_{\text{Medium}} (\text{Perm}) = 0.5 \quad \text{for } \log(\text{Perm}) = -3
\]

\[
0.5 < \mu_{\text{Medium}} (\text{Perm}) < 1 \quad \text{for } -3 < \log(\text{Perm}) < -2
\]

\[
\mu_{\text{Medium}} (\text{Perm}) = 1 \quad \text{for } \log(\text{Perm}) = -2
\]

\[
0.5 < \mu_{\text{Medium}} (\text{Perm}) < 1 \quad \text{for } -2 < \log(\text{Perm}) < -1
\]

\[
\mu_{\text{Medium}} (\text{Perm}) = 0.5 \quad \text{for } \log(\text{Perm}) = -1
\]

\[
0.5 < \mu_{\text{Medium}} (\text{Perm}) < 0 \quad \text{for } -1 < \log(\text{Perm}) < 0
\]

\[
\mu_{\text{Medium}} (\text{Perm}) = 0 \quad \text{for } \log(\text{Perm}) = 0
\]

These characteristics were represented by a \( \Pi \) type function with \( \gamma = -2, \beta = -2 \) (Figure 3.6). The characteristics of the membership function for High permeability are:
Figure 3.6. Membership functions for permeability of soils and bedrock.
\[ \mu_{\text{High}} (\text{Perm}) = 0 \quad \text{for } \log(\text{Perm}) = -2 \]

\[ 0 < \mu_{\text{High}} (\text{Perm}) < 0.5 \quad \text{for } -2 < \log(\text{Perm}) < -1 \]

\[ \mu_{\text{High}} (\text{Perm}) = 0.5 \quad \text{for } \log(\text{Perm}) = -1 \]

\[ 0.5 < \mu_{\text{High}} (\text{Perm}) < 1 \quad \text{for } -1 < \log(\text{Perm}) < 0 \]

\[ \mu_{\text{High}} (\text{Perm}) = 1 \quad \text{for } \log(\text{Perm}) = 0 \]

These characteristics were represented by an S type function with an \( \alpha = -2, \beta = -1, \gamma = 0 \) (Figure 3.6). In addition to these primary classes, the linguistic hedge "Very" was used to define additional derived classes "Very Low", and "Very High" permeability. The membership of a value in the class "Very Low" permeability is given as:

\[ \mu_{\text{Very Low}} (\text{Perm}) = [\mu_{\text{Low}} (\text{Perm})]^2 \]

The membership of a value in the class "Very High" permeability is given as:

\[ \mu_{\text{Very High}} (\text{Perm}) = [\mu_{\text{High}} (\text{Perm})]^2 \]

A plot of the membership functions for the derived classes is given in Figure 3.6. The models of the primary soil permeability classes are given in Table 3.22, in terms of the parameters of their membership functions.
Table 3.22. Models of Soil-Permeability classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Percolation rate (cm/sec)</th>
<th>log (percolation)</th>
<th>Type of function</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>~ &lt; 10^{-3}</td>
<td>&lt; -3</td>
<td>S'</td>
<td>-4</td>
<td>-3</td>
<td>-2</td>
</tr>
<tr>
<td>Medium</td>
<td>~ 10^{-1} - 10^{-3}</td>
<td>-1 - -3</td>
<td>Π</td>
<td>-</td>
<td>-2</td>
<td>-2</td>
</tr>
<tr>
<td>High</td>
<td>~ &gt; 10^{-1}</td>
<td>&gt; -1</td>
<td>S</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
</tr>
</tbody>
</table>

The permeability of soils can be inferred from the drainage characteristics of the site. Fine Drainage-Texture implies fine textured soils of low permeability, coarse textured drainage is the result of coarse soils of moderate permeability, and internal drainage implies granular material with very high permeability. The bpn assigned to the various soil permeability classes, by the evidences, Drainage-Texture, and Drainage-Type are given in Table 3.23.

Table 3.23. Models of modifiers for Soil-Permeability

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>Soil Permeability</th>
<th>bpn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Type</td>
<td>Internal</td>
<td>Very High</td>
<td>0.75</td>
</tr>
<tr>
<td>Drainage Texture</td>
<td>Coarse</td>
<td>High</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>Low</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Bedrock-Permeability: The terms used to characterize the permeability of
bedrock, and the typical ranges of values of permeability, are the same as the ones for soil permeability. The permeability of bedrock is affected by, the type of bedrock, and by the presence of faults and fractures. These factors can be partially inferred from the drainage characteristics of the site. Fine Drainage-Texture indicates impervious bedrock and coarse texture indicates permeable bedrock. The Rectangular and Angular drainage patterns are caused by bedrock jointing and fractures, which increase the permeability. Internal drainage is characteristic of highly porous rock materials. The bpn assigned to the bedrock permeability classes, by the evidences, Drainage-Texture, and Drainage-Type is given in Table 3.24.

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>Bedrock Permeability</th>
<th>bpn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Type</td>
<td>Internal</td>
<td>Very High</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>Very High</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Rectangular</td>
<td>High</td>
<td>0.5</td>
</tr>
<tr>
<td>Drainage Texture</td>
<td>Coarse</td>
<td>High</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>Low</td>
<td>0.5</td>
</tr>
</tbody>
</table>

3.1.3 Models of Landforms

A model of a landform is it's description in terms of the pattern elements employed in terrain analysis. Typically, a landform has multiple values for a pattern element, and associated with each value is a measure of the frequency of
occurrence of that value in the landform. Frequency measures are given on a scale of 0 - 1. Associated with each landform are also expectations of engineering properties, which are used for site suitability evaluations. The model of the landform was expressed in terms of the pattern elements employed in TAX. The models of two of the landforms are given in Tables 3.25a, 3.25b. (The examples illustrating the inferencing procedure given in section 3.2 refer to these tables.) The frequency measures were estimated, by reviewing terrain analysis books and reports, and consultations with experts.

<table>
<thead>
<tr>
<th>Pattern Element</th>
<th>Value</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief</td>
<td>Strong</td>
<td>1</td>
</tr>
<tr>
<td>Drainage Type</td>
<td>Dendritic</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Rectangular</td>
<td>0.25</td>
</tr>
<tr>
<td>Drainage Texture</td>
<td>Coarse</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.33</td>
</tr>
<tr>
<td>Soil Tone</td>
<td>Light</td>
<td>1</td>
</tr>
<tr>
<td>Soil Tone Texture</td>
<td>Uniform</td>
<td>1</td>
</tr>
<tr>
<td>Gully Type</td>
<td>V-shaped</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.25a. Model of Humid-Sandstone
Table 3.25a. Model of Humid-Sandstone (Contd.)

<table>
<thead>
<tr>
<th>Pattern Element</th>
<th>Value</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landuse.Slopes</td>
<td>Forested</td>
<td>1</td>
</tr>
<tr>
<td>Landuse.Summits</td>
<td>Forested</td>
<td>1</td>
</tr>
<tr>
<td>Landuse.Valleys</td>
<td>Forested</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Cultivated</td>
<td>0.33</td>
</tr>
<tr>
<td>Depth to Bedrock</td>
<td>Low</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.25</td>
</tr>
<tr>
<td>Depth to Water-table</td>
<td>Medium</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.5</td>
</tr>
<tr>
<td>Soil Permeability</td>
<td>Medium</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.5</td>
</tr>
<tr>
<td>Bedrock Permeability</td>
<td>High</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Table 3.25b. Model of Humid-Shale

<table>
<thead>
<tr>
<th>Pattern Element</th>
<th>Value</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief</td>
<td>Moderate</td>
<td>1</td>
</tr>
<tr>
<td>Drainage Type</td>
<td>Dendritic</td>
<td>1</td>
</tr>
<tr>
<td>Drainage Texture</td>
<td>Medium</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>0.5</td>
</tr>
<tr>
<td>Soil Tone</td>
<td>Dull Gray</td>
<td>1</td>
</tr>
<tr>
<td>Soil Tone Texture</td>
<td>Mottled</td>
<td>1</td>
</tr>
<tr>
<td>Gully Type</td>
<td>Sag-and-Swale</td>
<td>1</td>
</tr>
<tr>
<td>Landuse.Slopes</td>
<td>Forested</td>
<td>1</td>
</tr>
<tr>
<td>Landuse.Summits</td>
<td>Forested</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Agricultural</td>
<td>0.75</td>
</tr>
<tr>
<td>Landuse.Valleys</td>
<td>Forested</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Cultivated</td>
<td>0.33</td>
</tr>
<tr>
<td>Depth to Bedrock</td>
<td>Medium</td>
<td>1</td>
</tr>
<tr>
<td>Depth to Water-table</td>
<td>Medium</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.75</td>
</tr>
<tr>
<td>Soil Permeability</td>
<td>Low</td>
<td>1</td>
</tr>
<tr>
<td>Bedrock Permeability</td>
<td>Low</td>
<td>1</td>
</tr>
</tbody>
</table>
3.1.4 Models of Engineering Applications

In this section models are developed which enable the evaluation of the potential of a site for some terrain related engineering application. Models of engineering applications describe the effect of the properties of a site on the suitability for an application. For some applications, there are regulations regarding some of the properties, and any site chosen for the application must meet these requirements. For other applications, the properties determine how suitable a site is for the selected application.

The evaluation of the suitability of a site for an application was performed, by considering the properties of site as evidences, which supported or weakened the hypothesis that the site was suitable for the application. This was achieved, by designing a basic probability assignment for each property. The bpa assigned a basic probability number (bpn) for the suitability corresponding to each of the possible values of the property. The details of the combination of the effect of all the properties on the suitability, are given in section 3.2.3. For a given model of an application, for each property that bears an influence on the suitability of a site, a bpn is associated with all the possible values that the property can have. A bpn of 1, for Unsuitable indicates, that the site is completely unsuitable for the application. Values of bpn from 0 to 1 for the property values reflect varying levels of suitability for the application. These values also indicate how critical a property is for an application.

The engineering applications that have been considered in this study are solid waste disposal by Sanitary-Landfill and sewage disposal by Septic-Tank-Leaching-Fields. These applications are highly influenced by the terrain conditions, and a terrain analysis approach to a reconnaissance study for location of these facilities in an area has been quite successful (Way, 1978). Similar models can be
developed for other applications, as long as the criteria for their suitability can be expressed in terms of the properties of the site. It should also be feasible to compute the values of these properties either directly from available data, or by association with the landforms of the site.

Sanitary-Landfill: In this method of waste disposal, wastes are deposited in thin layers in the disposal pit and are covered daily with soil material. The ideal location for a sanitary landfill operation is a natural or manmade depression underlaid by an impervious stratum. Such a situation prevents the leakage of leachate into the groundwater resource. Typically, the ground water table should be at least 10 feet beneath the bottom of the depression, to allow any leachate that may inadvertently leak out to be adequately filtered. The soil materials covering each day’s deposit of wastes should be adequate to provide an impervious layer, so that rainwater does not penetrate and form leachate. Table 3.26, summarizes the property values, and their effect on site suitability, as represented by bpn. The bpn were estimated by reviewing literature pertaining to terrain analysis and this engineering application (Way, 1978; Garofalo and Wobber, 1974).
### Table 3.26. Model of Sanitary-Landfill

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>m(Suitable)</th>
<th>m(Unsuitable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to Water table</td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Depth to Bedrock</td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Edgar Steerbee</td>
<td>Medium</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Soil Permeability</td>
<td>Very High</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Bedrock Permeability</td>
<td>Very High</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Septic-Tank-Leaching-Fields: A septic tank system operates by carrying sewage effluent out of a residential unit to a septic tank unit where it is temporarily stored while bacteria work to decompose much of the solid matter. The liquid effluent slowly overflows the tank unit and is carried by pipes to a leaching field. The leaching field contains a series of segmented or perforated clay pipes, buried approximately 2 feet beneath the surface in rows 6 to 8 feet apart.
The effluent slowly seeps through the perforations or open joints of the pipes into the soil, and as it filters through the soil the process of decomposition by aerobic bacteria continues.

The capability of a site to support this type of sewage system depends upon its characteristics of Slope, Depth-to-Water-Table, Depth-to-Bedrock, and soil percolation rate. Most states have legal minimum standards which attempt to guarantee and protect the quality of the surface and groundwater resources when such systems are installed. For instance, a typical state standard specifies that a site have a Slope of less than 12%, a high water table more than 4 feet below the trench bottom, and bedrock or other impervious stratum at least 4 feet below the trench bottom (Way, 1978). To ensure proper filtering, soils are required to have a percolation rate of about 1 inch/hr. Table 3.27, summarizes the property values, and their effect on site suitability, as represented by bpn.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>m(Suitable)</th>
<th>m(Unsuitable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to Water table</td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Depth to Bedrock</td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Soil Permeability</td>
<td>High</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Slope</td>
<td>Gentle</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steep</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
3.2 Inexact Inference in Terrain Analysis

3.2.1 Overview

The goal of the terrain analysis process was to evaluate the suitability of a site for some terrain related engineering application (APPLN). The goal tree of the process is shown in Figure 3.7. The top level goal (0), was broken down into a conjunction ("and") of three subgoals. The first subgoal (1), involved the identification of the properties (AP.PROPs) which had an influence on the suitability of the site for the application (APPLN). In sub-goal (2), each of the AP.PROPs, was computed for the site (SITE.PROP.VAL), and finally in sub-goal (3), the suitability of the site for the APPLN was updated based on SITE.PROP.VAL.

Identification of AP.PROPs was achieved (sub-goal 1), simply by extracting them from the model of the APPLN (as given in Tables 3.26, 3.27). Computation of the AP.PROPs (2), was achieved by extracting it directly from available data (2.1), if possible, or by inferring it from evidences (2.2). Some of the AP.PROPs, like Slope, were computed by extracting them from digital elevation data (subgoal 2.1). However, other AP.PROPs, like Depth-to-Bedrock, had to be inferred from evidences. The inference of AP.PROP of the site from evidences (sub-goal 2.2), involved the identification of the evidences (PROP.EVs) (sub-goal 2.2.1), which provide a clue about AP.PROP. The values for the identified evidences (PROP.EVs), were then computed for the site (SITE.PR.EV.VAL) (sub-goal 2.2.2). The value of AP.PROP of the site (SITE.PROP.VAL) was then updated based on SITE.PR.EV.VAL (sub-goal 2.2.3). Finally, the suitability of the site for APPLN was then updated, based on SITE.PROP.VAL (sub-goal 3). This resulted in the satisfaction of the top goal 0.
Figure 3.7. Inference strategy in TAX.
The most important evidence for inferring AP.PROPs, is the landform type of the site (SITE.LF). Once the landform type of the site was computed, the default properties of SITE.LF were inherited by the site. The computation (identification) of the landform types of the site is discussed in the following section.

3.2.2 Landform Identification

The methodology employed for the identification of landforms is general enough, so that a relatively large study area, of the order of tens of square kilometers, can be analyzed. Such a study area may be composed of more than one landform. The possibility of a site having more than one landform was taken into account, by providing a facility for segmenting the site into uniform sub-sites, and identifying the landform type of the individual sub-sites. A schematic diagram of the landform identification process is presented in Figure 3.8. First, ancillary information about the site, such as the physiographic section (PS) of the site was obtained. The next step in landform analysis, was the identification of the water bodies of the site (WBs). The "Hypothesize-Establish" cycle was then entered. Hypotheses about the landforms expected in the site were made, based on the physiographic section (PS) of the site (PS.LFS), and the landforms expected to be found associated with the identified sub-sites (ASS.LFS). [HYP.LFS = PS.LFS + ASS.LFS]. During the first iteration of the Hypothesize-Establish cycle, the only sub-sites identified were the water bodies of the site (if any water bodies were present in the site). The site was then segmented into sub-sites, based on the topographic form of the hypothesized landforms. The pattern element values of the individual sub-sites were then obtained. If some pattern element was not uniform over the entire sub-site, the sub-site was further segmented, so that each of the sub-sites had uniform pattern element values. The landform type of the sub-site
Figure 3.8. Landform identification process.
was then established, based on the pattern element values obtained for the sub-site (Narasimhan and Argialas, 1989). The establishment of the landform type of the sub-sites, led to new hypotheses about landforms associated with them, that is, to the start of the Hypothesize-Establish cycle. This cycle continued until a significant portion (> 90%) of the site was identified.

The first step in landform analysis, involved the identification of the physiographic section of the site. This was achieved by asking the user to choose the name of the section from a menu. The rest of the procedure involved in landform identification is explained in detail in the following sections.

3.2.2.1 Identification of Water Bodies

The approach followed for the identification of water bodies, was the "Establish-Refine" paradigm (Chandrasekaran, 1982). The presence of water bodies was first established, by checking if there was a significant amount of water in the site. Water has a very low reflectance in the near infrared band. The area of the site covered by water was computed by taking a histogram of the reflectance values in the near infrared band, and obtaining the count of picture elements (pixels) which have a reflectance less than a defined threshold value. (The threshold value was arrived at, by manually analyzing the image if the site. It is possible to estimate the threshold value automatically, if a calibrated digital image is available.) If the area covered by water pixels was significant (> 5%), the water bodies were manually outlined. (Experiments to delineate the water bodies automatically using a "Centroid-Linkage" based "Region-Growing" program was not successful because of the complex shapes of natural water bodies. A more sophisticated algorithm for region-growing may however be more successful.) If a water body touched the border of the image, the user indicated that the outlined
area was an "open" body of water. Once the presence of water bodies was established, the type of the water body (river, lake, ocean etc.) was determined, by computing the shape attributes of the outlined area. The parameters computed for the identification of the type of water body are, area, perimeter, elongation, and "open/closed"ness. The elongation of an area was estimated by the heuristic formula given below:

\[
\text{Elongation}(A) = \frac{[\text{Perimeter}(A)]^2}{\text{Area}(A)}
\]  

These parameters aided in classifying the water body into one of river, stream, pond, lake, and ocean. A "large", "open" body of water which was elongated was classified as river. Oceans are "large", "open" bodies of water which are not elongated. A stream has the same characteristics as a river, except that it is much smaller in size. A "large" closed body of water is a lake; whereas a "small" closed body of water was classified as a pond. (Problems associated with such simplistic schemes of classification, and suggestions for overcoming them are discussed in chapter 6.)

