A method for analyzing environmental effects of impacting activities
by Louis Theodore Egging

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Industrial and Management Engineering
Montana State University

Abstract:
The public land manager is directed by law to manage for multiple use and sustained yield of goods and services. This must be accomplished without long term detriment to the environment. He must also analyze the environmental consequences of any proposed management action. These impacts might not only be short term effects, but may be long range as well.

The ecosystem, impacted by the activity, is a complex maze of relationships. An impact directed at one resource will influence not only that resource but others as well. Some effects are immediate, others are not apparent until after a considerable time period. This complexity requires the ecosystem to be analyzed as a whole. It must be perceived as a complete system.

A method is proposed to help the manager analyze the environmental impacts of an activity. Using systems analysis and computer simulation techniques, a two-phased simulation model is presented. This approach models the activity as the micro phase. If desired, this phase can be modeled in detail suitable for productivity optimization, or it can be modeled simply. The macro phase of the approach models the ecosystem. This phase simulates the dynamic response of the ecosystem to the impact.

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ABSTRACT

The public land manager is directed by law to manage for multiple use and sustained yield of goods and services. This must be accomplished without long term detriment to the environment. He must also analyze the environmental consequences of any proposed management action. These impacts might not only be short term effects, but may be long range as well.

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Chapter 1

INTRODUCTION

Multiple Use Management

Society's growing concern for "conservation" and "ecology" has caused the U.S. Forest Service to pursue with renewed vigor, the directive of "multiple use" and "sustained yield" in its public land management. This policy was established by Congress in 1960 when Public Law 86-517 was handed down on June 12. This, the Multiple Use - Sustained Yield Act states in part:

> It is the policy of the Congress that the national forests are established and shall be administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes.
>
> The Secretary of Agriculture is authorized and directed to develop and administer the renewable surface resources of the national forests for multiple use and sustained yield of the several products and services obtained therefrom. (USDA, 1963).

The objective of multiple use management is to manage the resource complex for the most beneficial combination of both present and future uses. This idea of deriving maximum benefit from a given resource base is not new, but it becomes more important and complicated as the competition for limited and interrelated resources increases.

While the basic concept of multiple use is generally accepted, its application is still a difficult process. As outlined by Ridd (1964) the term "multiple use" may be applied to areas of land or to particular resources available on that land. When applied to land areas, it refers to the production and management of the various resources or resource combinations on that land area. These managed resources may be competative or complementary to one another. When applied to resources, "multiple use" refers to the various uses of those resources. For example, the water resource can be used for irrigation, municipal and industrial water, esthetics or recreation. Timber can be used for lumber, pulpwood, esthetics or recreation. Figure 1 (Ridd, 1964) provides an overview of possible relationships between resources and resource uses.

Multiple use land management involves both the multiple use of individual resources and the multiple use of the land areas. A demand for a particular resource for a specific use will place demands on a land area where that resource is produced.

When speaking of multiple use, the four resources; water, timber, forage, and wildlife, are generally discussed along with recreation. However, recreation is actually a use to which the resources are put. This recreational use is centered primarily on one resource; however, the "quality" of the recreation is influenced by several resources comprising the environmental complex.

In managing a land area, no resource or use can be isolated. Any management action, even when directed at one resource, is going to have an affect on the other resources and their uses. A logging operation started in any forest will affect not only the timber resource, but also

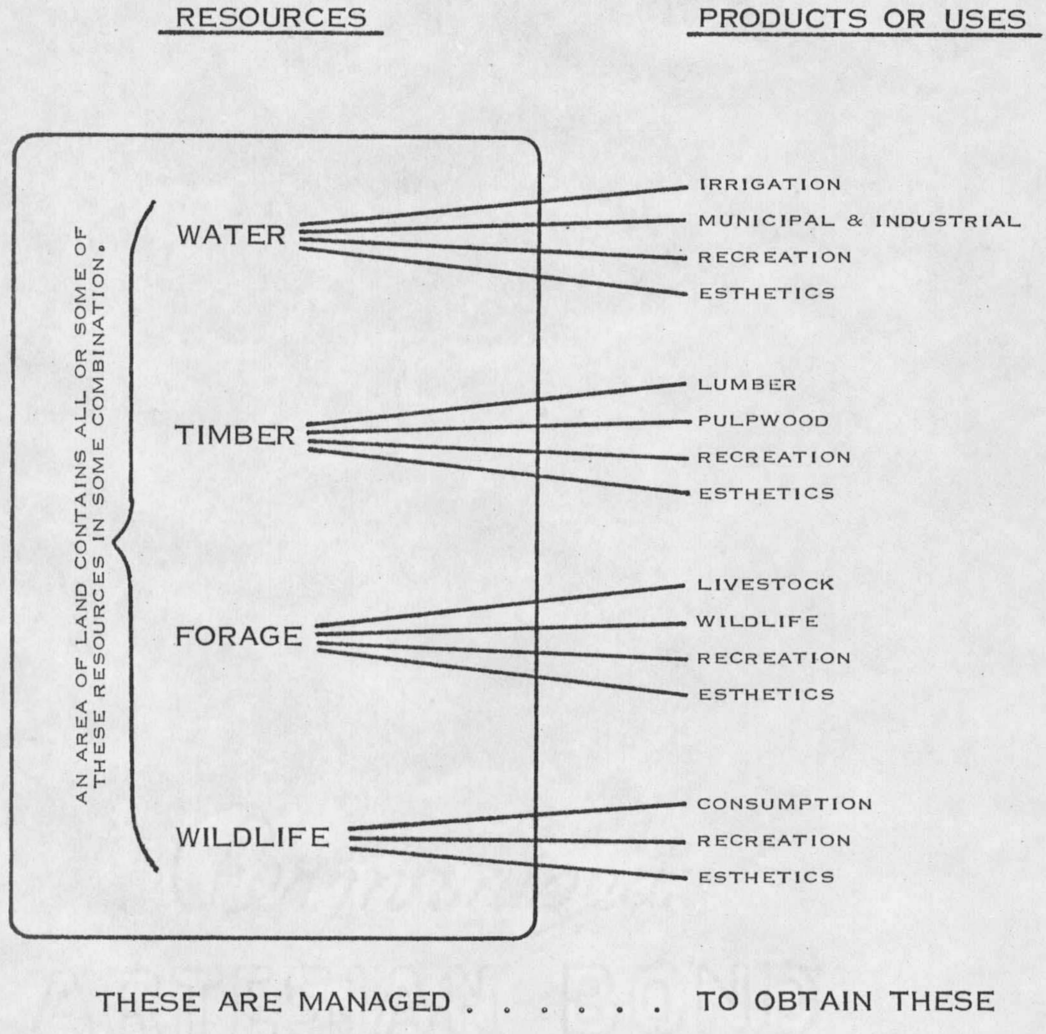

Figure 1. Resources and Resource Uses

the water, forage, and wildlife resources. For this reason, the overall area with all its resources must be viewed as a whole in making any management decisions on a proposed activity.

Land Use Planning

Over half the land area in the United States is in forest, brush, or rangeland. Of this area, the Forest Service has the responsibility for managing 187 million acres to obtain sustained flows of goods and services under the multiple use management concept. This philosophy requires the balancing of various land uses to minimize conflicts while providing for a sustained yield over an extended time period.

With growing pressures from timber and cattle interests for specific resource uses, the Forest Service became more and more production oriented in its management. This was at times accomplished to the long term detriment of the total environment. Timber and forage production increased to satisfy demand. Irreversible consequences to the ecosystem were not a prime consideration.

In 1968, Congress enacted into law the National Environmental Policy Act. This Act directs the land manager to assess his management activities from an environmental impact standpoint. The Act declared it "a national policy [to] encourage productive and enjoyable harmony between man and his environment; [and] to promote efforts which will prevent or eliminate damage to the environment" (USDA, 1974:243). "This policy is one of balancing the amenities or quality of life against the continued use of renewable resources" (Leopold, 1975:609). Recognizing that man's activities do impact the interrelationships of the ecosystem components, the manager must prepare a detailed statement of the environmental impacts of any proposed action that might have an effect on the quality of the human environment.

The Forest Service has been preparing "Multiple Use" or "Land Use" Plans to implement these directives. A Land Use Plan is intended to be a planning document directed at a specific area of land. Resource capabilities are identified, demands and resource uses are estimated for the present and future, and management alternatives are identified and presented to the public for scrutiny. These documents are prepared and presented to the public soliciting and encouraging public involvement and participation in determining management direction. Coupled with the Land Use Plan is the Environmental Impact Statement which must be prepared for any proposed management action. This statement is an attempt to identify and quantify the environmental impacts of the activity. These impacts must include not only the short term immediate effects, but also the long range effects of the activity.

The public land manager is directed by law to manage on a multiple use and sustained yield basis. He must analyze and document the environmental consequences of proposed activities. This can be a difficult task as the system being impacted consists of numerous interacting relationships. The area must be viewed as a whole in making management decisions.

