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A GIS application for assessment of nonpoint source pollution risk on managed forest lands

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A GIS Application for Assessment of

Nonpoint Source Pollution Risk on Managed Forest Lands

by

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Legislation in recent years has required states and federal agencies to control, assess, and monitor nonpoint source pollution resulting from land management. A methodology to assess the risk of water quality degradation resulting from timber harvest activities using geographic information systems is presented.

An erosion-impact matrix is developed assigning risk values to differing silvicultural practices based on land-type information. Data assimilation and spatial analysis for the study area is conducted using GIS. The risk matrix is developed using a modified Delphi technique. Results from two pilot studies in western Montana suggest the utility of GIS in watershed management. The capability of advanced GIS technology allows editing, storing, and spatial analysis to be conducted in a timely and cost efficient manner.

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To my wife, Christina, and my children Kenric (DUKE) and Krystal, I owe you my everlasting love, sincere thanks, and gratitude. Above all else, your sacrifice, patience, and support were immeasurable and will never be forgotten. I dedicate this thesis to all three of you. Thanks guys.

DEDICATION

For Krystal and Duke. You can do and be anything. Follow your dreams and remember that I love you. God bless you both. Your dad.

THE ROAD NOT TAKEN

**Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;**

**Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,**

**And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet Knowing how way leads on to way,
I doubted if I should ever come back.**

**I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I -
I took the one less traveled by,
And that has made all the difference.**

ROBERT FROST

ORGANIZATION

There are two major portions of this study, they will be discussed independently.

Chapter I - Erosion Hazard Matrix Development - includes detailed explanation of erosion hazard matrix construction, definition of matrix components, and product risk values for forested watersheds in western Montana.

Chapter II - Geographic Information System (GIS) risk assessment application - describes the process of combining spatial and nonspatial data simultaneously in conjunction with erosion risk values. Includes description and results for two pilot watersheds in western Montana.

CHAPTER 1
EROSION-IMPACT MATRIX DEVELOPMENT

INTRODUCTION:

Cumulative watershed effects can be thought of as the "total" impact on aquatic resources resulting from a combination of varying land-use activities upstream. A primary pollutant from these nonpoint source activities is sediment. Nonpoint source (NPS) pollution generally results from diffuse, uncontrolled surface runoff caused by various activities, including agriculture and silviculture operations (Myers & Wise, 1989). In a 1986 Environmental Protection Agency report to congress, NPS pollution was responsible for failure to meet water quality standards in 76% of the lake acres reported by states, 65% of the stream miles, and 45% of the estuarine waters.

The subtle nature of NPS pollution presents significant difficulties to agencies charged with monitoring and management (Myer & Wise, 1989). Impacts from individual disturbance activities may be minimal, but collectively and cumulatively significant. Hence, NPS pollution is among the nation's most serious natural resource problems (Myers, 1986).

Forest management and multiple-use encroachment into forested watersheds may result in negative impacts to both soil and water resources. For example, construction of a logging road compacts bare soil, which reduces infiltration and percolation, and can change runoff processes. Harvesting and site preparation activities also expose bare mineral soil which in turn can lead to soil erosion and stream sedimentation during heavy rainstorms. If these events combine with increased peak flows because of timber harvest (which reduces evapotranspiration) during a heavy rain or snowmelt event, mass wasting, channel erosion and aggradation can accelerate beyond natural levels (Coburn, 1989). Potential impacts include a decline in fish spawning habitat, increased costs associated with watershed rehabilitation, and financial burdens due to flood damage on public and private property.

As a result of public and scientific concern over water quality protection, various federal laws have been enacted. An important precursor of the major legislation of the 1970's was the Multiple Use and Sustained Yield Act of 1960 (Wilkinson & Anderson, 1985). The guiding principle of sustained yield was defined as "the achievement and maintenance in perpetuity of high-level annual yield or regular periodic output of various renewable resources of the national forests without impairment of the productivity of the land" (Coburn, 1989).

The National Environmental Policy Act of 1969 (NEPA- P.L. 91-190), requires federal agencies to assess the cumulative and long term effects of proposed land-use actions. Additionally, Section 102 (2c) calls for the preparation of an environmental impact statement on projects that may significantly affect the quality of the environment as part of the planning process.

The next significant piece of federal legislation to set requirements for consideration of cumulative effects was the 1977 Clean Water Act Amendments (P.L. 95-217). This act established, in Section 208, a process for controlling nonpoint sources of pollution and required states to prepare water quality standards that are determined by the highest "beneficial uses" of the water in question (Coburn, 1989).

Section 319 of the Clean Water Act of 1987 (P.L. 100-4) additionally requires individual states to, as a minimum, initiate plans that encompass three primary objectives: 1) assessment, identification , and definition of water quality problem areas and their causes - point and nonpoint; 2) targeting action priorities applied to assessed waters based on indicators such as public health, environmental risks, and value of aquatic habitat; and 3) identification and implementation of Best Management Practices (BMPs) for rehabilitation and prevention of further degradation of targeted waters (Meyers & Wise, 1989).

In an effort to curb the detrimental impacts of NPS pollution and comply with federal legislation, cumulative watershed effects analysis is necessary. Cumulative watershed effects (CWE) analysis is basically an advanced means of controlling nonpoint source pollution (Coburn,1989). The process includes predicting impacts that may deteriorate water quality which might be missed if planning were carried out only at the project proposal level. By recognizing that a watershed is a fluvial system and an ecological entity, cumulative watershed effects analysis assumes that hydrologic effects, erosion processes, and biological responses are considered from the outset (Coburn, 1989). Long term benefits include maintenance of

water quality and cold water fisheries.

Definition of the term CWE has been slow and is still not universally accepted. Cumulative effects have been called the UFOs of hydrology (Grant, 1985). Haskins (1986) described CWE as the additive and/or synergistic effects of land management activities on water quality and beneficial uses, which occur away from the site of primary development, and are transmitted to the fluvial system. The current confusion about cumulative effects stems in a large part from a lack of conceptual models and research tools for analyzing the complex nature of drainage basin response to disturbance. Without such models or techniques, the term cumulative effects is sometimes invoked to explain phenomena we observe but are unable to attribute to a specific cause (Grant, 1985).

Forest land managers are concerned about the potential cumulative effects of multiple management activities over time and space within a watershed on the downstream aquatic ecosystem (Klock, 1985). The most appropriate approach to determine the cumulative effects of forest practices on water quality would be a large watershed study. However, in light of such vast financial and resource commitments, watershed analysis at this scale is often not very practical. Thus, an alternative approach is to develop a

"watershed cumulative effects analysis model which best reflects the multitude of potential downstream impacts forest practices may generate" (Klock, 1985). Rickert et al (1978) suggests the use of an erosion-hazard, or risk analysis model, in order to predict potential NPS pollution problem areas.

Coburn (1989), recommends a computerized database, using state-of-the-art geographic information systems to enable long-term tracking and maintenance of sensitivity and land disturbance inventories.

A geographic information system is designed to accept large quantities of spatial data derived from a variety of sources. Such a system is also designed to store, retrieve, manipulate, analyze, and display those data according to user-defined specifications (Marble and Penquet, 1983). Geographic information systems (GIS) are becoming increasingly important in natural resource management (Morgan and Nelepa, 1982). Using a geographically referenced system with soil erosion and non-point source pollution models can account for every parcel of land and, therefore, allow researchers to evaluate large geographic areas in much less time (Pellitier,1985).

OBJECTIVES

In keeping with the ever-expanding needs of natural resource management and the advanced capabilities of computer graphic and database management systems, the goal of this project was to develop a nonpoint source risk analysis procedure for use in geographic information systems. The following methodology is based on a nonpoint source risk analysis procedure developed in Oregon (Rickert et al. 1978; Brown III et al. 1979), but differs in that all cartography and spatial analysis will be done through the use of GIS. There are two major components to this study: 1) the development of an erosional-impact risk matrix; and 2) the implementation of the risk procedure using GIS on two pilot study areas in western Montana.

MATRIX CONSTRUCTION

Maps and associated topographic attributes have long been used by resource managers in decision making and land-use planning. The utility of the land-type map can be greatly enhanced, however, with the use of a scheme for ranking the erodibility of different land surfaces under different management scenarios for a given watershed. The

scheme, in this case, is an erosion-impact matrix which provides a systematic basis for making estimates of the relative impact or risk of NPS water quality degradation of human activity on different types of terrain. In the matrix developed by Brown III et al. (1979), the horizontal axis is composed of order-of-magnitude NPS risk factors for geology and slope combinations. The vertical axis is composed of order-of-magnitude erosional-impact factors for selected land-use activities.

The erosion-impact matrix developed for this study is similar in that the land-use activities are on the horizontal axis and slope and geology are on the vertical axis (See Figure 1). The matrix was modified to reflect user needs based upon geography and resource concerns more specific to western Montana. It is suggested that matrix construction be based on the socio-economic importance of the basin for a given region (Brown III et al. 1979). Therefore, it was decided that the emphasis of the erosion -impact matrix for this study focus on the implications of forest harvest activities. The same matrix is used for both pilot watersheds.

The use of the erosional-impact matrix allows the generation of a new family of map products by the GIS, derived from the original slope/substrate maps and based

TYPES		LAND-USE ACTIVITIES
SLOPE	SOIL EROD.	
0-5%	HIGH	EROSION -IMPACT RISK VALUES
	MED.	
	LOW	
5-20%	HIGH	
	MED.	
	LOW	
20-40%	HIGH	
	MED.	
	LOW	
> 40%	HIGH	
	MED.	
	LOW	

FIGURE 1: MONTANA EROSION-IMPACT MATRIX

upon modification of land-use activities. A nonpoint source risk map founded on existing watershed conditions may also be developed, given some basic assumptions about recovery periods following disturbance. Both of these applications will be discussed in the following sections and in Chapter 2.

A major problem with the use of an erosion matrix centers on the order-of-magnitude values within the body of the matrix itself. It is relatively easy to obtain agreement on the overall parameters which comprise the horizontal and vertical administrative data (i.e. slope/geology and land-use activities), however, placing values internally within the matrix is extremely difficult. In an attempt to solve this problem, it was decided that "best professional judgement" would be used and that an approach similar to the Delphi Technique be applied.

THE DELPHI TECHNIQUE

As previously described, the Oregon matrix for management practices and land-type erosion factors was modified for use in western Montana. Risk potential ratings for the Montana erosional-impact matrix were obtained through the Delphi method. This was done in coordination

with the Montana Riparian Association.

A primary objective of a Delphi study is to obtain consensus about judgmental information from a group of expert respondents (Dajani et al., 1979). Typically, members of a Delphi panel are knowledgeable in the special field of application and they try in a discussion-type procedure to contribute their experience in order to solve problems or answer certain questions (Rauch 1979, Khan 1989).

A similar procedure was used in the Fall of 1988 to obtain erosional-impact matrix values for the study area. Experts in soil science, hydrology, silviculture, ecology, and fisheries were included in the Delphi panel. Each panel member was sent an initial survey and information packet that explained Delphi procedures, matrix construction, and the objectives of the study. A blank erosional-impact matrix was included in each mailing and the panel members were asked to evaluate variable land-use activities with respect to given slope and parent material soil erodibility categories in terms of the potential risk of NPS pollution production and cumulative watershed effects. Each activity was given a rating from 1 to 5 with the following risk values assigned: a) 5- very high risk; b) 4- high risk; c) 3- moderate risk; d) 2- low risk; and e) 1- very low risk.

For example, a cable-logging seed tree harvest with full suspension on a soils derived from alluvial parent materials might receive a risk erosion-impact rating of 3.0, moderate. The objective in using the Delphi format is to try to obtain consensus from all panel members that this activity does indeed pose a risk value of 3 in terms of potential NPS pollution production. Once all cells of the matrix have been filled in, they can be used to evaluate the potential risk of future activities, as well as those already existing, on an areal basis.

There are several very important factors which must be evaluated before a Delphi-like approach can be effectively utilized. First, and probably the most important, is anonymity. Anonymity is essential to guarantee that ideas, concepts and/or arguments are not influenced by other panel members (Rauch, 1979). The director of the Delphi study should insure, at least in theory, that the results lead to an unbiased and complete picture and solution to the problem at hand.

In general terms, the Delphi procedure exists in 2 distinct forms. The most common version is commonly referred to as a "Delphi Exercise". This typically requires a "paper-and-pencil" drill on behalf of the moderator. In a

Delphi exercise, a small monitor team designs a questionnaire which is sent to a larger respondent group. The respondent group is usually given at least one opportunity to reevaluate its original answers based upon examination of the group response. This form of Delphi is a combination of a polling procedure and a conference procedure which attempts to shift a significant portion of the effort needed for individuals to communicate from a larger respondent group to a smaller monitor team. This is essentially the procedure that was used to obtain erosion-impact risk values for our matrix. However, interspersed between mailings was a meeting of all panel members to discuss the previous rounds results.

The second and newer form is often called "Delphi Conference". It replaces the monitor team with a computer which has been programmed to carry out the compilation of group results. This latter approach has the advantage of eliminating the delay caused in summarizing each round of Delphi, thereby turning the process into a real time communications system (Linstone and Turoff, 1975). Discussions on computer applications of Delphi can be found within articles published elsewhere, namely Johansen et al. (1974), Johansen and Shuyler (1975), and Turoff (1972). The University of Montana does not have the automated capability

or the software to conduct computer Delphi procedures and therefore the procedure used in this study is classified as a "Delphi Exercise". Further elaboration on computer Delphi methods is beyond the scope of this text.

Delphi procedures usually consist of four major phases. The first phase is characterized by exploration of the subject under discussion, wherein individual members of the panel and monitor team contributes additional information that he of she feels pertinent to the issue. The second phase involves the process of reaching an understanding of how group members view the issue (i.e. were the members in agreement or disagreement on what they mean by relative terms such as importance, desirability, or feasibility). If there is significant disagreement, than it must be explored in the third phase to bring out the underlying reasons for the differences and possibly to evaluate them. The last phase, a final evaluation, occurs when all previously gathered information has been initially analyzed and the evaluations have been fed back for consideration (Linstone and Turoff, 1975).