3.2.2.2 Hypotheses Generation

In order to identify the landforms of the site, it was desirable to first construct hypotheses about the landforms that were expected in that area. This pruned the search space (the list of all possible landforms) considerably, and made the landform identification process much more efficient. One of the ways for constructing the hypothesis is based on the physiographic knowledge of the site under investigation. If the physiographic section of the site is known, it is possible to get a rough idea of the landforms found in that area from physiographic and geomorphologic books and maps (Fenneman, 1931; Fenneman, 1938). For instance, the landforms that are most likely to be found in the Cumberland-
Plateau-Section are listed in Table 3.28.

<table>
<thead>
<tr>
<th>Landform</th>
<th>Belief measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid-sandstone</td>
<td>0.2</td>
</tr>
<tr>
<td>Humid-shale</td>
<td>0.2</td>
</tr>
<tr>
<td>Humid-limestone</td>
<td>0.05</td>
</tr>
<tr>
<td>Others</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Associated with each of the landforms is a measure of belief in the hypothesis, that a site located in that physiographic section is the given landform. The belief measures are given on a scale of 0 to 1. It is not necessary to list exhaustively, all of the landforms that are known to occur in the physiographic section. The category "Others" includes all other landforms, that potentially could be found in the physiographic section, and the belief measure associated with "Others", indicates the likelihood of a site containing a landform, which has not been explicitly included.

The approach followed for the establishment of landform hypotheses was, the Dempster-Shafer theory of evidence. The frame of discernment $\Theta$, for a site in Cumberland-Plateau-Section is,

$$\Theta = \{\text{Humid-sandstone, Humid-shale, Humid-limestone, Others}\}.$$  

Since the hypotheses in $\Theta$ are required to be exhaustive (Shafer, 1976), the hypothesis "Others" is included in $\Theta$. This takes care of all the landforms, which have not been explicitly included in $\Theta$, but which can occur in the physiographic
section. The belief measure associated with each of the landforms is considered to be the basic probability number (bpn), assigned to them by the evidence, the physiographic section. An important point to note is that the sum of the bpn need not be 1. The deficit (the difference between 1 and $\sum bpn$) is the factor of ignorance associated with the information about the physiographic section.

Consider a site which is located in the Cumberland-Plateau-Section. The belief committed to each of the members in the frame of discernment $\Theta$ is

$m_1($Humid-sandstone$) = 0.2$

$m_1($Humid-shale$) = 0.2$

$m_1($Humid-limestone$) = 0.05$

$m_1($Others$) = 0.2$

The sum of the beliefs committed exactly to the individual members in the frame of discernment is 0.65. However, any bpa must satisfy the constraint

$$\sum_{A \in \Theta} m_1(A) = 1.$$  

The difference (0.35) is therefore assigned to the factor of ignorance, that is, to the belief that the landform is any one of those in the frame of discernment.

$m_1 ($Humid-sandstone V Humid-shale V Humid-limestone V Others$) = m_1($ $\Theta$ $) = 0.35$

A clear distinction needs to be made between the belief assigned to "Others" and that assigned to $\Theta$. $m($Others$)$ represents the belief in the knowledge, that the landform of the site is something other than what has been explicitly included in $\Theta$. $m(\Theta)$ on the other hand, represents the current state of ignorance or the lack of knowledge about the landform of the site.

Another approach for generating hypotheses is based on the association of landforms with water bodies and other landforms already identified in the site. For
instance, if a river has been located, it is likely that there is a Flood-plain adjacent to it, the identification of a Flood-plain leads to a hypothesis about Terraces, and so on. Such hypotheses are represented by a bpa. The bpa corresponding to the hypotheses about landforms associated with rivers is:

\[ m_2(\text{Flood-plain}) = 0.5 \]

The hypothesis generated from the expected association of landforms with identified water bodies (WBs), and other landforms identified in the site (LFs), is combined with the hypotheses about landforms based on the physiographic section of the site (PS.LFS), according to Dempster's rule of combination. The result is a new hypotheses list about landforms associated with the water bodies and other landforms identified in the site (ASS.LFS).

3.2.2.3 Segmentation

At this stage in landform identification, we have a set of water bodies, and/or a set of landforms (WB/LFs) and a set of hypotheses about the landforms likely to be found associated with each of the identified sub-sites (ASS.LFS WB/LF). The hypotheses set also included the hypotheses which was based on the physiographic section of the site (PS.LFS). Following the principle of "specificity" (Winston, 1984), a more specific hypotheses (ASS.LFS), associated with water bodies and landforms, was examined before examination of the general hypotheses (PS.LFS), based on physiographic section alone. In order to determine the landform of a sub-site, occurring next to an identified WB/LF, it was necessary to first delineate the sub-site for further investigation. The question was "What should be the criteria for delineating a sub-site, as a potential site of an individual landform?". In TAX, the topographic form of the landforms in the hypotheses list, was used as the criterion. Landforms manifest themselves as mountains, uplands, lowlands,
plains, basins, escarpments and so on. The topographic form of the landform with the largest certainty in the hypotheses (ASS.LFS) was determined, and the user was asked to outline this form (if it existed) next to the WB/LF. Next, hypotheses about landforms for the outlined sub-site are made. This hypotheses was a subset of the hypotheses (ASS.LFS) originally associated with the WB/LF. This modified list contained only those members of the hypotheses whose topographic form matched the topographic form of the outlined area.

If there were no water bodies in the site, then the hypotheses (PS.LFS) based on the physiographic section of the site, was examined. The topographic form of the landform with the largest certainty in the hypotheses list was determined, and the user was asked to outline this form anywhere on the image. The landforms hypothesized for the outlined sub-site are the landforms in the hypotheses (PS.LFS), whose topographic form matched the topographic form of the outlined area.

3.2.2.4 Computation of Pattern Element Values

After segmentation of the site into sub-sites, pattern element values were obtained for each of the sub-sites. Aerial imagery, and topographic data in the form of digital elevation models were used for extracting pattern element values. Values for some of the pattern elements were obtained automatically, without any user assistance. The image processing routines of the ELAS (Earth resources Laboratory Application Software) package were used for obtaining values for those pattern elements. Other pattern elements, however, had to be computed manually. In these cases, the user was asked to supply the values for pattern elements by consulting the topographic and aerial images.

The initial segmentation of the site into sub-sites, as discussed in section
3.2.2.3, was done based on topographic form. However, a sub-site outlined by the user might contain more than one landform. This could happen, in the case where two landforms which manifest themselves as the same topographic form, occur adjacent to one another. For example, Humid-shale and Humid-limestone manifest themselves as plains, and are often found adjacent to each other. In such a case, the values for some of the pattern elements will not be homogeneous over the entire sub-site. Whenever the user was asked to supply the value for a pattern element, the user was also asked if the pattern element value was homogeneous over the sub-site. If the pattern element was not homogeneous, the user was asked to further segment the sub-site into sub-sites of uniform pattern element value. Landform analysis was then continued on each of the sub-divided areas.

Relief of an area has been defined as the difference in elevation between the highest and lowest points. It is possible that an area might contain some isolated pits or peaks, which might influence the value of Relief considerably. In order to overcome this problem, the difference between 1 percentile and 99 percentile elevation was taken to be the value of Relief. (1 percent of the site has elevation values less than the 1 percentile elevation value.) The histogram of the elevation values in an area was computed using ELAS routines, from which the 1 percentile and 99 percentile elevation was obtained.

Slope of a landform in a mountainous region, is characterized by the average slope of the side-slopes. If the outlined form was mountainous, the side-slopes in the sub-site were manually outlined. A histogram of the slope values on the side-slopes was then computed from which the average slope of the sub-site was calculated. If the outlined form was a plain, the slope corresponding to the 75 percentile value was considered to be the average slope of the side-slopes of any raised form in the plain.
Automatic identification of Drainage-Types is an extremely complicated task. Argialas et al. (1988) identified 8 major drainage pattern types from digitized line drawings of drainage patterns. The extraction and identification of Drainage-Types from aerial images and digital elevation data, is however, still in the research stage. In TAX, the Drainage-Type in the sub-site was identified manually, by observing topographic data and aerial imagery. It was possible that the Drainage-Type of the sub-site did not exactly fit the description of any of the Drainage-Type prototypes. The Drainage-Type of the sub-site was therefore described, as it's compatibility with the descriptions of prototype Drainage-Types. The degree of compatibility was given as one of "Slightly compatible", "Moderately compatible", "Highly Compatible", and "Completely compatible", corresponding to the numerical measures of compatibility 0.25, 0.5, 0.75 and 1.0 respectively.

The Drainage-Texture was defined as the total length of drainage network in a unit area of the sub-site. The drainage network was approximated, by all the valley points in the area of interest. Valley points were extracted by comparing the elevation of each point in the sub-site, with it's immediate neighbors. Let Figure 3.9, represent the numbering scheme for a pixel and it's immediate neighbors.
Figure 3.9. Numbering scheme for pixels.

The center pixel "0" was labelled a valley pixel, if any one of the following relations was satisfied (Band, 1986):

\[
\text{Elevation}(0) + \text{Constant} < \text{Min} \{ \text{Elevation}(4), \text{Elevation}(5) \} \quad \text{OR}
\]

\[
\text{Elevation}(0) + \text{Constant} < \text{Min} \{ \text{Elevation}(2), \text{Elevation}(7) \} \quad \text{OR}
\]

\[
\text{Elevation}(0) + \text{Constant} < \text{Min} \{ \text{Elevation}(1), \text{Elevation}(8) \} \quad \text{OR}
\]

\[
\text{Elevation}(0) + \text{Constant} < \text{Min} \{ \text{Elevation}(3), \text{Elevation}(6) \}
\]

The constant was typically chosen to be 1m. While not all valley pixels are part of a drainage network, the algorithm given above, resulted in a pretty good approximation to extracting valley pixels which were part of a drainage network.

After all the valley pixels were identified and labelled, the total length of drainage lines in the sub-site was computed, by multiplying the length of each pixel by the total number of valley pixels. Drainage-Texture was then computed as the total length of drainage lines in the sub-site, divided by the area of the sub-site.

Interpretation of Soil-Tone from black and white photographs is difficult because, natural vegetation or cultivation often either obstruct tones or have tones that can be confused with those of soils. In TAX, Soil-Tones were identified
manually through breaks in the vegetation. The Soil-tone of the sub-site was described in terms of the standard tonal classes, White, Light Gray, Dull Gray, or Black. Intermediate values were assigned to the Soil-tone of the sub-site by specifying the Soil-tone with respect to its compatibility with the standard tonal classes. Compatibility values were given as in the case of drainage patterns (e.g. Partly Light Gray and Partly Dull Gray). The Soil-Tone of the site is described by the user, based on its appearance in black and white panchromatic images. The texture of Soil-tone was obtained manually as one of Uniform, Mottled, Banded and Scrabbled.

Gullies can be observed only on large scale photographs. The cross-sectional shape of Gullies in an area was described manually as its compatibility with the standard Gully shapes V-shaped, U-shaped, Box-shaped and Sag-and-swale.

The Landuse of an area was obtained by requesting the user to choose from one of the USGS level I landuse/landcover classes. The Landuse classes were considered distinct, and incompatible with one another. Therefore, the user was not permitted to give intermediate values, and describe the Landuse of the sub-site, in terms of its compatibility with two or more Landuse classes. However, if the user does not wish to give a single value for Landuse, (s)he can segment the sub-site so that each of the sub-divisions are uniform with respect to Landuse.

3.2.2.5 Establish Landform Hypotheses

After the pattern element values for a sub-site were obtained (SITE.PEVAL), the beliefs (basic probability numbers) associated with the hypothesized landforms of the sub-site (HYP.LFS) were updated, by matching the pattern elements of the sub-site (SITE.PEVAL) with the prototype models of HYP.LFS (given in Tables 3.25a, 3.25b). Each pattern element was examined, and the compatibility (μ)
between SITE.PEVAL and the pattern element value of HYP.LFS (LF.PEVAL) was computed. This value of compatibility (μ) is considered to be the support or the basic probability number (bpm) assigned to HYP.LFS by a pattern element. The basic probability number assigned to a hypothesis was equal to the membership value (μ) of SITE.PEVAL in the fuzzy set representing LF.PEVAL:

\[ m(HYP.LF) = \mu_{LF.PEVAL}(SITE.PEVAL) \]  \hspace{1cm} (3.2)

Often, a landform exhibits multiple values for a pattern element. In such a case, the basic probability number for the landform was taken to be the weighted average of the membership in each of the pattern element values. The weights were the frequency of occurrence of the values as recorded in the model of the landform (Tables 3.25a, 3.25b). The bpm for a HYP.LF was then given by:

\[ m(HYP.LF) = \frac{\sum_{LF.PEVAL} \mu_{LF.PEVAL}(SITE.PEVAL) \times Freq(LF.PEVAL)}{3.3} \]

In the case of pattern elements with well-defined base variables, such as Relief or Slope, the SITE.PEVAL is numerical. The membership functions for the fuzzy sets representing LF.PEVAL, for such pattern elements (pattern elements with well-defined base variables), were given by standardized S, S' and H functions with adjustable parameters \(\alpha, \beta, \gamma\). The membership of SITE.PEVAL in LF.PEVAL, was then computed using the equations 2.12.1 - 2.14.2.

Consider for instance, a sub-site, whose frame of discernment, \(\Theta\), consists of the landforms \{Humid-sandstone (HS), Humid-shale (HSh)\}. Let the current level of confidence in the HYP.LFS, be given by the function \(m_1\):

\[ m_1(HS) = 0.2 \]
\[ m_1(HSh) = 0.2 \]

The effect of the evidence, the Relief of the sub-site (SITE.REL), on the beliefs in the HYP.LFS is illustrated below. Let the Relief of the sub-site
(SITE.RELVAL) be 100m. The Relief of Humid-sandstone (HS.RELVAL) is Strong (as given in the model of Humid-sandstone, Table 3.25a). The membership function for Strong Relief is an $S$ type function with $\alpha = 200, \beta = 300, \gamma = 400$ (Table 3.3). The membership of 100m in the fuzzy set Strong Relief is obtained by substituting the values in eqn. 2.12.1.

$$\mu_{\text{Strong}}(100) = S(100; 200, 300, 400)$$

$$= 0 \quad \text{(from eqn. 2.12.1)}$$

Let the basic probability assignment corresponding to the evidence, Relief, be given by the function $m_2$. The bpn assigned to Humid-sandstone (HS) is:

$$m_2(\text{HS}) = \mu_{\text{Strong}}(100) \times \text{Freq}(\text{Strong}) \quad \text{(from eqn. 3.3)}$$

$$= 0 \times 1.0 = 0$$

The Relief of Humid-shale is Gentle 50% of the time and Moderate the rest of the time (Table 3.25b). The membership function for Gentle Relief is an $S'$ type function with $\alpha = 0, \beta = 100, \gamma = 200$ (Table 3.3). The membership of 100m in the fuzzy set Gentle Relief is obtained by substituting these values in equation 2.13:

$$\mu_{\text{Gentle}}(100) = S'(100; 0, 100, 200)$$

$$= 1 - S(100; 0, 100, 200)$$

$$= 1 - 2 \times \left\{ \frac{100 - 200}{200 - 0} \right\}^2$$

$$= 0.5$$

The membership function for Moderate Relief is a $\Pi$ type function with $\beta = 200, \gamma = 200$ (Table 3.3). The membership of 100m in the fuzzy set Moderate Relief is obtained by substituting these values in equation 2.14.1.

$$\mu_{\text{Moderate}}(100) = \Pi(100; 200, 200)$$

$$= S(100; 0, 100, 200)$$

$$= 1 - 2 \times \left\{ \frac{100 - 200}{200 - 0} \right\}^2$$
The basic probability number assigned to the hypothesis Humid-shale (HSh) is calculated as:

\[ m_2(HSh) = \sum_{HSh.RELVAL} \mu_{HSh.RELVAL}(SITE.RELVAL) \times \text{Freq}(HSh.RELVAL) \]

(where HSh.RELVAL stands for the possible values of Relief exhibited by a prototype Humid-shale)

\[ = \mu_{\text{Gentle}}(100) \times 0.5 + \mu_{\text{Moderate}}(100) \times 0.5 \]

\[ = 0.5 \times 0.5 + 0.5 \times 0.5 \]

\[ = 0.5 \]

The sum of the basic probability numbers due to Relief is:

\[ \sum m_2(HYP.LFS) = m_2(HS) + m_2(HSh) \]

\[ = 0 + 0.5 = 0.5 \]

The fact that the beliefs summed up to only 0.5 indicates that the evidence supports some other landform which is not in the hypotheses list. This is why, it is necessary to have a hypothesis "Others", to which an evidence will contribute belief, if the evidence does not support the landforms in HYP.LFS. The support for this hypothesis ("Others"), due to an evidence, is that portion of the belief that could not be assigned to any of the HYP.LFS. In the present case

\[ m_2(\text{Others}) = 1 - \sum m(HYP.LFS) = 1 - 0.5 = 0.5. \]

In the case of pattern elements with ill-defined base variables, such as Drainage-Types, the compatibility between SITE.PEVAL and LF.PEVAL was obtained directly from the models of the pattern element values (Table 3.10). Consider a frame of discernment

\[ \theta = \{\text{Humid-sandstone, Humid-shale, Others}\}. \]
The assignment of beliefs by the evidence, the Drainage-Type of the sub-site (SITE.DTVAL) is illustrated below. Let, the Drainage-Type of the sub-site be Dendritic. The Drainage-Type of Humid-sandstone (prototype), and their frequency of occurrence are Dendritic - 50%, Angular - 25% and Rectangular - 25% (Table 3.25a). The compatibility of the Dendritic pattern with the Angular pattern is 0.37 and the compatibility with Rectangular pattern 0.5 (Table 3.10). Let, $m_3$ be the bpa corresponding to the evidence Drainage-Type. The belief assigned to Humid-sandstone (HS) due to Drainage-Type is,

$$m_3(\text{HS}) = \sum_{\text{HS.DTVAL}} \mu_{\text{SITE.DTVAL}}(\text{HS.DTVAL}) \times \text{Freq(HS.DTVAL)}$$