The Problem

The problem is basically that of identifying the impacts or effects of a given activity upon an area's ecosystem. The impacts cannot be limited only to short term immediate effects, but must also include the long range time dependent effects. The system being impacted is a complex maze of interrelated interacting cause-effect relationships.

As an example of man's activities impacting the ecosystem, we might look at timber harvesting. The interactive influences of timber harvesting on the system might be illustrated as in Figure 2. For measurable impacts, we are primarily interested in the effects on the other resources and resource uses for the area. The harvesting of timber from a given area and the method used in harvesting will have a direct effect upon other resources such as water quality and quantity, timber availability now and in the future, forage quality and quantity, and the amount of type of wildlife present. These can be both short and long range effects.

In addition to these primary effects, the changes brought on by the primary influences in the available resources will also cause secondary changes in the resources and uses of the area. Recreation and esthetics will be influenced secondarily. Changes in the resources will change the recreational appeal of the area. There are also secondary

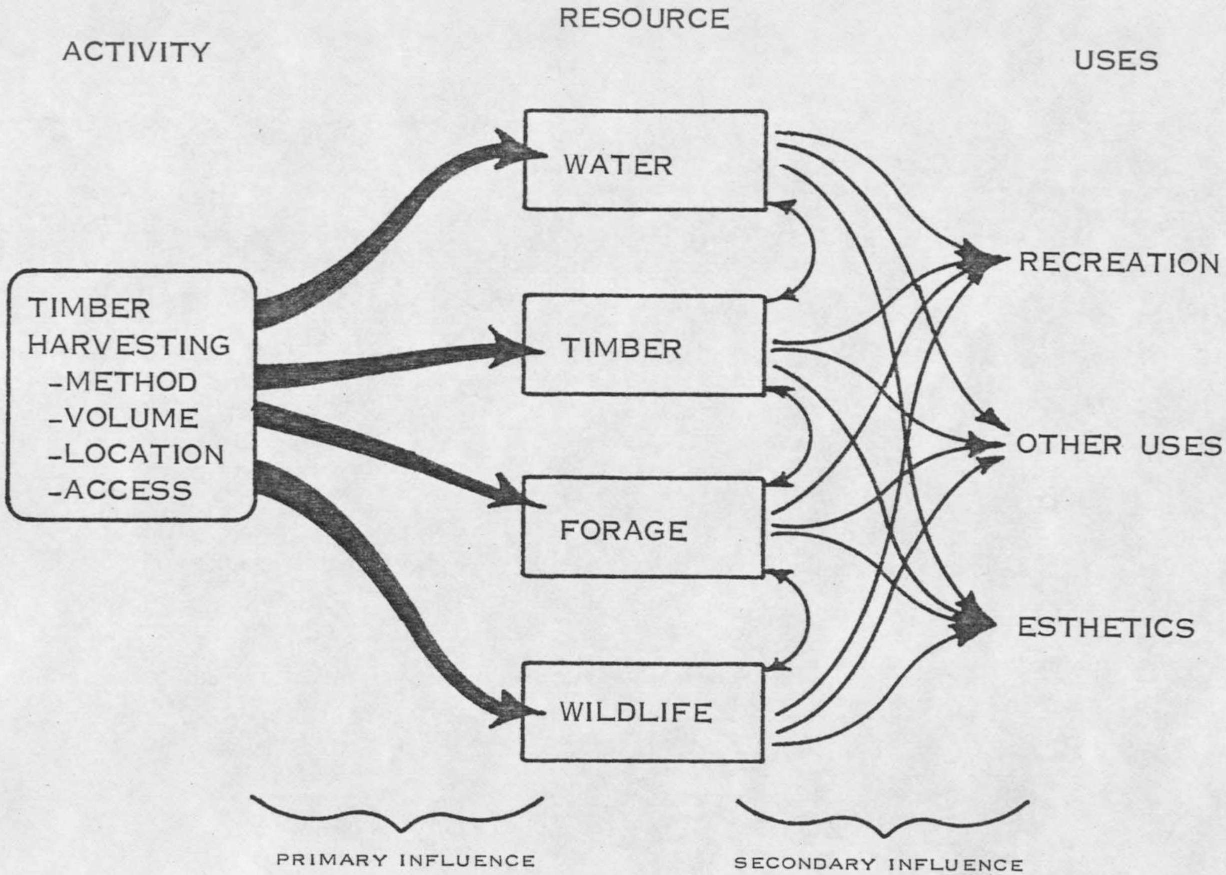

Figure 2. The Influence of Timber Harvesting Activity on Resources and Uses

influences between resources, that is, a change in water quality might affect timber or wildlife.

A natural force which will impact the system in a similar fashion might be fire. Fire will remove vegetation much like timber harvesting. The manager is interested in knowing how sensitive the ecosystem is to fire. How will the system respond to suppression activities: suppression road construction, fire breaks, etc? What happens if a major portion of a drainage burns? Once again there are both short and long range effects which must be evaluated.

It is this maze of complex, interacting influences which makes multiple use management such a difficult principle to practice in a "real" world situation. The resources of an area are affected over a period of time when a particular activity impacts the system. A change in one resource causes change in the other available resources and their uses.

In this study, a procedure and methodology is developed to aid the manager in analyzing the environmental effects of an impacting activity. The area is viewed as a whole with resource responses portrayed over extended time periods.

Chapter 2

SYSTEMS AND SIMULATION: A METHOD

With continued advances in computer technology and capabilities, insights are being gained into complex problems by the use of systems analysis and simulation. Major components of the system can be identified and the relationships between components quantified. These can then be organized in a manner allowing the designer and manager to monitor the dynamic responses of the modeled system for extended time periods. The sensitivity of the system to various inputs or decision criteria can be presented and evaluated.

The Systems Approach

Much has been written in recent literature on systems analysis. Its major impetus began with the success of military scientific teams during the second World War. After the war, much effort was put into applying this kind of thinking to nonmilitary problems. This school of thought was labeled "operations research" and was applied to rather small problems in production, marketing, and finance. Following these initial applications of science to management, the electronic computer grew in its capabilities.

As the computer grew, so did the scientist's ability to look at and solve larger and more complex problems. This increased ability led to the expansion of the scientist's perspective, out of which grew what is now commonly referred to as the systems approach. C. West Churchman

(1968) in his book, The Systems Approach, points out in the preface:

> As the scientist's perspective widened, he began to think of his approach as the "systems approach". He saw that what he was chiefly interested in was characterizing the nature of the system in such a way that the decision making could take place in a logical and coherent fashion and that none of the fallacies of narrow-minded thinking would occur. Furthermore, using his scientific knowledge, he expected to be able to develop measures which would give as adequate information as possible about the performance of the system.

Throughout this growth process, the word "systems" has been defined in many different ways by people claiming to be "experts" in the field. No matter how it is defined, most people will agree that "a system is a set of parts coordinated to accomplish a set of goals" (Churchman, 1968:29). From this definition, anything that operates for a common purpose can be thought of as a system. A system can be simple or it can be extremely complex. This body of techniques and theories developed for analyzing systems has come to be known as systems analysis.

Churchman (1968:231) concludes his book by stating four principles of a deception-perception approach to systems:

1. The systems approach begins when first you see the world through the eyes of another.
2. The systems approach goes on to discovering that every world view is terribly restricted.
3. There are no experts in the systems approach.
4. (He presents his own bias) The systems approach is not a bad idea.

Though there is no universally right way to describe a system, a great deal can be learned by a clear statement of the approach taken so that its opponents may state their opposition in as cognate a fashion as possible. Churchman concludes that the systems approach really consists of a continuing debate between various attitudes of mind with respect to society.

In looking at systems, Churchman stresses the importance of the scientific approach. For this approach, he identifies five basic considerations. These include the total system objectives; the systems environment; the resources of the system; the components of the system; and the management of the system. These considerations will be explored further in the next chapter on the development of the systems macro-model.

As noted by Bjerke (1973), Churchman's approach also implies the need for interdisciplinary study teams. When studying complex problems, each discipline with its specializations can contribute to a clearer understanding of the whole system. However, a truly worthwhile systems analysis can be developed only when each discipline begins to see the world through the eyes of the other, and recognizes that his world view might be terribly restricted.

The book by Kenneth E.F. Watt (1966), Systems Analysis in Ecology, is a collection of works done by nine writers. This work is a comprehensive account of the need for and the benefits of applying systems analysis to the field of ecology and environment. In an ecological system, it is seen that everything affects everything else, and the complexity of interlocking cause-effect pathways confronts the analyst with a superficially baffling problem in scientific analysis. It is this interlocking network which is the most identifying characteristic of the ecological system. For the ecologists, an operational definition of a system is "An interlocking complex of processes characterized by many reciprocal cause-effect pathways" (Watt, 1966:2). A principal attribute of an ecological system is that we can only understand it by viewing it as a whole.