Creating the panel of experts is usually the first task. It is prudent to choose qualified but diverse panel members in order to cover all aspects of the problem at hand. For creating a successful mix of panelists, Scheele

(1975) suggests using three types of personalities. These include: 1) stake-holder, those who are or will be directly effected; 2) experts, those who have an applicable speciality or relevant experiences; and 3) facilitators, those who have skills in clarifying, organizing, synthesizing, stimulating....plus, individuals who can supply alternative global views of the culture and society.

Schiebe et al. (1975) describes a possible step by step procedure which in theory can be applied to most Delphi case studies. The process follows:

Step 1: The process administrator (PA) explains the Delphi method to the panel.
Step 2: PA administers a Pre-Delphi questionnaire. This helps to draw a personnel profile of panel members and may be used to facilitate the removal or addition of panel members.
Step 3: Panel fills out the questionnaire.
Step 4: The PA describes a hypothetical situation to panel.
Step 5: Panel defines objectives.
Step 6: PA categorizes objectives and panel assigns ratings or ranks the goals.
Step 7: The PA compiles the 1st round rankings and returns feedback to the panel.
Step 8: The panel rates goals for round two with written comments.
Step 9: The PA compiles ratings and written comments and returns all information to the panel.

This procedure repeats itself up to four consecutive but distinct rounds. Between each round it is suggested that the panel have a formal meeting under the direction of the PA to discuss the previous rounds results. This leads to

group interaction and allows panel members to share personal experience. At the end of the fourth round, the PA compiles and analyzes all ratings for individual rounds. Correlation of the questionnaires and publication of results is now in order. A graphical representation of this process as published by Schiebe et al. (1975) can be seen in Figure 2.

Termination of Delphi processes is often not clearly defined in the literature. Dejani et al. (1979) presents a hierarchical stopping criterion for Delphi studies. Assuming that respondents have exhibited stability in their responses in two consecutive rounds, termination of the Delphi procedure may take place, but only if stability manifests in any of the following ways:

1. Consensus: occurs when unanimity is achieved concerning any given issue. When consensus results the study may be terminated.

2. Majority: occurs when more than 50% of the respondents exhibit consistency. When a majority occurs and is coupled with an apparent agreement among the minority respondents, that the study may be terminated.

3. Bipolarity: occurs when respondents are equally divided over an issue. When bipolarity occurs one should determine the nature of the stability among the two bipolar

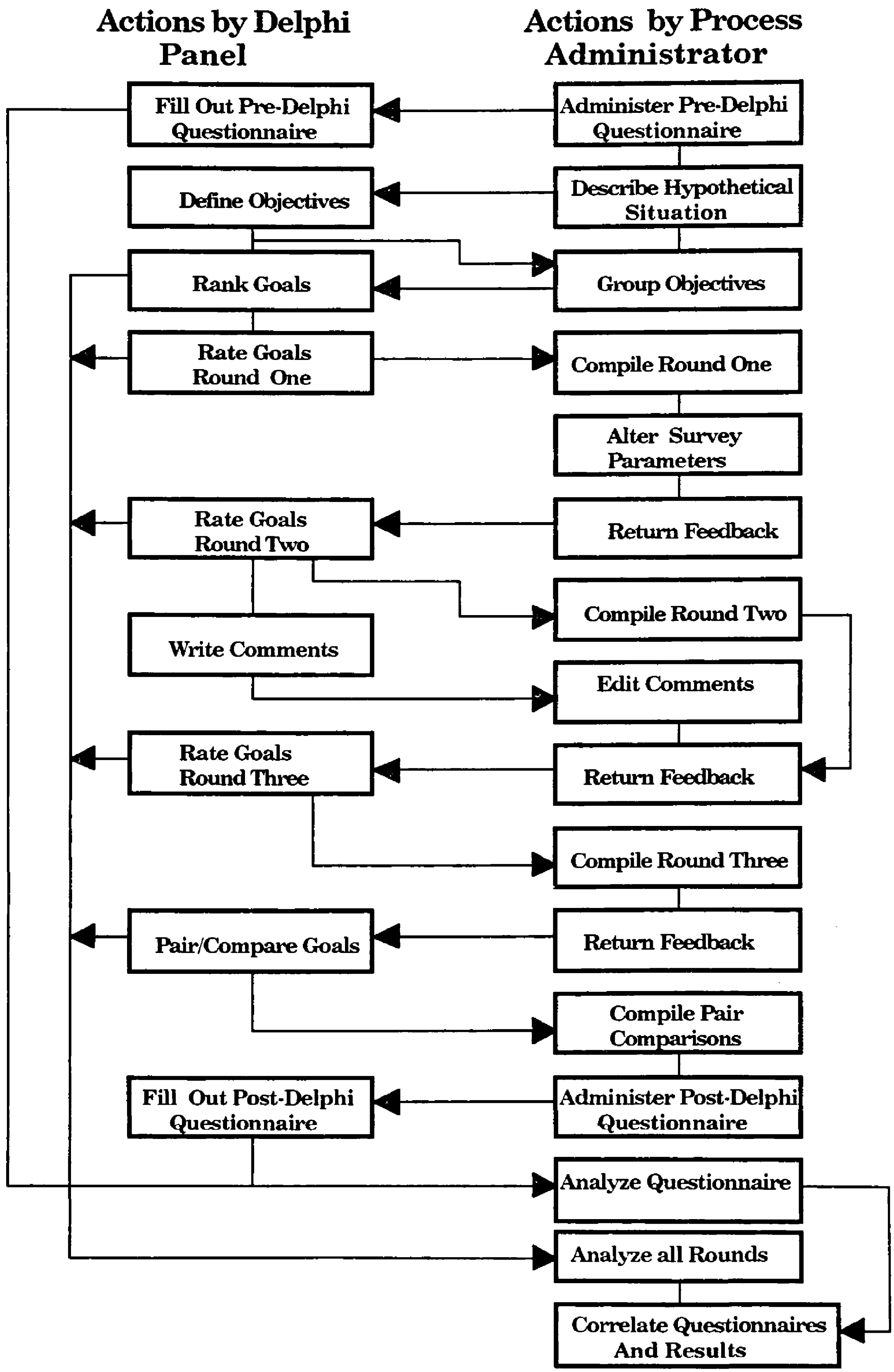

Figure 2 - The Goals Delphi Experimental Design
(Schiebe et al., 1975)

groups. A decision must then be made as to whether to terminate or rewrite the particular question. If the latter choice is made, a new round is administered using the rephrased question. This question, in turn, must pass the stability test before it is dropped from the study.

4. Plurality: occurs when the larger portion of the respondents (but less than 50%) reach agreement. When plurality occurs one should check for consensus within the pluralistic group and for the nature of stability, if any, among other individual respondents or clusters of respondents. If stability is not established, a new round of questions is administered. If, on the other hand, stability is established, there is a choice of terminating the particular question or of rephrasing it and including it in the following rounds.

5. Disagreement: occurs when each respondent maintains views independent of each other respondent, such that the responses cannot be brought into consonance. Whenever stable disagreement is achieved for a given question, the decision must be made as to whether to terminate or rephrase the question statement. If the latter choice is made, the rephrased question will be included in the following rounds and will be dropped when it passes the test of stability and when no further benefits can be expected from rephrasing it (Dejani et al., 1979).

For example, in a Delphi study with 20 respondents, consensus would be achieved with unanimity among the 20, majority with 11-19 responding the same way, bipolarity with a 10-10 split, plurality with the largest subgroup of respondents between 2 and 9, and disagreement with respondent subgroups numbering 0-1 (Dejani et al., 1979). A graphical representation of Dejani's stopping criterion is presented in Figure 3.

Upon completion of each Delphi round, the mode, mean, and median value of the responses can be calculated. While it would be desirable to obtain 100 % consensus from all panel members, it is extremely unlikely. Therefore, it is necessary to determine a means of stopping the Delphi process and determining a response/value.

For the purposes of this study, the mode value for risk was used. In other words, a cell in the matrix was assigned a risk value if consensus or majority of the respondents answered the same way. In all but 19 cells (out of 156) the use of the mode was an acceptable means of assigning risk to a particular activity on a given slope/geology. For cases where using the mode value did not result in one value, the mean of all responses was used to assign the risk value. The reader must bear in mind, that the matrix, as presented in this thesis, is not as yet

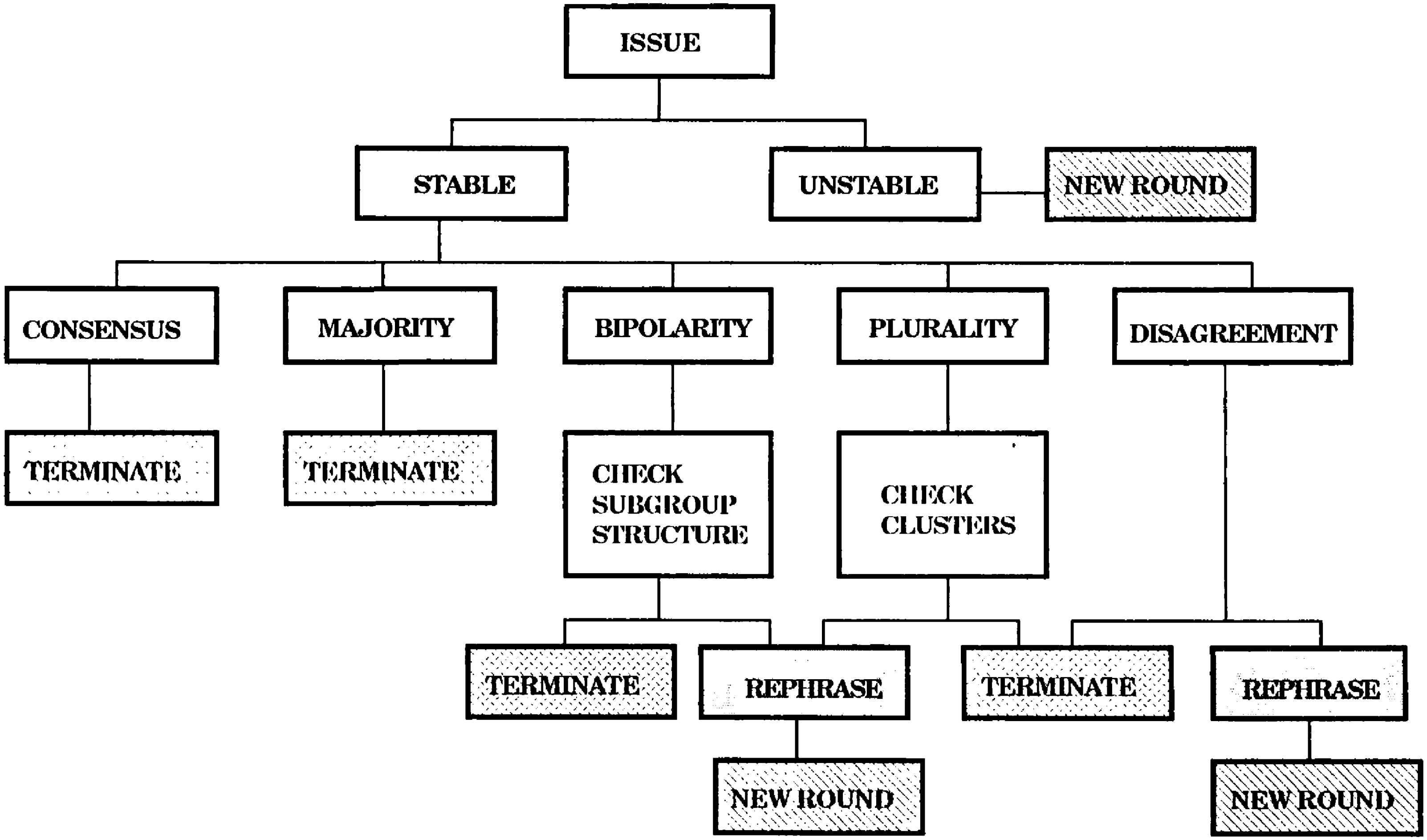

FIGURE 3 : Hierarchial Stopping Criteria For Delphi Studies

complete. The Delphi procedure is ongoing and these results where obtained after two rounds. Cells where disagreement still remained after two rounds are delineated by an asterisk (*). The final erosion-impact matrix after 2 rounds of Delphi is presented in Figure 4.

DEFINITION AND JUSTIFICATION FOR MATRIX FORMAT

Design of a simple and easy-to-use erosion-impact matrix is essential. The matrix developed in this study was patterned after the one used in Oregon (Rickert et al., 1978), though it has been modified to better fit common management concerns in western Montana. The matrix is composed of an X-axis and a Y-axis. These axes include slope/geology and variable land-use activity classifications (See Figures 1 & 4).

The scope of this research deals specifically with the effects of forest practices on water quality degradation from nonpoint source pollution. These activities may include such things as silvicultural system design, logging methods, site preparation, road construction and road maintenance. Therefore, the X-axis of the matrix is comprised of variable land-use activities associated with tree harvest operations.

The X-axis is broken down into 4 major categories. These are as follows: 1) clearcuts; 2) partial cuts; 3) site preparation; and 4) roads. Each category is subsequently broken into different practices at a lower level. Clearcuts and partial cuts are subdivided by the type of logging activities which are possible during tree removal. Each category delineates harvest operations into 4 sub-categories, these are: 1) tracked equipment, 2) rubber tire skidder, 3) partial suspension of logs during harvest, and 4) full suspension. It is necessary to distinguish among logging methods due to the variable effects of different types of equipment on soil stability, permeability, and infiltration. For example, a log that is skidded to a landing via D-7 dozer will have much more impact on soils than one which has been fully suspended during harvest operations.

Site preparation considers 3 basic treatments: 1) Machine piling/scarification; 2) broadcast burning; and 3) other methods (hand piling, spot burning, chemical application and none). Extensive soil damage may occur during site preparation. Therefore, it is necessary to consider the potential impact of site preparation within the matrix.