(where HS.DTVAL stands for the possible values of Drainage-Type exhibited by a prototype Humid-sandstone)

$$m_3(\text{HS}) = \mu_{\text{Dendritic}}(\text{Dendritic}) \times 0.5$$

$$+ \mu_{\text{Dendritic}}(\text{Angular}) \times 0.25$$

$$+ \mu_{\text{Dendritic}}(\text{Rectangular}) \times 0.25$$

$$= 1 \times 0.5 + 0.37 \times 0.25 + 0.5 \times 0.25$$

$$= 0.72$$

The Drainage-Type of Humid-shale is Dendritic - 100% (Table 3.25b). The belief assigned to Humid-shale due to Drainage-Type is

$$m_3(\text{HSh}) = \mu_{\text{Dendritic}}(\text{Dendritic}) \times 1.0$$

$$= 1 \times 1$$

$$= 1$$

The sum of the beliefs (bpn) due to Drainage-Type is, $\Sigma m(\text{HYP.LFS}) = 1.72$. This violates the definition of a basic probability assignment, which requires that $\Sigma m(\text{Hypotheses}) = 1$. The beliefs assigned to the hypotheses are therefore normalized, by dividing them by $\Sigma m(\text{HYP.LFS})$. The normalized basic probability numbers are:

$$m_4(\text{Humid-sandstone}) = 0.72 / 1.72 = 0.42$$
\[ m_4(\text{Humid-shale}) = 1 / 1.72 = 0.58 \]

The support for "Others" is that portion of belief, which cannot be assigned to any HYP.LF. In the present case, the evidence - the Drainage-Type of the sub-site is Dendritic, gives a strong support to both Humid-sandstone and Humid-shale. In fact, the support is so strong that, the beliefs had to be scaled down (normalized). This indicates that there is no evidence to support the hypothesis, that the sub-site could be some 'other' landform, which is not explicitly present in \( \Theta \). The belief assigned to "Others" is therefore,

\[ m_4(\text{Others}) = 1 - \sum m(\text{HYP.LF}) = 1 - 0.52 - 0.48 = 0. \]

The effect of multiple evidences on the beliefs associated with hypotheses is illustrated below. Beliefs from multiple evidences are accumulated according to Dempster's rule of combination. Consider a frame of discernment \( \Theta = \{\text{HS}, \text{HSh}, \text{Others}\} \). Let the beliefs associated with the members in \( \Theta \) be given by the function \( m_1 \):

\[ m_1(\text{HS}) = 0.2 \]
\[ m_1(\text{HSh}) = 0.2 \]
\[ m_1(\text{Others}) = 0.2 \]

The rest of the belief, which represents the ignorance associated with the function \( m_1 \) is allocated to the entire frame of discernment:

\[ m_1(\Theta) = 0.4 \]

Consider now, the basic probability assignment associated with a new piece of evidence. Let the beliefs be given by the function \( m_2 \):

\[ m_2(\text{HS}) = 0.5 \]
\[ m_2(\text{HSh}) = 0.3 \]
\[ m_2(\text{Others}) = 0.2 \]

The combination of the belief function \( m_2 \) with \( m_1 \) is given by applying equation
The resultant measure of belief \((m_1, m_2)\) assigned to Humid-sandstone (HS) is,

\[
m_1 \oplus m_2(\text{HS}) = \sum_{H_{1i} \cap H_{2j} = \text{HS}} m_1(H_{1i}) \ast m_2(H_{2j})
\]

where \(H_{1i}\) and \(H_{2j}\) are the focal elements of the bpa \(m_1\) and \(m_2\).

\[
= m_1(\text{HS}) \ast m_2(\text{HS}) + m_1(\theta) \ast m_2(\text{HS})
\]

\[
= 0.2 \ast 0.5 + 0.4 \ast 0.5
\]

\[
= 0.3
\]

\[
m_1 \oplus m_2(\text{HS}_H) = \sum_{H_{1i} \cap H_{2j} = \text{HS}_H} m_1(H_{1i}) \ast m_2(H_{2j})
\]

\[
= m_1(\text{HS}_H) \ast m_2(\text{HS}_H) + m_1(\theta) \ast m_2(\text{HS}_H)
\]

\[
= 0.2 \ast 0.3 + 0.4 \ast 0.3
\]

\[
= 0.18
\]

\[
m_1 \oplus m_2(\text{Others}) = \sum_{H_{1i} \cap H_{2j} = \text{Others}} m_1(H_{1i}) \ast m_2(H_{2j})
\]

\[
= m_1(\text{Others}) \ast m_2(\text{Others}) + m_1(\theta) \ast m_2(\text{Others})
\]

\[
= 0.2 \ast 0.2 + 0.4 \ast 0.2
\]

\[
= 0.12
\]

\[
m_1 \oplus m_2(\theta) = \sum_{H_{1i} \cap H_{2j} = \theta} m_1(H_{1i}) \ast m_2(H_{2j})
\]

\[
= m_1(\theta) \ast m_2(\theta)
\]

\[
= 0.2 \ast 0
\]

\[
= 0
\]
The sum of the beliefs is now:

\[ \sum m_1 \circ m_2(H_i) = 0.3 + 0.18 + 0.12 = 0.6 \]

As before, the beliefs are normalized so that they sum to 1. The normalized beliefs are:

- \( m_2(\text{HS}) = \frac{0.3}{0.6} = 0.5 \)
- \( m_2(\text{HSh}) = \frac{0.18}{0.6} = 0.3 \)
- \( m_2(\text{Others}) = \frac{0.12}{0.6} = 0.2 \)

Using Dempster's rule of combination, one evidence sometimes has the effect of completely overturning the conclusions drawn from the observation of a number of evidences. For example, consider the scenario, where the effect of observation of a number of evidences has resulted in the following basic probability assignment:

- \( m_1(\text{HS}) = 0.75 \)
- \( m_1(\text{HSh}) = 0.1 \)
- \( m_1(\text{Others}) = 0.1 \)
- \( m_1(\emptyset) = 0.05 \)

Let us assume that a new evidence is observed, which supports the hypothesis of Humid-shale completely. The basic probability assignment corresponding to this new evidence is:

- \( m_2(\text{HS}) = 0 \)
- \( m_2(\text{HSh}) = 1 \)
- \( m_2(\text{Others}) = 0 \)
- \( m_2(\emptyset) = 0 \)

The combination of \( m_2 \) with the beliefs corresponding to the sum of all the prior evidences \( (m_1) \) is the following:
\[ m_1 \circ m_2(HS) = m_1(HS) * m_2(HS) + m_1(\theta) * m_2(HS) \]
\[ = 0.75 * 0 + 0.05 * 0 \]
\[ = 0 \]

\[ m_1 \circ m_2(HSh) = m_1(HSh) * m_2(HSh) \]
\[ + m_1(\theta) * m_2(HSh) \]
\[ = 0.1 * 1 + 0.05 * 1 \]
\[ = 0.15 \]

\[ m_1 \circ m_2(Others) = m_1(Others) * m_2(Others) + m_1(\theta) * m_2(Others) \]
\[ = 0.1 * 0 + 0.05 * 0 \]
\[ = 0 \]

\[ m_1 \circ m_2(\theta) = m_1(\theta) * m_2(\theta) \]
\[ = 0 * 0 \]
\[ = 0 \]

The sum of the beliefs is now:

\[ \sum m_1 \circ m_2(H_i) = 0 + 0.15 + 0 + 0 = 0.15 \]

As before, the beliefs are normalized so that they sum to 1. The normalized beliefs are:

- \[ m_1 \circ m_2(HS) = 0 \]
- \[ m_1 \circ m_2(HSh) = 1 \]
- \[ m_1 \circ m_2(Others) = 0 \]
- \[ m_1 \circ m_2(\theta) = 0 \]

As can be seen, the effect of just one piece of evidence, which strongly supports a hypothesis, is to completely alter the beliefs associated with all other hypotheses; which may be arrived at after evaluating a number of evidences. Furthermore, any further evidence supporting other hypotheses, would have no impact on the beliefs. For instance, combining

\[ m_3(HS) = 0.6 \]
\[ m_3(HSh) = 0.2 \]
\[ m_3(Others) = 0.1 \]
\[ m_3(\theta) = 0.1 \]

with \( m_1 \odot m_2 \) would result in:

\[ m_4 (\text{HS}) = 0 \]
\[ m_4 (\text{HSh}) = 1 \]
\[ m_4 (\text{Others}) = 0 \]
\[ m_4 (\theta) = 0 \]

Such a situation, where one evidence completely supports a hypothesis, is not unlikely. It is quite likely, that the pattern element value for a site is incorrect, or that the model of a landform has erroneous values for a certain pattern element. In such a case, a pattern element may incorrectly support a landform completely. Such an effect, where one piece of evidence completely overturns the beliefs in the hypotheses, is quite undesirable. It was therefore necessary to associate with each evidence, a measure of it's strength, in contributing to the beliefs. The strength of an evidence is a number in the interval 0 to 1. It represents the fraction of the belief that is available to be apportioned to various hypotheses. The rest is the factor of ignorance, and is allocated to 0. The strength of an evidence represents a number of factors, such as, the reliability of the procedure in extracting the evidence (pattern element value), the confidence one has in the model of the landform with respect to this particular evidence, and lastly in the importance of this evidence in establishing a landform. Reconsider the scenario presented earlier, where it was assumed that:

\[ m_1(\text{HS}) = 0.75 \]
\[ m_1(\text{HSh}) = 0.1 \]
\[ m_1(\text{Others}) = 0.1 \]
\[ m_1(\theta) = 0.05 \]

and
Let the strength of the new evidence be 0.5. Since the strength of the evidence is only 0.5, the total amount of belief that can be allocated to the various hypotheses is only 0.5. Let \( m_3 \) be the new bpa for the evidence, taking into account the strength of the evidence. \( m_3 \) for a hypothesis \( H \) is given by:

\[
m_3(H) = m_2(H) \times \text{Strength}.
\]

The basic probability numbers for the hypotheses in \( \Theta \) are given by:

\[
m_3(HSh) = 1 \times 0.5 = 0.5
\]

\[
m_3(HS) = 0 \times 0.5 = 0
\]

\[
m_3(\text{Others}) = 0 \times 0.5 = 0
\]

The belief allocated to \( \Theta \) is

\[
m_3(\Theta) = 1 - \sum m_3(H) = (1 - \text{Strength}) = 0.5.
\]

The combination of \( m_3 \) with \( m_1 \) is:

\[
m_1 \odot m_3(HS) = m_1(HS) \times m_3(\Theta)
\]

\[
= 0.75 \times 0.5
\]

\[
= 0.375
\]

\[
m_1 \odot m_3(HSh) = m_1(HSh) \times m_3(HSh)
\]

\[
+ m_1(\Theta) \times m_3(HSh)
\]

\[
+ m_1(\Theta) \times m_3(\Theta)
\]

\[
= 0.1 \times 0.5 + 0.05 \times 0.5 + 0.1 \times 0.5
\]

\[
= 0.125
\]

\[
m_1 \odot m_3(\text{Others}) = m_1(\text{Others}) \times m_3(\Theta)
\]

\[
= 0.1 \times 0.5
\]

\[
= 0.05
\]

\[
m_1 \odot m_3(\Theta) = m_1(\Theta) \times m_3(\Theta)
\]
\[= 0.05 \times 0.5\]
\[= 0.025\]

The sum of the beliefs is now:

\[\sum m_1 \circ m_3 (H_i) = 0.375 + 0.125 + 0.05 + 0.025 = 0.575\]

As before, the beliefs are normalized so that they sum to 1. The normalized beliefs are:

\[m_4(\text{HS}) = \frac{0.375}{0.575} = 0.65\]
\[m_4(\text{HSh}) = \frac{0.125}{0.575} = 0.22\]
\[m_4(\text{Others}) = \frac{0.05}{0.575} = 0.09\]
\[m_4(\theta) = \frac{0.025}{0.575} = 0.04\]

The above combination portrays a more reasonable effect of one evidence on the beliefs. The results of the computations involved in Dempster's rule of combination for establishing landforms are summarized in Table 3.29. The strengths of the pattern elements used in TAX, are given in Table 3.30.

<table>
<thead>
<tr>
<th>bpa</th>
<th>HS</th>
<th>HSh</th>
<th>Others</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m_1] (a priori belief)</td>
<td>0.75</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>[m_2] (new evidence)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[m_3 = m_2 \circ \text{Strength}]</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>[m_1 \circ m_3]</td>
<td>0.375</td>
<td>0.125</td>
<td>0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>[m_4] (normalized [m_1 \circ m_3])</td>
<td>0.65</td>
<td>0.22</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Pattern Element</td>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relief</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drainage-Type</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drainage-Texture</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landuse/Landcover</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gully Type</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil-Tone</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil-Tone-Texture</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Justification for the strengths assigned to pattern elements is given below. Soil-Tone has a very low strength associated with it, because observation of Soil-Tone is quite difficult, as discussed in section 3.2.2A. Further, the tonal values referred to in the models are relative, so it is difficult to classify a tonal value into one of the standard classes with confidence. Observation of the Soil-Tone-Texture is as difficult as the observation of the Soil-tone itself. However, the classification of a texture does not pose much of a problem. Gullies are very difficult to observe except on large scale photographs, and so the strength associated with it is moderate (0.5).

Classification of Landuse into one of USGS level I classes, from aerial images is possible, especially by an experienced person. However, not much confidence can be placed in the knowledge base, with regard to the models of
landforms. This is because, a piece of land can be put to radically different uses. For instance, a landform which is normally intensely cultivated, because of the rich soils found in it, may be left in it’s natural state and may be forested in virgin areas. The same landform, located close to a metropolis, may have a residential colony or an industry located on it. It is difficult to encapsulate all these possible variations in Landuses in the models.

The method employed in TAX, to automatically extract Drainage-patterns is simplistic, hence only a moderate strength is associated with the pattern element Drainage-Texture. The pattern elements Relief and Slope can be quite accurately estimated and meaningful inferences can be drawn from it. The photo-interpretation of Drainage-Patterns, though not trivial, is possible with experience, and provides a very important clue for the identity of a landform, and hence it was given the same strength measure as Relief and Slope.

3.2.3 Inferring Engineering Properties

After all the pattern elements were computed, or obtained from the user, and the beliefs associated with the HYP.LFS updated, the engineering properties of the sub-site (SITE.PROP.VALs) were inferred. SITE.PROP.VALs were computed by inheriting the properties from the models of the HYP.LFS. Each of the possible values of the property (PROPVAL) of the sub-site was considered to be a hypothesis, and the HYP.LFS were considered as evidences which supported a particular PROPVAL. The strength of the evidence (SITE.LF), was taken to be the total amount of belief in the landform [Bel(SITE.LF)]. The total amount of belief in a hypothesis Hi, is calculated from the bpn for the hypothesis using equation 2.15.

\[ Bel(H_i) = m(H_i) + \sum_{H_j \in H_i} m(H_j) \]  

(2.15)
where $m$ is the bpa associated with the frame of discernment.

For instance, consider an area, whose frame of discernment $\theta$ has the following belief function associated with it:

\[
\begin{align*}
\text{Bel}(HS) &= 0.5 \\
\text{Bel}(HSh) &= 0.35 \\
\text{Bel}(Others) &= 0.05
\end{align*}
\]

Let us assume, that the property of interest is the Depth-to-Bedrock (DBR) of the site. The possible values of Depth-to-Bedrock are Low, Medium and High (DBRVALs).

The frame of discernment is, therefore, $\theta = \{\text{Low, Medium, High}\}$.

The values of DBR and the frequency of their occurrence in the prototype Humid-sandstone are Low - 50%, Medium - 25%, High - 25% (Table 3.25a). The basic probability assignment due to Humid-sandstone for a DBRVAL is taken to be the frequency of occurrence of the DBRVAL in the prototype Humid-sandstone.

That is, $m(\text{DBRVAL}) = \text{Freq(DBRVAL)}$. The bpa corresponding to Humid-sandstone is,

\[
\begin{align*}
m_1(\text{Low}) &= 0.5 \\
m_1(\text{Medium}) &= 0.25 \\
m_1(\text{High}) &= 0.25
\end{align*}
\]

However, the strength of the evidence, $\text{SITE.LF} = \text{Humid-sandstone}$, is $\{\text{Bel(Humid-sandstone)}\} = 0.5$. So, the beliefs are multiplied by 0.5. The new beliefs are:

\[
\begin{align*}
m_2(\text{Low}) &= 0.5 \times 0.5 = 0.25 \\
m_2(\text{Medium}) &= 0.5 \times 0.25 = 0.125 \\
m_2(\text{High}) &= 0.5 \times 0.25 = 0.125
\end{align*}
\]
The rest of the belief (0.5) is assigned to the entire frame of discernment.

\[ m_2(\theta) = 0.5 \]

The DBRVALs and the frequency of their occurrence in Humid-shale are Medium - 50%, High - 50% (Table 3.25b). The basic probability assignment due to Humid-shale is:

\[ m_3(\text{Low}) = 0 \]
\[ m_3(\text{Medium}) = 0.5 \]
\[ m_3(\text{High}) = 0.5 \]

Since, the strength of the evidence is 0.35, the beliefs are multiplied by 0.35. The new beliefs are:

\[ m_4(\text{Low}) = 0 \times 0.35 = 0 \]
\[ m_4(\text{Medium}) = 0.5 \times 0.35 = 0.175 \]
\[ m_4(\text{High}) = 0.5 \times 0.35 = 0.175 \]
\[ m_4(\theta) = 0.65 \]

Combining the belief functions \( m_2 \) and \( m_4 \) gives:

\[ m_2 \odot m_4(\text{Low}) = 0.25 \times 0 + 0.25 \times 0.65 + 0.5 \times 0 = 0.16 \]
\[ m_2 \odot m_4(\text{Medium}) = 0.125 \times 0.175 + 0.125 \times 0.65 + 0.5 \times 0.175 = 0.19 \]
\[ m_2 \odot m_4(\text{High}) = 0.125 \times 0.175 + 0.125 \times 0.65 + 0.5 \times 0.175 = 0.19 \]
\[ m_2 \odot m_4(\theta) = 0.5 \times 0.65 = 0.325 \]

The beliefs are normalized, so as to sum to 1. The normalized beliefs are:

\[ m_5(\text{Low}) = 0.18 \]
\[ m_5(\text{Medium}) = 0.22 \]
\[ m_5(\text{High}) = 0.22 \]
\[ m_5(\theta) = 0.38 \]

The expected value of depth to bedrock is however not uniform over the entire area, but varies depending on the topographic position as given in Table 3.20.
The modification of engineering properties based on site-specific characteristics is illustrated below. Let the sub-site A under consideration be subdivided into \( A_{\text{summit}1}, A_{\text{summit}2}, \ldots, A_{\text{side-slope}1}, A_{\text{side-slope}2}, \ldots, A_{\text{valley}1}, A_{\text{valley}2}, \ldots \). The effect of the Topographic-position "valley" on the Depth-to-Bedrock is given by the basic probability assignment \( m_6 \) (Table 3.20):

\[
\begin{align*}
    m_6(\text{Low}) &= 0 \\
    m_6(\text{Medium}) &= 0 \\
    m_6(\text{High}) &= 0.75 \\
    m_6(\theta) &= 0.25
\end{align*}
\]