Watt identifies some of the most important concepts of systems thinking insofar as they can be applied in ecology. Perhaps the most basic component of this thinking is the operating maxim...extremely complex processes can be easier understood by dissecting them into a large number of very simple components. A second important notion is complex historical processes in which all variables change with time, can be dealt with in terms of recurrence formula that express the state of a system at time t+1 as a function of the state of the system at time t. Thus the understanding of the process is acquired not in terms of its entire history, but rather in terms of the cause-effect relationships that operate through a typical time interval.

Watt points out that another important tenet of systems analysis is that optimization of the process is the central aim of research. Combining this optimization aim and the notion of recurrence relationships leads to the idea that "the central aim of systems analysis is that of making the optimal choice from among an array of alternative strategies at each of a sequence of times" (Watt, 1966:4). This leads to the idea of multistage decision process. The multistage decision process, due to its high degree of dimensionality and the need to use an iterative process for solution, indicates the use of an electronic computer and simulation for its analysis.

Watt points out three reasons for the prominence of simulation as a tool to the systems analyst. Most systems optimization problems are so complex they cannot be worked out in any straightforward fashion on paper. Therefore, a system of trial and error is used to solve them. Various combinations of variables are tried to determine how the system will react in given conditions. This could not be done with actual experiments in the real world because of the prohibitive costs. Secondly, apart from the cost, there is often not enough time available to follow the experiments through to completion especially if there are repeated experiments to be conducted. Finally, the actual experiments may not be feasible because the outcomes might have a "ruinous" effect on the system being experimented with.

The book goes on to discuss such subjects as the organization and management of complex systems studies, the acquisition of data, and the building of models. These subjects are presented by the individual authors in the light of their individual experiences. Much of the discussion is built from actual studies which were conducted on ecologically related problems.

Systems and Simulation

Simulation is an important tool of the systems analyst. However, it should be kept in mind that systems analysis does not mean you must use simulation, and systems analysis is not equated to simulation. There is much knowledge and understanding to be gained about the system merely by studying it from the systems point of view, without carrying the study through to simulation. For this research, simulation is used so systems simulation in general will be discussed here.

James R. Emshoff and Roger L. Sisson (1970) introduce the reader to simulation models in their book, Design and Use of Computer Simulation Models. This book takes the reader step-by-step through the background and technical skills required to learn and use simulation. The reader is introduced to simulation as a management aid and how it is used in decision making processes. There is discussion of the technical aspects of using simulation and general discussions of the nature and uses of various types of simulations. Much of the discussion centers around detailed examples explaining basic techniques.

In Chapter 6, the authors review some of the popular simulation languages. The advantages and disadvantages of the various languages are compared by a review of the process of translating a problem into a simulation program. It should be noted that though the use of an established language is not necessary for simulation, it does have some definite advantages to the user. Probably the major advantage in using a canned simulation language is user time saved in preparing and debugging the simulator. As noted by Emshoff and Sisson (1970:117), "It is not uncommon for this reduction to be a factor of ten". The simulator resulting from the use of an established language is also generally easier to modify than one written in a multipurpose language such as FORTRAN.

There are other dramatic changes which occur as a result of using specially designed simulation languages. As the authors note, "Some of these are actually languages in the more general sense; that is, they are useful in describing a situation independent of the fact that they can be translated by a computer into machine language" (Emshoff, 1970:117). These languages have a "syntax" and a "vocabulary" which can be quite descriptive. It is often the case that the user, after becoming experienced with a simulation language, will begin to think in that language. Thus the language becomes useful in the actual problem formulation.

The languages considered by the authors include:

GASP — a set of subroutines in FORTRAN that performs functions useful in simulations.

GPSS — a complete language oriented toward problems in which items pass through a series of processing and/or storage functions (latest version: GPSS/360).

SIMSCRIPT — a complete language oriented toward event-to-event simulations in which discrete logical processes are common (latest version: SIMSCRIPT II).

CSMP — a complete language oriented toward the solution of problems stated as nonlinear, integral-differential equations with continuous variables (CSMP permits a digital computer to simulate an analog computer).

DYNAMO — a complete language oriented toward expressing macro-economic models of firms by means of difference equations.

JOB-SHOP SIMULATOR — a program package that can be set up to represent a variety of job shops by means of parameters (Emshoff, 1970:139).

These languages can be classified in terms of orientation and scope or generality of application as illustrated in Figure 3.

FORTRAN is included in Figure 3 as an example of a multipurpose computer language which can be used to write simulation programs. Though it is not a simulation language in itself, FORTRAN is a widely used language and has the capability of representing any sort of state-change process. GASP and SIMSCRIPT are simulation languages that are very general. Both are written in FORTRAN and have the capability of doing anything that FORTRAN can.

On the other end of the graph, DYNAMO and the JOB-SHOP SIMULATOR are much more problem oriented. In fact, the JOB-SHOP SIMULATOR is so specific that it is not really a simulation language at all. It is actually a simulation program that is written general enough to adequately describe various job-shop situations and sizes. DYNAMO as a language is oriented toward problems formulated in terms of nonlinear

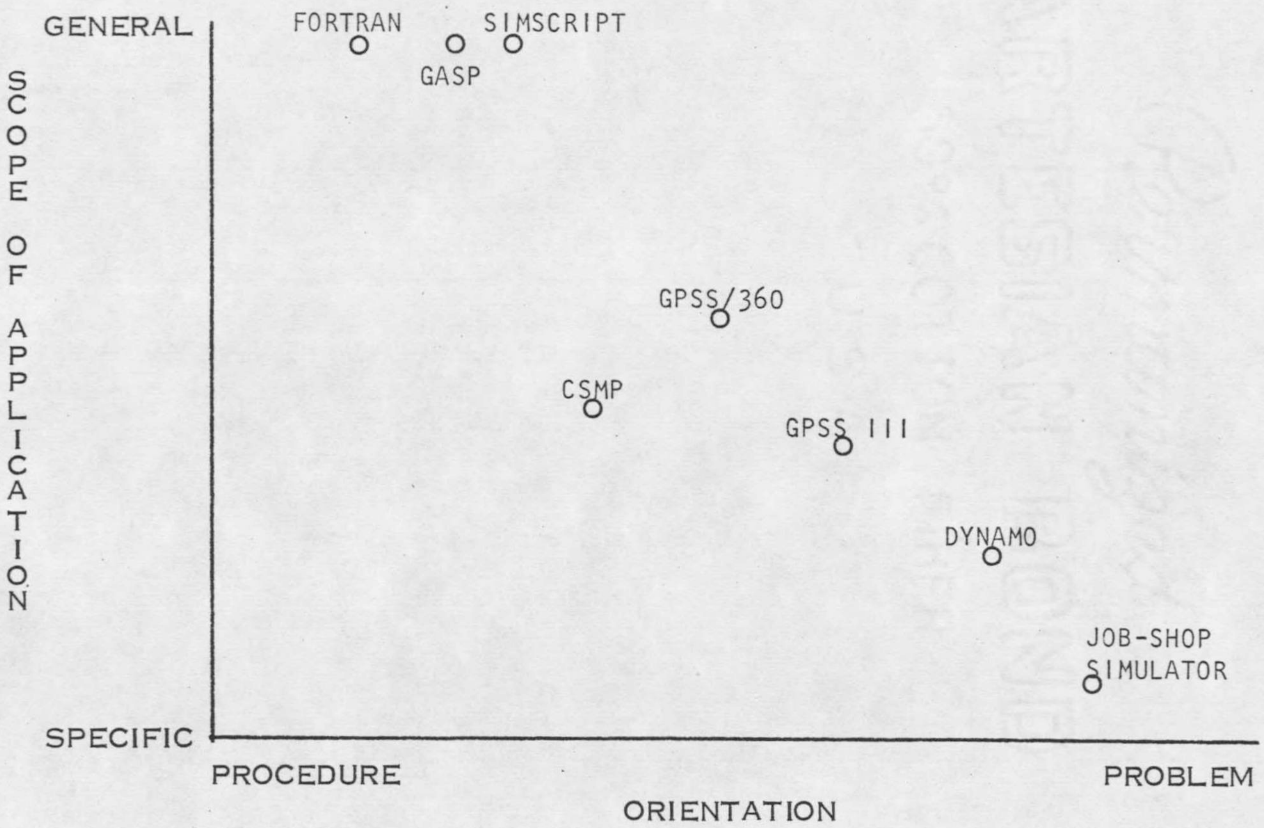

Figure 3. Classification of Simulation Languages (Relative Location Only)

differential or difference equations. It handles variables that are continuous or nearly so over their entire range.

One distinction that should be made is how a simulation language perceives the problem. As Emshoff and Sisson point out, the variables in a simulation may change in any of four ways:

1. In a continuous fashion, but at any point in time.
2. In a discrete fashion, but at any point in time.
3. In a discrete fashion and only at certain points in time.
4. In a continuous fashion, but only at discrete points in time.