Temporary and permanent roads are considered by the process. Megahan and Kidd (1972), studied erosion following road construction and jammer logging in granitic soils of south-central Idaho. He reported an increase in erosion due to roads of 770 times that of natural, and 220 times natural due to logging activity. This fact indicates the importance of roads in the production of NPS pollution and lends support for the inclusion of roads into the erosion-impact matrix.

The vertical component, or Y-axis, of the Montana erosional-impact matrix consists of slope/soil erodibility risk classes. The first part of the Y-axis are the slope categories. Initially, four slope classes were defined based upon slope breaks recognized as limitations with respect to land management activities as well as ease in mapping. These are outlined as follows:

SLOPE CLASSES	JUSTIFICATION
0-20%	Used in the Flathead N.F. land system Inventory (Basko et al., 1983). 20% slope is recognized as the maximum slope for which the the Universal Soil Loss Equation may be used (Brown III et al.,1979).

20-40%	40% is the recommended upper limit for certain mechanical cultivation activities (Basko et al. ,1983).
40-60%	60% is recognized as the approximate angle of repose for soils and angular rock fragments (Rickert et al.,1978 and Basko et al., 1983)
>60%	

However, after the 1st round of Delphi, panel members decided that the first slope class, 0-20%, was too broad and as a result of committee deliberation, was changed. The new slope categories for the erosion-impact matrix were modified as follows: 1) 0-5%; 2) 5-20%; 3) 20-40%; and 4) >40%. Justification for the breaks at 20% and 40% are the same as those for the initial slope classes.

The second major components of the Y-axis are the soil erodibility classes. There are 3 proposed soil erosion classes. They are 1) H-High; 2) M-Medium; and 3) L-Low. These classes were based primarily upon groupings of geologic erosion factors for soils derived from various parent materials as described in the R1-R4 Sediment Yield Prediction Procedure (Cline et al.,1981). The categories are reproduced from R1-R4 sediment yield models in Table 1.

There are 8 classes of materials identified by Andre and Anderson (1961) described in Table 1. These 8 classes

CATEGORIES	GEOL. EROSION FACTOR
1. Highly Erodible	
a. Acid Igneous (Granitics)	1.0
b. Alluvium	1.05
2. Moderately Erodible	
a. Schist	.75
b. Soft Sediments	.66
c. Hard Sediments	.52
3. Slightly Erodible	
a. Basic Igneous	.42
b. Metamorphics (Belt Series)	.39
c. Serpentine	.35

TABLE 1: GEOLOGIC EROSION FACTORS FOR SOILS OF VARIOUS ROCK TYPES (Cline et al.,1981)

are based upon mean surface areas (cm^2) of silt and clay size particles over the mass of aggragated silt and clay. Their study of materials in northern California indicated a strong relationship between these values and erodibility (Cline et al., 1981). Therefore, since they are in widespread use in the R1-R4 Sediment Yield model and have acquired some professional acceptance, it was decided that use in the Montana erosional-impact matrix was justified.

CONCLUSION

Risk analysis can provide resource managers with a powerful tool to assist in land-use decision making. Recent laws requiring states to plan for, assess, and monitor waters vulnerable to nonpoint source pollution, have required the development of new techniques which can assist in this endeavor. Modeling watershed responses to human encroachment is undoubtedly the most cost effective means of predicting possible responses.

This study was designed to develop a methodology to assist in assessing NPS pollution and cumulative watershed effects. This was done by combining risk assessment with advanced computer technology through the use of geographic information systems.

Step 1 of the process required the construction of a risk matrix. Associated risk ratings were assigned to the matrix based upon proposed silvicultural land-use activity and slope/geology upon which it was to take place. Values for the risk matrix were obtained through a variation of the Delphi technique. The final Montana erosion-impact matrix for risk is presented in Figure 4.

The final phase in this procedure is to test the risk matrix on one or more pilot watersheds in western

Montana, and to conduct all spatial analysis through the use of GIS. Presentation of GIS risk integration, and results of areal calculations for the 2 pilot studies are presented in Chapter 2.

MONTANA "RISK" MATRIX

TYPE		CLEARCUT				PARTIAL CUT				SITE PREP			ROADS	
SLOPE	SOIL EROD.	TRACKED EQUIP.	RUBBER SKID	PARTIAL SUSP.	FULL SUSP.	TRACKED EQUIP.	RUBBER SKID	PARTIAL SUSP.	FULL SUSP.	MACHINE PILE/SCAR	BRDCAST BURN	OTHER	PERM.	TEMP.
0-5%	H	2	2	2	1	3*	3*	1	1	2	1	1	3*	2
	M	2	1	1	2	2	2	1	1	1	1	1	1	1
	L	1	1	1	1	1	1	1	1	1	1	1	1	1
5-20%	H	4	3	2	1	4*	3	2	1	4	2	1	3	4
	M	3	2	1	1	3*	2	1	1	3	2	1	2	3
	L	2	2	1	1	2*	2*	1	1	2	1	1	2	2
20-40%	H	5	5	4*	2	5*	5*	4*	1	5	4*	1	4	5
	M	4*	4	3	1	3	3	2	1	4	3	1	3	4*
	L	3*	2	2	1	2	2	2	1	3	2	1	3*	3
> 40%	H	5	5	4	3*	5	5	4	2	5	5	1	5	5
	M	5	5	4	2*	5	5	3	1	5	4	1	5	5
	L	5	5	3	1	5	5	2	1	5	3*	1	4	4

FIGURE 4 : Completed Montana Erosion-Impact Matrix

(* INDICATES MEAN VALUE USED)

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CHAPTER 2
GIS RISK ASSESSMENT APPLICATION

INTRODUCTION

Inadequate processing power, insufficient memory capacity, and other limitations prevented implementation of GIS software on the first generation of microcomputers (Cooney & Tucker, 1986). However, in recent years advances in microcomputer technology have made the use of GIS by land management agencies possible. Because environmental information is often spatial, geographic information systems are becoming recognized as powerful tools for resource management (Robinson et al. 1987, Bailey 1988, Berry and Sailor, 1987).

With the use of GIS, planners can correlate land cover and topographic data of drainage networks, drainage basin area, and terrain configuration (Walsh, 1985). This makes GIS available for assessing the potential effects of land-use activities on water quality.

Development and use of an automated GIS can expedite data integration problems and the time-consuming process of synthesizing tremendous amounts of information for spatial examination of nonpoint pollution (Walsh, 1985). Wilson and Thomas (1977) maintains that an automated information system through which geographically-referenced data can be entered, manipulated, and analyzed, can immeasurably improve the decision making process of land management organizations.

As a result, many federal agencies have incorporated or plan to incorporate GIS into their management schemes. For example, the Bureau of Land Management, which has management responsibility for over 340 million acres, is committed to using GIS technology to help manage mineral, range, wildlife, and forest resources, by assessing the impact of proposed development (Hatch 1986, Parker 1986).

The U.S. Fish and Wildlife Service has been developing GIS for natural resource problems, and now has predictive

techniques that model the effects of channel deepening on the distribution of various shellfish and finfish species (Hatch 1986, Robinson et al. 1987).

Another example of GIS use in the federal government is the U.S. National Park Service. The Park Service created a GIS field unit, charged with developing, applying, and supporting GIS technology throughout the Park Service (Fleet, 1986). A prototype GIS has recently been evaluated for planning aerial spray block layout for fighting spruce budworm (Jordan and Vietinghoff 1987, Robinson et al., 1987).

ADVANTAGES/DISADVANTAGES OF GIS

A GIS can generally be described as a computer system for entering, storing, managing, retrieving, transforming, analyzing, and displaying spatial data (Coughlan and Olliff. 1988, Cowan 1987, Robinson et al. 1987). However, as with any advanced technology there are several advantages and disadvantages that must be considered before implementation.

The major strength of GIS in resource management is its ability to link spatial and nonspatial data simultaneously. The big advantage here is that large amounts of nonspatial

data can be associated with graphical representations (maps) immediately. Information such as stand density, soil type, habitat type, erosion classification, ownership, and land-use history can be coupled to spatial representations such as polygons, points, or lines. Nonspatial attributes can be stored and accessed through a database management system that is either externally or internally linked to the GIS. This allows for increased speed and efficiency in data manipulation and may expedite the decision-making process.

Land-use planners, and resource specialists use maps or images displaying soil type, geology, land-use, hydrology, and other natural resource data on a daily basis. Walsh (1985) suggests that another major advantage of archiving these data in a GIS include ease of retrieval, variety of output products to fit almost any need, and the ability to discover and display information gained by testing the interactions between natural resources phenomena and to organize and appraise variable coefficients for predictive models.

Numerous models have been developed to predict hydrologic watershed responses to various activities. Watershed-type models require updates of land cover, precipitation, and other data and an assessment of the

dynamic spatial patterns affecting runoff, infiltration,and potential nonpoint source pollution (Walsh, 1985). The use of GIS for data organization and manipulation would greatly benefit model speed and efficiency.

Another intriguing aspect of GIS is the potential to receive and utilize satellite data. Remote sensing is a discipline that generates volumes of spectral data on landscape features (Coughlan and Olliff, 1988). Various GIS systems are able to integrate this information for use in creating quality graphical representations. The ability of a GIS to integrate raster data (grid cell) from a satellite sensor with data digitized from a map sheet is one of its primary strengths (Robinson et al., 1987).

On the other hand, there are several disadvantages to be considered before implementing a GIS. The first major consideration is money. Implementing a GIS requires a substantial initial investment, both in dollars and in time to digitize maps, build a database and develop customized reporting (Devine & Field 1986, Reisinger & Davis 1987). Software modules alone range from $10,000-$100,000 for micro-based systems (Coughlan and Olliff, 1988), and the cost of keeping data current can quickly outstrip the initial investment (Devine & Field 1986).

Antenucci (1986) recommends a detailed feasibility cost-benefit analysis be conducted before implementation. He maintains that the feasibility analysis will allow an organization to determine if conversion to an automated GIS can be justified by calculating the costs to be incurred by the organization compared against the benefits of automation.

Four additional disadvantages of GIS are: 1) a substantial amount of hardware must be available, including a digitizer and computer plotter, a photogrammetric triangulation instrument, and relatively large computer memory capacity; 2) although automated mapping processes requires less total time than traditional methods, longer lead times and careful planning are required to link many intermediate tasks into a completed data base; 3) GIS do not lend themselves to single-purpose operations. In other words, they are most efficient when creating a multifaceted information base where the integration of several separate data sources is required. And finally, 4) it is necessary that people from different disciplines work together in building and using a common database (Martin, 1985).

The final disadvantage can be the advanced and intricate nature of GIS technology itself. Most software and hardware packages are complicated and can be very difficult to understand. Therefore, staffing is a primary consideration. Adequately trained personnel are a must if maximum benefit and equipment potential is to be realized. However, GIS technology can be very difficult to teach (Berry, 1986). Practical experience is required as well as theory, yet very few classrooms can provide extensive hands-on learning. More systems have failed due to inadequately trained staff, than for any other reason (Antenucci, 1986).

PREVIOUS USE OF GIS IN WATERSHED MANAGEMENT

While there are some negative implications that may arise in the implementation of a new GIS, the benefits of automated mapping can be immeasurable. There are numerous examples where GIS have been used for natural resource management planning, specifically for watershed management and NPS pollution control.

Atkinson (1987) conducted a study on 21 watersheds draining into the Trinity River in the Dallas-Fort Worth (Texas) Metroplex. The study utilized geographic

information systems to address the question of whether or not Trinity River water quality could be protected from NPS pollution by using wet detention basins. Results indicated that a GIS modeling approach was successful in determining the most feasible sites for the detention basins and was instrumental in the planning and design process.

A similar study by Berry and Sailor (1987) describe the use of generalized GIS for analyzing the spatial aspects of storm runoff prediction using the US Soil Conservation Service (SCS) technique (Sailor & Berry, 1980). The objective of their study was to familiarize environmental planners with application of geographic information system to storm runoff prediction. The results of their study indicated that the use of GIS to generate watershed data to be used in the SCS storm runoff prediction method greatly enhanced precision and speed over manual procedures. The management and analytical capabilities of GIS technology provided them with the opportunity to fully integrate spatial conditions into hydrologic inquiries. They concluded that with advent of GIS systems for microcomputer environments and the increasing availability of digitally-mapped data, GIS technology will play an important role in other spatial studies in environmental planning, as well as in storm water monitoring (Sailor and Berry, 1980).

Prato et al. (1989), described how geographic information systems were used to assemble and retrieve the physical parameters required to estimate sheet and rill erosion and water quality impacts of multiple resource management techniques on 16 farms in northern Idaho. One of the study's main objectives was to demonstrate how a GIS could be used to estimate soil erosion from fields and farms in a watershed and to estimate sediment and nutrient pollution in receiving waters for alternative resource management (Prato et al., 1989). Results indicated that the use of GIS in data acquisition and spatial analysis was paramount in the overall success of the study.

OBJECTIVES(GIS)

As a result of recent successes in the application of GIS in natural resource management, particularly in watershed management, the integration of GIS in the assimilation and development of a risk analysis procedure for use in forested lands is presented. This procedure was tested on 2 pilot watersheds in western Montana. The first pilot study was conducted on Howard Creek, a third order watershed on the Lolo National Forest. The second pilot watershed, Jones Meadow Creek, is in the Lubrecht Experimental Forest.

The Study Areas

Howard Creek is located approximately 32 kilometers southwest of Missoula, Montana, in the Lolo National Forest. It was selected as a pilot study area because of its diversity in past land-use history. Currently, Howard Creek is managed by the Lolo National Forest, Champion International, and Plum Creek Timber, Inc.

Jones Meadow Creek is located in the Lubrecht Experimental Forest, managed by the University of Montana, School of Forestry. It was selected as a pilot study area because most of the spatial information required to calculate risk values had been previously digitized.

Topography

The Howard Creek watershed encompasses an area of approximately 5015 hectares. It exhibits a dendritic drainage pattern typical of small watersheds in western Montana. Relief within the basin ranges from a maximum elevation of 1767.8 m to a low of 1188.7 m; with an average watershed elevation of approximately 1480 m. The main stem

of Howard Creek is oriented east-west while the 3 sub-basins, Teppee, North Fork, and Krystal, are oriented north-south (See Figure 5).

