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Hydrological and Multiple-Resource Simulation Models: Applications in Mountainous Areas

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INTRODUCTION

Mountainous areas are being subjected to many changes, both planned and unplanned, which affect the hydrological and other resources found on them. These changes can have either beneficial or adverse impacts on people. Therefore, that predictions of these impacts are needed before extensive land and resource modifications are implemented or otherwise allowed to occur.

Large numbers of field observations and studies have been made on the effects of land use changes on the hydrological and other resources in mountainous areas. Information from these investigations is invaluable and should be enlarged upon. However, source data that are obtained from one location seldom can be applied directly to estimate impacts at other locations. Alternative means of predicting consequences of land use on mountainous areas are required in many instances. One such means can be the application of hydrological and multiple-resource simulation models.

Hydrological and multiple-resource simulation models are representations of how some part of the real-world operates. These models can be essential for the solution of complex problems, although models do not have to be complex to be useful. Models can vary in structure from simple statements of logic, to network diagrams, to detailed mathematical equations. With use of present-day computer systems, development and subsequent applications of hydrological and multiple-resource simulation models have progressed rapidly.

When hydrological and multiple-resource simulation models can be structured to represent actual processes in a mountainous ecosystem, they can be applied under a variety of conditions. Modeling is likely to become a principal means of utilizing and extending limited data sets to predict the effects of land management practices on water. and related natural and agriculture resources.

It is not the purpose of this paper to present the details of hydrological and multiple-resource simulation modeling and simulation techniques. These topics are described in a number of standard references, such as Larson (1971), Haan et al. (1982), and Roberts et al. (1983). It is hoped, instead, that the reader will attain a greater appreciation of how these simulation methodologies can be applied to evaluate impacts of land management practices, before they are implemented, through application of hydrological and multiple-resource simulation models.

Hydrological and multiple-resource simulation models can be deterministic or stochastic in structure. A deterministic model illustrates relationships among variables without consideration of randomization of occurrences, while a stochastic model presents relationships among variables in terms of probability distributions (Larson 1971, Loucks et al. 1981, Haan et al. 1982). Both types of simulation models are useful in the evaluation of land management practices.

Models also can be classified as physically-based or conceptual (Larson 1971). A physically-based model is derived from knowledge of the actual processes being described. Furthermore, parameters of a "physically-based" model are physical, chemical, or biological characteristics that relate directly to the processes involved. Parameters can be observed and, in general, are measurable. Therefore, a physically-based model is a "measured-parameter" model. A conceptual model, on the other hand, also represents a particular process, but abstractly. Parameters of a conceptual model are not measured in most instances. Instead, these parameters are evaluated by "fitting," which is defined as varying parameters until model output approximates the observed output. A conceptual model can be considered as a "fitted-parameter" model. Physically-based and conceptual hydrological simulation models are both widely used in land management evaluations.

Simulation techniques are employed to reproduce behavior of a system in the form of a model that closely represents the real-world situation. Through simulation, appropriate models are operated to obtain alternative solutions to land management problems. Simulation models do not necessarily generate optimal solutions (Roberts et al. 1983). However, they do show alternative results that allow a user to make a decision on the feasibility of obtaining a specific impact.

Through use of electronic computer systems has come the synthesis of computerized simulation models. Mathematical equations that previously were interpreted manually can be analyzed on a computer, allowing the models to be operated rapidly. Consequently, models can be increased in complexity and sophistication. This increased speed of computation facilitates the application of hydrological and multiple-resource modeling techniques seldom used before, due largely to their excessive time requirements.

Numerous hydrological and multiple-resource computer simulation models have been developed for applications in mountainous areas throughout the world. A complete listing of these models serves little useful purpose, since many of the models are in various stages of development and testing and, therefore, not available for immediate application. Furthermore, to describe all of these models is not the purpose of this paper. However, comprehensive listings of hydrological and multiple-resource simulation models commonly used in the United States are available.