GASP II can be thought of as a discrete simulation language where the variables can change at any point in time or at specific points in time depending upon the discretion of the user. DYNAMO is primarily a language where the variables change in a continuous fashion but only at certain points in time. A newly revised version of GASP, GASP IV, combines both the continuous and discrete possibilities of variable changes. In fact, with GASP IV the variables can change either discretely, continuously, or both discretely and continuously. The variables can be changed at specific points in time or at variable points in time. GASP IV will be discussed in greater detail in a later section.

Systems Dynamics

J. W. Forrester (1961; 1968) has done much to improve the "art" of describing and simulating large scale macro-economic problems. He has named his form of analysis and simulation "Industrial Dynamics". One might begin by looking at some concepts about organization, decision making, and the relationship between information and managing. Management then can be thought of as "...the process of converting information into action" (Forrester, 1961:93). The conversion process is what we generally recognize and define as decision making. The success of the manager depends upon what information is available to him and how he converts it into action. Forrester (1961:38) has made this observation:

> The manager sets the stage for his accomplishments by his choice of which information sources to take seriously and which to ignore. After choice has been made of certain classes of information and certain information sources to carry the highest priority, managerial success depends on what use is made of this information. How quickly or slowly is it converted to action? What is the relative weight given to different information sources in the light of desired objectives? How are these desired objectives created from the information available?

Forrester sees the modern manager not as converting the information himself into action, but rather he outputs a stream of information or decisions which directs the efforts of the human or nonhuman elements of the organization towards some goal. This might be illustrated as the information flow and feedback process as in Figure 4.

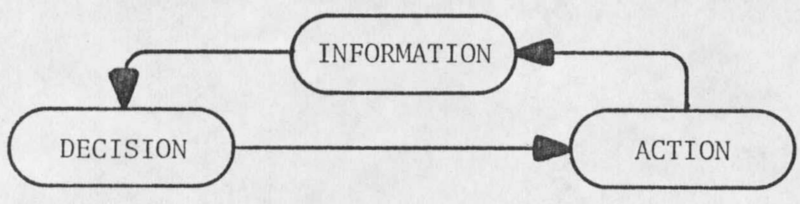

Figure 4. Decisions and Information Feedback

This illustrates an important characteristic of the information network in a firm. The decision that leads to control over a physical process is based on information about the prior state of that process. Information about the state of the system is said to be fed back through the information network to the decision point. Forrester (1961:14) defines the information-feedback system in the following manner. "An information-feedback system exists whenever the environment leads to a decision that results in action which affects the environment and thereby influences future decisions."

In studying feedback processes, the investigator deals with the way information is used for the purpose of control. The information-feedback control process is a continuous regenerative process with new results leading to new decisions. This cycling keeps the system in continuous motion. These systems as pointed out by Forrester need not behave in a predictable and satsifactory manner. In fact, a complex information-feedback system designed by happenstance or in accordance with what may be intuitively obvious will usually be unstable or ineffective.

There are three factors or characteristics of a system that result in the system's behavior. These include structure, delays, and amplification. As might be expected, the structure of the system tells how the parts are interrelated. Delays exist in the generation and transmission of information. Delays are further encountered in the information conversion or decision making process and in taking action on the decisions. Amplification as noted by Forrester usually exists throughout such systems, especially in the decision making process of our industrial and social systems. "Amplification is manifested when an action is more forceful than might at first seem to be implied by the information inputs to the governing decisions" (Forrester, 1961:16).

This concept of servomechanisms or information-feedback systems is one of the most important foundations for industrial dynamics. Until recently, the effect of time delays, amplification and structure on the behavior of systems was of little concern. Only now are investigators becoming aware of the fact that the interactions between system components can be more important than the components themselves.

A second foundation on which industrial dynamics was developed is a better understanding of the decision making process gained during the 1950's with the automation of military tactical operations. A third foundation is the development of experimental approaches to understanding complex systems. This has been accomplished through the use of models. The fourth foundation to the development of industrial dynamics has been the growth of the electronic computer and its computative capabilities.

From these foundations, Forrester has developed the industrial dynamics approach to enterprise design. This approach progresses through the following steps:

1. Identify the problem.

2. Isolate the factors that appear to interact to create the observed symptoms.

3. Trace the cause-and-effect information-feedback loops that link decisions to action to resulting information changes and to new decisions.

4. Formulate acceptable formal decision policies that describe how decisions result from the available information streams.

5. Construct a mathematical model of the decision policies, information sources, and interactions of the system components.

6. Generate the behavior through time of the system as described by the model (usually with a digital computer to execute the lengthy calculations).

7. Compare results against all pertinent available knowledge about the actual system.

8. Revise the model until it is acceptable as a representation of the actual system.

9. Redesign, within the model, the organizational relationships and policies which can be altered in the actual system to find the changes which improve system behavior.

10. Alter the real system in the directions that model experimentation has shown will lead to improved performances (Forrester, 1961:13).

Probably the most important step of this approach as with any other is the definition of the problem. Once the problem is defined, the manner in which it is defined will affect how it is perceived and studied by any investigating team.

The last two steps of this approach are worth mentioning. Any conceptual model of a system, be it computerized or not, is only as good as it helps the user gain a fuller understanding of the operation of the system. The objective of building the model should be to gain this understanding and hopefully apply this understanding to the system and thereby improve its performance.

To help gain an understanding of the structure of any feedback system, Forrester (1968:7-1) suggests the use of the flow diagram.

> Feedback systems are elusive. Their structure and dynamic implications are hard to grasp and to keep in mind. One needs as many viewpoints as possible. From each viewpoint he may see something that was missed in a different exposure. A verbal description is one approach to a system; equations describing behavior of the separate parts is another. But to show the relationship between the parts and to accentuate the loop structure of a system, the flow diagram is best.

The flow diagram is not intended to show minute details of the system's workings but rather give broader perspective of the problem. The flow diagram should show how the cause-effect interactions of the system are interconnected to produce the feedback loops and how these loops are interlocked to create the system.

A simplified summary of this flowcharting method is represented in Figure 5. This summary illustrates the representation of levels; flows that transport the contents of one level to the next; decision functions that control the rates of flow between levels; and information channels that connect the decision functions to the levels. Also represented are auxiliaries which transform the information obtained from levels to a workable form for decision making.