Combining \( m_6 \) with \( m_5 \) gives:

\[
\begin{align*}
    m_5 \circ m_6 \ (\text{Low}) &= 0.25 \times 0.18 = 0.045 \\
    m_5 \circ m_6 \ (\text{Medium}) &= 0.25 \times 22 = 0.055 \\
    m_5 \circ m_6 \ (\text{High}) &= 0.22 \times 0.75 + 0.22 \times 0.25 + 0.38 \times 0.25 = 0.315 \\
    m_5 \circ m_6 \ (\theta) &= 0.38 \times 0.25 = 0.095
\end{align*}
\]

Normalizing the values results in the final confidence associated with the values for Depth-to-Bedrock:

\[
\begin{align*}
    m_7(\text{Low}) &= 0.09 \\
    m_7(\text{Medium}) &= 0.11 \\
    m_7(\text{High}) &= 0.62 \\
    m_7(\theta) &= 0.18
\end{align*}
\]

The results of the computations involved in Dempster's rule of combination for inferring engineering properties are summarized in Table 3.31.
Table 3.31. Illustration of Dempster’s rule of combination for inferring properties

<table>
<thead>
<tr>
<th>bpa</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$ (HS)</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>$m_2 = m_1 \ast \text{Bel}(HS)$</td>
<td>0.25</td>
<td>0.125</td>
<td>0.125</td>
<td>0.5</td>
</tr>
<tr>
<td>$m_3$ (HSh)</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>$m_4 = m_3 \ast \text{Bel}(HSh)$</td>
<td>0</td>
<td>0.175</td>
<td>0.175</td>
<td>0.65</td>
</tr>
<tr>
<td>$m_2 \circ m_4$</td>
<td>0.16</td>
<td>0.19</td>
<td>0.19</td>
<td>0.32</td>
</tr>
<tr>
<td>$m_5$ (normalized $m_2 \circ m_4$)</td>
<td>0.18</td>
<td>0.22</td>
<td>0.22</td>
<td>0.38</td>
</tr>
<tr>
<td>$m_6$ (Valley)</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>$m_5 \circ m_6$</td>
<td>0.045</td>
<td>0.055</td>
<td>0.315</td>
<td>0.095</td>
</tr>
<tr>
<td>$m_7$ (normalized $m_5 \circ m_6$)</td>
<td>0.09</td>
<td>0.11</td>
<td>0.62</td>
<td>0.18</td>
</tr>
</tbody>
</table>

3.2.4 Evaluating Suitability for Engineering Application

The hypotheses to be examined in this case are, whether a site is suitable for an application (Suitable) or it is not suitable (Unsuitable) for the application. The frame of discernment is $\theta = \{\text{Suitable, Unsuitable}\}$. The properties of the site (SITE.PROP.VALs) are considered to be evidences which support or weaken these hypotheses. In order to evaluate the suitability of an area for an application, the values for all the relevant engineering properties are first determined. Corresponding to each value of a property, is a measure of it's effect on the suitability for the application, as given in the model of the application (Tables...
3.26, 3.27). This measure is considered to be the basic probability assignment for the hypotheses. The properties of the site are however not known with absolute certainty. Instead, there are belief measures associated with each of the possible values for a property. The basic probability number for the hypotheses about suitability is calculated as,

\[ m((Un)Suitable) = \sum belief\ (PROPVAL_i) \cdot (Un)Suitability\ (PROPVAL_i) \]  

(3.4)

For instance, consider an area whose suitability is being evaluated for a Sanitary landfill operation. The influence of Depth-to-Bedrock on the suitability is given below (from Table 3.26):

- Suitability(High.DBR) = 0.5
- Unsuitability(Medium.DBR) = 0.25
- Unsuitability(Low.DBR) = 0.5

Let the beliefs in the Depth-to-Bedrock values be given by the function \( m_1 \):

\[ m_1(Low) = 0.14 \]

\[ m_1(medium) = 0.16 \]

\[ m_1(High) = 0.43 \]

The basic probability assignment for the suitability is (from equation 3.4):

\[ m_2(\text{Suitable}) = m_1(High) \cdot \text{Suitability(High.DBR)} \]
\[ = 0.43 \cdot 0.5 \]
\[ = 0.22 \]
\[ m_2(\text{Unsuitable}) = m_1(Medium) \cdot \text{Unsuitability(Medium.DBR)} \]
\[ + m_1(Low) \cdot \text{Unsuitability(Low.DBR)} \]
\[ = 0.16 \cdot 0.25 + 0.14 \cdot 0.5 \]
\[ = 0.11 \]
\[ m_2(\theta) = 1 - 0.22 - 0.11 \]
\[ = 0.67 \]

Similarly, let \( m_3 \) represent the beliefs in the Depth-to-Water-Table values:

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$m_3(\text{Low}) = 0.15$

$m_3(\text{Medium}) = 0.2$

$m_3(\text{High}) = 0.4$

The influence of Depth to Water table on the suitability is (from Table 3.26):

Unsuitability (Low.DWT) 0.75

Unsuitability (Medium.DWT) 0.5

Suitability (High.DWT) 0.5

The basic probability assignment for the suitability is (from equation 3.4):

$m^{\text{Suitable)} = m^{\text{High)} * \text{Suitability (High.DWT)}$

$= 0.4 \times 0.5$

$= 0.2$

$m^{\text{Unsuitable)} = m^{\text{Medium)} * \text{Unsuitability (Medium.DWT)}$

$+ m^{\text{Low)} * \text{Unsuitability (Low.DWT)}$

$= 0.2 \times 0.5 + 0.15 \times 0.75$

$= 0.21$

$m_4(\theta)= 1 - 0.2 - 0.21$

$= 0.59$

The combination of the effect of Depth-to-Bedrock and Depth-to-Water-Table is given by Dempster's rule of combination:

$m_2 \odot m_4 (\text{Suitable)} = 0.22 \times 0.6 + 0.2 \times 0.67 = 0.26$

$m_2 \odot m_4 (\text{Unsuitable)} = 0.11 \times 0.6 + 0.2 \times 0.67 = 0.2$

$m_2 \odot m_4 (\theta) = 0.6 \times 0.67 = 0.4$

Normalizing the beliefs, results in:

$m_5(\text{Suitable)} = 0.3$

$m_5(\text{Unsuitable)} = 0.23$

$m_5(\theta) = 0.47$

The results of the computations involved in Dempster’s rule of combination for
evaluating the suitability of a site for an engineering application are summarized
in Table 3.32.

<table>
<thead>
<tr>
<th>bpa</th>
<th>Suitable</th>
<th>Unsuitable</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_2$ (DBR)</td>
<td>0.22</td>
<td>0.11</td>
<td>0.67</td>
</tr>
<tr>
<td>$m_4$ (DWT)</td>
<td>0.2</td>
<td>0.21</td>
<td>0.59</td>
</tr>
<tr>
<td>$m_2 \circ m_4$</td>
<td>0.26</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$m_5$ (normalized $m_2 \circ m_4$)</td>
<td>0.3</td>
<td>0.23</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 3.32. Illustration of Dempster's rule of combination
for site suitability

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3.3 Formalization in a Frame System

Frame languages provide the knowledge-base builder with an easy means of describing the types of domain objects that the system must model. The advantages of frame languages are considerable. They capture the way, experts typically think about much of their knowledge and provide a concise structural representation of useful relations (Fikes and Kehler, 1985). The advantages of frame systems, led to the decision to formalize terrain knowledge in frames (Argialas, 1989). The models of terrain objects were represented in frames, and the attributes of these objects were represented as slots of these frames (Narasimhan and Argialas, 1988b). The objects represented in TAX were the models of pattern elements, such as Relief, Slope, Drainage-pattern, and the values of these pattern elements like Gentle Relief, Dendritic Drainage and so on. Similarly, models of engineering properties like Depth-to-bedrock, Soil-permeability and the values of these properties were formalized in frames. Frames were used to formalize the models of landforms in terms of the frames developed for pattern elements and engineering properties. The constraints for engineering applications were formalized as slots in the frame for applications.

The inferencing process was represented as rules. The rules were grouped into rule-classes based on their function. The rule-class Applications.Rules, grouped together rules which evaluated the suitability of a site for an application. The rule-class Identify.Landform.Rules was a collection of rules which identified the landforms of the site. Procedural knowledge about computing the Relief of a site, slope of a site etc. were formalized as methods, and stored in slots.

3.3.1 Representation of Models in Frames

The frame for a pattern element contained attributes for defining the values of
pattern elements. In the case of pattern elements with well-defined base variables such as Relief, Slope and Drainage-Texture, standardized functions with adjustable parameters were used to represent the membership functions of the fuzzy sets representing the pattern element values. The slots (attributes) of these pattern elements were the parameters defining the membership functions. The children of each pattern element frame were frames which represented each of the possible values the pattern element could have. Figure 3.10 shows the hierarchical structure of Relief. The Relief classes Gentle.Relief, Moderate.Relief etc. were linked to the Relief frame by "Member" links. This ensured that the default descriptions of Relief classes stored at the parent level (Relief), got inherited by the classes. The frame for the pattern element Relief is shown in Figure 3.11. This frame contained default descriptions of its Members. The descriptions were represented in the form of Member slots. The Member slots of Relief were Alpha, Beta, Gamma, and Type. These were the parameters which defined the membership functions for the fuzzy sets representing the various Relief classes. The type of these slots, "Member", indicates that these slots describe characteristics of the frame's members or children, rather than of the frame Relief itself. These slots did not have any values associated with them. However, they did impose restrictions on the values, the slots could have. Such restrictions were placed in ValueClass facet of the slot. For the slot Type, the possible values were "S", "S1" and "P", corresponding to the standardized functions S, S' and II. Such a restriction was represented by the clause (ONE.OF S S1 P). This restriction was inherited by the Relief classes Gentle.Relief, Moderate.Relief, and Strong.Relief. The representation of the attributes of the Relief classes, as member slots of the Relief frame with associated restrictions on values, obviated the need to explicitly define these attributes for each of the individual Relief classes. This was possible.
Figure 3.10. Hierarchical structure of Relief
Figure 3.11. Frame representing the pattern element Relief.
because of the taxonomical organization of Relief and the default inheritance mechanism provided in frame systems.

The pattern element frame also contained descriptions of the pattern element itself, in the form of Own slots. For instance, Relief of an area was defined as the difference between the 1 percentile and 99 percentile elevation. This definition was represented by the Slot Definition which had facets Low% and High% with the values 1 and 99 respectively. The strength of the pattern element for establishing hypotheses about landforms was represented in the slot Strength.

In addition to declarative knowledge, frames were also used to store procedural knowledge. The knowledge about computing the Relief of an area is procedural. This was stored in the Slot Compute. The ValueClass restriction for this slot was "Method". This imposed the restriction that the value of this slot be a LISP procedure or the name of a LISP function. (LISP is the name of a computer language which is used to program artificial intelligence applications.) The value of the Compute slot in Relief was the function "COMPUTE.RELIEF". This function computed the value of Relief by first obtaining the histogram of elevation values in the area of interest. Next, the histogram was processed to yield the elevation values corresponding to the percentile values in the facets Low% and High% of the Slot Definition. Relief was then computed as the difference between these two values.

A frame for a pattern element value contained the parameters, Alpha, Beta, Gamma and Type for defining the membership function of the fuzzy set representing the value (as defined in Tables 3.3, 3.5 and 3.8). These definitions were used to compute the compatibility of the site's pattern element value with those of prototype landforms. The parameters of the membership functions were represented in slots of the frame representing the pattern element value. These
slots were inherited from the parent, pattern element frame as Own slots. The frame for Gentle.Relief is shown in Figure 3.12. Associated with each frame was also a comment field, which was used to store the range of values for the particular pattern element value class, as obtained from experts and literature review.

In the case of pattern elements with ill-defined base variables, such as Drainage-Types, the various pattern element value classes can not be defined by fuzzy membership functions. They were however defined by their compatibility with one another (as given in Tables 3.10, 3.12 etc.). The frame representing the pattern element Drainage.Type is shown in Figure 3.13. Such pattern elements have a member slot \( \mu \) which was inherited by the frames representing the value classes. The Compute slot of these frames contained the name of a LISP function which obtained the pattern element value for the site from the user. The taxonomical organization of Drainage.Type is shown in Figure 3.14. The members of Drainage.Type are the different types of drainage patterns such as Dendritic, Rectangular, Angular, etc. The frame representing Dendritic Drainage-Type is given in Figure 3.15. The Comment field in the frame gives the description of the pattern as found in textbooks. The Slot \( \mu \) contained a list of the compatibilities of this pattern with all other patterns. The compatibilities were given on a scale of 0 to 1 (as given in Table 3.10).

Frames representing engineering properties were similar to those that represented pattern elements. Engineering properties which have a well-defined base variable such as Depth.to.Bedrock (Figure 3.16), had slots Alpha, Beta, Gamma and Type for characterizing the membership functions of the value classes. In addition, these frames also contained information about how these properties could be inferred, and the site specific conditions which modify the inferred

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<table>
<thead>
<tr>
<th>Slot</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA</td>
<td>0</td>
<td>Range of 0 - 100 m</td>
</tr>
<tr>
<td>BETA</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>GAMMA</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>TYPE</td>
<td>(ONE.OF S S1 P)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.12. Frame representing the pattern element value**

Gentle Relief.
Unit: DRAINAGE.TYPE in knowledge base TERRAIN
Created by rn on 5-22-88 14:35:39
Modified by rn on 3-13-90 19:00:18
Superclasses: PATTERN.ELEMENTS
Member Of: CLASSES in GENERICUNITS
Members: DERANGED, INTERNAL, PARALLEL,
         PINNATE, ANGULAR, RECTANGULAR,
         DENDRITIC

| Member slot: MU from DRAINAGE.TYPE |
| Inheritance: OVERRIDE.VALUES       |
| Cardinality.Min: 1                 |
| Comment: "Compatibility with other Drainage Types" |
| Values: UNKNOWN                    |

| Own slot: COMPUTE from DRAINAGETYPE |
| Inheritance: METHOD                |
| ValueClass: METHOD                 |
| Values: QUERY.DRAINAGE.TYPE        |

| Own slot: STRENGTH from DRAINAGE.TYPE |
| Inheritance: OVERRIDE.VALUES         |
| Values: 0.75                          |

Figure 3.13. Frame representing the pattern element Drainage Type.
Figure 3.14. Taxonomical organization of Drainage Type.
Unit: DENDRITIC in knowledge base TERRAIN
Created by rn on 12-19-88 11:12:17
Modified by rn on 1-30-90 10:47:57
Member Of: DRAINAGE.TYPEx
Comment: Irregular branches flowing in many directions

Own slot: MU from DENDRITIC
Inheritance: OVERRIDE.VALUES
Cardinality.Min: 1
Comment: "Compatibility with other Drainage Types"
Values:
  (RECTANGULAR 0.5),
  (PARALLEL 0.37),
  (TRELLIS 0.5),
  (PINNATE 0.5)

Figure 3.15. Frame representing Dendritic Drainage Type.
Figure 3.16. Frame representing the engineering property

Depth to Bedrock.

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values. The attributes which provide a clue about these properties were stored in the slot *Infer.from*. The value for *Infer.from* in the frame *Depth.to.Bedrock* was "Landform". The value of Depth-to-Bedrock is modified by the topographic position of the area being evaluated. This value "Topographic.Position", was stored in the slot *Modified.by*. The soil profile is thicker in the valleys due to creep, slumping and so on; and very thin on the side-slopes. This information was represented in the slot *Topographic.Position* by the facets *Valley, Side-slope*. The *Valley* facet of *Topographic.Position* contained the bpa corresponding to "Valley" (Table 3.20), which increases the belief in the value "High.DBR". The *Side-slope* facet contains the bpa corresponding to "Side-Slope" (Table 3.20), which lends support to the value "Low.DBR". The frame representing *Low.DBR* is shown in Figure 3.17. This frame inherited the slots *Alpha, Beta, Gamma* and *Type* from *Depth.to.Bedrock* as Own slots. The top level generic frame *Engineering.Properties* (Figure 3.18), contained procedural information about how properties may be inherited from landforms, and the methodology for the modification of properties based on site specific characteristics. The procedural knowledge about inheritance was stored in the slot *Inherit* whose value "INHERIT.PROPS" was the name of a LISP function, which combined the default values of properties from the established landforms, according to Dempster-Shafer theory of evidence. Modification of the confidence associated with the property values was done by the LISP function "MODIFY.PROPS", which was stored in the slot *Modify*. The hierarchical organization of *Engineering.Properties* is shown in Figure 3.19. Such an organization enabled the abstraction of the attributes representing the values of engineering properties, as member slots in the frames representing engineering properties.
Figure 3.17. Frame representing the engineering property value

Low Depth to Bedrock.
Figure 3.18. Frame representing Engineering Properties
Figure 3.19. Hierarchical organization of Engineering Properties.
A model of a prototype landform is its description in terms of its pattern element values, and an expectation of its engineering properties. Landforms were represented as frames, with the slots of the frame describing the pattern element values and the default engineering properties of the landform. The frame representing the landform *Flood.Plain* is shown in Figure 3.20. Multiple values for pattern elements and properties were represented by a list of the values and their frequency of occurrence in the landform (Table 3.25a and 3.25b). The frequency of occurrence was given on a scale of 0 to 1. Landforms were grouped by their geomorphic origin and represented as Members of the frames representing the different types of origin. The generic *Landforms* frame was the superclass of the frames representing geomorphic origins (Figure 3.21). The *Landforms* frame (Figure 3.22), contained all the attributes for describing the individual landforms. These attributes were represented as Member slots in the *Landforms* frame and were inherited as Own slots by the frames representing the landforms. The generic *Landforms* frame also contained procedural knowledge about the accumulation of evidence for establishing the hypotheses about landforms. The combination of beliefs based on distinct bodies of evidence (as discussed in section 3.2.2.5) was performed by the LISP function "CERTAINTY.UPDATE.LANDFORM" stored in the method slot *Certainty.Update*. The Compute slot of the *Landforms* frame contained the LISP procedure which deduced the landforms of the site.