An annotated bibliography of approximately 400 computer simulation models and simulation programs in water resources was compiled by Chu and Bowers (1977). Renard et al. (1982) summarized 80 hydrologic computer simulation models in terms of processes simulated, geographic area of application, and land use category of concern. Multiple-resource computer simulation models of growth and yield of forest overstories in the United States and Canada have been listed by Alig et al. (1984). Mitchell (1983) listed commonly applied simulation models in which forage production was an integral component. Other listings of multiple-resource computer simulation models have been prepared by Hawkes et al. (1983), Joyce et al. (1983), and Miller (1984).

To illustrate use of hydrological and multiple-resource simulation models in simulating effects of land use modifications in mountainous areas, a group of computer simulation models that have been developed in the United States is described in the following paragraphs.

ILLUSTRATIVE COMPUTER SIMULATION MODELS

The group of hydrological and multiple-resource simulation models to be described was developed originally for application in montane forests of the western United States (Carder et al. 1978, Larson et al. 1978). Subsequently, the conceptual framework for this group of simulation models was extrapolated to temperate forests of the northern United States, where a second group of hydrological and multiple-resource simulation models were structured (Ffolliott et al. 1984). A version of the group of simulation models has been developed for the arid lands of Mexico (Rasmussen and Ffolliott 1981). There is interest in undertaking a similar effort in the humid forests of Southeast Asia (Saplaco 1985). It is conceivable that this conceptual framework also could be applied in other regions of the world, if the required developmental information is available.

The group of computer simulation models was formulated to predict the impacts of land use modifications in forest ecosystems of mountainous areas. Importantly, the capacity of a single model to simulate a broad spectrum of interactions within an ecosystem is limited. A single model, like a forest overstory growth and yield model, may not reflect how changes in forest density affect water, sediments, nutrients, livestock forage, wildlife habitat, or soils. However, compatible models can be linked together to do so. The group of computer simulation models to be described is comprised of compatible models, called modular components, that can be coupled in flexible combinations for use in a variety of situations. Together, these modular components can simulate natural processes and land management actions, and describe the extent to which they affect one another throughout a range of ecological and topographical conditions.

The modular components to be described are structured to operate in two modes. Depending upon the simulation objective, a component can be operated either individually or coupled with other components.

The computer simulation models described below are contained in three main modules: WATER to assess streamflow runoff yield, sedimentation amounts, and chemical quality parameters; FLORA to describe forest overstories growth and yield, herbaceous understories production, and organic material accumulations; and FAUNA to evaluate animal habitats, animal carrying capacities, and animal population dynamics. An overall command system enables a user to operate the models through a common language written in straightforward terminology. When required, appropriate data bases also can be accessed. This design provides flexibility in representing land management activities by operating selected computer simulation models interactively. Furthermore, other models can be incorporated into the command framework, as required.

The computer simulation models have been designed to be used at remote locations to obtain reliable predictions from readily available input data and modest computer equipment. To this time, models have been developed to evaluate the effects of land management practices in forest ecosystems of mountainous areas. However, the general methodology is adaptable to studying the problems of shifting agriculture, severe livestock grazing, and many other land use practices that prevail in many countries throughout the world.

WATER Module

The WATER module is comprised of modular components to estimate the magnitude of streamflow runoff yield, and suspended sediment amounts and chemical quality parameters of streamflow water.

Streamflow Runoff Yield

The need for an operational model with simple data requirements to represent streamflow runoff yield led to the development of a component called YIELD II, in which there are a number of simulation routines (Ffolliott et al. 1988). One routine predicts a water balance on a daily basis. Required data inputs are few and commonly available, in many instances. Another routine is a water balance model developed to handle various textures and depths of soil, and either coniferous or deciduous types of forest vegetation.

Coupled with the streamflow runoff yield component are other hydrologic subroutines, such as those which predict accumulation and melt of snow (Leaf et al. 1973, Solomon et al. 1976). There are two routines in YIELD II that predict streamflow yield from the release of water in snow. One routine is based on the degree-day concept of snowmelt. Another models intermittent snowpacks, depending largely upon daily inputs of maximum and minimum temperatures, precipitation, and solar radiation. A general subroutine, which simulates streamflow runoff yield from a watershed for all times of the year, includes a model for both snow and snow-free conditions.