Using this basic scheme of charting, complex systems can be

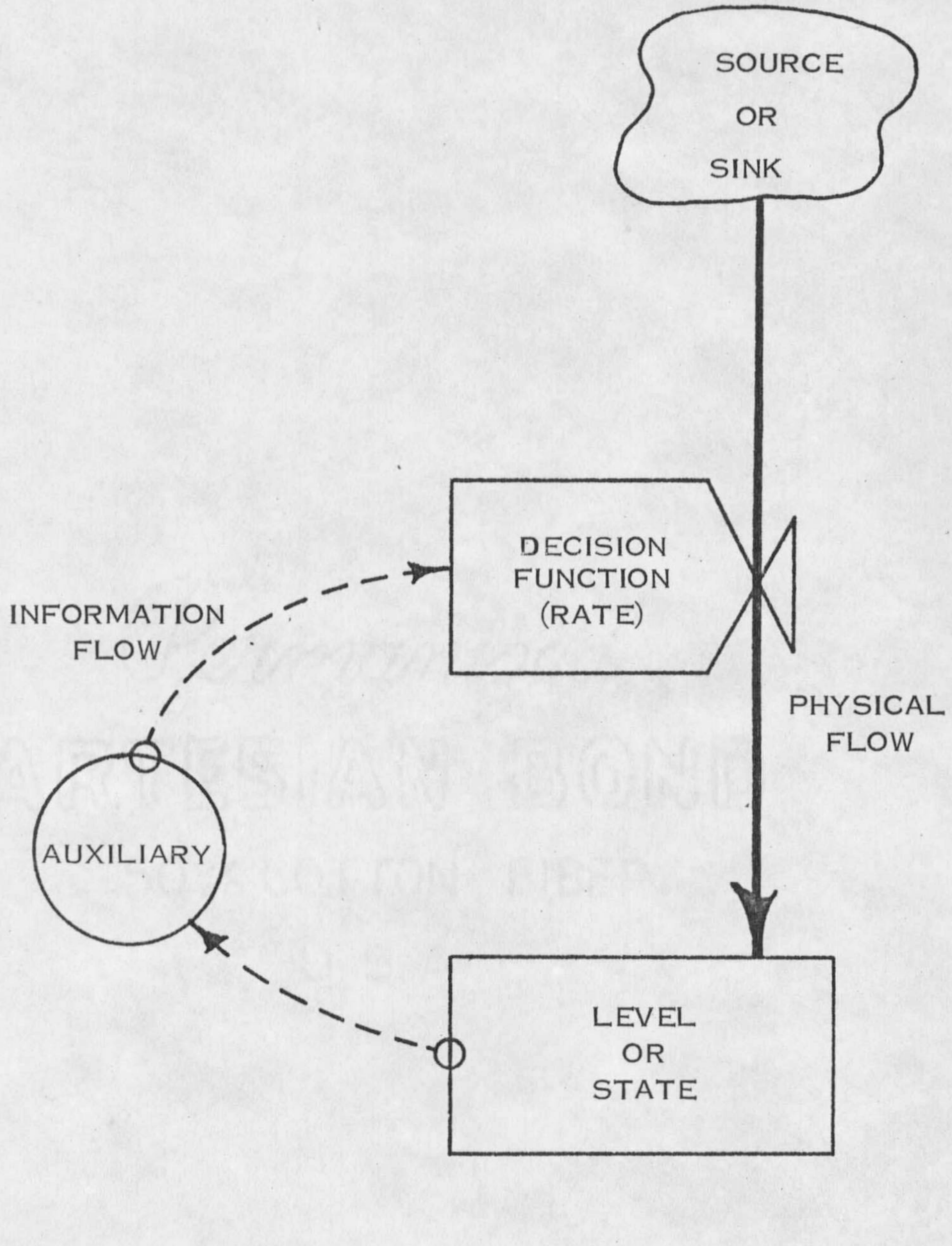

Figure 5. Forrester's Flowcharting Method

represented. This method will be used in the model development portion of this thesis.

GASP IV

GASP IV is a FORTRAN based simulation language designed for modeling a system in two dimensions: time and state-space. The language was developed by Alan B. Pritsker and Nicolas R. Hurst at Purdue University as an extension of the simulation structure of the discrete event language, GASP II (Pritsker and Kiviat, 1969; Pritsker and Hurst, 1973; Pritsker, 1974).

As outlined by Pritsker (1974) in his book GASP IV, a necessary first step in building a GASP IV simulation model is breaking down time and state-space into manageable elements. For the time dimension, this decomposition involves defining events and changes that will result when the event occurs. The user must specify the mathematical-logical relations that transpire at an event occurrence and the casual mechanism by which events occur. He is relieved, however, from the need for sequencing events or modeling the timing of events during the simulation. This is provided by the GASP IV routine.

In the state-space dimension, the system model is broken down into entities, which can be described by their attributes. These attributes can be further classified as discrete or continuous. The discrete attributes are characterized by their static nature between event times. That is, their values remain constant between event occurrences. The value of a continuous attribute is dynamic, for its value changes over the time span between event occurrences. These attributes represent the dynamic behavior of the system being modeled and are referred to as state variables. These state variables can be thought of as levels in Forrester's Industrial Dynamics model. The user is compelled to specify only the relationships whereby these values change. This can be done in terms of difference or differential equations. GASP IV provides the mechanism for integrating these relationships over time and thereby updating the values of the state variables.

The philosophy of GASP IV grows out of a broader definition of event than is normally attributed to a discrete-event language. An event is defined as:

> A point in time beyond which the status of a system cannot be projected (Pritsker, 1974:13).

Though events generally cause change in the status of the system, they can also occur at decision points where the decision is made not to change the status.

It is useful to describe events in terms of the mechanism by which they are scheduled. There are those that occur at a specified point in time which has been projected by the user. This type of event is referred to as a time-event and is commonly thought of when working with "next event" or "discrete" simulation models. Another type, referred to as state-events, occur when the system reaches a specified state. These events are not scheduled to occur at a specified point in time, as events, but occur when state variables meet predetermined conditions. In GASP IV, time events can initiate state events, and state events can initiate time events. This is left to the discretion of the user.

As a GASP IV simulation run progresses, the values of the state variables are computed at small time steps. The values of the discrete variables are computed at scheduled event times. When an event, either state or discrete, occurs, the status of the system can change: by altering the values of state or discrete variables; by altering the relationships that exist between variables; and by changing the number of entity variables that exist. Between event times, only the values of the continuous state variables can change.

The formalized world view of GASP IV can be summarized as follows:

> The world view specified that the status of a system be described in terms of a set of entities, their associated attributes, and state variables. The GASP IV simulation philosophy is that a dynamic simulation can be obtained by modeling the events of the system and by advancing time from one event to the next (Pritsker, 1974).

The fact that GASP IV is a FORTRAN based simulation language makes it attractive to the experienced user. GASP provides the framework for analyzing a complex problem but gives the user complete control of the system and with programming expertise, the extended capabilities of the FORTRAN language.

Approach to the Problem

The land manager is faced with the problem of identifying and evaluating the effects of a given activity upon an area's ecosystem. This study, using the systems approach and systems simulation, focuses on an approach to aid the manager analyze these dynamic effects over extended time periods. The basic model will be developed with timber harvesting as the impacting activity. This will be expanded to include fire as an impacting force and road building as an impacting activity. These latter impacts are included to demonstrate the flexibility of this modeling approach.

In looking at harvesting and how it effects the ecosystem from the multiple use viewpoint, two distinct simulation approaches are indicated. The logging system can be thought of as a micro-system which is production oriented. The manager is interested in productivity at least cost. The area or ecosystem is time oriented and can be thought of as the macro-system. In this case, the manager is interested in responses over an extended time frame.

For the micro-phase of this model, extensive work has been done by Johnson (Biller and Johnson, 1972; Johnson, 1970; Johnson et al., 1972) in simulating the harvesting system. The approach taken was event oriented GASP II simulation language. The model contains minute details of the harvesting activity. Effectiveness of the system is measured in terms of man and machine productivity and cost. No attempt is made to measure the impacts on other resources.

For the macro-phase of this systems model, the effectiveness measure will be the availability or levels of all resources over time. This phase will be designed based on the continuous modeling approach. The ecosystem will be represented as levels with flows that transport the contents of one level to another with decision functions controlling the rate of flow between levels and information channels that connect the decision functions to the levels. This approach is described by Forrester (1961; 1968) as Industrial Dynamics.

GASP IV, based on the traditional FORTRAN programming language with the capability of combining both discrete and continuous elements of a system into one simulation model, offers a good approach to analyzing complex problems. The language has been used to analyze the chemical electroplating process for production efficiency with environmental considerations (Sigal, 1973). Using GASP IV, Sigal was able to effectively analyze environmental factors, cost factors, and various aspects of the production process in evaluating the recovery process.

This thesis is directed at designing the macro-phase of the model and the linking of the two phase concept into a working model. The GASP IV simulation language will be used. It is hoped that this thesis will demonstrate the usefulness of such a modeling approach in analyzing such complex problems.

Chapter 3

MODEL DEVELOPMENT

The public land manager is directed by law to evaluate the environmental impacts of proposed activities. These activities must be planned with due consideration for "multiple use" and "sustained yield". Systems simulation is an approach which allows the manager to test the dynamic responses of an ecosystem to activity impacts.

For this study, an ecosystem impact model is presented. This model will be developed from a general description of the system, followed by the development of general relationships and then lastly the regimentation of these relationships into a mathematical model which will be computerized and simulated. The model will be based on general cause-effect relationships, many of which are gross assumptions on the author's part. The modeling approach is presented here.

The Systems Description

In developing the system model, the five step scientific approach suggested by Churchman (1968) will be used. This approach begins with the imperative first step of identifying the total system objectives. This might also be stated as identifying the measures of performance of the whole system. This first step is worthy of considerable attention as all subsequent thinking about the system is influenced by how the true objectives are perceived.

The second step of this approach is to identify the environment or the fixed constraints of the system. The environment of the system is that over which the system, as it is defined, has no control. In addition to lying outside the control of the system, the environment or fixed constraints also influence how the system performs.

The next step in the scientific approach is to identify the resources of the system. In contrast to the environment, resources lie within and can be changed by the system. In fact, the resources are used by the system to obtain its objectives.

The fourth step of this approach is to identify the components of the system. The components are those parts that use the resources to contribute to the overall operations of the system. The components have a specific job to perform in the system.

The final step in the scientific approach to study systems as presented by Churchman is to identify the management of the system. Management is that function which sets the goals of the components, allocates all of the resources, and has direct control over the systems performance. The management is the decision maker in the system.

System objectives. Defining the objectives of an ecosystem is a problem. If left to its own design the ecosystem will continue to cycle and function as it has since the beginning of time following the natural laws of growth, death, recovery, and succession. Like it or not, man is also a very important part of that ecosystem. With more and more people inhabiting the same land area, there is bound to be more pressures placed on the land and its uses. But man is the one component of the ecosystem who has the ability to choose his role and decide how he will interact with his environment. He has the ability to influence his own destiny if you will.

So what is the role of our forested lands? What is the objective used to manage these lands? For our National Forests this goal, derived from the interpretation of all legislation that applies to Forest Service operations, might be stated as follows:

> To optimize public benefits from the National Forests while maintaining the long term productivity of the land (Brown and Dane, 1974:1-6).