Models of engineering applications expressed the effect of various properties of a site on its suitability for the application (Tables 3.26, 3.27). A frame representing the model of *Sanitary.Landfill* is shown in Figure 3.23. The slots of the frame were the properties which affect the suitability. Corresponding to each of the possible values of the property was a measure of its effect on the suitability.
<table>
<thead>
<tr>
<th>Own slot: BEDROCK.PERMEABILITY from LANDFORMS</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values:</td>
<td>(HIGH.DBR 0.75),</td>
</tr>
<tr>
<td></td>
<td>(MEDIUM.DBR 0.25)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: DEPTH.TO.WATER.TABLE from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values:</td>
<td>(LOW.DWT 1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: DRAINAGE.TYPE from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values:</td>
<td>(DERANGED 1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: LANDUSE.PLAINS from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comment: &quot;landuse in valleys or plains&quot;</td>
<td>(AGRICULTURAL 0.66),</td>
</tr>
<tr>
<td></td>
<td>(WETLAND 0.33)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: RELIEF from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comment: &quot;topographic relief&quot;</td>
<td>(FLAT.RELIEF 1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: SLOPE from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values:</td>
<td>(FLAT.SLOPE 1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: SOIL.PERMEABILITY from</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values:</td>
<td>UNKNOWN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: TOPOGRAPHIC.FORM from FLOOD.PLAIN</th>
<th>Inheritance: OVERRIDE.VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values: PLAINS</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.20. Frame representing the landform Flood Plain.
Figure 3.21. Hierarchical organization of Landforms.
Figure 3.22. Frame representing Landforms.
Figure 3.23. Frame representing the engineering application

Sanitary Landfill.
The values of the slot contain a list of the possible values along with a measure of its effect on the suitability. A property value which decreases the suitability for an application was listed in the Negative.Values facet of the slot. Property values which supported the suitability of the site for the application were listed in the Values facet of the slot. The effect of properties on the suitability was given on a scale of 0 to 1. The generic frame Engineering.Applications (Figure 3.24), contained "Member Slots" for all the properties that affect the suitability for any application. The slot Certainty.Update contained the LISP procedure "CERTAINTY.UPDATE.APPLICATION" which updated the suitability of an area for a selected application based on the most recently computed property.

3.3.2 Inferencing using Rules

The inferencing strategy developed in section 3.2, was formalized in rules. The rules were grouped into rule-classes based on their function. The two main rule-classes were Applications.Rules and Identify.Landform.Rules (Figure 3.25). Applications.Rules was concerned with the identification of the properties affecting the suitability of a site for an application, the computation of these properties and finally the evaluation of the suitability of the site for the application. Identify.Landform.Rules identified the landforms of the site, in order to infer the properties of the site. The rules in Identify.Landform.Rules were further divided into subclasses, for carrying out specific tasks involved in landform identification. Ancillary.Information.Rules obtained ancillary information about the site, such as the physiographic section of the site. Identify.Water.Bodies.Rules established the presence of water bodies and identified the type of each of the water bodies in the site. Hypothesize.Landforms.Rules generated hypotheses about the landforms that could be found in the site based on the physiographic section of the site, and the
Unit: ENGINEERING.APPLICATIONS in knowledge base TERRAIN.
Created by rn on 3-14-88 16:15:04
Modified by rn on 1-30-90 23:15:24
  Superclasses: ENTITIES in GENERICUNITS
  Member Of: CLASSES in GENERICUNITS
  Members: SEPTIC.TANK.LEACHING.FIELDS,
           SANITARY.LANDFILL, GROUNDWATER.SUPPLY,
           LAKE.CONSTRUCTION

| Member slot: BEDROCK.PERMEABILITY from ENGINEERING.APPLICATIONS |
| Inheritance: OVERRIDE.VALUES |
| Values: UNKNOWN |

| Member slot: DEPTH.TO.BEDROCK from ENGINEERING.APPLICATIONS |
| Inheritance: OVERRIDE.VALUES |
| Values: UNKNOWN |

| Member slot: DEPTH.TO.WATER.TABLE from ENGINEERING.APPLICATIONS |
| Inheritance: OVERRIDE.VALUES |
| Values: UNKNOWN |

| Member slot: SOIL.PERMEABILITY from ENGINEERING.APPLICATIONS |
| Inheritance: OVERRIDE.VALUES |
| Values: UNKNOWN |

Own slot: CERTAINTY.UPDATE from ENGINEERING.APPLICATIONS
  Inheritance: METHOD
  ValueClass: METHOD
  Values: CERTAINTY.UPDATE.APPLICATION

Figure 3.24. Frame representing Engineering Applications.
Figure 3.25. Rule-classes in TAX.
expected association of landforms with identified water bodies and landforms in the site. *Segment.Rules* was concerned with the segmentation of the site into sub-sites based on the topographic form of the hypothesized landforms. The pattern element values of the sub-sites were then obtained by *Get.PE.Values.Rules*. The landform type of the sub-site was then established based on the pattern element values that were obtained.

In the following discussion, a correspondence between the inference strategy developed in section 3.2 and its formalization in rules will be made. A goal driven approach was followed for performing terrain analysis in TAX. (Figure 3.7). The user of TAX was first asked to choose the application, for which the site was being evaluated. The goal of a session with TAX, was the classification of the site into areas which were more or less suitable for the desired application (goal 0). (All goal numbers refer to the number of the goal nodes in Figure 3.7.) This was achieved by backward chaining on the rule-class *Applications.Rules* with the goal "The Suitability of the Engineering.Application of Site is Evaluated". The members of the rule-class *Applications.Rules* were *Properties.Affecting.Application* and *Properties.of.Site* (Figure 3.26). The top level goal matched the conclusion of the rule *Properties.Affecting.Application* (Figure 3.27). This rule ensured that, all the properties that affected the suitability of the site for the selected application, were computed for the site (goals 1 and 2). Next, the effect of the property on the suitability was taken into account by sending a message to the slot *Certainty.Update* of the *Engineering.Applications* frame (Figure 3.23) (goal 3). Some of the relevant properties such as Slope, could be computed directly from the available data, however, other properties such as Depth-to-Bedrock had to be inferred indirectly from evidences. If the property had to be inferred from evidences, those evidences were computed for the site, by
Evaluate Site Suitability for Engr. Application (APPLN)

1. Identify Properties Affecting APPLN (AP_PROP s)
2. Compute AP_PROP of Site (SITE_PROP.VAL)
3. Update Site Suitability for APPLN based on SITE_PROP.VAL

2.2

2.2.1 Compute SITE_PROP.VAL from Digital Data
2.2.2 Infer AP_PROP from Evidences (PROP_EV)
2.2.3 Update AP_PROP of Site Based on SITE_PR_EV.VAL

Figure 3.7. Inference strategy in TAX.
Figure 3.26. Rules for the evaluation of suitability for Engineering Applications.

APPLICATIONS, RULES, PROPERTIES, AFFECTING, APPLICATION, PROPERTIES, OF, SITE
(IF (THE ENGR.APLLN OF ?SITE IS ?APPLN)
  (FOR (THE ?PROP OF ?APPLN IS ?CONSTRAINT)
    ALWAYS
    ((THE ?PROP OF ALL ?SITE IS ?VAL) AND
     (LISP (UNITMSG
            (ENGINEERING.APPLICATIONS
             'CERTAINTY.UPDATE
             ?SITE
             ?APPLN
             ?PROP))))
    THEN
    (THE SUITABILITY
     OF
     THE
     ?APPLN
     OF
     ?SITE
     IS
     EVALUATED))

Figure 3.27. Rule Properties Affecting Application.
sending a message to the *Compute* slot of the evidence (goal 2.2.1 and 2.2.2). This was accomplished by the rule *Properties.of.Site* (Figure 3.28) which satisfied the goal "Property of site is value" by sending a message to the *Compute* slot of the frames from which this property could be inferred. After the evidences were computed, the property was inferred by sending a message to the *Inherit* slot of *Engineering.Properties* (Figure 3.18), which set the properties of the site as the default values of the properties from the computed evidences (goal 2.2.3). A property such as Depth-to-Bedrock can be inferred from the landform type of the site. Therefore, Depth-to-Bedrock values for a site were typically inferred by computing the landforms of the site, and then inheriting the values for Depth-to-Bedrock from the default values of the landform of the site. Often, these engineering properties were not uniform over the entire landform, but varied depending on site specific conditions. Such site specific conditions were stored in the *Modified.by* slot of the property frame (Figure 3.16). All the modifiers affecting the property were computed by sending a message to the *Compute* slot of the modifier frame (goal 2.2.2). The effect of the modifier on the property was computed by sending a message to the *Modify* slot of the *Engineering.Properties* frame (Figure 3.18).

The principal approach to infer the properties of a site was by deducing the landforms of the site. The procedure associated with the *Compute* slot of the *Landforms* frame (Figure 3.21), identified the landforms of the site, by forward chaining on the rule-class *Identify.Landform.Rules*. (Figure 3.8 is reproduced here to show the correspondence between the conceptual landform identification process and it's formalization in rules.) The subclasses of *Identify.Landform.Rules* were *Ancillary.Information.Rules, Identify.Water.Bodies.Rules, Hypothesize. Landforms.Rules, Segment.Rules, Get.PE.Values.Rules* (Figure 3.24). The
(IF (OR
   (FOR (THE COMPUTE OF ?PROP IS ?METHOD)
     ALWAYS
     (LISP (UNITMSG ?PROP 'COMPUTE ?SITE)))
   ((FOR (THE INFER.FROM OF ?PROP IS ?CUE)
     ALWAYS
     ((LISP (UNITMSG ?CUE 'COMPUTE ?SITE)) AND
     (LISP (UNITMSG 'ENGINEERING.PROPERTIES 'INHERIT ?PROP)))))
   (FOR (THE MODIFIED.BY OF ?PROP IS ?MODIFIER)
     ALWAYS
     ((LISP (UNITMSG ?MODIFIER 'COMPUTE ?SITE)) AND
     (LISP (UNITMSG 'ENGINEERING.PROPERTIES 'MODIFY ?PROP ?MODIFIER)))))
THEN
(THE ?PROP OF ?SITE IS ?PROPVAL))

Figure 3.28. Rule Properties.of.Site for computing the engineering properties of site.
physiographic location of the site was obtained by the rule
*Physiographic.Unit.Rule* which was a member of *Ancillary.Information.Rules*. The
next step in landform identification was the identification of water bodies in the
site (Figure 3.8). This was accomplished by forward chaining on the rule-class
*Identify.Water.Bodies.Rules*. The members of this rule-class were
located water body as one of *River, Ocean, Stream, Pond, and Lake* (Figure 3.29).
The rule *Establish.Water.Bodies* established the presence of water bodies in the
site by sending a message to the *Establish* slot of the *Water.Body* frame (Figure
3.30). The method associated with the *Establish* slot was the LISP function
"ESTABLISH.WATER.BODIES". This function first obtained the histogram of the
near infrared reflectance values in the site and then processed the histogram to
yield the percentage of water pixels in the site. A pixel was classified to be a
water pixel if its near infrared reflectance was less than a threshold defined in the
*Less.Than* facet of the *Near.Infra.Red* slot. If there was a significant amount of
water pixels in the site, as defined in the *Minimum.Percent.Area* slot, then the fact
"Site has water bodies" was asserted. This caused the rule *Locate.Water.Bodies* to
be fired. This rule displayed the near infrared channel of the image and requested
the user to outline the water bodies on the image. After all the water bodies were
outlined, certain characteristics of each outlined area, such as the Area, Perimeter
and Elongation were computed. These characteristics were then matched with the
characteristics of the various water bodies in the knowledge base. The matching
was done by rules like *River.Rule* (Figure 3.31). *River.Rule* checked if the
outlined body of water was OPEN (i.e if it touched one of the borders of the
image), and if the Elongation of the body was greater than a threshold Elongation
for river, and if the Area of the body of water was greater than a threshold Area
Figure 3.29. Rules for the identification of water bodies.
<table>
<thead>
<tr>
<th>Member slot: ESTABLISH from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: METHOD</td>
</tr>
<tr>
<td>ValueClass: METHOD</td>
</tr>
<tr>
<td>Percent: 5</td>
</tr>
<tr>
<td>Values: ESTABLISH.WATER.BODIES</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: NEAR.INFRA.RED from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Greater.Than: 0</td>
</tr>
<tr>
<td>Less.Than: 30</td>
</tr>
<tr>
<td>Values: UNKNOWN</td>
</tr>
</tbody>
</table>

Figure 3.30. Frame representing Water Bodies.
(IF (THE LANDFORM/WATER.BODY
    OF
    ?POLY
    IS
    WATER.BODY)
   (THE ENCLOSURE OF ?POLY IS OPEN)
   (THE ELONGATION
    OF
    ?POLY
    IS
    ?ELONG.POLY)
   (THE GREATER.THAN
    OF
    THE
    ELONGATION
    OF
    RIVER
    IS
    ?ELONG.RIVER)
   (LISP (> ?ELONG.POLY ?ELONG.RIVER))
   (THE AREA OF ?POLY IS ?AREA.POLY)
   (THE GREATER.THAN
    OF
    THE
    AREA
    OF
    RIVER
    IS
    ?AREA.RIVER)
   (LISP (> ?AREA.POLY ?AREA.RIVER))
   THEN
   (CHANGE.TO
   (THE LANDFORM/WATER.BODY OF ?POLY IS RIVER)))

Figure 3.31. Rule for identifying a river (River.Rule).
for river. If all the conditions were met, then the body of water was declared to be a river.

After all the water bodies were identified, the "Hypothesize-Establish" cycle (Figure 3.8), in landform identification was entered. Hypotheses about landforms associated with the identified water bodies, were made by invoking the rule-class Hypothesize.Landforms.Rules. The members of this class were Hypothesize.Assoc.Landforms, River.Lake.Assoc.Landforms, River.Ocean.Assoc.Landforms, Stream.Mountain.Assoc.Landforms, Landforms.in.Physiographic.Unit, and Check.Done. (Figure 3.32). Hypothesize.Assoc.Landforms was a general rule which hypothesized about landforms in the site, based on the expected association of landforms with water bodies and other landforms (WB/LF) already identified in the site. This hypothesis was combined (according to Dempster's rule of combination), with the expectation about landforms based on the physiographic section of the site (PS.LFS). The resultant hypothesis (ASS.LFS) was stored in the slot Assoc.Landforms of the WB/LF frame. The rules River.Ocean.Assoc.Landforms, Stream.Mountain.Assoc.Landforms etc. were specific rules which formed the hypotheses about landforms at the mouth of a river, and where a stream flows from a mountainous area into a plain and so on. Landforms.in.Physiographic.Unit (Figure 3.33), obtained the landforms in the Expected.Landforms slot of the physiographic section of Site and installed it in the Hypothesized.Landforms slot of Site. The rule Check.Done stopped the landform identification process if less than 10% of the site's area remained to be identified. If no more hypotheses could be made the rule-class Segment.Rules was invoked.

The members of the rule-class Segment.Rules were Pick.Max.Assoc.Landform, Pick.Max.Landform, Locate.Assoc.Form, Locate.Form, Update.Assoc.Hypotheses, Update.Hypotheses. (Figure 3.34). The rule Pick.Max.Assoc.Landform selected
Figure 3.32. Rules for generating hypotheses about landforms.

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Figure 3.33. Rule for hypothesizing about landforms based on the physiographic section of the site.
Figure 3.34. Rules for segmenting a site.
the landform with the maximum certainty (MAX.ASS.LF) associated with it from ASS.LFS in the slot Assoc.Landforms of a WB/LF frame for further examination. The rule Locate.Assoc.Form obtained the topographic form of the landform selected by Pick.Max.Assoc.Landform (FORM.ASS.LF), and asked the user to outline this form if it was present next to the WB/LF. After all the sub-sites had been outlined, hypotheses about landforms of the sub-sites were made. The hypothesized landforms of these sub-sites (HYP.LFS), were initially set equal to ASS.LFS of the WB/LF. Next, all the landforms whose topographic form was different from FORM.ASS.LF, was removed from HYP.LFS. The rule Pick.Max.Landform picked the landform which had the maximum certainty associated with it (MAX.LF) from PS.LFS, and asserted it as the landform to be further examined. The rule Locate.Form obtained the topographic form of the landform selected by Pick.Max.Landform (FORM.LF), and asked the user to outline this form if it was present anywhere in the site. After all the sub-sites had been outlined, hypotheses about landforms of the sub-sites were made. The hypothesized landforms of these sub-sites (HYP.LFS), were initially set equal to PS.LFS of the site. Next, all the landforms whose topographic form was different from FORM.LF, was removed from HYP.LFS. Update.Assoc.Hypotheses, removed MAX.ASS.LF from the Assoc.Landforms slot of WB/LF, and Update.Hypotheses removed MAX.LF from the Hypothesized.Landforms slot of Site. The Update rules ensured that in the next cycle of Hypothesize-Establish, the landform with the next largest certainty would be selected for examination, by the rules Pick.Max.Assoc.Landform, Pick.Max.Landform.

After a sub-site was outlined for further examination, the values for pattern elements in the sub-site were obtained by forward-chaining on the rule-class Get.PE.values.Rules. This rule-class had members corresponding to each of the
pattern elements used for identifying landforms (Figure 3.35). The rule *Get.Relief* obtained the Relief of the sub-site by sending a message to the slot *Compute* of the *Relief* frame (Figure 3.11). After the Relief was obtained, the certainty associated with the hypotheses was updated by sending a message to the *Certainty.Update* slot of the *Landforms* frame (Figure 3.22). Drainage pattern of a sub-site was obtained by asking the user to choose from standard drainage pattern types. If the observed pattern did not completely conform to any of the standard patterns, the user was asked to describe the drainage pattern of the sub-site in terms of its compatibility with two standard patterns.