The Jones Meadow watershed totals 635.4 hectares. Relief within the basin ranges from 1250 m to 1615 m. The watershed is oriented north-south with primary aspects facing north.

Climate

The Lolo National Forest is under a modified maritime climate regime (Sasich and Lamotte-Hagen, 1989). The Continental Divide creates a physical barrier which effects climatic processes in Montana. Areas west of the Divide are dominated by a maritime (North Pacific Coast) climate and those east of the Divide are dominated by a continental climate. Howard Creek is located west of the Continental Divide.

Precipitation results from orographic and frontal activity associated with low pressure systems originating off the Pacific coast. Approximately two-thirds of the precipitation received falls as snow. Howard Creek averages 100 cm of annual precipitation. Temperatures range from an

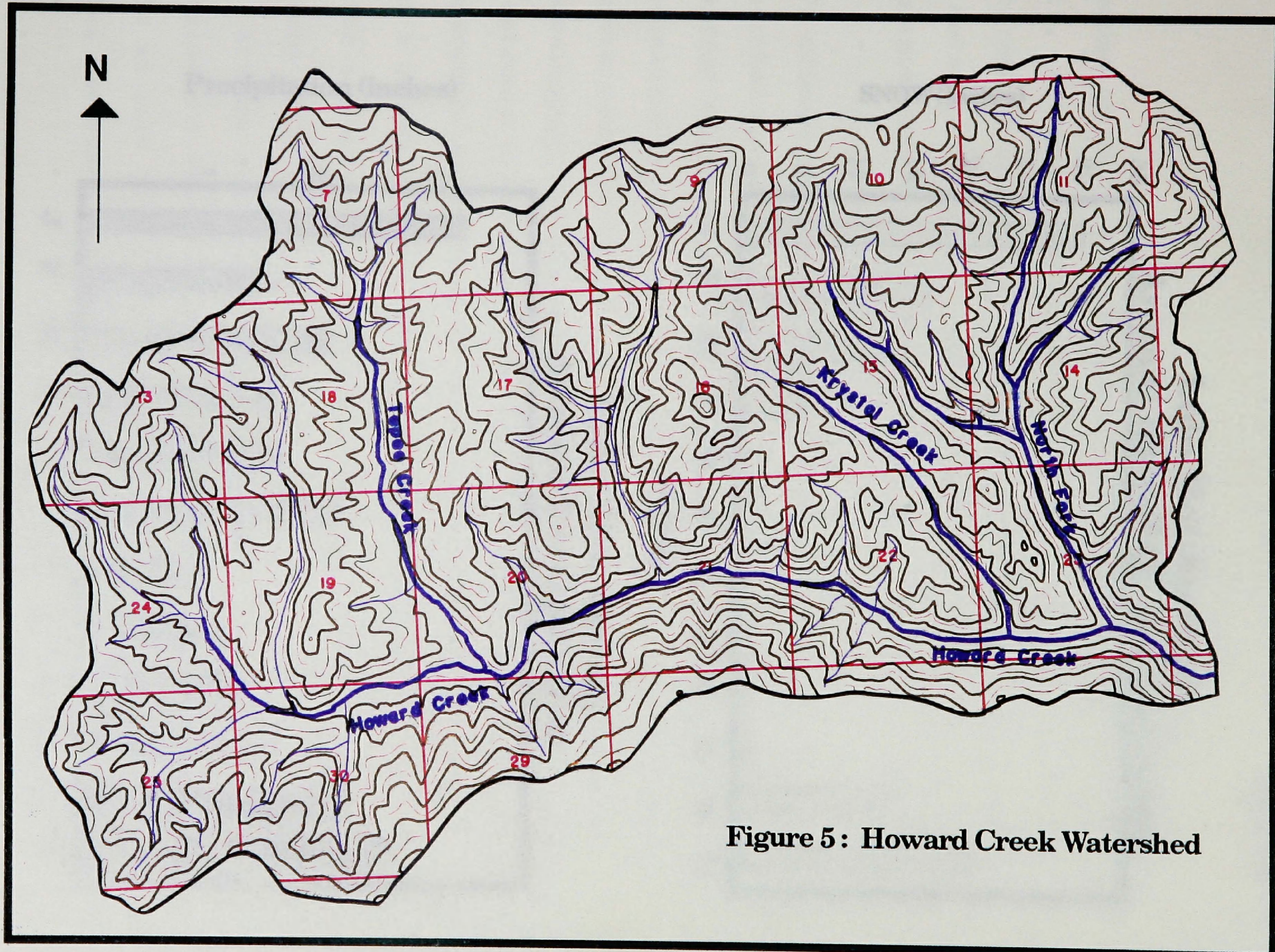
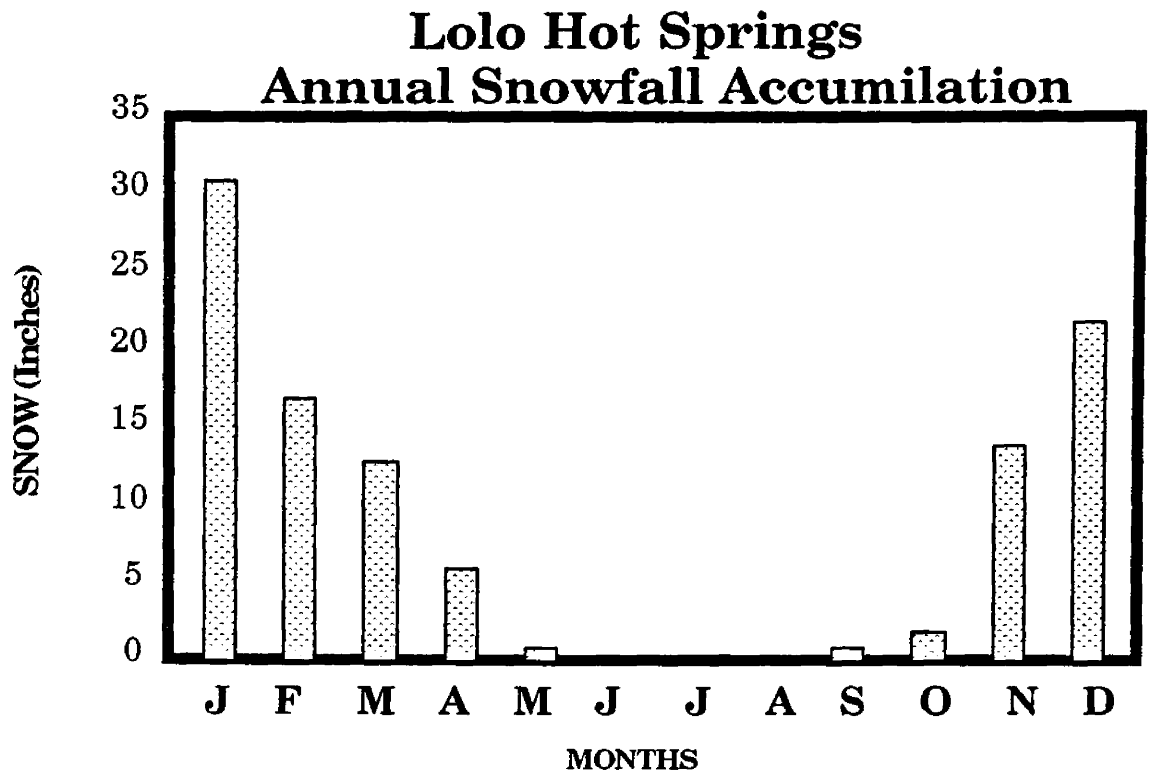


Figure 5 : Howard Creek Watershed



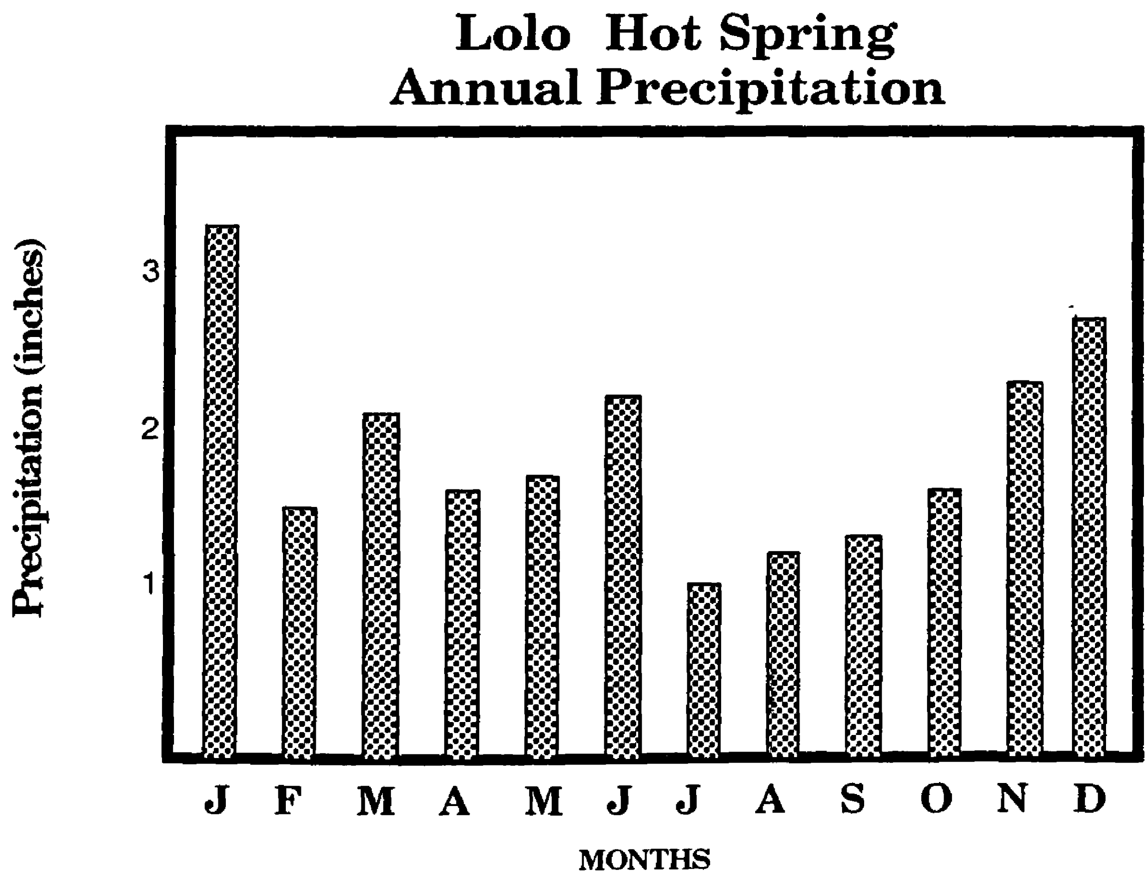


Figure 6: Annual Precipitation and Snow Data For Lolo Hot Springs (1959-1984)

average of -5.5° C in January to an average of 19.4° C in July. Estimates for Howard Creek can be extrapolated from information compiled at the nearest weather station located at Lolo Hot Springs. A graph of the average annual precipitation for Lolo Hot Springs is presented in Figure 6.

Climate for the Lubrecht Experimental Forest is described as modified temperate continental regime. Modified temperatures result from maritime influences originating in the northern Pacific ocean. Monthly average temperatures for Lubrecht Experimental Forest headquarters, approximately 1.5 kilometers (km) to the west, can be used to estimate climate for the Jones Meadow watershed. Temperature extremes at the headquarters facility ranged from a summer high of 40° C to a summer low of -6.0° C; winter extremes range from a minimum of -42.5° C to a maximum of 20° C (Goetz, 1989).

Average annual precipitation for the Lubrecht experimental watershed is about 45.5 cm. Approximately 44% falls as snow in the winter months (Nov-Mar) and 24% falls during the summer (Jun-Aug).

Geology

Soil parent materials are in part determined by bedrock and surficial geology. The Lolo National Forest Land Systems Inventory (Sasich and Lamotte-Hagen, 1989) maps the primary geologic groups found in Howard Creek as metasedimentary and undifferentiated.

Metasedimentary rocks contain parent materials derived from Belt Super Group quartzite, argillite, and siltite. Rock fragment hardness is variable depending upon the degree of rock weathering. Weathering is dependent on associated faults, preponderance of argillites, and calcium carbonate content. These materials were classified as either L-low or M-moderate within of the erosion-impact matrix.

Undifferentiated geology is composed of materials derived from Belt Super Group metasedimentary rocks or weakly weathered granitic rocks. Materials include alluvium on terraces and flood plains; shallow soils on flood scoured foot slopes and stream breaklands, strongly frost churned broadly convex ridges, and glacial outwash on plains (Sasich and Lamotte-Hagen, 1989). This group would be classified as H-highly erodible in the Montana erosion-impact matrix.

Geology for Howard Creek was mapped using GIS. A graphic representation of the 3 erosion hazard groups, high, medium, and low, can be seen in Figure 7.

Brenner (1964) mapped geology of Lubrecht and this is summarized by Nimlos (1986) in, Soils of Lubrecht Experimental Forest. These include belt rocks, limestone, granite, tertiary, and unconsolidated transported material.

The first type of parent material found in Jones Meadow are belt rocks. They are the oldest rocks in the Belt Super Group and were deposited during the precambrian about one billion years ago. They are originally formed as marine deposits which have metamorphosed into quartzite, argillite, and siltites (Nimlos, 1986). These deposits are included in the erosion-impact matrix in the LOW erodibility classification.