The above goal is limited by the following constraints:

> Land Capability - No activity may be allowed if it will result in the destruction, depredation, or diminishment of the land's long term productivity;
>
> Sustained Yield Management - All resources are to be managed on a sustained yield basis;
>
> Funding - The intensity of local management is constrained by the level of funding and the manner in which these funds are allocated (Brown and Dane, 1974:1-6).

The responsibility of National land management is awesome. Public inputs are required. Within the Forest Service a Land Use Planning process is evolving which is directed at making land use decisions. Research is continually conducted to improve this process (Barney, 1976; Brown and Dane, 1974).

With this overall land management objective in mind we can now look at the specific objective toward which this thesis is directed. One important element of the management objective is to test any proposed management action against the lands "long term productivity" and "sustained yield capability". Another element is to "optimize public benefits from the National Forest land".

The planner must evaluate the proposed activity not only against its optimization, but also against its impacts on the area in general. In the case of timber harvesting, the planner wishes to remove a given quantity of timber by the most efficient means possible while minimizing the impacts on other resources. Therefore, the objective of this systems model might be stated:

> To represent the impacts of an activity on an area's ecosystem in terms of the dynamic responses of the area's resources over time while optimizing the activity.

Environment. The environment or fixed constraints of the system are primarily related to the area's location in time and space. This includes such elements as climatology, geography, physiography, and existing cultural forces. Climatological elements include moisture received in the form of rain and snow, temperature, and length of growing season. The form of the land and its relation to surrounding areas are part of its geography. The soil characteristics and production potential are elements of physiography. Cultural forces of the area include existing timber harvested areas, existing roads and any developments.

The environment consists of those elements which fall outside the system's boundary, but which influence the workings of that system. This might be presented as shown in Figure 6.

Resources and components. In this model the resources and components as defined by Churchman are intermixed. Area, timber, forage, wildlife, moisture, and existing roads would be classified as resources. They are consumed or used by the system and lie within the system boundaries. At the same time timber, forage, wildlife, and roads would be classified as components as they each use other resources; timber uses the area and moisture resource; wildlife consumes forage, etc.

In addition to those already listed, the activities of timber harvesting, road construction, and fire would be components. The decision maker has direct control over harvesting and road construction. He also has some control over fire.

System manager. The manager of this system is assumed to be the Forest Service. The Forest Service is responsible to the public for the management of lands entrusted to it. It has control over allowable timber cuts and harvesting practices. The Forest Service sets road construction standards and allowable access routes and is also

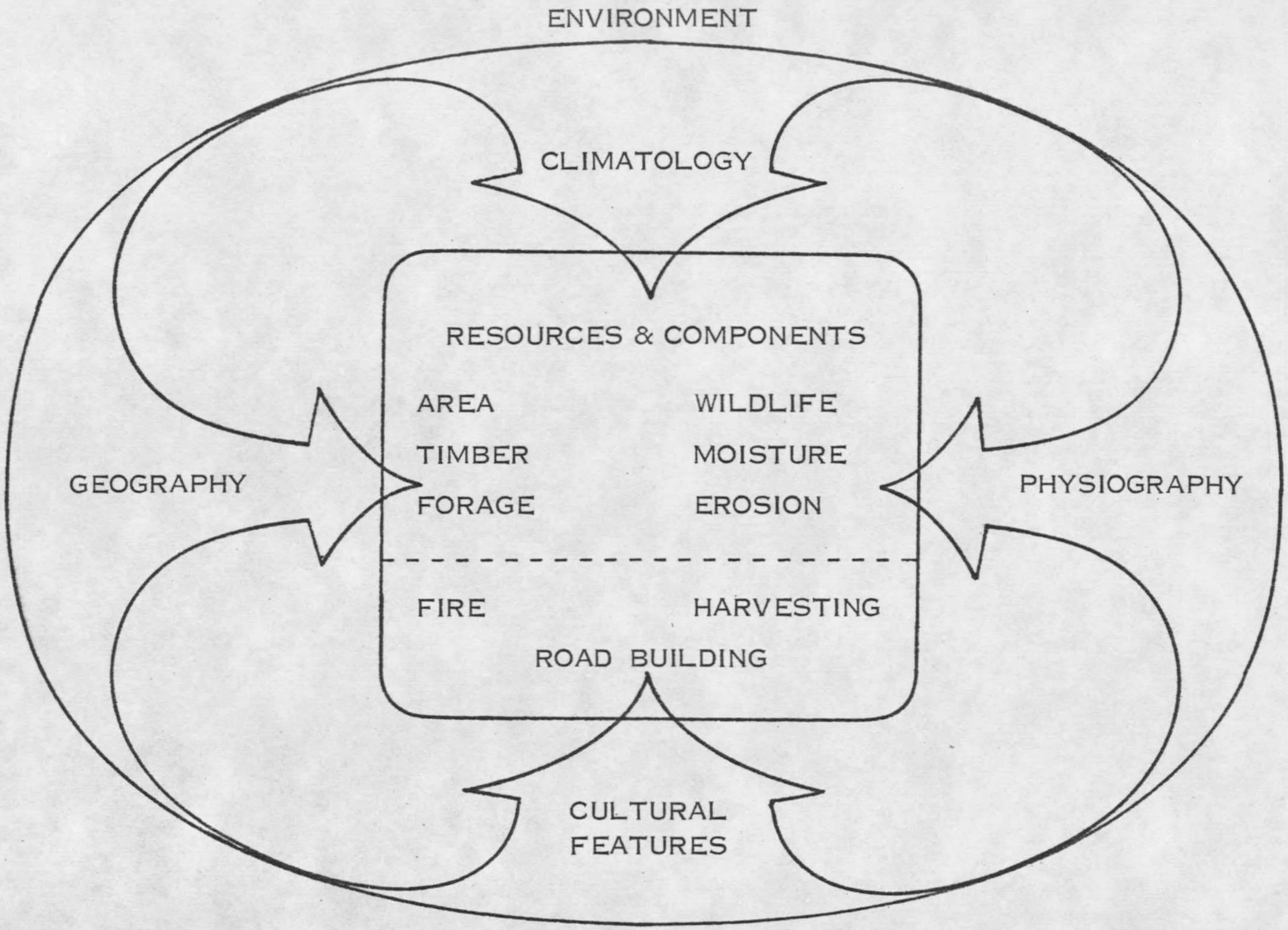

Figure 6. Ecosystem Diagram Showing Environment, Resources, and Components

responsible for fire protection on the National Forests and Grasslands.

Ecosystem - Harvesting Productivity Model

With the previous discussion as background, we will now look at the model developed to portray ecosystem impacts. Because of the two phased objective we are addressing; namely (a) ecosystem response to activity, and (b) optimization of activity productivity, it is logical to divide the model into two phases. The black box diagram of these phases is shown in Figure 7.

In the ecosystem phase, time is the key element. The planner is interested in changes in the system over extended time periods such as one to three hundred years. This phase of the model is represented by combinations of recurrence formula. These equations are written:

$$SS(t) = SS(t-1) + (RATE_i - RATE_d) \times DELTA_t.$$

SS(t) is the calculated systems status at time t. SS(t-1) is systems status at time t-1 or the last update time. Change in status is represented by $RATE_i$, the rate of increase, and $RATE_d$, the rate of decrease. This change rate is then multiplied by the time increment between updates, $DELTA_t$. These equations represent a continuous flow mechanism which can be written in terms of differential equations as $DELTA_t$ approaches zero. However, for this general model, $DELTA_t$ is set to one month.