The primary initialization variable in YIELD II is a daily precipitation regime, while the "driving" variable is a measure of forest overstory density conditions. Outputs from YIELD II are values representing daily streamflow yield, changes in soil moisture, evapotranspiration, snowmelt, and deep seepage. Linkages to other modules in the group of computer simulation models can be used to obtain estimates of forest overstory density, a required input variable, while outputs of daily streamflow runoff yield are inputs to modular components used to simulate sediment and chemical quality.

Sedimentation

Another component in the WATER module, named SED, predicts amounts of suspended sediment in streamflow water. This modular component is structured to offer a choice between two sets of input data requirements. Depending upon the information available, a user can select either forest overstory density conditions or spatial distributions of organic material on a forest floor. These inputs are entered directly or generated by other models in the group. The other input needed, streamflow yield, can be obtained from YIELD II. The program outputs maximum concentrations of suspended sediment on a daily basis, maximum stream discharge, and total weight of suspended sediment produced under the alternative land practices simulated.

SED does not simulate the amount of bedload movement. Therefore, estimates of total sediment yield are unavailable. However, as bedload frequently is a relatively small component of the total sediment yield from the hydrological systems simulated to date, this omission is not considered serious.

Chemical Quality Parameters

A modular component in the WATER module has been developed to estimate maximum concentrations and daily volumes of selected dissolved chemical constituents in streamflow water. This component, called CHEM, is designed specifically to describe chemical qualities of streamflow discharges from watersheds in forest ecosystems (Ffolliott et al. 1990). The primary ""driving" variable is streamflow yield, the magnitude of which will vary generally with alternative land management practices. This input variable can be entered directly by a user or obtained from outputs from YIELD II.

Thirteen chemical constituents are estimated within the CHEM framework: calcium, magnesium, sodium, chloride, sulfate, carbonate, bicarbonate, fluoride, nitrate, phosphate, total soluble salts, the hydrogen ion (pH), and conductivity.

Most investigations of chemical qualities of streamflow water have measured dissolved ion concentrations, but they have ignored nutrient and heavy metal losses resulting from transported sediment. However, from data collected in a study of nutrient and heavy metal transport capacities of suspended sediment in the surface runoff from watersheds in the mountainous areas of the western United States, a computer simulation model was developed to estimate these water quality parameters (Gosz et al. 1980). This model, called SEDCON, is structured to estimate impacts of alternative land management practices on nutrient and heavy metal losses due to transported sediments.

To operate SEDCON, knowledge of forest type, geology, and sediment production is required. By evaluating alternative land management practices through seasonal sediment production functions, a user can employ SEDCON to predict consequences of particular land management options in terms of nutrient and heavy metal losses.

FLORA Module

The FLORA module consists of components that predict growth and yields of forest overstories, production and compositions of herbaceous understories, and development and accumulations of organic material on a forest floor.

Forest Overstories

Computer simulation models designed to estimate the growth and yield of forest overstories fall generally into two categories: models that are structured broadly to represent a wide variety of tree species; and models that are structured specifically to represent a particular tree species.

In the first category, three simulators, called TREE, STAND, and FOREST, are available in the FLORA module to estimate growth and yields of individual trees, a forest stand (a community of trees possessing sufficient uniformity in composition, age, spatial arrangement, or condition to be distinguishable from adjacent communities), and an entire forest property, respectively.

TREE simulates growth of individual trees from knowledge of diameter, height, and volume (Pierce 1976). One easily can see how individual tree growth is influenced by tree size and age. The approach exemplified by TREE differs from that of others who have employed mathematical formulas to simulate the tree growth phenomena.

The simulation objective of STAND is to predict growth and yields of forest stands prior to and following implementation of land management practices. Inputs to this modular component include a listing of trees per hectare by size class, diameter growth rates, and tree volume expressions. As management is prescribed to change these inputs, estimates of post-treatment growth and yield are generated interactively. Land management practices that can be simulated within STAND represent an array of options for forest compositions being considered.

FOREST is a user-friendly version of a large-scale computer model structured to simulate growth and yields of entire forest properties comprised of single or mixed tree species and even-aged or uneven-aged forest structures (Ek and Monserud 1974). This modular component addresses topics of seed production, dispersal and germination, competition, mortality, and stocking manipulation by man.