The next major parent material found in the Jones Meadow watershed are tertiary deposits. Tertiary rocks are derived from sediments deposited 60 million years ago. These became consolidated in weakly cemented and interbedded conglomerate, sandstone, siltstone, and mudstone (Nimlos, 1986). Tertiary parent materials are considered with alluvium as highly erodible and are assigned a HIGH classification in the erosion-impact matrix. Figure 8 shows

Figure 7 : Geology Map for Howard Creek

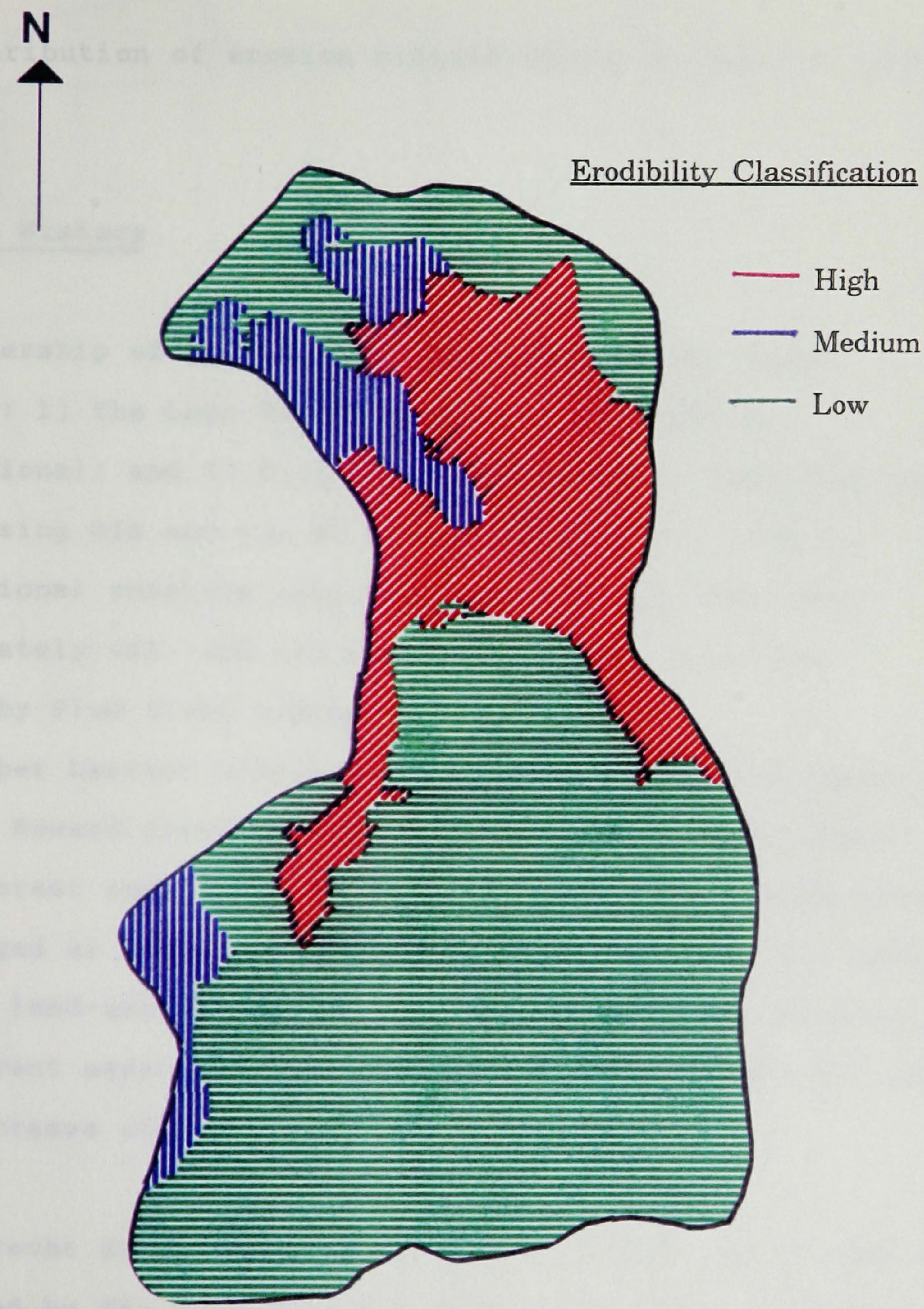


Figure 8: Geology Map for Jones Meadow

the distribution of erosion classification groups for Jones Meadow.

Land-Use History

Ownership of Howard Creek is divided among three entities: 1) the Lolo National Forest; 2) Champion International; and 3) Plum Creek Timber Inc. Ownership was mapped using GIS and can be seen in Figure 9. Champion International controls approximately 34%, the USFS owns approximately 42%, and the remaining 23% is owned and managed by Plum Creek Timber Inc.

Timber harvest activities in recent years have impacted 27.4% of Howard Creek's total acreage. In a recent report to the forest supervisor, cumulative watershed effects have been judged as extremely detrimental (Munther et al., 1987). In fact, land-use activities in Howard Creek have resulted in a current sediment load increase of 50% and current water yield increase of 8%.

Lubrecht Experimental Forest is on state owned lands and is managed by the School of Forestry, University of Montana. It consists of a tract of 11,331.5 hectares and is located about 48 kilometers (km) northeast of Missoula. The forest