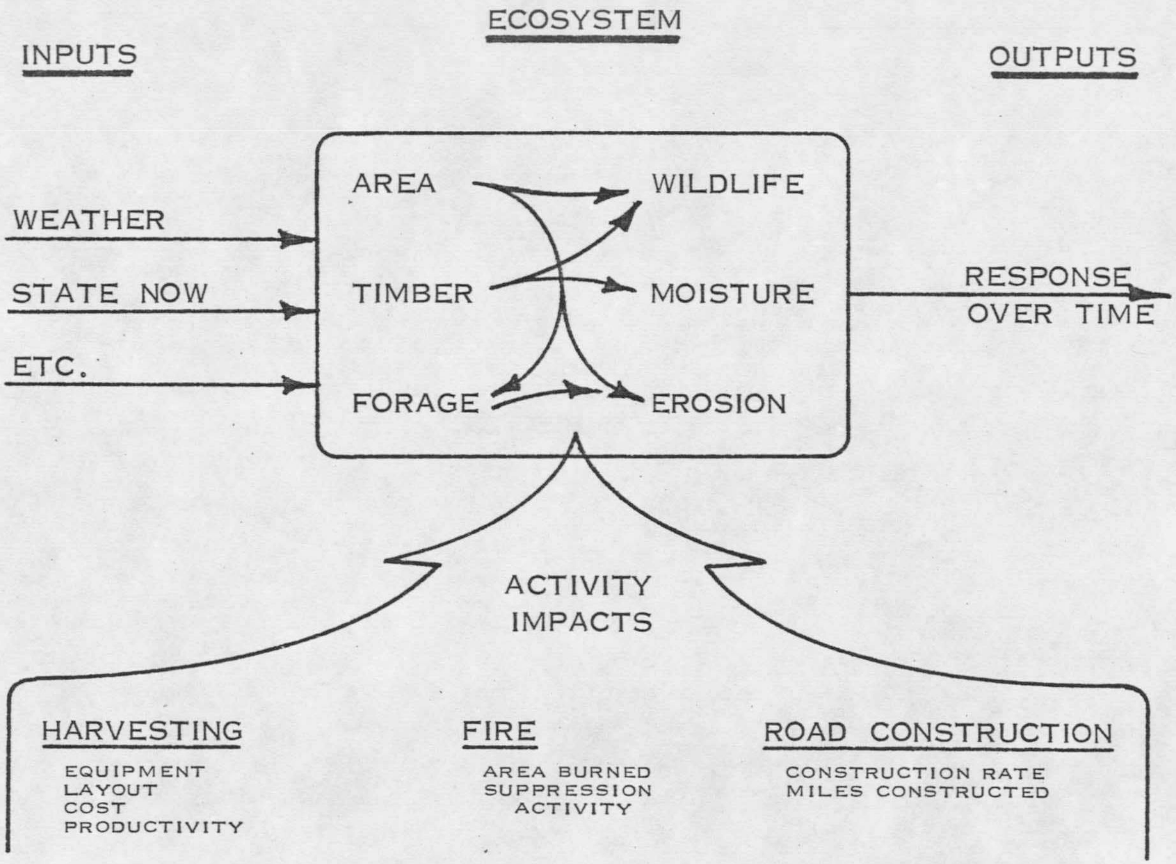

Figure 7. Black Box Diagram of Ecosystem Response to Activity Impacts

Inputs to the ecosystem phase of the model are controlled by the user to represent the environment. These inputs include such factors as weather, the state of the system now, and the physiography of the system. With these inputs, the systems resources and components interact by specified recurrence formula to provide output in terms of the response of given levels or state variables over time.

The activity impact phase of the model is of two types. The first type is represented by the harvesting model. This model is directed at activity production and is presented in Figure 8. This phase requires considerably more detail than the ecosystem phase as internal activities are occurring on a much smaller time scale than months.

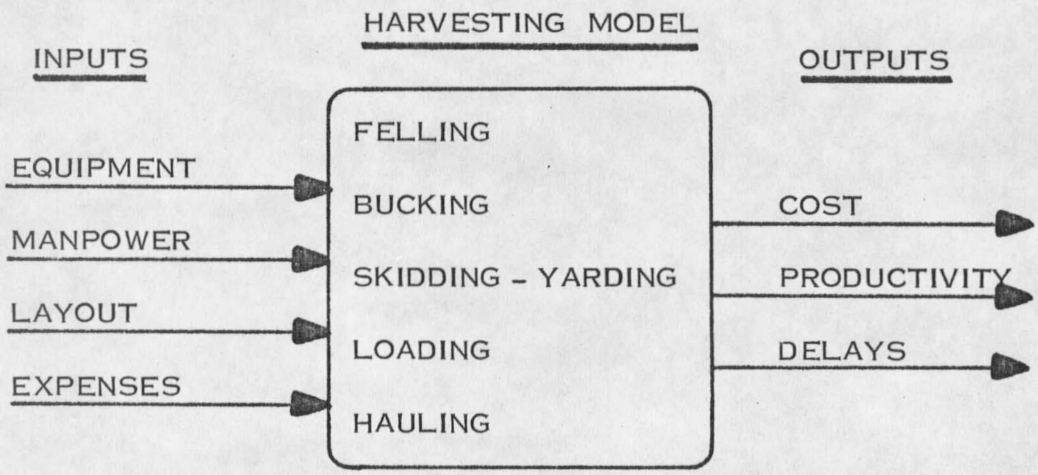

Figure 8. Black Box Diagram of Harvesting Productivity Model

This phase of the model is analyzed by the discrete simulation method. Detailed analysis of this phase is provided by an existing timber harvesting system simulation called SAPLOS. A refined version of this package is utilized to represent in great detail the interrelationships and productivity of logging operations. This simulator is a next-event type model where each event is scheduled at some future time based on the status of the system now. The time scale used in this model is minutes.

Utilizing this detailed simulator, the planner has the capability of looking at the harvesting system in great detail. He can design and lay out the logging operation for optimal efficiency. Inclusion of the macro-phase of this model allows him to also look at environmental responses of the proposed layout.

The second type of activity impact is represented by fire and road construction. These impacts can be thought of as discrete for they are scheduled at a specified point in time. They directly influence state variables in the macro-phase model as specified by input parameters. These impacts are not simulated in great detail and no productivity optimization capability is provided. The user is merely interested in determining how the ecosystem will respond to the impacts.

Combining Model Types

The mechanism for combining these various model types is provided by GASP IV. Being a generalized FORTRAN based simulation language combining both discrete and continuous variables, GASP IV is ideally suited to the task at hand, with several coding changes in its output plotting subroutine. These coding changes were made, varying the time increment, to improve output presentation.

The model progresses through the two phases as depicted in Figure 9. Starting at "time now", the macro-phase operates in the steady state. This represents the ecosystem as it might be before harvesting. At a specified point in time, say 1990, harvesting begins. At this point, the simulation model shifts to the micro-phase with its operation controlled by the discrete events of harvesting. System status is recorded weekly during this phase. At the completion of harvesting, the model once again returns to the macro-phase monitoring the responses of the ecosystem. During this phase, system status is recorded yearly.

Options are provided allowing the user to request status reporting on a monthly basis. This is particularly useful if the system is subjected to a fire or road building impact. The systems immediate response to these activities can be monitored over a given time period. Seasonal trends can also be observed at any time. This capability gives the user considerable control of the model.