There are many examples of computer simulation models designed to estimate growth and yields of forests consisting of a particular tree species (Alig et al. 1984). A user generally initializes these models by entering the number of trees per hectare by size class. Wood harvests and silvicultural treatments the can be specified at time intervals through a sequence of questions and answers to meet a given land management objective.

Herbaceous Understories

A modular component in FLORA, termed UNDER, has been structured to estimate production of herbage, that is, all understory vegetative production, from knowledge of forest overstory parameters, precipitation amount, and when appropriate, time since implementation of a land management practice.

Many of the previous attempts at structuring computer simulation models to estimate herbage production have been dependent upon input variables describing forest overstory density conditions (Myers and Currie 1970, Mitchell 1983). Although this approach is employed in several subroutines, UNDER also can utilize knowledge of forest growth rates. Estimates of herbage production that are based upon knowledge of this latter variable consistently appear to be more accurate than those based upon forest overstory densities alone.

To estimate compositions of herbaceous understories, UNDER partitions simulated herbage production into grasses and grass-like plants, forbs and half-shrubs, and shrubs.

Organic Material

Three modular components describe development, accumulation, and distribution of organic material on a forest floor. One component, referred to as FLOOR, estimates accumulations of tree leaves and needles by layer of decomposition, rate of accumulation with respect to time, and spatial distribution in space. Other components, called CROWN and BOLE, predict magnitudes of tree crown and branchwood accumulations, respectively, associated with alternative land management practices.

FLOOR outputs parameters that describe development, accumulation, and distribution of tree leaves and needles as a function of forest overstory density levels for different land management practices. In terms of accumulation at a point-in-time, layers of decomposition considered are litter, fermentation, and humus. Rate of litter accumulation is the only output in a time dimension. Regarding spatial distribution, only the total accumulation of organic material, that is, all layers, is represented.

CROWN and BOLE present knowledge of tree crown and branchwood volumes by area for a forest prior to the implementation of a land management practice. These volumes provide a reference point to analyze the amounts of tree crowns and branchwood that will occur as vegetative residues once a land management treatment has been implemented.

FAUNA Module

The FAUNA module includes modular components that predict habitat quality for a variety of animal species, animal carrying capacities on an area, and dynamics of animal populations within specified forest ecosystem situations.

Habitat Assessments

Simulators that assess habitat quality fall into two categories: models broadly structured to represent a variety of animal species; and models structured specifically to represent a particular animal species.

An example of a model in the first category is HABRAN (HABitat RANking). This modular component synthesizes ranked response productions which can be summarized and arrayed as pattern recognition models. Animal habitats are assigned numerical values ranging from 0 to 10 in HABRAN, with good habitat quality increasing with numerical value. Specific assignment of these values is achieved through analyses of functions that relate habitat preference to readily available parameters, the magnitude of which are altered by alternative land management practices.

By comparing numerical habitat quality values for existing conditions with those predicted for habitats modified by land management, either an increase (+), a decrease (-), or no change (0) is determined. A matrix of plus and minus signs, and zeros then is arrayed for all of the animal habitats and land management alternatives of interest. This matrix is a pattern recognition model, a displayed that provides insight into comparative land management impacts.

Many computer simulators exist to represent habitat quality of a particular animal species. In most instances, changes in food, water, cover, and diversity resulting from implementation of a land management practice are used to simulate changes in rating of habitat quality.

Animal Carrying Capacities

In a modular component that has been structured in FAUNA to predict animal carrying capacities, termed CARRY, herbage production is partitioned into usable forage for domestic livestock and wildlife species. Appropriate plant species included in each forage component have been ascertained from existing literature on the preferred foods for these animals.

It has been assumed that the proper use factors, which are desired levels of forage consumption, to be applied in CARRY will be introduced by a user to meet specific land management objectives. For example, it may be necessary to reduce a proper use factor on a grazing land that has experienced prolonged over-grazing pressures. The amount of usable forage required per animal unit month (AUM) for the species considered is input directly by a user. By definition, an animal unit month is recognized as a mature animal grazing for a one-month period. With respect to the number of months that domestic livestock or wildlife species will be consuming forage, this value is variable, depending largely upon weather factors that characterize the particular ecosystem. Only estimates based on local knowledge of "average" situations in the long-run can be made.