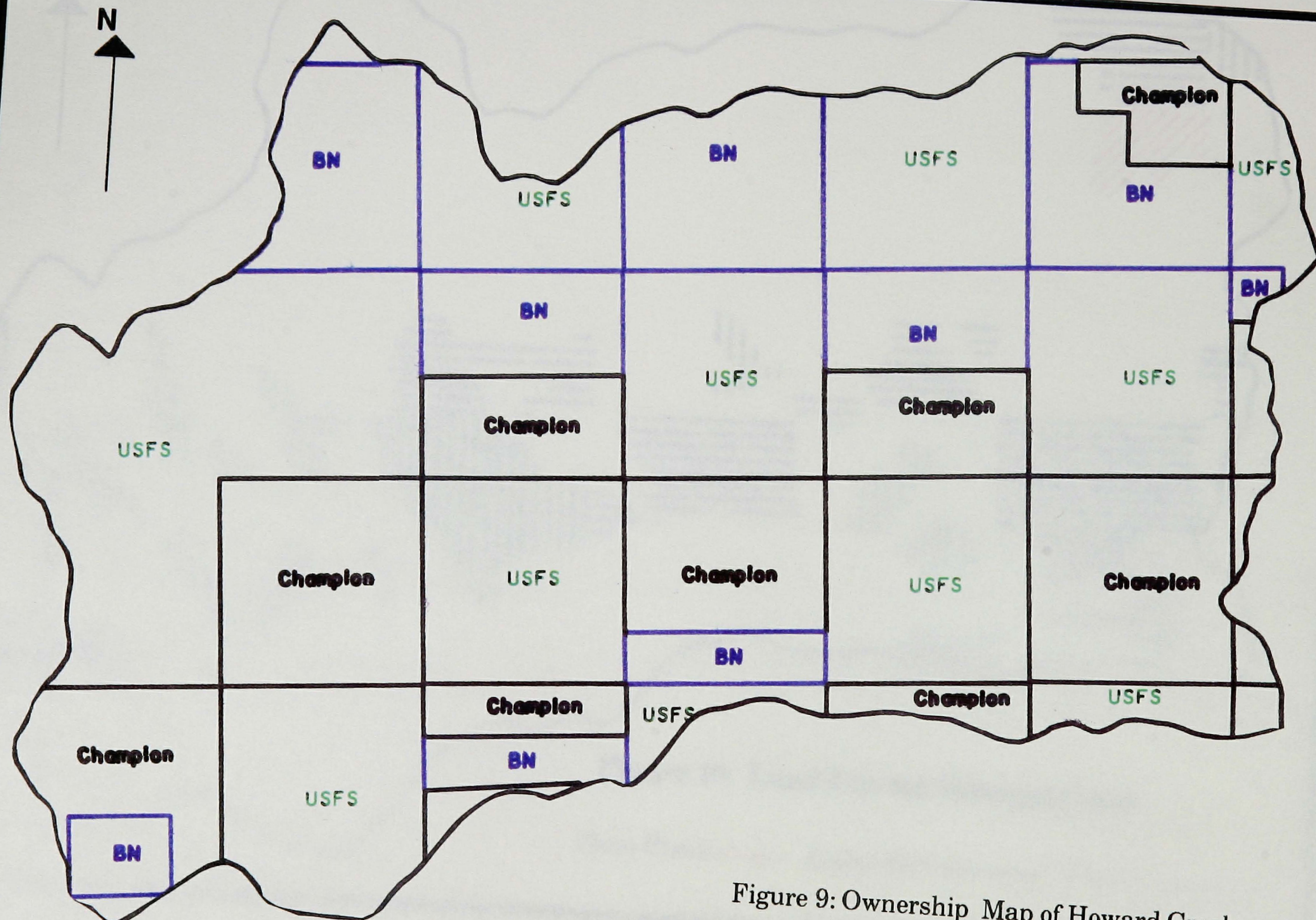


Figure 9: Ownership Map of Howard Creek

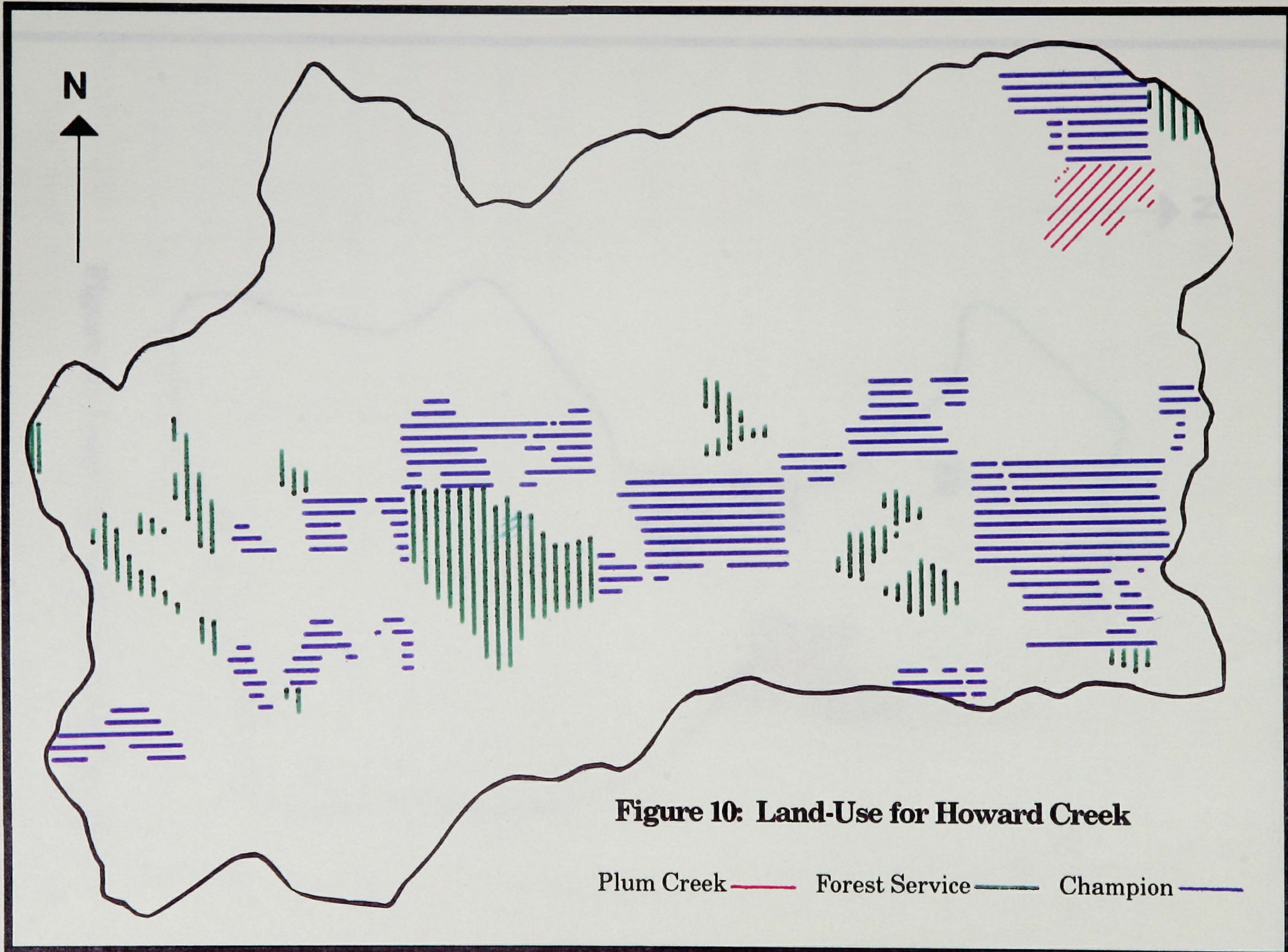


Figure 10: Land-Use for Howard Creek

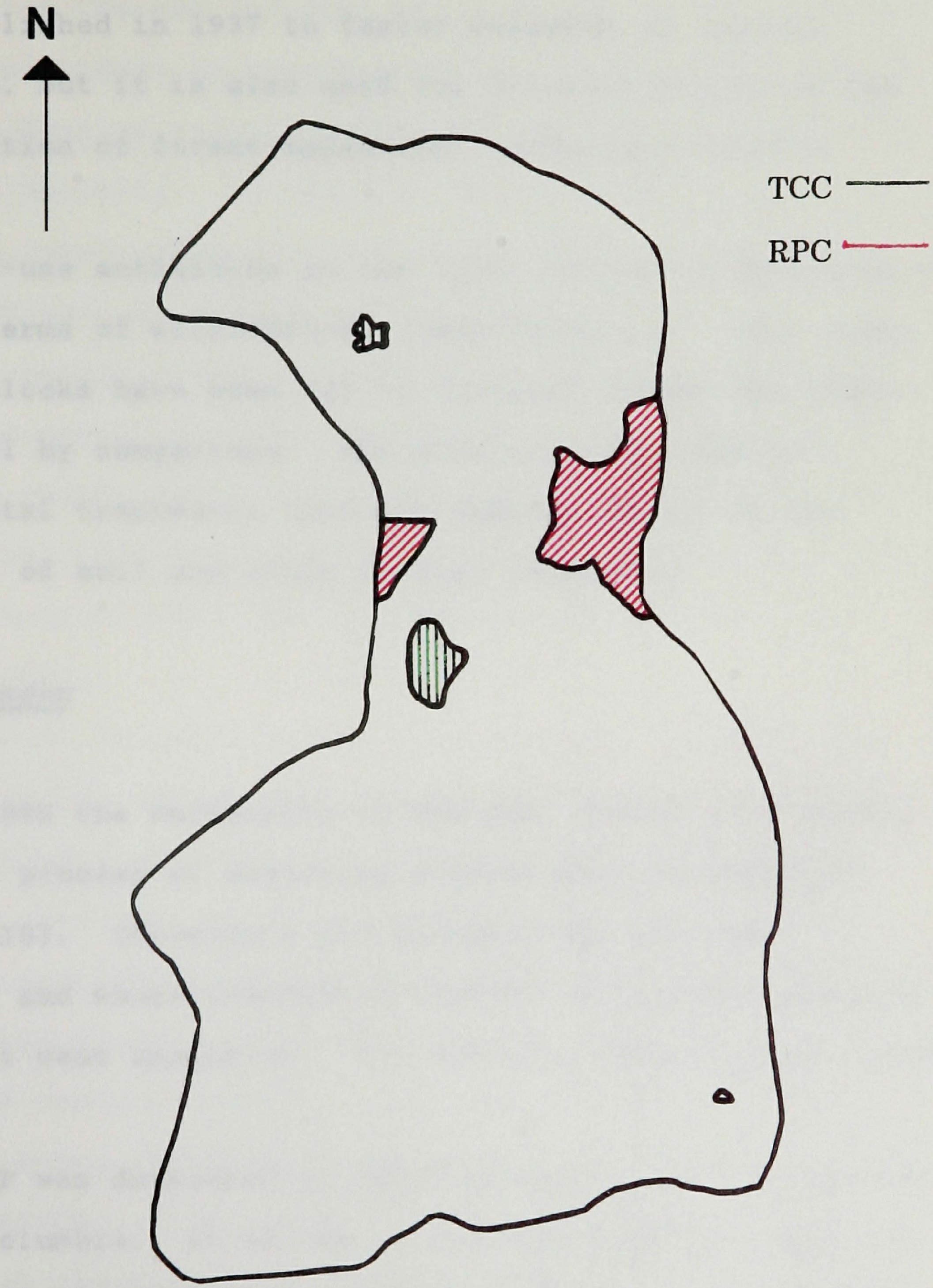


Figure 11: Land-Use Map for Jones Meadow

was established in 1937 to foster research on natural resources, but it is also used for forestry education and demonstration of forest management techniques (Nimlos, 1986).

Land-use activities in the Jones Meadow watershed have not, in terms of silviculture, been extensive. Only seven harvest blocks have been cut in the past decade and these were small by comparison. The area was subjected to experimental treatments that had minimal impact on the stability of soil and other natural resources.

GIS Processes

In 1988 the University of Montana, School of Forestry. began the process of acquiring a Geographic Information System (GIS). Choosing a GIS package that was cost efficient and whose foundation focused on natural resource management were essential. The School of Forestry selected PAMAP.

PAMAP was developed by PAMAP Graphics LTD in Victoria, British Columbia. It is one of the most powerful analytic tools available in today's automated mapping environment (PAMAP, 1989).

The need for computer mapping and data manipulation

spawned from the ever-growing value of information generated by such techniques as remote sensing. Paper maps, simply could not keep up and are extremely limited in what can be displayed visually. In addition to performing as poor databases, paper maps were also ill-suited to depict the results of various analytical functions.

As a result, PAMAP was instrumental in creating the ability to merge computers and cartography. PAMAP was developed in the early 1980's and soon proved itself as a mapping tool ideally suited to processing and analyzing great volumes of data, and producing high-quality maps (PAMAP, 1989).

Its most valuable asset is its ability to model the physical world. Since data can be accessed, transformed, and manipulated interactively, GIS allows one to test processes, analyze trends, and anticipate the outcome of planning initiatives without ever touching whatever part of the physical world being considered (PAMAP, 1989).

PAMAP software consists of 4 primary modules which perform 5 basic functions. The modules include: 1) MAPPER; 2) TOPOGRAPHER; 3) ANALYZER; and 4) INTERPRETER. The 5 fundamental functions are: 1) Data Input and Verification - which covers all aspects of transforming data from existing maps, field measurements, and satellite sensors into a usable digital format; 2) Data Storage and Database

Management - defines the structure and organization of the data map position, its corrections to other elements (topology) and the non-graphic attributes of geographical elements such as points, lines, and area; 3) Data Output and Presentation - output is directed to either a plotter or color copier; 4) Data Transformation Functions - including error removal and data analysis that can affect the location of the data, its non-spatial attributes, or both ; and 5) Interaction With User - allows direct access to systems data and lets the user manipulate attributes if necessary (PAMAP, 1989).

MAPPER

GIS MAPPER is PAMAP's interactive data entry module. It is used to digitize new maps and edit existing ones. MAPPER requires that paper maps be converted into digital form. This can be done manually, or with a optical digitizing scanner. Once the map data is in the central processing unit (CPU), the full range of GIS tools is accessible by the user. MAPPER can easily modify existing lines, and redraw them if needed.

MAPPER can input data in four coordinate systems: 1) Geographic Units (Longitude and Latitude), 2) UTM projection, 3) polyconic projection, and 4) Lambert

conformed projection. Additionally, each map can include 64 layers, or levels, of geographic information, each supported by attribute data.

ANALYZER

ANALYZER opens the door to PAMAP's powerful analysis tools by converting the lines, points and polygons of map line work, together with attribute data, into a grid-cell format. As it converts a thematic map layer to grid-cell format, ANALYZER automatically forms polygons, computing their area and perimeters and storing them in the data base.

ANALYZER analyses geographic data by performing 2 tasks: conversion and overlaying. ANALYZER may simply convert one map level from a given format to another, and then use the resulting map for overlaying operations. Overlaying, requires one raster cover to be overlayed upon another raster cover. This procedure creates a third raster map for which resulting statistics can be generated.

TOPOGRAPHER

TOPOGRAPHER is a sophisticated, yet easy-to-use tool for manipulating three-dimensional data. It can accept and integrate both vector (points) or raster (grid) formats.

TOPOGRAPHER can generate elevation models based on a variety of interpolation routines. Derivative surfaces such as slope and aspect may be produced, as well as perspective views (PAMAP, 1989). Another very important feature of this module is its ability to import elevation and data from numerous sources, including irregular ASCII data from external sources and contours digitized in MAPPER.

INTERPRETER

The final PAMAP module, and one of the most important, is INTERPRETER. PAMAP Graphics LTD has worked for several years with the Canada Centre for Remote Sensing; recently developing a technique for integrating the two technologies (PAMAP, 1989); INTERPRETER is the result.

It's major function is to convert remote sensing data into a high-resolution graphic display in MAPPER. This makes INTERPRETER one of the most valuable features of PAMAP's GIS. It provides a means for resource managers to automatically incorporate the hordes of data generated by satellite platforms into a useable format.

All modules in PAMAP are linked to one another through GIS (Figure 12).

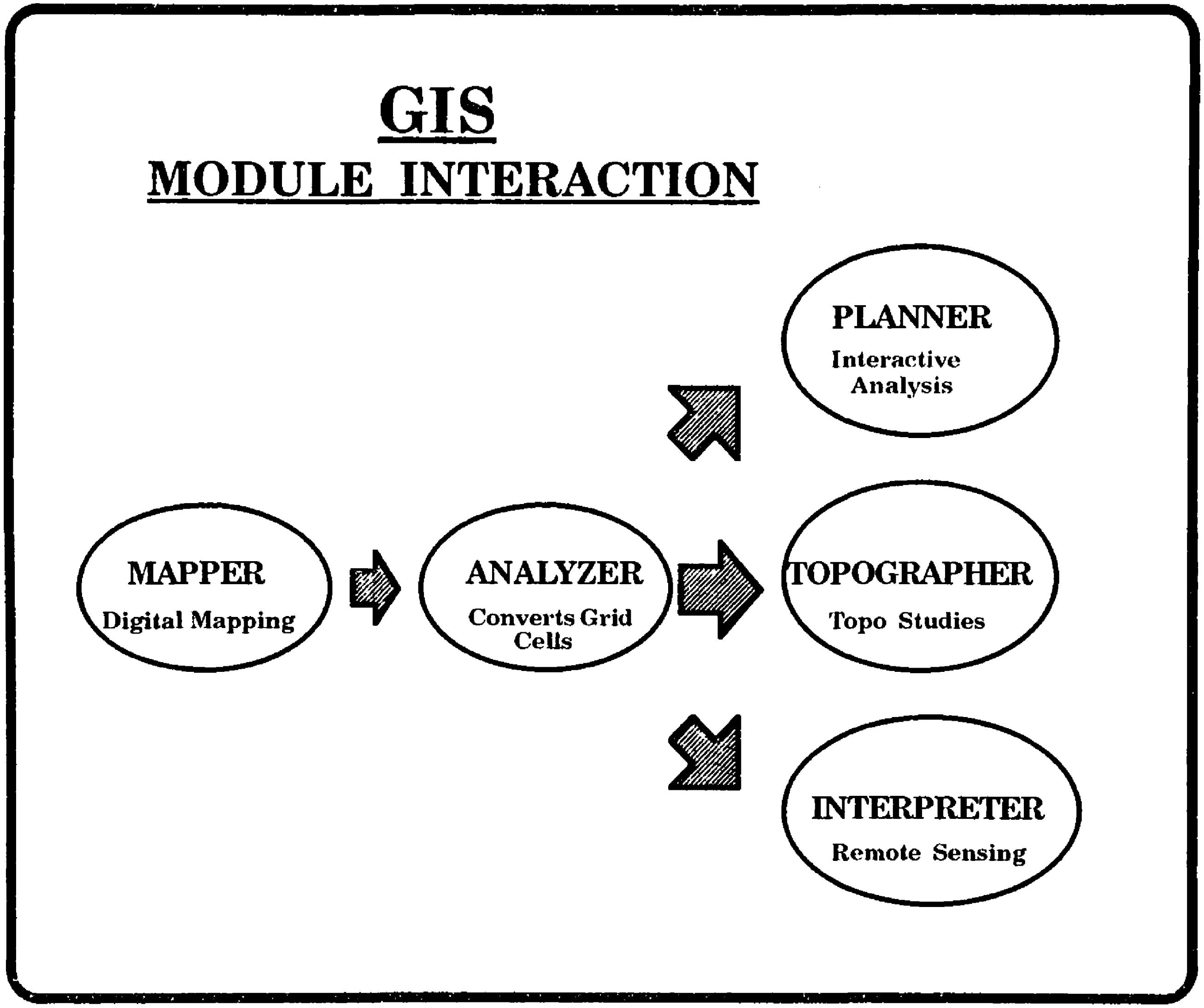


FIGURE 12: PAMAP Module Interaction

Data Requirements

In order to apply risk analysis techniques on any given watershed, initial data assimilation is required. Fundamentally, information on 4 primary spatial attributes must be obtained before risk analysis and digitizing can begin. These are: 1) soil/geology; 2) topography (elevation); 3) land-use history; and 4) system and temporary road networks.

Information on soils can be obtained from geology and soil maps that are produced by the U.S Geological Survey, the Soil Conservation Service, U.S. Forest Service Service and from various state agencies. It is important to obtain accurate soil data and to remain consistent in its integration into the GIS. Most soil maps include soil classifications based on soil taxonomy. Some maps will include information about parent materials from which soils are derived. For application of the Montana erosion-impact matrix, it was decided that for ease of mapping and since the R1/R4 Sediment yield model is based upon them, that parent materials and not soil classifications be mapped.

SCS soil maps for Howard Creek and Jones Meadow were used and soil classifications were grouped into parent

materials categories for mapping purposes. The results are shown as geologic (erodibility) maps in Figure 7 and 8.

The next vital link in the digitizing process is topographic information (contours). Topographic data can pose a major problem in terms of man hours and complexity in digitizing. Fortunately, topographic information for most areas is accessible from the USGS in the form of Digital Line Graphs (DLG) or a Digital Elevation Model (DEM). This saves numerous hours of manual digitizing time. However, expense and delays in shipping may make DLGs and DEMs not practical. Therefore, as in the case of this study, manual digitizing is often the answer. It took approximately 24 hours at the digitizing pad to input contour information for Howard Creek.

The third element which is essential in the analysis process is past land-use history. This can pose a major hurdle in terms of accuracy and timeliness of assimilation. Land-use history may be obtained from local or regional planning offices, federal agencies such as the Forest Service, Bureau of Land Management, or the USGS and from private industry which may control or own a portion of the watershed. If the basin lies in a relatively pristine location, as does Howard Creek, then urbanization is not a factor and acquiring data may be much easier. For this

project, all information on land-use was obtained from the primary landowners. Sources of data ranged from paper maps in old filing cabinets to advanced computer graphics and files. Land-use history for the past decade was obtained and maps showing all major silviculture operations are shown in Figure 10 and Figure 11, Howard Creek and Jones Meadow respectively.

The final geographic spatial attribute needed is the road network. Since roads can have major negative effects on runoff characteristics, roads are vital for inclusion into the matrix design and in risk assessment (Megahan 1980, Haskins 1986, and Rickert et al. 1978).

As with many other forms of spatial information, road systems can be found on paper maps. The USGS 1:24000 scale maps are usually outdated. Therefore, road system information must be obtained from the various landowners. Perhaps the very best source for acquiring accurate road information is through aerial photography. This was done for Howard Creek and proved to be invaluable.

Once all required information has been assimilated it is necessary to consolidate it onto one or two databases. While paper maps have their utility, it is not a good idea to rely upon them as a database from which to begin digitizing. Paper map products are easily bent, torn,

stretched, and destroyed. It is strongly suggested that mylar map sheets be used for all digitizing purposes. Mylar is a plastic material made from a synthetic polyester compound, polyethylene, and can be obtained with all map information printed on it from local printing or blueprint shops. However, it is very expensive in comparison to paper map products but will be well worth it in the long run.

Once all spatial information is combined onto one mylar map sheet digitizing may begin. Hence, starts the long and somewhat tedious process of data entry.