After all the pattern elements of the sub-site were obtained and the certainty associated with the hypotheses about landforms updated, the procedure (obtaining pattern element values and updating landform hypotheses) was repeated for all the sub-sites. Another cycle of Hypothesize-Establish was then started, where hypotheses were made about associated landforms based on the landforms identified in the previous cycle. If more than 10% of the site remained to be identified, the user was asked to outline new sub-sites. If more than 90% of the site was identified, the forward chaining process, to identify the landforms of the site was stopped. Control then got transferred back to the rule *Properties.of.Site* (Figure 3.28), which computed the properties of the site by inheriting them from the hypothesized landforms. Next, the effect of modifiers such as the topographic position of the area on the properties was computed. The final step was the computation of the suitability of each of the outlined areas for the selected application, which was done by the rule *Properties.Affecting.Application* (Figure 3.27).
Figure 3.35. Rules for obtaining the pattern element values for a sub-site.
4. IMPLEMENTATION

4.1 Computer Systems Employed in the Development of TAX

The Terrain Analysis eXpert (TAX) system was implemented using the computer hardware and software available in the Remote sensing and Image Processing Laboratory (RSIP) at the Louisiana State University. TAX was built with the help of the hybrid expert system development tool KEE (Knowledge Engineering Environment) developed by Intellicorp Inc. The platform for TAX was the SUN 3/260 workstation. The SUN workstation had 16 Mbytes of main memory and 280 Mbytes of hard disk storage. The SUN stations employed a window-based operating environment and a high-resolution bit-mapped screen capable of displaying both raster and vector images. The display and manipulation of the digital data was accomplished with the help of the ELAS (Earth resources Laboratory Application Software) image processing system. The platform for ELAS was the UNISYS 7000/40 computing system with 8 Mbytes of main memory and about 2 Gbytes of disk storage.

The KEE system is a set of software tools designed to assist knowledge engineers in building special purpose knowledge-based expert systems. It is a development system containing an integrated set of tools such as Frames for the representation of knowledge, a Rule-System for reasoning, Object-oriented programming for data independent modular programming and graphics for a powerful user interface medium.

The frame-based representation facility in KEE is highly sophisticated, providing for "IS-A" and "A-KIND-OF" connections using Member and Subclass links. Frames are allowed to have multiple parents, and a variety of inheritance schemes are provided from which a choice can be made. The Rule-system in
KEE, provides a choice of two modes of reasoning, backward chaining or forward chaining. The choice of the reasoning strategy can be postponed until the actual run-time, so, the same set of rules can be employed in both the forward and the backward chaining modes. Rules are allowed to be grouped into rule-classes, so as to enable control over the inferencing process. Object-oriented programming is another aspect important aspect of the KEE system. Object-oriented programming allows descriptive and procedural attributes of an object to be associated directly with that object in a frame. The advantages of Object-oriented programming are provided through the use of a facility in KEE called Methods.

Other advanced features of KEE include the concept of "Worlds". This facility provides modelling of multiple situations and allows the exploration of multiple alternatives. Incorporated into the reasoning capabilities of the KEE system is an assumption-based truth maintenance system (ATMS). The ATMS serves to update derived facts during state changes in worlds. Details concerning the features of KEE and their applications to expert system development can be found in KEE manuals (Intelligent, 1989).

The ELAS image processing system is designed for analyzing and processing digital imagery such as those collected by multi-spectral scanners or digitized from maps and photographs. ELAS was developed by NASA (National Aeronautics and Space Administration) Earth Resources Laboratory. It has been extensively modified and enhanced to run under a UNIX operating system by the research staff at RSIP.

4.2 System Overview

A schematic diagram of the system is shown in Figure 4.1. The system for terrain analysis consisted of TAX - the Terrain Analysis eXpert, which interacted
Figure 4.1. System organization.
with the USER and evaluated a site for an application specified by the user. TAX relied on the ELAS image processing system for the display and manipulation of the digital data of the site. TAX ran on a SUN machine under KEE. ELAS, on the other hand ran on the UNISYS computer. TAX started the process "rlogin" on SUN and communicated with it by opening up input and output channels to it. The "rlogin" process served all the image processing requests of TAX, by starting the ELAS process on the UNISYS and transmitting the requests of TAX to ELAS.

The knowledge in TAX was partitioned into Domain, Tools and the Short Term Memory. (Figure 4.2). Domain consisted of knowledge about terrain analysis, which included models of pattern elements, landforms, engineering properties and engineering applications. Tools contained knowledge about other software systems used by TAX for performing terrain analysis. In the present version, Tools contained knowledge for the use of the ELAS system. Short Term Memory contained knowledge about the current session of TAX. It contained information about the site under investigation, details about the digital data of the site and so on.

4.3 Domain Knowledge Base

The most important component of the domain knowledge base was the knowledge about terrain analysis. This was represented by frames containing models of pattern elements, landforms, engineering properties and engineering applications. The knowledge about pattern elements was grouped under the class frame Pattern.Elements. The individual pattern elements such as Relief, Slope, Drainage.Type and so on were connected to the Pattern.Element frame by "Sub-class" links, whereas the frames representing each of the possible values of a pattern element were connected to their respective pattern element frame by
Figure 4.2. Knowledge modules in TAX.
"Member" links (Figure 4.3). Such a hierarchy ensured that the attributes set up for the description of pattern element values in the *Pattern.Element* frame got inherited through the individual pattern element frames, to the frames representing pattern element values.

Knowledge about engineering properties was grouped under the frame *Engineering.Properties* (Figure 3.19). The individual engineering properties such as *Depth.to.Bedrock*, *Depth.to.Water.Table*, etc. were subclasses of the *Engineering-properties* frame. The values of these properties such as *Low.DBR*, *High.DWT* etc. were "Members" of the respective pattern element frames. Frames representing engineering applications were created as "Members" of the *Engineering.Applications* frame (Figure 4.4).

The *Domain* knowledge base also contained knowledge about the landforms found in various physiographic sections of the USA. This knowledge was useful for hypothesizing about the landforms expected in an area. Background knowledge was organized hierarchically into physiographic divisions at the top level, which was broken down into a number of provinces, which were further subdivided into physiographic sections (Figure 4.5). The frame for the physiographic section *West.Gulf.Coastal.Plain* is shown in Figure 4.6. The landforms which occur in that section were stored in the slot *Expected.landforms*. Associated with each landform was a measure of the certainty of finding the landform in that area.

In addition to knowledge about terrain analysis, the *Domain* knowledge base also contained knowledge about water bodies. The hierarchy of the *Water.Bodies* frame is displayed in Figure 4.7. The *Water.Bodies* frame (Figure 4.8) contained the default characteristics common to all water bodies, namely, low reflectance values in the near-infra-red band. The frame also contained the attributes such as *Area*, *Elongation* etc. which were used for classifying water bodies. The frame
Figure 4.3. Hierarchical organization of Pattern Elements
Figure 4.4. Hierarchical organization of Engineering Applications.
Figure 4.5. Hierarchical organization of knowledge about Physiographic Units.
Figure 4.6. Typical frame for a physiographic section.
Figure 4.7. Organization of knowledge about Water Bodies.
<table>
<thead>
<tr>
<th>Member slot: AREA from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: UNKNOWN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: ELONGATION from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: UNKNOWN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: ENCLOSURE from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: UNKNOWN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: ESTABLISH from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: METHOD</td>
</tr>
<tr>
<td>ValueClass: METHOD</td>
</tr>
<tr>
<td>Hide.Me: NIL</td>
</tr>
<tr>
<td>Percent: 5</td>
</tr>
<tr>
<td>Values: ESTABLISH.WATER.BODIES</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: NEAR.INFRA.RED from WATER.BODIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Greater.Than: 0</td>
</tr>
<tr>
<td>Less.Than: 30</td>
</tr>
<tr>
<td>Values: UNKNOWN</td>
</tr>
</tbody>
</table>

Figure 4.8. Frame representing Water Bodies.
River (Figure 4.9) shows the attributes defining a typical water body. The GreaterThan facet of the slot Area contained the minimum area in sq. meters for a water body to be classified as a river. Similarly, the minimum value of elongation (as calculated by equation 3.1) was stored in the GreaterThan facet of the slot Elongation. (The values for these facets were obtained heuristically, by analyzing a number of water bodies.) The fact that rivers are "open" bodies of water, was represented in the slot Enclosure. The AssociatedLandforms slot contained the landforms expected to be found associated with rivers.

4.4 Tools Knowledge Base

The Tools knowledge base contained knowledge about using the software systems, necessary for running TAX. The current version of TAX interacted with the ELAS image processing system, to display and process images. ELAS was invoked at the beginning of every session, by sending a message to the Start slot of the ELAS frame (Figure 4.10). This invoked the LISP function "Invokeelas". The specific functions of ELAS used by TAX were:

- Access and release files; obtain information about files
- Display images
- Get histogram
- Outline areas

Knowledge about these functions was encapsulated in the following frames: Files Display Polygon Histogram The Files frame is displayed in Figure 4.11. The Access slot contained the name of a LISP function "Access.File", which took as arguments the file name and the access mode. The access mode could be "input", "output" or "display". The slot Get.Info contained a LISP procedure which
Figure 4.9. Frame for a typical water body.
Figure 4.10. Frame encapsulating the startup procedure for

the ELAS image processing system.
Figure 4.11. Frame encapsulating the knowledge for file manipulations.
obtained the information found in the header record of the file accessed for input. Some of the header information used in TAX were the size of the file - number of lines and number of elements, the size of each pixel of the image, the data found in the various channels of the image file, the parameters needed for transforming the grey level value in the image to the relevant units of reflectance or topographic data and so on. The information regarding the format of the header record and the output generated by the procedure Get.Info was encapsulated in a procedural format, and stored in the slot Proc.Info.

The Display frame (Figure 4.12) contained information about the various display devices available, their characteristics and the commands for displaying images on these devices. The names of the devices were stored in the slot Available.Devices. The user was asked to choose a display device from a menu of available devices, when ELAS was first invoked. This device was then accessed for "display" and its name was stored in the slot Chosen.Device. The characteristics of each of the display devices such as the size of the display frame, the number of bit planes etc. were stored as facets of the slot. This information was used for deciding the scale for displaying the image.

The Polygon frame (Figure 4.13) contained information about outlining areas on the screen for interactive segmentation, retrieving previously outlined areas, getting statistics on areas and so on. The slot Pick contained a LISP procedure "Pick.Polygon", which fired ELAS commands for outlining areas. The user was asked to pick the vertices of the enclosing polygon with the help of a trackball or mouse (depending on the display device), and type return to select a point. The user was also prompted for a name to save the outlined polygon. The slot Recall contained the LISP function "Recall.Polygon" which retrieved a previously outlined polygon. The slot Attributes invoked the LISP function
Figure 4.12. Frame encapsulating the knowledge about Display devices and procedures.
Figure 4.13. Frame encapsulating the knowledge about Polygon manipulations.
"Attributes.Polygon", which obtained the area and perimeter of a retrieved polygon.

Histograms were used in TAX, for establishing the presence of water bodies, obtaining the relief of an area and so on. Histograms were obtained by sending a message to the Get slot of the Histogram frame (Figure 4.14). If a histogram of values over an outlined area were desired, the enclosing polygon was first retrieved by messaging the Recall slot of the Polygon frame, and then obtaining the histogram for the retrieved area. The knowledge about the format of the output of histogram was encapsulated in the slot Process, which contained the LISP procedure "Process.Histogram". This function handled a variety of queries such as, the grey level corresponding to a "cumulative less than" value of frequency, the total number of pixels having a grey level less than a given value, and so on.

4.5 Short Term Memory

The Short.Term.Memory knowledge base was created dynamically at the beginning of every run of TAX. It contained knowledge pertinent to the current run of TAX. The units in this knowledge base were Image.Info, Site and all the subclasses of Site. The frame Image.Info (Figure 4.15) contained information about the raster data of the study area. The slot FileName contained the UNIX file name of the raster data. Maxdimn contained the maximum of the number of lines and number of elements in the raster data. The slot Elevation slot contained the channel number of elevation data in the Channel facet, and the parameters for converting the value in the elevation channel into meters of elevation in the facets Start.Value and Increment. The actual value of
Figure 4.14. Frame encapsulating knowledge about obtaining Histograms of digital data.
Figure 4.15. Frame encapsulating the knowledge about the digital data of the site.
elevation (in meters) was obtained by converting the value stored in the elevation image, using the following equation:

\[
\text{Elevation} = \text{Start.Value} + \text{Grey.Level} \times \text{Increment}
\]

The facet Function contained the name of the function used by the "Display" routine to enhance the image for a better visual appeal. The file name of the image data was obtained from the user, but the rest of the information is obtained from the header record of the data file. Other slots of the frame such as Slope, Near-Infra-Red etc. were similar to the Elevation slot.

The frame Site denoted the entire study area. Figure 4.16 shows the hierarchical structure of Site and its subclasses. The subclasses of Site were the various segments that have been outlined and identified. Some of the subclasses such as Lake1, River1 etc. were water bodies in the image, which were outlined by the user and identified by TAX. The other subclasses such as Plain1.R1, Plain2.R1 were plains that were outlined adjacent to River1 by the user. Mountain1 was a mountainous form located and outlined by the user. The subclasses of Mountain1 were the various facets of the mountainous form Mountain1. Valley1.M1, Valley2.M1 were valleys in Mountain1; Summit1.M1, Summit2.M1 were summits of Mountain1; and Side-slope1.M1, Side-slope2.M1 were side-slopes of Mountain1. In all the above cases, the names of the units correspond to the names of the respective polygons outlined on the screen.

The Site frame (Figure 4.17) contained the planimetric area of the site under study in the slot Area. The area of the site was computed by multiplying the size (in sq. meters) of each pixel in the image, with the number of rows and columns in the image. All of the above information was obtained from the header record of the image file. The information about the area of the site was used along with the data about the areas outlined and identified in the site, to decide, when to stop.
Figure 4.16. Hierarchical organization of knowledge about the study area.
Figure 4.17. Frame representing the entire study area.
outlining and identifying subsites for investigation. The physiographic section of
the site was recorded in the slot Physiographic.unit. The principal use of this
information was to formulate hypotheses about the expected landforms, which was
stored in the slot Hypothesized.Landforms.

The subclasses of Site, Plain1.R1, Plain2.R1, etc. contained the values for
pattern elements which were obtained from the user and computed from digital
data (Figure 4.18). The Hypothesized.Landforms slot of these frames contained
the updated certainties associated with landforms based on the pattern element
values. The topographic form of the outlined areas were stored in the slot
Topographic.Form. The frames Valley1.M1, Summit2.M1, etc. contain an
additional slot, Topographic.Position, which contained the topographic position of
the area (Figure 4.19). This information was used to modify the certainties
associated with the default engineering properties inherited from the landforms in
the Hypothesized.Landforms slot. The engineering properties of an area were
stored in the slots Depth.to.Bedrock, Depth.to.Water.Table, Soil.Permeability etc.
of the area. The suitability of an area for a selected application was stored in the
slot having the same name as the application. For instance, in the present case, the
suitability of various areas for "Sanitary.Landfill" was stored in the slot
Sanitary.Landfill.
Figure 4.18. Frame representing a typical sub-site.
Figure 4.19. Frame representing a typical facet of a sub-site.
5. TESTING

5.1 Study Area

The study area is located north-east of the Toledo Bend reservoir, in De Soto parish, Louisiana. A color infrared aerial photograph of the site is shown in Figure 5.1. The photograph was taken as part of the NHAP (National High Altitude Photography) program. The scale of the photograph is 1:58,000 (photograph number 711-120). The site lies in the West Gulf Coastal Plain section of the Coastal Plain province.

5.2 Traditional Photointerpretation of Site

The following data were studied for performing the manual analysis; color infrared stereo transparencies (1:58,000 scale) of the site, 7½' topographic map of the study area (Logansport East quadrangle) (Figure 5.2), 15' topographic map of the same area (Logansport quadrangle).

5.2.1 Partitioning of the site

The most distinctive feature of the study area is the Sabine river flowing from north to south. The site also contains a number of small lakes, and two fairly large lakes close to the river. The areas adjacent to the river contain meander scrolls and oxbow lakes clearly suggesting a flood plain. After studying the area stereoscopically, and examining the topographic map of the area, the boundary of the flood plain was taken to be the 200 ft. contour on either side of the river. On the northern side, the flood plain is demarcated by a small escarpment which separates the upland forests from the wetlands in the flood plain. At the southern border, the terrain changes from a nearly flat area to one that is moderately dissected. The site was segmented into three areas; Plain, Upland1 and Upland2,
Figure 5.1. Color infrared photograph of site.

(Scale 1:58,000)
Figure 5.2. Topographic map of site.

(original Scale 1:24,000)
as shown in Figure 5.3. An analysis of each of the areas follows.

5.2.2 Landform Identification

PLAIN:

<table>
<thead>
<tr>
<th>Topographic Form</th>
<th>Flat Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
<td>Deranged</td>
</tr>
<tr>
<td>Gullies</td>
<td>None</td>
</tr>
<tr>
<td>Landuse/Landcover</td>
<td>Predominantly Wetland (forested), Some Agricultural (pastureland)</td>
</tr>
<tr>
<td>Special Features</td>
<td>Meander Scrolls, Oxbow Lakes</td>
</tr>
</tbody>
</table>

The outlined area is definitely a Flood-plain. The observations which lead to this conclusion are; the area’s proximity to a meandering river, the presence of special features which are characteristic of a flood plain such as meander scrolls, and oxbow lakes, the flat topography and the deranged drainage.

UPLAND1:

<table>
<thead>
<tr>
<th>Topographic Form</th>
<th>Flat Upland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
<td>Internal to Coarse Dendritic</td>
</tr>
<tr>
<td>Gullies</td>
<td>None Visible</td>
</tr>
<tr>
<td>Landuse/Landcover</td>
<td>Predominantly Forested</td>
</tr>
</tbody>
</table>

The physiographic section of the site (West Gulf Coastal Plain) leads to the hypothesis that the upland could be a coastal terrace. The proximity of this area to a flood plain however suggests that Upland1 could be a riverine terrace, that is, part of an old flood plain. The pattern element values of both types of terraces are similar. It is therefore difficult to identify the landform type unequivocally. A riverine terrace is rather flat and has much less undulations than a coastal terrace.
Figure 5.3. Partitioning of site by user.
An examination of the topographic map indicates that Upland 1 is quite flat and so is likely to be a riverine terrace.

**UPLAND2:**

<table>
<thead>
<tr>
<th>Topographic Form</th>
<th>Slightly Dissected Upland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
<td>Coarse to Medium Texture, Dendritic</td>
</tr>
<tr>
<td>Gullies</td>
<td>None Visible</td>
</tr>
<tr>
<td>Landuse/Landcover</td>
<td>Predominantly Forested</td>
</tr>
</tbody>
</table>

This area is likely to be part of a coastal terrace. The slight dissection of the area and the dendritic drainage support this conclusion.

### 5.2.3 Suitability Evaluation

Next, the suitability of the site for locating septic tank leaching fields was evaluated. A location suitable for this application must have adequate depth of permeable soils to ensure aerobic decomposition of wastes. The depth to water table must be high enough to prevent contamination of ground water resources. There are also regulations regarding the maximum permissible slope of the site.