Topography and fences restrict animal movements. Consequently, portions of a grazing land can be eliminated from that activity because of movement constraints, which necessitate appropriate reductions in animal stocking rates.

Effects of alternative land management practices on animal carrying capacities are evaluated largely through predictions of changes in levels of herbage production. As forest overstories are reduced in density, a corresponding increase in herbage production commonly occurs. Increased production of herbage is partitioned into forage which is converted into AUM values that are distributed over the area.

Animal Population Dynamics

A population dynamics model, called DYNAM, simulates impacts of land management practices on the reproduction, growth, mortality, and structure of selected animal populations. More specifically, this modular component is structured to predict the manner by which a population will respond to changes in food, cover, and diversity that are attributed to land management practices. Emphasis has been placed on the dynamics of large herbivore populations.

The Command System

The command system for the group of hydrological and multiple-resource simulation models is dispersed largely into the respective modules. There is little evidence of a command system in the overall operation of the group of models. However, initial selection of the modules and components to be used and subsequent assignment of default values needed in the operation are handled by the command system. Timing and sequencing in the operation of individual modular components also are carried out by the system. Additionally, summary displays, including tables, graphs, and maps, of the simulation results are achieved through the command system.

All of the hydrological and multiple-resource simulation models in the group have been structured to have three modes of operation: initialization, cycling in time, and summarization.

All of the needed data are introduced either directly by a user or from data files stored in the initialization mode. The second mode of operation is a cycling in time of the processes being simulated, for example, daily streamflow yields, yearly forest growth rates, etc. The third mode of operation is summary and other "book-keeping" activities at the end of a simulation exercise.

When a user informs the command system which modular components are to be operated, the user also states when they are to be used sequentially in the simulated exercise. For example, the component CHEM may be required to operate only in the fifth year of simulation, while other modular components, such as STAND and CARRY, are to be operated every year. The command system stores this directive and acts accordingly.

The entire system is designed to operate with minimal input data.

Default values are offered for almost all of the interactive questions so that the simulation exercise can proceed, whether or not a user has the required input data. Similarly, when a modular component is not included directly in a simulation exercise, default values are loaded into the system to provide estimates of needed parameters normally obtained as output from the modular components not used.

Once the system exercise cycles through the specified number of simulation years, individual modular components are entered into the summary mode of operation. Any needed computations to allow display summaries of the operation to be output are made at this point. Output summaries can be obtained either on a "local" computer terminal or at a central computer location. These summaries are brief or detailed, depending upon the user's need. In general, parameters shown are representative of the various modules and components employed in solving the simulation problem. If a component is not used and default values are utilized, parameters for the unused component will not alter the display.

Specifications

As previously mentioned, the group of hydrological and multiple-resource simulation models has a modular structure, with a user-friendly interface for initialization and data entry. The modular components are written in the FORTRAN/77 computer language, using a DOS 3.0 operation system. These simulation models, which are designed for microcomputer use, are adaptable to most IBM compatible machines. Modular components have minimum memory requirements, varying between 30k and 100k, and can be executed from either floppy disk or hard disk drives.

EXAMPLE OF APPLICATION

Application of the group of hydrological and multiple-resource simulation models can be shown with a hypothetical, but realistic example. In this example, YIELD, STAND, and CARRY are operated to simulate the impacts of alternative land management practices in the montane ponderosa pine forests of the western United States. From an analysis of outputs for the simulation exercise, a course of action is selected to satisfy a specific management land objective.

In the example, three alternative land management practices have been examined, namely the existing management system (M0), conversion of moist sites (along stream channels) to grass (M1), and changing the forest structure from uneven-aged to even-aged in form (M2). Levels of annual outputs for the alternative land management practices are presented in Table 1. Annual outputs for the existing land management system (M0) have been obtained through on-site measurements and inventories. However, anticipated annual outputs attained with conversion of moist sites to grass (M1) or in changing forest structures from uneven-aged to an even-aged form (M2) have been simulated through operations of YIELD, STAND, and CARRY. The resultant product-mix representation in Table 1 can be used as a basis to select the best course of management action.

Table 1. -- Annual Outputs of Alternative Land Management Practices in the Montane Ponderosa Pine Forests of the Western United States.