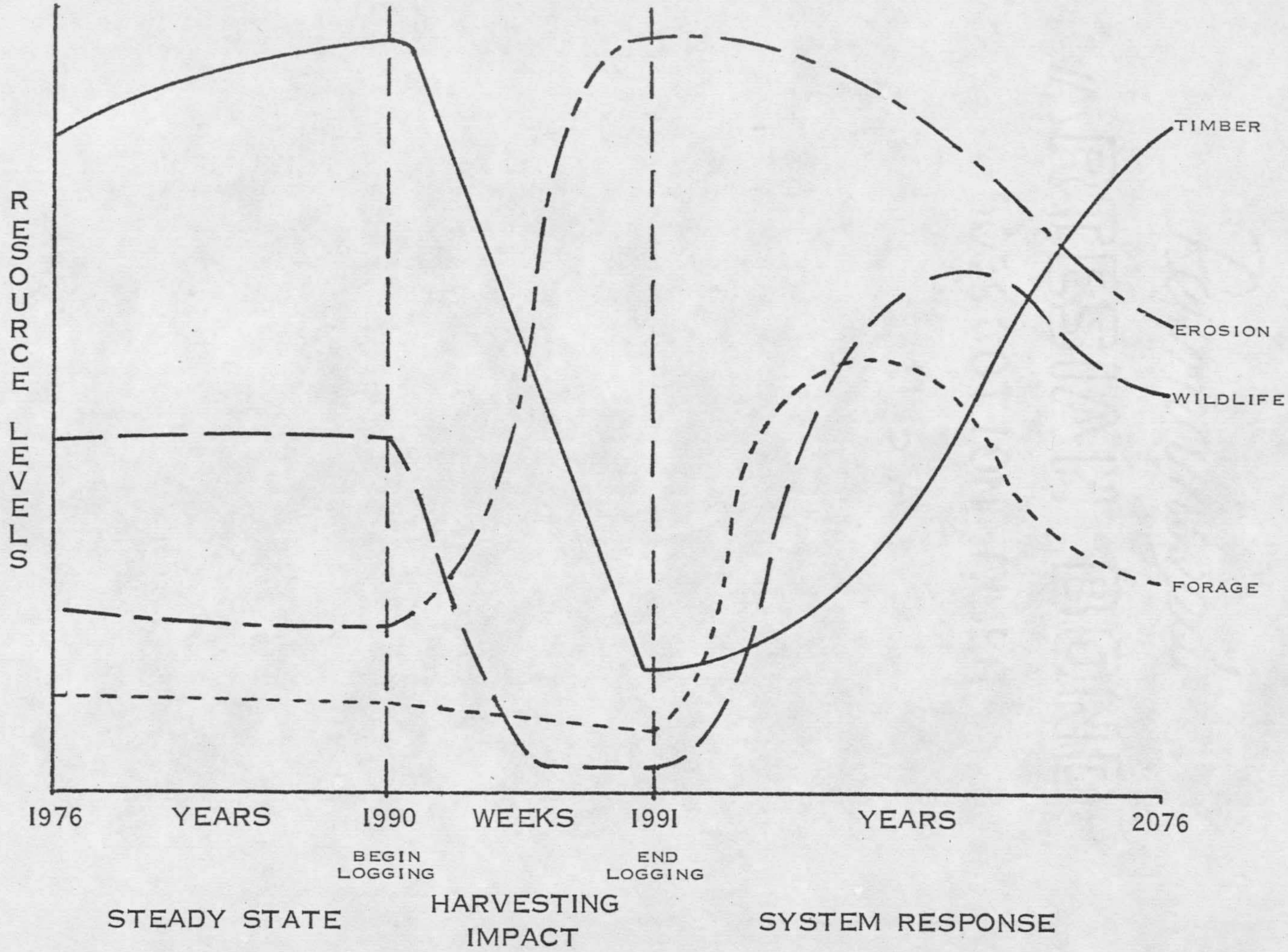

Figure 9. Time Scales of Combined Macro - Micro Simulation Model

Chapter 4

MACRO-MODEL PHASE

The ecosystem model is divided into six subsystems: 1) area, 2) moisture-water, 3) timber, 4) forage, 5) wildlife, and 6) erosion. This was done to facilitate understanding from an interdisciplinary perspective. The climatologist is primarily interested in the moisture-water subsystem. The silviculturalist and timber specialist function within the timber subsystem. Range specialists are concerned with the forage subsystem. Wildlife and its interactions are portrayed in the wildlife subsystem. The hydrologist would be concerned with both the erosion and moisture-water subsystem.

In dividing the macro phase into these segments, physical flows are contained entirely within a subsystems boundary. However, information about a state variable is used to influence the rates of flow in other subsystems. These information links represent the interactions of the ecosystem.

The remainder of this chapter is devoted to describing each subsystem of the macro phase in detail. The basic flow charting scheme used is derived from that used by Forrester (1968). The symbols and their intended meanings are discussed in Appendix A. Complete systems diagrams and model equations for each subsystem are provided in Appendix B.

Area Subsystem

The area subsystem provides the sizes of major area classes for the ecosystem model. The generalized flow diagram for this subsystem is shown in Figure 10. This complex is represented by five distinct area classes. For modeling purposes, these categories are assumed to be mutually exclusive. Each class is identified depending on the dominant use or influence of the area.

Burned area includes all which has recently been subjected to fire. This area is characterized by little or no vegetation with patches of exposed mineral soil. The assumption is made that this area has production potential and will eventually return to range and finally forest production. The major influence of this area on the system is in terms of moisture holding capacity and erosion. There is also the immediate effect of removing the area from biomass production.

Range area is dominated by its forage production. This classification includes all biomass productive area that is not producing timber. Though forage does grow under standing timber, this area is not included in the range classification.

The state variable, forest area, is that whose major influence to the system is timber production. This area includes all with growing timber. The last area classes presented as state variables are for roads. This road area is subdivided into two classes, open and closed. Open

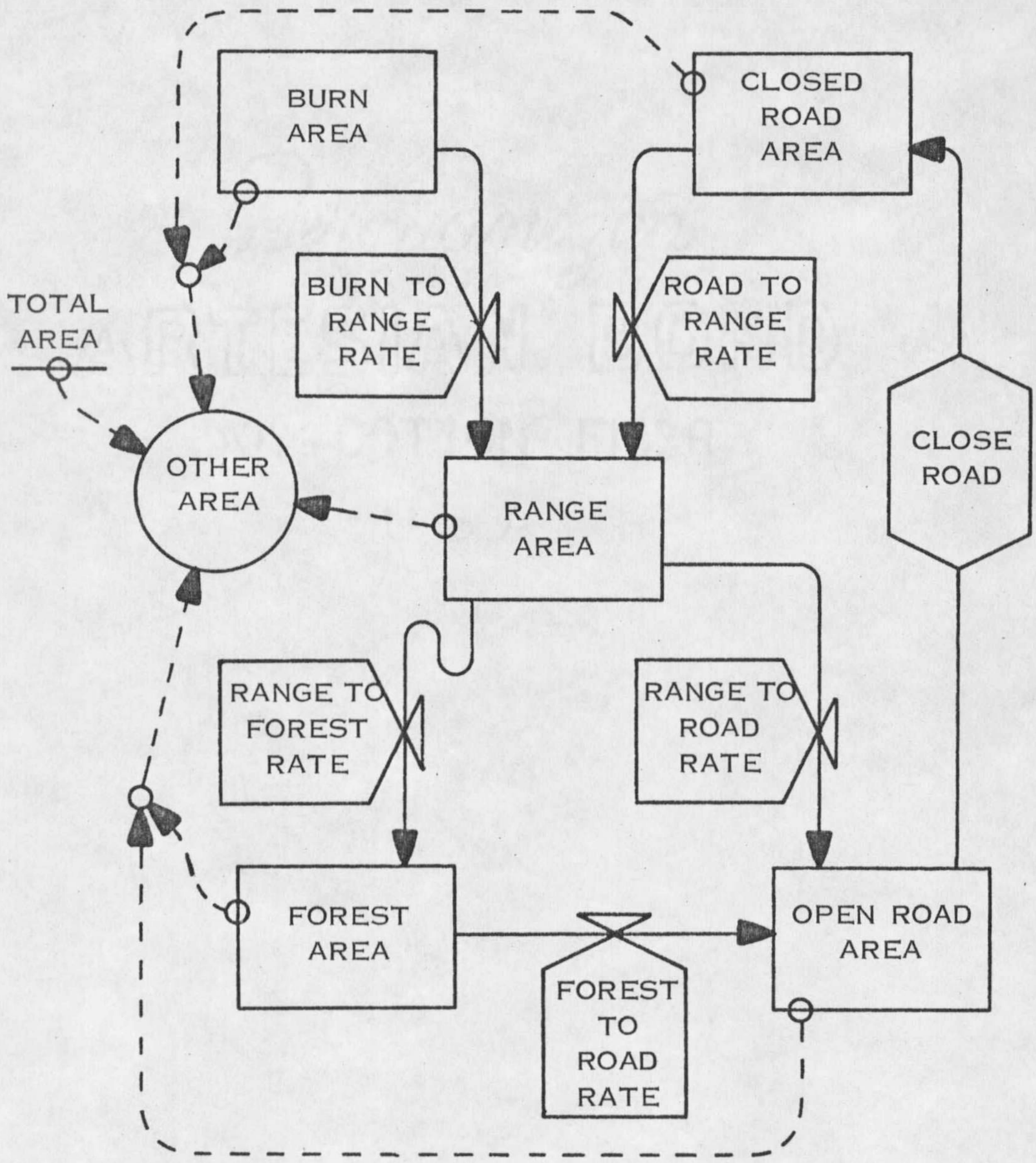

Figure 10. Area Subsystem Flow Diagram

roads are maintained in such a condition that, vegetation is not allowed to become established in the area. Closed roads on the other hand are allowed to return to their natural state of biomass production.

Provisions are made in this subsystem to classify the unproductive area in the ecosystem. This is identified in the model as auxiliary information and is represented in the diagram as a circle. The size of this area is calculated by subtracting from total area all biomass productive area, burned area, and road area.

Flows of area within this subsystem are assumed to follow the natural progression from burned or closed road area to range area and finally forest area. Provisions are included in the model for converting range and forest area to road area. The rates of these flows are controlled by road construction and are explained further in the next chapter.

The rates of flow, burn to range and closed road to range, are set up in the model as inverse decay functions. The magnitude of these decays is specified by the user. The flow from range to forest is dependent upon area sizes and average tree height. The distance seeds will travel depends on tree height and the assumption is made that timber encroachment into range results from this seed travel. This distance-height relationship is derived from user inputs.

Moisture-Water Subsystem

The moisture-water subsystem is the primary driving component of the ecosystem model. All vegetation growth is dependent upon the available moisture which in turn affects wildlife capacity. In addition to this, erosion is caused directly by the amount of runoff occurring. The generalized flow chart of this regime is given in Figure 11. For more detail, the specific flow chart and accompanying equations are provided in Appendix B.

The moisture-water subsystem receives two primary inputs; snow and rain. Snow is allowed to accumulate as snow pack and is stored until spring runoff. This runoff plus any rain which might be received contributes to the available surface water.

The surface water that accumulates is dispersed by three modes: absorption into the soil, runoff over the surface, and evaporation back into the atmosphere. Surface water absorption and runoff are dependent upon the area class on which the moisture is received. The three area classes, burn, range, and forest, are assumed to have different moisture absorption capabilities. These values are determined by the surface water available and the areas field capacity or soil moisture holding capacity.

Once the moisture becomes trapped by the soil, there are two ways provided for its consumption. One is the use of the moisture in the soil by the area's biomass. This consumption is determined by the biomass load being supported by the site. The other method of soil moisture loss is through percolation. The percolation rate for each land area