**PLAIN:**

The flood plain is definitely ruled out for this application. Flood plains typically have very high water tables and in the present case the presence of wetlands suggests that the water table is actually at the surface. This makes the area unsuitable for leaching fields.
UPLAND 1:
The depth to water table in a terrace is usually medium, and there is usually adequate soil materials for the sewage to filter through. The soils are likely to be quite coarse, so ponding of the sewage effluent should not be a problem. However, terraces often have gravel deposits, which have very high percolation rates. Such areas may not provide enough detention times for an adequate treatment of the wastes, and the effluent may contaminate ground water. Care must be taken to avoid gravel bearing strata, if leaching fields are sited in this area.

UPLAND 2:
The depth to water table in coastal terraces is medium to high, and the depth to bedrock is also rather high. The permeability of soils is usually moderate. The light soil tones in the area suggest that the soils may be well drained. This area is therefore considered suitable for septic leaching fields.

5.3 Analysis by TAX
The site shown in Figure 5.1, was analyzed by TAX. The "USER" was a graduate student, with three years experience in manual terrain analysis.

The data set for the analysis was composed of digital elevation data for the 7 ½ ' quadrangle and digitized color infrared image of the site. The digital elevation data obtained from USGS, had a ground sampling size of 30 m. The 16 bit elevation data was converted to 8 bit data and reformatted to be compatible with ELAS file formats. A color infrared aerial transparency of the site was obtained from the USGS NHAP archives (photograph number 711-120). The transparency was at a scale of 1:58,000. The transparency was digitized using a scanner, and digital reflectance data in the three channels (Green, Red and Near Infrared) were obtained. The scanned image had geometric distortions, which were caused by the
scanning camera. These distortions were removed by "rubber-sheeting" the image using ground control points on the topographic map. The geometrically corrected image was then resampled to a ground cell size of 30m X 30m, and overlaid with the elevation data.

5.3.1 Startup Procedure

The TAX system was invoked by typing "TAX" at the UNIX prompt. After the window system was initialized, the analysis was started by typing "(START)". This invoked the LISP procedure which sent a message to the Start slot of ELAS (Figure 4.10). The procedure "INVOKEELAS" associated with this slot, first asked the user to choose the display device from a menu (Figure 5.4). The chosen device (IIS), was entered in the Chosen.Device slot of the Display frame (Figure 4.12). Next, the file name of the raster data of the site was obtained from the user and was stored in the FileName slot of the Image.Info frame (Figure 4.15). The ELAS process was then started, and the display device and the raster data file were accessed by sending a message to the Access slot of the Files frame (Figure 4.11). Information about the raster data was obtained by sending a message to the Info slot of the Files frame. The LISP procedure associated with the slot accessed the header record of the raster file, and the information contained in the header was represented in the frame Image.Info (Figure 4.15). This completed the initial set up for ELAS.

Next, the user was asked to choose the application for which the site was to be evaluated (Figure 5.5). The choice (Septic Tank Leaching Fields) was stored in the Engineering.Applications slot of the Site frame, and a new slot Septic.Tank.Leaching.Fields was created (Figure 5.6). This slot contained the suitabilities for the application as they got evaluated.
Figure 5.4. Menu for Display Devices.
Figure 5.5. Menu for Engineering Applications.
Figure 5.6. Initial configuration of Site frame.
5.3.2 Constraints Identification

The evaluation of the suitability was triggered by backward chaining on the ruleclass Applications.Rules (Figure 3.26), with the goal (0) "The Suitability of the Septic.Tank.Leaching.Fields of Site is Evaluated" (Figure 5.7). Goal(0) matched the conclusion of the rule Properties.Affecting.Application (Figure 3.27), and was broken into a conjunction of sub-goals (1,2). The first sub-goal (1) "The Engineering.Application of Site is Septic.Tank.Leaching.Fields" was satisfied immediately, since it was found to be true in the knowledge base, that is, in the Site frame (Figure 5.6). The second sub-goal (2) is actually a conjunction of four sub-goals (2.1, 2.2, 2.3, 2.4), corresponding to the four constraints for Septic Tank Leaching Fields (Table 3.27). Each of the sub-goals corresponds to an instantiation of the goal 2, with the variable ?prop set to the constraint for Septic Tank Leaching Fields. The evaluation of the sub-goals is shown in Figure 5.8. The sub-goals 2.11, 2.21 etc. were found to be true in the knowledge base and were satisfied. Since none of the properties of Site had yet been computed, the second sub-goal "The Soil.Permeability of Site is ?value" was matched with the conclusion of the rule Properties.of.Site (Figure 3.28) and was further broken down into sub-goals 2.121 and 2.122 as shown in Figure 5.9. The value of Infer.From of Soil.Permeability is "Landforms". The instantiation of the sub-goal 2.121 with "Landforms" for the value of "?cue", is given in Figure 5.10. A message was then sent to the Compute slot of the Landforms frame (Figure 3.22), in order to identify the landforms of the site.

5.3.3 Landform Identification

The procedure associated with the Compute slot of Landforms (Figure 3.22), triggered the rule-class Identify.Landforms.Rules in a forward-chaining mode with
The Suitability of the Septic. Tank. Leaching Fields of Site is Evaluated

Properties Affecting Application

and

The Engineering. Application of Site is Septic. Tank. Leaching. Fields

(satisfied)

For (The ?prop of Septic. Tank. Leaching. Fields is ?constraint)
Always (The ?prop of Site is ?value)
AND
UNITMSG
*Engineering. Applications
*Certainty. Update

Figure 5.7 - Backward chaining on "Properties Affecting Application"
Figure 5.8. Evaluation of constraints of

Septic Tank Leaching Fields.
The Soil Permeability of Site is Evaluated

Properties of Site

For (The Infer.From of Soil Permeability is ?cue)
Always
UNITMSG
?cue Compute
AND
UNITMSG
Engineering.Properties
Inherit
Soil.Permeability

For (The Modified.by of Soil Permeability is ?modifier)
Always
UNITMSG
?modifier Compute
AND
UNITMSG
Engineering.Properties
Modify Soil.Permeability
?modifier

Figure 5.9 - Backward chaining on "Properties of Site"
The Infer. From of Soil.Permeability is Landforms (satisfied)

2.121.11

UNITMSG
Landforms Compute

2.121.12

UNITMSG
Engineering.Properties Inherit Soil.Permeability

2.121.13

2.121.1

?cue = Landforms and

Figure 5.10 - Inferring properties
the assertion "Compute Landforms of Site". This triggered the rule *Physiographic.Unit.Rule* which obtained the physiographic section of the site (West.Gulf.Coastal.Plain) from the user (Figure 5.11) and stored it in the *Physiographic.Unit* slot of *Site*.

Next, the water bodies in the site were examined by forward chaining on the rule-class *Identify.Water.Bodies.Rules* (Figure 3.29). The rule *Establish.Water.Bodies* was triggered, which determined if the site had water bodies, by sending a message to the *Establish* slot of *Water.Bodies* (Figure 3.30). The method "Establish.Water.Bodies" obtained the histogram of the reflectance values in the near infrared channel, by sending a message to the *Get* slot of the *Histogram* frame (Figure 4.14). The histogram was then processed (by sending a message to the *Process* slot) to yield the percentage of pixels with a reflectance value satisfying the signature of water pixels (NIR reflectance less than 30). A significant number of water pixels were found (17.51%), so the fact "Site has Water.Bodies" was asserted. This triggered the rule *Locate.Water.Body*. This rule displayed the near infrared channel of the image, by sending a message to the *Display* frame, and asked the user to outline water bodies on the screen (Figure 5.12). Each outlined water body was given a name by the user, and frames were created corresponding to each water body. These frames were connected to the *Site* frame by subclass links (Figure 5.13). Shape attributes of the water bodies were then computed by sending a message to the *Attributes* slot of the *Polygon* frame (Figure 4.13). The attributes were stored in the individual frames representing the water bodies. The identification of the type of water bodies was accomplished by forward chaining on the rule-class *Identify.Water.Bodies.Rules* (Figure 3.29). The attributes of the outlined water bodies were compared with the models of water bodies in the knowledge base, by rules like *River.Rule, Lake.Rule,*
Figure 5.11. Cascading menu for physiographic unit.
Figure 5.12. User assisted segmentation of water bodies using a near infrared image.
Figure 5.13. Organization of water bodies in the Site hierarchy.
etc. If an exact match was found, the type of water body was recorded in the frame. TAX identified one river (R1) and eight lakes (L1, L2, L3, L4, L5, L6, WL1, WL2). The water body OLL could not be classified.

The Hypothesize-Establish cycle was then entered (Figure 3.8). Hypotheses about the landforms expected in the site were formulated by forward chaining on the rule-class Hypothesize.Landforms.Rules (Figure 3.32). The rule Landforms.in.Physiographic.Unit (Figure 3.33), hypothesized about the landforms based on the physiographic section of the site. The Hypothesized.Landforms of Site were initialized to the Expected.Landforms of "West.Gulf.Coastal.Plain" (Figure 4.6). The rule Hypothesize.Associated.Landforms hypothesized about landforms based on the landforms found associated with the water bodies identified in the site. The landforms associated with a river are "Flood.Plain" and "Others" (Figure 4.9). This hypothesis was combined orthogonally with the hypothesis based on the physiographic section of the site to yield the resultant hypothesis about landforms associated with R1 (Figure 5.14).

After the hypotheses about landforms was formulated, the rule-class Segment.Rules was invoked (Figure 3.34). The rule Pick.Max.Assoc.Landform picked the landform with the maximum certainty from the Associated.Landforms slot of R1 (Figure 5.14), and asserted it (Flood.plain) as the landform to be examined. This triggered the rule Locate.Assoc.Form

which obtained the topographic form of flood plain, that is Plains (Figure 3.20), and asked the user to outline these forms adjacent to R1, if they existed. To ease the process of locating plains, the elevation channel of the image was displayed. The user outlined two areas Plain1.R1, Plain2.R1, next to R1 (Figure 5.15). Frames were created corresponding to each of these outlined forms and were linked to Site by member links. The hypothesized landforms of these areas were
Figure 5.14. Frame representing the water body R1.
Figure 5.15. Location of plains adjacent to R1.
obtained from the associated landforms of \( R1 \). However, only those landforms whose topographic form matched the topographic form of the outlined area (Plains) were included in the hypothesis list. The rule \textit{Update.Assoc.Hypotheses} then removed the hypotheses corresponding to Flood Plain from the \textit{Associated.Landforms} slot of \( R1 \).

The landform type of the outlined areas was established by forward chaining on the rule-class \textit{Get.PE.Values.Rules} (Figure 3.35). \( Plain1.R1 \) was the first area to be examined. The values for the pattern elements for \( Plain1.R1 \) and their influence on the confidence associated with the hypotheses about landforms are given in Table 5.1.

<table>
<thead>
<tr>
<th>Pattern Element</th>
<th>Value</th>
<th>Cert(Flood Plain)</th>
<th>Cert(Others)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Value</td>
<td></td>
<td>0.43</td>
<td>0.35</td>
</tr>
<tr>
<td>Landcover</td>
<td>Wetland</td>
<td>0.4</td>
<td>0.46</td>
</tr>
<tr>
<td>Drainage Type</td>
<td>Deranged</td>
<td>0.77</td>
<td>0.17</td>
</tr>
<tr>
<td>Relief</td>
<td>10 m</td>
<td>0.93</td>
<td>0.05</td>
</tr>
<tr>
<td>Slope</td>
<td>4 %</td>
<td>0.97</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 5.16 displays the structure of the frame representing \( Plain2.R1 \), after all the pattern element values were obtained.

Since the landform type of the outlined plains was established with a significant degree of confidence (\( > 0.5 \)), the landform with the highest certainty (Flood Plain) was stored in the \textit{Landform/Water.Body} slot of the area. This
Figure 5.16. Frame representing the sub-site Plain2.R1.
assertion led to hypotheses about landforms associated with flood plains, namely Terraces. The hypotheses were formulated by the rule Hypothesize.Associated.Landforms. The rule Pick.Max.Assoc.Landform picked "Terrace" from the Associated.Landforms slot of Plain2.R1 and Plain1.R1, and asserted it as the landform to be examined. This triggered Locate.Assoc.Form, which asked the user to outline the topographic form of Terraces (Uplands) adjacent to each of the flood plains. However, the user was able to locate only one upland area (Upland1), adjoining a flood plain, the one adjacent to Plain1.R1 (Figure 5.17). The pattern element values and the final certainties associated with the landform hypotheses for Upland1 are presented in Figure 5.18. The frames for Riverine.Terrace and Coastal.Terrace are shown in Figure 5.19 and 5.20. Upland1 was declared to be a Terrace.

Next, the hypotheses corresponding to the physiographic section of the site was examined. Pick.Max.Landform picked the landform with the maximum certainty associated with it from the Hypothesized.Landforms slot of Site, and asserted it (Coastal Terrace), as the landform to be examined. The rule Locate.Form obtained the topographic form of Coastal.Terrace (Figure 5.20), that is Uplands, and asked the user to outline these forms, if they existed. The user outlined Upland2 (Figure 5.21). Update.Hypotheses then removed the hypotheses corresponding to Coastal Terrace from the Hypothesized.Landforms slot of Site. The landform type of the outlined upland was determined by forward chaining on the rule-class Get.PE.Values.Rules (Figure 3.35). For the pattern element Landuse, the user indicated that there was more than one predominant landcover type. Upland2 was therefore segmented into Upl2.C and Upl2.F by the user (Figure 5.22). Values for the pattern elements were obtained for each of the segments and the landform type determined. The results are presented in Figures
Figure 5.17. Location of upland adjacent to Plain1.R1.
| Member slot: DRAINAGE.TYPE from UPLAND1 | Inheritance: OVERRIDE.VALUES | Symbolic: (INTERNAL 1) | Values: SYMBOLIC |
| Member slot: ENGINEERING.APPLICATION from SITE | Inheritance: OVERRIDE.VALUES | Values: SEPTIC.TANK.LEACHING.FIELDS |
| Member slot: HYPOTHESIZED.LANDFORMS from UPLAND1 | Inheritance: OVERRIDE.VALUES | Values: (OTHERS 0.0176), (RIVERINE.TERRACE 0.75198), (COASTAL.TERRACE 0.222) |
| Member slot: SEPTIC.TANK.LEACHING.FIELDS from SITE | Inheritance: OVERRIDE.VALUES | Values: UNKNOWN |
| Member slot: SLOPE from UPLAND1 | Inheritance: OVERRIDE.VALUES | Numeric: 7 | Values: NUMERIC |
| Member slot: TOPOGRAPHIC.FORM from UPLAND1 | Inheritance: OVERRIDE.VALUES | Values: UPLAND |
| Own slot: LANDFORM/WATER.BODY from UPLAND1 | Inheritance: OVERRIDE.VALUES | Values: RIVERINE.TERRACE |

Figure 5.18. Final frame for Upland1.
Figure 5.19. Frame for a prototype Riverine Terrace.
Figure 5.20. Frame for a prototype Coastal Terrace.
Figure 5.21. Location of Upland2.
Figure 5.22. Segmentation of Upland2.
5.23 and 5.24.

The total area segmented and identified at this point was 80%. So, the Hypothesize-Establish cycle (Figure 3.8), was performed once again. PickMaxLandform picked Flood.Plain as the landform to be examined from the Hypothesized.Landforms slot of Site. (Coastal.Terrace which had the largest a priori certainty associated with it in the Hypothesized.Landforms slot, was removed by the rule Update.Hypotheses.) The rule Locate.Form asked the user to locate plains (the topographic form of flood plains) in the site. The user located Plain1, which was segmented into Pll.C and Pll.W based on landcover (Figure 5.25). The results of pattern element analysis and establishment of the landform type of these two areas are given in Figure 5.26 and 5.27. Check.Done then determined that more than 95% of the site's area had been identified; so the landform identification process was stopped.

5.3.4 Inferring Properties

The successful identification of the landforms of the site satisfied the sub-goal 2.121.12 (Figure 5.10). The next sub-goal 2.121.13, involved the inheritance of the values for soil permeability from the identified landform types of the site. This was accomplished by sending a message to the Inherit slot of Engineering.Properties frame (Figure 3.18), with the argument "Soil.Permeability" as the property to be inherited. The certainty associated with the various soil permeability classes for the segmented areas is given Table 5.2.
Figure 5.23. Frame representing sub-site UPL2C.
Unit: UPL2F in knowledge base SYN
Created by rm on 2-9-90 22:39:14
Modified by rm on 2-11-90 15:31:28
Superclasses: UPL2
Member Of: CLASSES in GENERICUNITS

<table>
<thead>
<tr>
<th>Member slot</th>
<th>Inheritance</th>
<th>Numeric</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDRNAGE.TEXTURE from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td>0.20666666</td>
<td>NUMERIC</td>
</tr>
<tr>
<td>BDRNAGE.TYPE from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td></td>
<td>((INTERNAL 0.75) (DENRITIC 0.25))</td>
</tr>
<tr>
<td>HYPOTHESIZED.LANDFORMS from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td></td>
<td>(OTHERS 0.0098418165), (TERRACE 0.318959), (COASTAL.TERRACE 0.6598399)</td>
</tr>
<tr>
<td>LANDUSE.PLAINS from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td></td>
<td>((FORESTED 1))</td>
</tr>
<tr>
<td>RELIEF from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td>37</td>
<td>NUMERIC</td>
</tr>
<tr>
<td>SLOPE from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td>7</td>
<td>NUMERIC</td>
</tr>
<tr>
<td>TOPOGRAPHIC.FORM from UPL2</td>
<td>OVERRIDE.VALUES</td>
<td></td>
<td>UPLANDS</td>
</tr>
<tr>
<td>LANDFORM/WATER.BODY from UPL2F</td>
<td>OVERRIDE.VALUES</td>
<td></td>
<td>COASTAL.TERRACE</td>
</tr>
</tbody>
</table>

Figure 5.24. Frame representing sub-site UPL2F.
Figure 5.25. Location of Plain1 in site.
Figure 5.26. Frame representing sub-site PL1C.
Figure 5.27. Frame representing sub-site PL1W.
Table 5.2. Inherited values of Soil Permeability

<table>
<thead>
<tr>
<th>Region</th>
<th>Cert(Low.SP)</th>
<th>Cert(Med.SP)</th>
<th>Cert(High.SP)</th>
<th>Cert(V.High.SP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upland1</td>
<td>0</td>
<td>0.07</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>UPL2C</td>
<td>0</td>
<td>0.31</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>UPL2F</td>
<td>0</td>
<td>0.57</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Properties were computed only for those areas which had not been sub-divided. For instance, Upland2 was composed of UPL2C and UPL2F, so, properties were computed for UPL2C and UPL2F, but not for Upland2. Soil permeability values for Plain1.R1, Pll.C and Pll.W could not be computed, since the landform type of these areas was Flood Plain. Flood plains contain such a wide variety of soils, ranging from coarse textured highly permeable sands to impermeable clays, that it is difficult to predict their soil properties.