Data Input To GIS

Data entry into any GIS is always an extremely challenging task. The vast amounts of spatial information for even the most basic map can seem insurmountable. Patience, diligence, and dedication are required if a project is to be successful. There are 7 primary steps involved in the initial data input and risk assessment. These steps are not software dependent. They include: 1) GIS preparation; 2) level definition; 3) conversion (vector to raster); 4) addition of non-spatial data; 5) data file manipulation; 6) three-dimensional analysis; and 7) spatial analysis.

The first task is GIS preparation. It is not practical to begin digitizing without extensive forethought. Most GIS can conform to user specific needs. In other words, data files can be set up with specific requirements in mind. Definition of map parameters are required before data can be entered.

These include such things as map scale, UOR (Units of Resolution), and coordinate systems. For example, PAMAP was designed in Canada and it was originally developed using the metric system (Systems International), therefore Howard Creek was configured entirely in metric units. The basic UOR is the centimeter.

Another important step in the design of a fluid working system is level definition. It is essential that planning and organization in terms of data files, levels, be maintained from the onset. There are 64 levels available in PAMAP. Each level can include 3 types of file: 1) vector (points); 2) polygonal (grid-cell); and 3) surface (also grid-cell). Therefore, the total number of possible levels, files, increases to 192. It is imperative that a good index, or reference system, be used to minimize confusion. This problem is not limited solely to PAMAP software, but is universal.

Once vector data has been put in the GIS, the next major step is conversion. The power of spatial analysis comes from the ability for the GIS to quickly assimilate information areally. GIS cannot calculate area based upon vector data. In the vector to raster conversion process, polygons are created and a grid-cell network is produced based upon where and how the vector information was input. This takes the form of polygonal or surface cover. At this point, non-spatial attribute information can be attached to the graphics files and various calculations such as area are possible. The raster file itself consists of a series of pixels (cells) that represent the surface of the ground as depicted on the map. Pixel size can be adjusted based upon the users desired resolution and is a key factor in the planning process.

The next major step in developing a useable product can be considered the most important. It is the creation of polygon database user attributes, or more precisely, the link of non-spatial data to digitized spatial graphic files. Here is where the GIS gets its tremendous advantage over traditional cartographic processes. The ability to store vast amounts of non-spatial information which is immediately accessible, makes GIS an invaluable planning tool. Thought and foresight must go into creating databases. Although GIS

is capable of storing incredible amounts of information, it is best to keep non-spatial information as precise as possible. The use of abbreviations is suggested. Once attribute information is entered, it is possible to use "theming" or coloring to highlight areas on the map that are of particular interest.

Once all data files have been created and are in the GIS, the power of the system can be realized. Levels may be overlaid,, or combined, creating a resulting map. Files can be manipulated to generate information with optimal land-use in mind. Corridor calculations can lay out streamside management zones and determine acreage of lost timber volume, by species if desired. Area, distance, and perimeter information can be determined instantly. Polygonal covers can be combined and the resulting level can be used for analysis and planning.

For example, 2 polygonal covers, one containing species information and one containing parent materials, are combined. The resulting polygonal cover contains both attributes. The user can query the system and obtain instant results on the new cover. If information is desired on all lodgepole pine that are located on soils derived from colluvium, the GIS will instantly highlight all areas meeting the specified criteria.

The sixth step is topographic analysis. Once elevation is put into a data file, the possibilities for three-dimensional manipulation are limitless. Slope and aspect polygons can be generated. Perspective views, or viewability from a certain point in the watershed, is also possible. This factor can be very important for planning purposes where visual aesthetics are essential, such as in timber harvest operations. Furthermore, detailed analysis of basin relief is possible. This is of particular interest to forest hydrologists. In PAMAP, all 3-D analysis is generated from a digital elevation model (DEM). A DEM for Howard Creek is presented in Figure 13.

The final step in the risk analysis process and in data entry is spatial analysis. Spatial analysis is basically an in depth examination of the physical geographic features that are present in a given watershed. Files and software can be manipulated in order to obtain relevant information. To calculate risk it is necessary to determine the percentage of the watershed that is sensitive to nonpoint source pollution production or further land-use. These areas can be retrieved from the database and risk on an areal basis can be calculated.

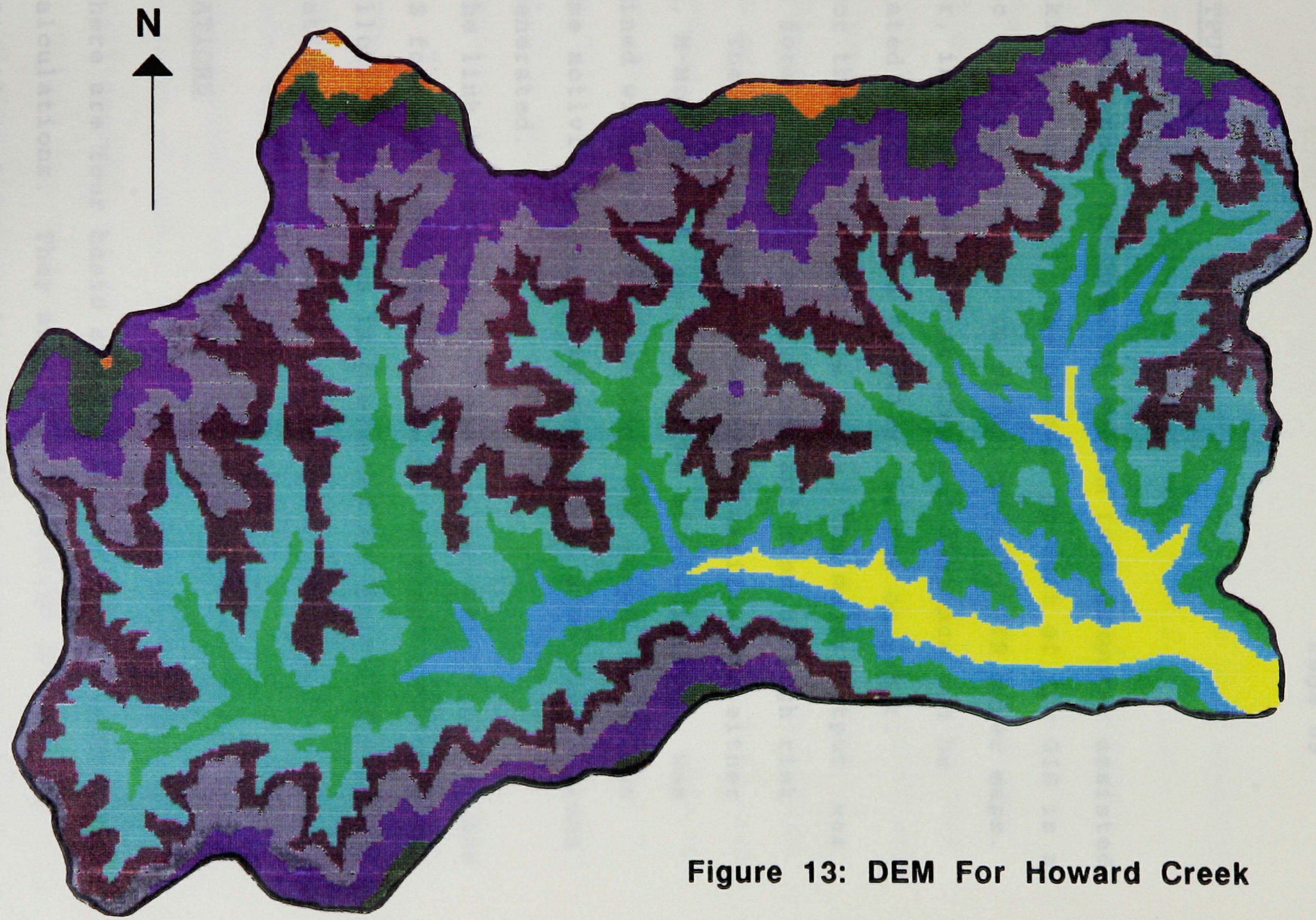


Figure 13: DEM For Howard Creek

GIS OUTPUT

A Geographic Information System is a computer assisted map making technology. The primary product of any GIS is a graphic representation. In other words, a GIS makes maps. However, information such as area and distance can be calculated and retrieved visually, if not on paper.

For the purposes of this study, the major output was in the form of areal calculations and maps of high risk areas. The area of each watershed classified as either H-High, M-Moderate, L-Low, in terms of erodibility, was determined with respect to geology and slope. Previous land-use activities were also mapped and area calculations were generated.

The link between the Montana erosion-impact matrix and the GIS for both watersheds in terms of areas sensitive to NPS pollution production is presented in the following calculations.

CALCULATIONS

There are four basic steps involved in total watershed risk calculations. They are: 1) calculation of erosion classifications by area; 2) calculation of risk areally

based on geology and slope; 3) calculation of risk areally based on past and planned land-use activities; and 4) summation of risk values for slope/geology and land-use activities.

Step one requires that areal calculations based upon erosion classifications be determined. This is relatively simple in that the GIS can instantly generate the total area of the watershed which have been classified as H-High erodibility, M-Moderate erodibility, and L-Low erodibility. At this point, the values obtained for H,M, and L land areas are divided by the total acreage of the watershed. This was done for both pilot watersheds and is presented in Table 3.

Calculations for risk based upon slope and geology are presented in Table 11. They are based upon areal distribution of erosion classifications as determined in step 1. The Montana Erosion-impact Matrix was developed on a relative scale of 1-5, with 1 equating to very low and 5 equating to very high (in terms of NPS pollution risk). Therefore, substrates within the watershed corresponding to H (highly erodible) are assumed to be equivalent to a value of 5 in terms of risk. Subsequently, substrates that are moderately erodible is assigned a risk value of 3, and any geology within the watershed which is determined low, with respect to erodibility, is assigned a risk value of 1. In

other words, the percentage of the watershed which is determined as H, M, or L is multiplied by a risk factor of 5, 3, and 1 respectively. These values are summed and the total for the watershed, based on geology, is determined. Howard Creek yielded a total risk value of 1.5 and Jones Meadow yielded a total value of 2.0. This process is presented in the formulas found in Table 18 and the results are depicted in Table 11.

The third step requires risk calculations based on past and future land-use activities. While this process may appear somewhat more complex, it is outlined in the following 8 steps:

Step 1: Determine the year/type/acreage of past and planned land-use activities.

Step 2: Determine the erosion classification of the terrain upon which the activity is to take place. This is generated by the GIS.

Step 3: Determine slope category upon which activity will or has taken place using GIS.

Step 4: Obtain risk value from the Montana Erosion-Impact Matrix based upon slope and erosion classifications.

Step 5: Determine the percentage of the watershed upon which the activity took place.

Step 6: Obtain a Recovery Coefficient (RC) for the age/type of activity using Table 12.

Step 7: Multiply the risk value times the percentage of the watershed times the RC to obtain the total impact in terms of risk for that activity. (Formula in Table 18)

Step 8: Sum all past and planned land-use totals.

Once the total impact of land-use activities is determined, summation with risk based upon slope/geology may be done. This is the final step of the calculation process. The total land-use risk values (Table 13-B: Howard Creek and Table 17: Jones Meadow) are added to the values obtained for slope/geology.

The results for total risk values, in terms of potential nonpoint source pollution, based on geology/slope and past land-use history are displayed in Table 11(A). Howard Creek is currently at a risk value of 1.73 and Jones Meadow, due mostly to geology, is at 2.1 Therefore, one might infer that Jones Meadow is at a higher inherent risk than Howard Creek and would be more likely to cause problems in terms of NPS pollution in the advent of future land-use.

Howard Creek			Jones Meadow		
H	0-5%	7.37	H	0-5%	69.5
	5-20%	4.68		5-20%	60.1
	20-40%	4.12		20-40%	8.3
	> 40 %	–		> 40 %	–
M	0-5%	103.6	M	0-5%	13.5
	5-20%	344.3		5-20%	21.8
	20-40%	721.31		20-40%	20.8
	> 40%	-		>40%	-
L	0-5%	234.7	L	0-5%	30.8
	5-20%	2236.5		5-20%	184.1
	20-40%	1363.1		20-40%	208.6
	> 40%	-		> 40%	17.3

Table 2 : Summary of Erosion Classifications by Slope (hectares)

Howard Creek			Jones Meadow		
Erosion Class	%	Area (hectares)	Erosion Class	%	Area (hectares)
H	.003	16.2	H	.217	137.9
M	.23	1164.5	M	.082	56.2
L	.76	3834.3	L	.694	439.4
TOTAL		5115.3	TOTAL		634.6

Table 3 : Summary of Erosion Classifications by Area

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	29.0	*	105.6	24.3	72.9	38.6	*	*	*
L	*	14.2	*	70.1	350	103.7	14	*	*	*

Table 4: Tractor Partial Cut (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	12.1	*	*	*	*	*	*	*	*	*
L	*	*	*	*	*	*	*	*	*	*

Table 5: Tractor Clear Cut (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	*	*	41.6	*	*	5.5	*	*	*
L	*	*	*	*	33.0	*	*	*	*	*

Table 6 : Cable Partial Cut (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	*	*	*	*	*	*	*	*	*
L	*	37.4	*	*	*	*	*	*	*	*

Table 7 : Rubber (Tire) Partial Cut (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	*	*	142.8	24.3	*	38.6	*	*	*
L	*	14.2	*	35.6	386.3	52.9	14.0	*	*	*

Table 8: Site Prep Dozer (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	*	*	4.5	*	*	*	*	*	*
L	*		*	*	*	*	*	*	*	*

Table 9: Broadcast Burn (Hectares)

Land-Use By Year: (Howard Creek)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	*	*	*	*	*	*	*	*	*	*
M	*	29.0	*	*	*	31.1	*	*	*	*
L	*	*	*	34.5	33.0	*	*	*	*	*

Table 10: Site Prep LOP (Hectares)

HOWARD CREEK		JONES MEADOW	
Erod. Class	% WS * "Risk"	Erod. Class	% WS * "Risk"
H	.003 * 5 = .015	H	.217 * 5 = 1.08
M	.232 * 3 = .69	M	.08 * 3 = .264
L	.765 * 1 = .76	L	.694 * 1 = .694
TOTAL	1.5	TOTAL	2.0