Item	M0 As Is	M1 Convert	M2 Even-Aged
Streamflow yield (centimeters)	15.0	22.5	18.7
Wood cut (cubic meters per hectare)	0.0	9.0	3.8
Forest growth (cubic meters per hectare)	4.2	2.5	5.2
Animal Carrying Capacity (AUM's per 100 hectares)	17.1	28.6	22.8

Explanation:

If things remain "as is," M0, annual outputs will be 15.0 centimeters of water (on an area basis), 4.2 cubic meters of forest growth per hectare, and an animal carrying capacity of 17.1 AUM's per 100 hectares. No wood will be cut.

With conversion of moist sites to grass, M1, simulated annual outputs will be 22.5 centimeters of water, 2.5 cubic meters of forest growth per hectare, and an animal carrying capacity of 28.6 AUM's per 100 hectares. Approximately 9.0 cubic meters of wood will be harvested on each hectare.

In changing forest structures from uneven-aged to an even-aged form, M2, the predicted annual outputs will be 18.7 centimeters of water, 5.2 cubic meters of forest growth per hectare, and an animal carrying capacity of 22.8 AUM's per 100 hectares. About 3.8 cubic meters of wood will be harvested on each hectare.

It has been assume that a decision to select the land management practice to maximize total benefits is required. It has been assumed that this objective must be satisfied within the following constraints:

- Increase water yield at least 5 percent.
- Maintain forest growth at a minimum of 3.0 cubic meters per hectare.
- Provide enough forage to increase the animal carrying capacities, in this example, cattle, at a minimum by 20 AUM's per 100 hectares.

Given the objective of land management and constraints, the appropriate decision is to select the even-aged forest management practice (M2). Through inspection of Table 1, it can be seen that this is the only alternative that satisfies the management objective within the framework of the stated constraints. Solution in this simplistic example is obvious. To answer more detailed questions, however, it may be necessary to employ more rigorous, but readily available problem solving techniques (Loucks et al 1981, Dykstra 1984).

FUTURE DIRECTIONS

Future work in development of the group of hydrological and and multiple-resource simulation models will following two general directions: synthesis of other modules and modular components; and extrapolation of the interactive system into other types of ecosystems.

Several other modules and modular components are recognized as part of the group of models. To facilitate overall planning with respect to a land management problem, a module called PLAN is available to generate network models. Components in this module are concerned with flows of activities through planning networks. Some of the network models consider uncertainties associated with the character of individual planning activities.

Another module, referred to as AREA, calculates adjusted surface areas of land management units within a mountainous ecosystem, correcting for sloping or broken terrain. As knowledge of site quality is required as input to some models in the group, a module called SITE generates measures of site quality directly through estimation of site indices or through analyses of plant indicators, physiology, and soil surveys.

To evaluate depth and quality of landscape views in terms of existing and anticipated conditions, a module named SEEN has been developed. Another module, called FIRE, predicts probabilities of occurrences of wildfires of given intensities from knowledge of fuel properties and sequencing of meteorological events. This module estimates the impacts of fire on an ecosystem. SNOW is a module that simulates snowpack accumulation and melt patterns within forests comprised of trees in varying spatial arrangements. ROAD allows for predictions of sediment loads resulting from the building of roads with alternative design criteria.

To further aid managers and planners in analyzing land management modifications, a module that facilitates development and subsequent display of economical trade-off relationships has been synthesized. This module, referred to as ECON, also includes components that represent various marketing conditions and mathematical programming techniques. Other modular components will be considered in the future to more completely provide socio-economical simulation capabilities.

Primary emphasis in initial developmental work on the hydrological and multiple-resource simulation models described above has been placed on simulation within forest ecosystems in the mountainous areas of the western United States and, to a lesser extent, Mexico and Southeast Asia. However, this work can be extrapolated to other forest ecosystems in the world, and to grasslands and other natural ecosystems. To attain this goal, many of the modular components in the group described above require only "localization" of technical coefficients for use in other ecosystems. Other models, particularly those structured to represent particular hydrologic systems or plant and animal communities, are appropriate in only simulating those ecosystems in which they occur. Consequently, these models must be replaced by specific models that characterize the ecosystems under consideration. However, even here, replacement is relatively easy within the overall structure of the command system.

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