The inheritance of the properties satisfied the sub-goal 2.121.13. The satisfaction of the sub-goals 2.121.11, 2.121.12 and 2.121.13 resulted in the satisfaction of sub-goal 2.121.1 (Figure 5.10). The next sub-goal to be achieved (2.122) was the computation of all the factors which modify soil permeability values, and the modification of soil permeability based on these factors. The modifiers of soil permeability are Drainage Type and Drainage Texture. The evaluation of the sub-goal 2.122 with the modifier instantiated to Drainage Type, is shown in Figure 5.28. Sub-goal 2.122.11 was satisfied since it was found in the knowledge base. The second sub-goal 2.122.12 was already satisfied, because Drainage Types had been computed for all the regions of the site during landform
Figure 5.28 - Modifying Properties
analysis. So, a message was sent to the *Engineering.Properties* frame (Figure 3.18), to modify the soil permeability values based on drainage types. This resulted in the satisfaction of goal 2.122.1. Similarly, goal 2.122.2 was satisfied by sending a message to the *Engineering.Properties* frame to modify soil permeability values based on drainage texture. The result of these modifications is presented in Tables 5.3 and 5.4. In *Upland1*, the drainage texture was not computed, because, the drainage type is completely Internal. (Drainage textures can be computed only in the case where the drainage pattern is visible.). Similarly, the user could not observe drainage patterns in the area *UPL2C*, so, neither the effect of drainage type nor the effect of drainage texture could be computed for *UPL2C*.

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>Cert (Low.SP)</th>
<th>Cert (Med.SP)</th>
<th>Cert (High.SP)</th>
<th>Cert (V.High.SP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inherited</td>
<td>Internal</td>
<td>0</td>
<td>0.07</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Drainage Type</td>
<td>Internal</td>
<td>0</td>
<td>0.03</td>
<td>0.44</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Table 5.4 - Modified Values of Soil Permeability in UPL2F

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Value</th>
<th>Cert</th>
<th>Cert</th>
<th>Cert</th>
<th>Cert</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Low.SP)</td>
<td>(Med.SP)</td>
<td>(High.SP)</td>
<td>(V.High.SP)</td>
</tr>
<tr>
<td>Inherited</td>
<td>0</td>
<td>0.57</td>
<td>0.07</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Drng.Typ</td>
<td>(Intl. 0.75)</td>
<td>0.31</td>
<td>0.27</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Dend. 0.25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drng.Txtr</td>
<td>0.21 /Km</td>
<td>0.22</td>
<td>0.48</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>

The inheritance of the soil permeability values and its modification completed the evaluation of the goal 2.12 (Figure 5.9). Goal 2.13 (Figure 5.8) was satisfied next, by sending a message to the *Engineering Applications* frame (Figure 3.24), to update the suitability for Septic Tank Leaching Fields, taking into account the soil permeability values. The suitability values for the various areas are given in Table 5.5.
The satisfaction of goal 2.13, resulted in the satisfaction of goal 2.1 (Figure 5.8). The next property to be evaluated was Depth.to.Water.Table (goal 2.2). This goal was broken down to goals 2.21, 2.22 and 2.23 as shown in Figure 5.8. The evaluation of the sub-goal 2.22 is shown in Figure 5.29. Depth to water table in an area can be inferred from the landform type of the area. The instantiation of the goal 2.221 with landforms as the cue, is shown in Figure 5.30. The sub-goal 2.221.12 was satisfied by sending a message to the Landforms frame to compute the landforms of the site. However, the landforms of site had already been identified, while inferring the soil permeability of site. So, the message yielded a "satisfied" value without invoking the forward chaining process to identify the landforms. The values for depth to water table were then inherited from the identified landforms, as it was done in the case of soil permeability. The expectation of depth to water table in a mountainous region is modified by the
Figure 5.29 - Evaluation of Depth to Water Table
Figure 5.30 - Inherit Depth to Water Table
topographic position of the area. In the present case, there are no mountainous forms in the site. The certainties associated with depth to water table values were therefore not modified. The suitability of the various areas for leaching fields was updated based on the inferred values depth to water table. This resulted in the satisfaction of goal 2.2. Goal 2.3 involved the evaluation of depth to bedrock for the various segments of the site (Figure 5.8). The satisfaction of goal 2.3 was similar to the satisfaction of goal 2.2. Goal 2.4 (Figure 5.8) involved the computation of the slope of the site, and the modification of the suitabilities based on slope. The slope values had already been computed during landform analysis, so, goal 2.4 was reduced to sending a message to the Engineering.Applications frame to update the suitabilities taking into consideration the slope values. The satisfaction of the sub-goals 2.1, 2.2, 2.3 and 2.4 resulted in the satisfaction of sub-goal 2 (Figure 5.7), which finally resulted in the satisfaction of the top level goal 0.

The final values of the inferred properties of Plain1.R1 and its suitability for leaching fields is shown in Figure 5.31. The suitability values are contained in the slot Septic.Tank.Leaching.Fields. The certainty associated with "Unsuitable", 1.0, indicates that the area is completely unsuitable for this application. This is because of the fact that the certainty associated with low depth to water table is 1.0. Similarly, Plain2.R1 (Figure 5.32) and PL1W (Figure 5.33) were found to be unsuitable for the proposed application. PLIC (Figure 5.34) is also not suited for leaching fields, however, the cultivation in the area suggested that the water table may not be at the surface, as in the case of the other flood plain areas. This resulted in a very small measure of suitability being assigned to this area. Upland1 (Figure 5.35) is moderately suitable for leaching field application. The depth to bedrock and depth to water table seem sufficient to satisfy the constraints imposed.
<table>
<thead>
<tr>
<th>Member Slot: ENGR.AFPIN from SITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: SEPTIC.TANK.LEACHING.FIELDS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: SEPTIC.TANK.LEACHING.FIELDS from PLAIN1.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Status: EVALUATED</td>
</tr>
<tr>
<td>Values: (SUITABLE 0.0),</td>
</tr>
<tr>
<td>(UNSUITABLE 1.0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Member slot: SLOPE from PLAIN1.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Numeric: 4</td>
</tr>
<tr>
<td>Values: NUMERIC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: DEPTH.TO.BEDROCK from PLAIN1.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: (MEDIUM.DBR 0.24293518),</td>
</tr>
<tr>
<td>(HIGH.DBR 0.72880554)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: DEPTH.TO.WATER.TABLE from PLAIN1.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: (LOW.DWT 1.0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Own slot: LANDFORM/WATER.BODY from PLAIN1.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inheritance: OVERRIDE.VALUES</td>
</tr>
<tr>
<td>Values: FLOOD.PLAIN</td>
</tr>
</tbody>
</table>

Figure 5.31. Final configuration of the frame Plain1.R1.
Figure 5.32. Final configuration of the frame Plain2.1.
Unit: PL1W in knowledge base SWM
Created by mn on 2-9-90 22:51:55
Modified by mn on 2-13-90 20:17:26
Superclasses: PL1
Member Of: CLASSES in GENERIC UNITS

| Member slot: ENG.APPLN from SITE | Inheritance: OVERRIDE.VALUES |
| Values: SEPTIC.TANK.LEACHING.FIELDS |

| Member slot: SEPTIC.TANK.LEACHING.FIELDS from PL1W | Inheritance: OVERRIDE.VALUES |
| Status: EVALUATED |
| Values: (SUITABLE 0.0), (UNSUITABLE 1.0) |

| Member slot: SLOPE from PL1W | Inheritance: OVERRIDE.VALUES |
| Numeric: 2 |
| Values: NUMERIC |

| Own slot: DEPTH.TO.BEDROCK from PL1W | Inheritance: OVERRIDE.VALUES |
| Values: (MEDIUM.DBR 0.24337076), (HIGH.DBR 0.73811225) |

| Own slot: DEPTH.TO.WATER.TABLE from PL1W | Inheritance: OVERRIDE.VALUES |
| Values: (LOW.DWT 1.0) |

| Own slot: LANDFORM/WATER.BODY from PL1W | Inheritance: OVERRIDE.VALUES |
| Values: FLOOD.PLAIN |

Figure 5.33. Final configuration of the frame PL1W.
Figure 5.34. Final configuration of the frame PL1C.
Figure 5.35. Final configuration of the frame Upland1.
on a site for leaching fields, however, riverine terraces may contain gravel deposits which have a very high permeability (indicated by the certainty associated with "Very.High.SP" in the slot Soil.Permeability), and this reduces the suitability for leaching fields. The landform type of UPL2C could not be identified with certainty. The pattern element values supported both the hypotheses, viz: Coastal Terrace and Riverine Terrace (Figure 5.23). The problems associated with a riverine terrace are therefore considered likely, so, the suitability is declared to be moderate (Figure 5.36). UPL2F (Figure 5.37) is highly suitable for septic tank leaching fields, since all the criteria for this application seem to be met by this area. Figure 5.38 shows the final results of the terrain analysis process. The site is segmented into areas which are more or less suitable for leaching fields. All the water bodies and flood plains are unsuitable, the riverine terrace is moderately suitable, and the coastal terrace is highly suitable for septic tank leaching fields.
Figure 5.36. Final configuration of the frame UPL2C.
Figure 5.37. Final configuration of the frame UPL2F.
Figure 5.38. Suitability of areas for Septic Tank Leaching Fields.
6. DISCUSSION AND CONCLUSION

6.1 Discussion of Results

A comparison of the classification of water bodies by TAX, to that by a human interpreter reveals that TAX was able to identify most of the water bodies correctly. The water body *OL1* (Figure 5.12), could not be classified, because its attributes did not match any of the known water bodies. The size and elongation of *OL1* matched the description of a lake, however, one of the borders of *OL1* touched the boundary of the image of the site, so, *OL1* was considered to be an open body of water. This conflicted with the description of a lake. One way to overcome this problem is to examine images of adjacent areas of the site, in order to determine whether a body of water is open or closed. Another approach is to treat the classification of water bodies similar to the identification of landforms. The geographic location of the site could be used to come up with a hypotheses about the type of water bodies that could be found in the region. The attributes of the water body could then serve as indicators to establish the hypotheses.

The areas *WL1* and *WL2* which are actually wetlands were misclassified as lakes. This problem occurred because the user was not able to discern the texture in the image, and outlined these two areas as water bodies. Using images with higher spatial resolution would overcome this problem.

The results of landform analysis by the human expert and by TAX are tabulated in Table 6.1.
Table 6.1. Comparison of landform analysis by TAX and human expert

<table>
<thead>
<tr>
<th>Area</th>
<th>Manual Analysis</th>
<th>Analysis by TAX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Landform</td>
<td>Landform</td>
</tr>
<tr>
<td>PLAIN</td>
<td>Flood Plain</td>
<td>PLAIN1.R1</td>
</tr>
<tr>
<td></td>
<td>PLAIN2.R1</td>
<td>Flood Plain</td>
</tr>
<tr>
<td></td>
<td>PC1</td>
<td>Flood Plain</td>
</tr>
<tr>
<td></td>
<td>PL1W</td>
<td>Flood Plain</td>
</tr>
<tr>
<td>UPLAND1</td>
<td>Riverine Terrace</td>
<td>UPLAND1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Riverine Terrace</td>
</tr>
<tr>
<td>UPLAND2</td>
<td>Coastal Terrace</td>
<td>UPL2F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastal Terrace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UPL2C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastal Terrace or Riverine Terrace</td>
</tr>
</tbody>
</table>

It can be seen that the landform labelling generated by TAX coincides with that generated by a human expert for most of the cases. In the case of UPL2C, the cultivation in the area decreased the confidence in the hypothesis that the landform could be a Coastal Terrace (Coastal terraces are usually forested). Some of the important indicators such as drainage patterns could not be observed by the user, which again contributed to the fact that the landform type could not be established.

A striking observation resulting from the comparison is that TAX generates
many more sub-sites than does a human expert. The human expert has the advantage of having a overall picture of the area, and can broadly segment the site into areas with distinctly different pattern element values. In doing this, he ignores the small amount of heterogeneity that occurs within each segment. The landform type of the segments is determined by analyzing the pattern element values. The variations in the pattern element values within each of the segments is studied, while inferring the properties of the area.

In TAX, however, areas are outlined in which the terrain pattern elements within, are uniform. Wherever any aspect of landform changes, it is presumed that, there is a basis for a boundary denoting some change in materials or conditions, or both. It is quite possible that in some of the cases, the changes in pattern element values are not significant in landform analysis. However, since TAX has no way of knowing which changes are significant and which are not, areas are outlined which are relatively uniform in pattern element values, and the landform type of these areas determined. The end result is the same.

The suitabilities of the various areas for septic tank leaching fields, as given by the expert and by TAX are given in Table 6.2.
Table 6.2. Comparison of suitability evaluation by TAX and human expert

<table>
<thead>
<tr>
<th>Area</th>
<th>Suitability</th>
<th>Area</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAIN</td>
<td>Unsuitable</td>
<td>PLAIN1.R1</td>
<td>Unsuitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLAIN2.R1</td>
<td>Unsuitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PL1C</td>
<td>Unsuitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PL1W</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>UPLAND1</td>
<td>Moderately Suitable</td>
<td>UPLAND1</td>
<td>Moderately Suitable</td>
</tr>
<tr>
<td>UPLAND2</td>
<td>Highly Suitable</td>
<td>UPL2F</td>
<td>Highly Suitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UPL2C</td>
<td>Moderately Suitable</td>
</tr>
</tbody>
</table>

There is general agreement on most areas, except for the area UPL2C, which TAX considered only moderately suitable, since this area is likely to be a riverine terrace.

In the case of landform analysis as well as the suitability evaluation, the uncertainty in the conclusions of TAX, is given by the measure of belief assigned to $\theta$ (ignorance). In case of inconclusive or missing evidences, the beliefs assigned to the various hypotheses will be small and the belief assigned to ignorance will predominate.
6.2 Directions of Future Research

Each and every facet of the problem of building expert systems for terrain analysis can be studied in more detail, and alternatives evaluated, to bring the goal of a fully automated system for terrain analysis, closer to realization.

In the area of uncertainty management, extensive interviews with experts may give a better idea about their thought process, of how they draw conclusions from observed clues, and how they mentally deal with uncertain and even conflicting evidences. The next step would be to model this inference process of experts, using perhaps a combination of the available models of uncertainty.

Knowledge acquisition, a key topic in building expert systems, has not been dealt with in this study. Strategies for eliciting domain knowledge from experts, based on structured interviews, have to be developed. A mechanism to synthesize knowledge acquired from a number of sources (experts, books, manuals) has also to be worked out.

There is ample scope for research in the area of feature extraction for terrain analysis. Computer extractable features need to be developed, that correspond to attributes used by experts in describing terrain. Systems are needed for the extraction and identification of drainage patterns, for the classification of landuse/landcover, etc.

Finally, for the actual site suitability studies, it may be necessary to build a separate sub-system for evaluating the suitability of a site for each of the applications.

6.3 Conclusion

A computational approach for performing terrain analysis was developed. The developed methodology was implemented using expert system techniques, and
tested with real data. The conclusions arrived at by the system compared favorably with those reached by human experts.

Models were constructed for landforms in terms of pattern element values, and for engineering applications in terms of the properties that affect the suitability of the application. The vagueness intrinsic in the terrain analysis terms was represented by fuzzy set theories. Fuzzy set theories were employed for modeling the vague classes that are used by human experts to describe pattern element values and properties of terrain. Accumulation of evidence for the establishment of landform hypotheses, and the suitability of an area for an application, were carried out according to Dempster-Shafer theory of evidence.

The models of terrain objects were formalized in frames and the attributes of the objects were represented as slots of the frames. Frames for pattern element values contained slots corresponding to the parameters for defining the fuzzy membership classes. Landform frames had slots for each of the pattern elements which served as indicators for their identification. Landform frames also contained the expected values of properties, which were inherited by the landforms of the site. Frames for engineering applications contained slots for each property that imposed a constraint on the suitability.

Frames were also employed for encapsulating procedural knowledge. The procedural knowledge for computing the values for pattern elements was stored in the slot *Compute* of the pattern elements. Procedures for inheriting the default values of properties from the landforms of the site were stored in the *Inherit* slot of engineering properties, and so on.

A goal driven, backward form of reasoning was adopted to evaluate the suitability of a site for an application. All the properties which had an influence on
the selected application were first identified, and each of these properties was computed for the site. The computation of the properties involved inferring them, by identifying the landforms of the site and inheriting the expected values of properties from the established landforms.

The first step in the identification of the landforms of the site, involved the identification of water bodies of the site. The identification of the type of bodies, together with the knowledge about the physiographic location of the site, was used to generate hypotheses about landforms that could be found in the site. The site was then segmented into a number of areas based on the topographic form of the hypothesized landforms. Pattern element values were obtained for each of the outlined areas, and the landform type of the area established.

The expert system was implemented in KEE (Knowledge Engineering Environment), a frame based shell. The ELAS (Earth resources Laboratory Application Software) image processing package was used by TAX, for analyzing the reflectance and digital elevation data. A TOOLS knowledge base was built in TAX, which contained the knowledge required for running ELAS. This enabled TAX to access the digital data and compute histograms, display images to the user, outline areas on the image and so on.

The TAX system was tested with a real data set, comprising of digital multispectral reflectance data, scanned from 1:58,000 color infra-red transparency, and digital elevation data of the site. The site was analyzed for locating septic tank leaching fields. TAX identified the landforms of the site, and located areas which were unsuitable, moderately suitable and highly suitable for leaching fields. The conclusions reached by TAX agreed with those reached by an expert who analyzed the same site manually.
REFERENCES


Vita

<table>
<thead>
<tr>
<th>Date</th>
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<tbody>
<tr>
<td>September 9, 1960</td>
<td>Born - Bombay, India</td>
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DOCTORAL EXAMINATION AND DISSERTATION REPORT

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