Table 11 : Areal "Risk" Calculations Based On Slope And Geology

HOWARD CREEK		JONES MEADOW	
Areal calculation for "risk"		Areal calculation for "risk"	
Slope/geology = 1.5 (+) Land-Use = .229		Slope/geology = 2.0 (+) Land-Use = .08	
TOTAL	1.73	TOTAL	2.1

Table 11 (A) : Areal "Risk" Calculations Based On Slope And Geology Plus Land-Use History

RECOVERY COEFFICIENTS
FOR LAND-USE ACTIVITIES

LAND-USE ACTIVITY		YEAR OF ACTIVITY									
		89	88	87	86	85	84	83	82	81	80
CLEARCUT	TRACKED EQUIPMENT	.45	.4	.35	.3	.25	.2	.15	.1	.05	0
	RUBBER SKIDDER	.45	.4	.35	.3	.25	.2	.15	.1	.05	0
	PARTIAL SUSPENSION	.35	.30	.25	.2	.15	.1	.05	.05	0	0
	FULL SUSPENSION	.2	.15	.1	.05	.05	.05	.05	.05	0	0
PARTIAL CUT	TRACKED EQUIPMENT	.35	.30	.25	.2	.15	.1	.05	0	0	0
	RUBBER TIRE	.35	.30	.25	.2	.15	.1	.05	0	0	0
	PARTIAL SUSPENSION	.2	.15	.1	.05	.05	.05	0	0	0	0
	FULL SUSPENSION	.1	.05	.05	.05	.05	.05	0	0	0	0
SITE PREP	MACHINE PILE/SCAR	.8	.8	.7	.6	.5	.4	.3	.2	.1	.05
	BROADCAST BURN	.6	.6	.55	.5	.4	.3	.2	.15	.1	.05
	OTHER	.1	.05	.05	.05	.05	.05	0	0	0	0
ROADS	PERMANENT	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	TEMPORARY	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9

Table 12 : Recovery Coefficients For Various Land-Use Activities
(Klock, 1985)

"RISK" CALCULATIONS FOR LAND-USE HISTORY

HOWARD CREEK, LOLO N.F.

"RISK" CALCULATIONS BY YEAR

YEAR	ACTIVITY	HECTARES	EROSION CLASS	SLOPE	"RISK" VALUE	AREAL % OF BASIN	RECOVERY COEFFICIENT	CUMULATIVE "RISK" VALUES
1981	SPD	14	L	5-20	2	.002	.1	.0004
1983	TPC	14	L	5-20	1	.003	.05	.0001
		52		20-40	2	.01		.001
		3		5-20		.0006		*
		33	M	5-20	3	.0065		.0009
		72		20-40	3	.014		.0021
	SPD	9	L	0-5	1	.002	.3	.0005
		22		5-20	2	.004		.003
		109	M	5-20	3	.021		.025
		33		20-40	4	.006		.005
	BB	4		20-40	3	.0008	.2	.0005
1984	TPC	24	M	5-20	3	.004	.1	.001
		23	L	0-5	1	.004		.0004
		180		5-20	2	.035		.007
		166		20-40		.032		.006
	CPC	33	L	20-40		.006	.05	.0006
	SPD	24	M	5-20	3	.004	.4	.005
		23	L	0-5	1	.004		.005
		172		5-20	2	.034		.027
		138		20-40	3	.026		.032
	LOP	33		20-40	1	.0006	.05	.0003

Table 13 - A : Summary of Land-Use "RISK" Calculations

(1980-1984)

LEGEND

SPD- SITE PREP. DOZER
TPC- TRAC. PART. CUT
CPC- CABLE PART. CUT
LOP- SITE PREP. LOP

"RISK" CALCULATIONS FOR LAND-USE HISTORY

HOWARD CREEK, LOLO N.F.

	YEAR	ACTIVITY	HECTARES	EROSION CLASS	SLOPE	"RISK" VALUE	AREAL % OF BASIN	RECOVERY COEFFICIENT	CUMULATIVE "RISK" VALUES
"RISK" CALCULATIONS BY YEAR	1985	TPC	3.2	M	0-5	2	.0006	.15	.0002
			19.4		5-20	3	.003		.0017
			50.2		20-40		.0098		.0147
			30.8	L	5-20	2	.006		.0018
			72.8		20-40		.014		.0043
		SPD	20.9	L	5-20	2	.004	.5	.004
			31.9		20-40	3	.006		.009
		LOP	31.1	M	20-40	1	.006	.05	.0003
	1986	TPC	4.8	M	0-5	2	.0009	.2	.0004
			10.2		5-20	3	.0019		.0011
			23.6		20-40		.0046		.0027
			14.0		20-40	2	.0027		.001
		SPD	4.7	M	0-5	1	.009	.6	.006
			10.2		5-20	3	.002		.004
			23.6		20-40	4	.005		.011
			10.2	L	5-20	2	.002		.002
			3.8		20-40	3	.0007		.001
		CPC	5.5	M	20-40	2	.001	.2	.0004
ROADS	PERMANENT		61.4	M	20-40	3	.012	1.0	.036
	TEMPORARY		21.3			4	.004		.012
								TOTAL	.229

Table 13 (B) : Summary of Land-Use "RISK" Calculations

Land-Use By Year: (Jones Meadow)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	11.1	*	*	*	*	*	*	*	10.5	*
M	*	*	*	*	*	*	*	*	*	*
L	*	*	*	*		*	*	*	*	*

Table 14 : Rubber Partial Cut (Hectares)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	4.0	*	*	*	*	*	*	*	*	*
M	*	*	*	*	*	*	*	*	*	*
L	*	*	*	*	*	*	*	*	*	*

Table 15 : Tractor Clear Cut (Hectares)

Erosion Class	Year Of Activity									
	80	81	82	83	84	85	86	87	88	89
H	4.0	*	*	*	*	*	*	*	5.4	*
M	*	*	*	*	*	*	*	*	*	*
L	*	*	*	*	*	*	*	*	*	*

Table 16 : Site Preparation Dozer (Hectares)

"RISK" CALCULATIONS FOR LAND-USE HISTORY

JONES MEADOW, LUBRECHT FOREST

"RISK" CALCULATIONS BY YEAR	YEAR	ACTIVITY	HECTARES	EROSION CLASS	SLOPE	"RISK" VALUE	AREAL % OF BASIN	RECOVERY COEFFICIENT	CUMULATIVE "RISK" VALUES
	1980	SPD	4.0	H	5-20	4	.007	.05	.001
	1988	RPC	11	H	5-20	3	.017	.3	.02
		SPD	5.0	H	5-20	4	.008	.8	.026
ROADS	PERMANENT		4.2	M	5-20	3	.006	1.0	.018
	TEMPORARY		2.1			4	.003	.9	.012
								TOTAL	.08

Table 17 : Summary of Land-Use "RISK" Calculations
(1980-1989)

LEGEND
SPD- SITE PREP. DOZER
RPC- RUBBER TIRE PARTIAL CUT

"RISK" Formulas
$\sum_{n=L}^{H}$ %WS * "RISK" Value (Geology) (a) "RISK" Formula Based on Geology
$\sum_{i=1}^{n}$ %WS * "RISK" Value (Activity) * RC (b) "RISK" Formula For Activity Based on Slope/Geology

Table 18 : Formulas For "RISK" Calculations

CONCLUSIONS

A risk analysis methodology was developed and applied to two small, third-order watersheds in western Montana. All spatial information was digitized using Geographic Information Systems. Spatial analysis was conducted using GIS to obtain values required for risk calculation.

Risk values for Howard Creek and Jones Meadow were determined to be 1.73 and 2.1 respectively. These numbers can be used as a comparative tool, on a relative basis, to evaluate watershed sensitivity with respect to potential nonpoint source pollution problems. Specifically, risk values based on soil erodibility/slope may be combined with those resulting from past land-use activity. This yields a risk assessment value for the entire watershed in it's current condition.

After an initial evaluation is made to obtain the existing risk value, the model can be used as a planning tool. The risk value may be increased by calculating additional land-use risk values for planned activities.

The objective of the risk calculation is to minimize potential impacts that might incur from planned land management activity. Ideally, the overall risk value for a given watershed be as low as possible.

Furthermore, areas which are innately more erodible should be avoided. The GIS can produce maps of sensitive areas and if possible, they should be recognized and avoided during planning.

However, it is left to the user of this methodology to determine whether or not a given risk value is acceptable for planning purposes. This thesis merely suggests a means of signaling caution for areas that are sensitive by nature or have been subjected to extensive land-use in the past.

The results of the initial risk assessment application for the pilot study areas is encouraging. However, additional research is required to refine the mechanics of the model. Other physical phenomena, such as precipitation and delivery distance between activity and stream channel, warrant consideration for possible inclusion into the risk matrix. Furthermore, the development of management guidelines concerning resulting risk values is necessary.

Runoff processes and cumulative effects should be estimated as functions of soil, vegetation, and land-use activity and simulated as past physically based elements of the natural system on a temporal and spatial basis (Walsh, 1985). Since watershed monitoring can be extremely expensive and time consuming, the use of a risk assessment methodology is suggested.

Organizing data in a geographic information system and integrating risk analysis, permits the appraisal of nonpoint pollution over extensive areas.

The capability of advanced GIS technology allows editing, data manipulation, and spatial analysis to be done in a timely and cost efficient manner. Land management agencies, including the U. S. Forest Service, are moving forward in the adoption of GIS as a tool to support natural resource management (Bailey, 1988). The ability to turn spatial information into a digital data and then to edit, store and display the data as maps or color images in combination with risk analysis makes this procedure an invaluable tool for the management of water resources.

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APPENDIX A: TABLE INTERACTION

The following discussion summarizes the interaction of the information contained in Tables 2-17. Tables 2 and 3 are used to calculate the risk value of the watershed based soley on geology. The results are depicted in Table 11. Tables 4-16 include a summary of land-use activity, by year, for both pilot watersheds. The land-use values are multiplied by recovery coefficients in Table 12, and the results are summed in Table 13/13A and 17 for Howard Creek and Jones Meadow respectively. Total risk values for geology and land-use are combined and the resulting "cumulative" risk value for both watersheds are shown in Table 11A (See Figure 14).

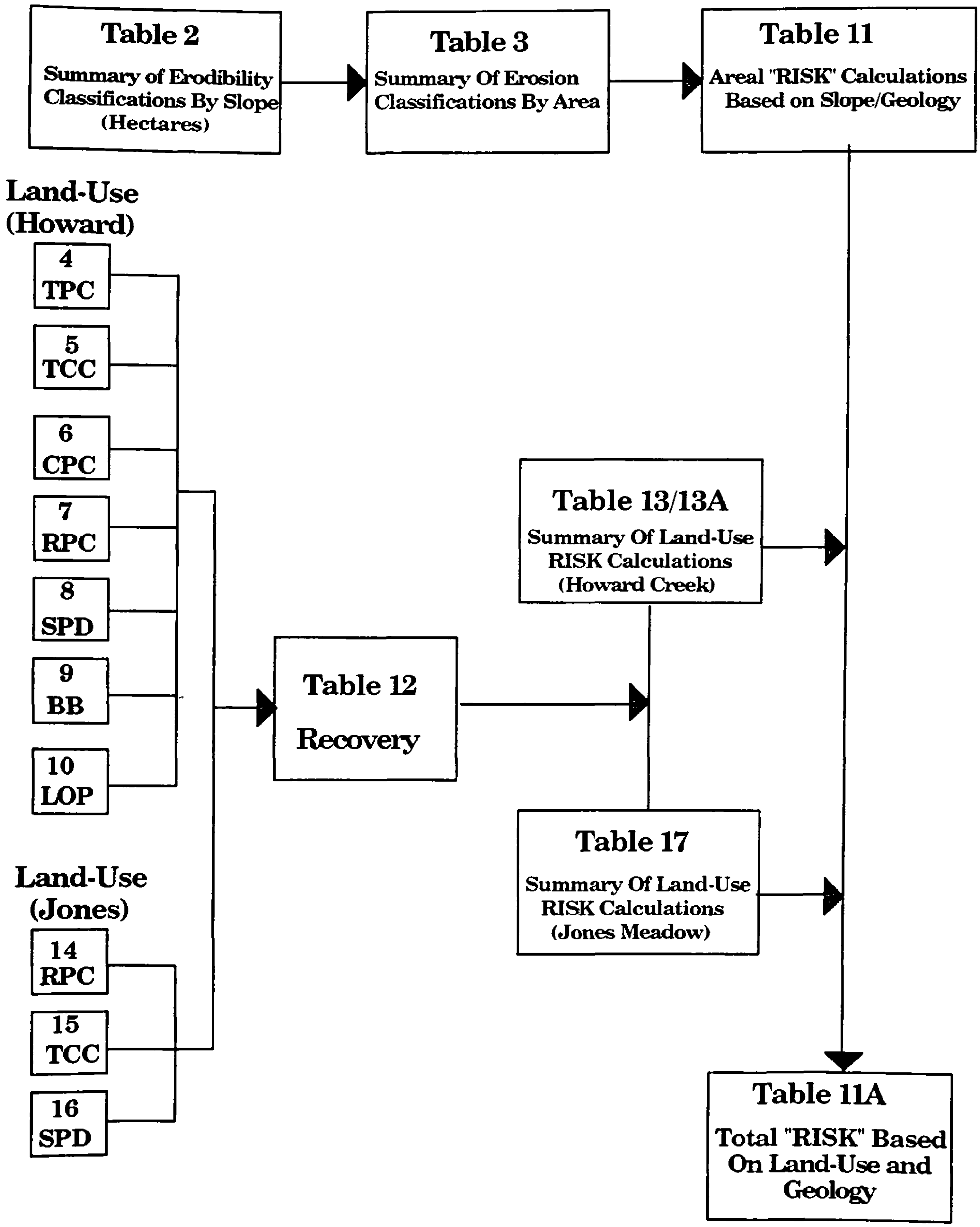

Figure 14: Summary Of Table Interaction