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SPUR—Simulation of Production and Utilization of Rangelands:

A Rangeland Model for Management and Research

ABSTRACT

Wight, J. R., editor. 1983. SPUR--Simulation of Production and Utilization of Rangelands: A Rangeland Model for Management and Research. U.S. Department of Agriculture, Miscellaneous Publication No. 1431, 120 p., illus.

This publication describes a rangeland simulation model which was developed to provide information relative to management and research. It provides a narrative description of the model's five basic components -- 1) climate; 2) hydrology; 3) plant; 4) animal; and 5) economic -- and their interfaces. An option for evaluating the impact of grasshoppers and their control is included. Input data requirements and model outputs are described. Application of the model to problems of resource management and research planning and administration is discussed. Model documentation and user guides are not included but will appear in subsequent publications.

KEYWORDS: Mathematical model, rangeland model, simulation, hydrology, plant model, livestock model, climate model, economics, erosion, range management, range research.

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PREFACE

The application of modeling technology to problems of range research and resource management received considerable impetus through the Grassland Biome Study headquartered in Fort Collins, Colorado, during the late 1960's and early 1970's. Publication of the Grassland Simulation Model (ELM) demonstrated that the processes within a grassland ecosystem could be modeled and provided methodology and direction for future modeling efforts. ELM also demonstrated the utility of a model as a research tool and an aid to resource management.

A program entitled "Improved Management and Production of Western Rangelands Using Predicting Models and Remotely Acquired Data," submitted by C. H. Herbel and W. O. Willis, was perhaps the first formal step toward the development of a range modeling effort by the Agricultural Research Service (ARS). Subsequently, a Research Planning Workshop on Range Modeling was held in Fort Collins, Colo., April 20-21, 1978. The participants of this workshop recommended that a range modeling effort be initiated immediately within ARS. The major goals stated were: "(a) increased use of modeling among range scientists as a research technique to guide and improve on-going research and provide data bases and submodels for use in more comprehensive models; and (b) development of comprehensive models that can be used effectively as planning and decision-making tools in the management of rangeland resources and administrative and research programs."

The SPUR modeling effort was initiated in September 1980 with the organization of a coordinating committee composed of R. A. Evans, R. H. Hart, G. B. Hewitt, C. L. Hanson, L. J. (Kelvin) Koong, K. G. Renard, P. L. Sims, J. R. Wight (project coordinator), and G. E. Carlson and J. C. Ritchie representing the ARS National Program Staff. At coordinating committee meetings in November 1980 and February 1981, objectives, organization, and procedures were established.

Model components and lead scientists were identified as follows:

(a) Climate -- C. L. Hanson, Boise, Idaho
(b) Hydrology -- K. G. Renard, Tucson, Ariz.
(c) Plant -- R. H. Hart, Cheyenne, Wyo.
(d) Animals -- Kelvin Koong, Clay Center, Nebr.
(e) Insects -- J. A. Onsager, Bozeman, Mont.
(f) Economics -- E. B. Godfrey, Logan, Utah

A range model workshop was held in early May 1981. Organization of the range model workshop was similar to that of the initial CREAMS (A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) Workshop. Workshop objectives were to: 1) review, refine, and adopt an approach; 2) establish lines of action and establish a timetable; 3) assign specific tasks; 4) identify data sets for validation and verification; and 5) complete a workgroup report.

A total of 54 persons, including participating scientists, administrators, user agency representatives, and interested visitors attended the workshop. The heterogeneous mix of scientific disciplines and management specialists, which is somewhat unique to range science and management, providing a stimulating environment for the discussion and development of modeling objectives and research plans.

Time tables of February 1, 1982, and October 1, 1982, were established for completion of the model components and component interfacing, respectively. With little exception, these timetables were met.

Everett Springer was hired as project modeler. Component interfacing and model testing and evaluation have been substantially enhanced through his efforts.

Spur components and their testing utilized existing data and knowledge. The help of non-USDA-ARS scientists, especially in the economic, animal, and plant components, is gratefully acknowledged. Suggestions and advice from potential user groups was continually sought and freely given throughout the course of the project.

At the time of this writing, an initial version of SPUR is operational and available for research. Documentation and user manuals will be completed in 1983, at which time an operational version of SPUR is scheduled for public release. User manuals, documentation, and FORTRAN programs of SPUR and test data on magnetic tape will be available.

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MODEL OVERVIEW

By J. R. Wight, E. P. Springer, and D. L. Brakensiek[1]

INTRODUCTION

An ARS range modeling effort was initiated in November 1980. The general objectives of this modeling effort were to enhance the application of modeling technology in ARS range research and to develop a comprehensive model or models that could be used for management and research. The SPUR model reported herein is a product of this modeling effort. It represents the combined effort of both ARS and non-ARS scientists working at several locations. Actual work on the model was begun following a planning workshop in May 1981. Interfacing of the components into a comprehensive model was accomplished at the Northwest Watershed Research Center in Boise, Idaho, during the summer of 1982. Components were individually tested and evaluated. Availability of the field data necessary for testing the entire model is limited. Documentation and development of user manuals will be completed in 1983 at which time the model will be available for general use. Model components were developed using currently available information. Extensive use was made of models such as ELM (Grassland Simulation Model) (Innis 1978),[2] CREAMS (A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel 1980), and EPIC (Erosion Productivity Impact Calculator) (Williams et al. 1982). In general, the components represent the state of the art in their application to rangeland ecosystems.

SPUR is a physically based, rangeland simulation model developed to aid both resource managers and researchers. It can be applied to a wide range of conditions with a minimum of "tuning" or "fitting." As a management tool, it provides a basis for management decisions by predicting herbage yields, livestock production, runoff, and erosion. As a research tool, it helps identify research needs, enhances organization and transfer of information, and provides a focus for ARS range research programs. SPUR is composed of five basic components: 1) climate; 2) hydrology; 3) plant; 4) animal (both domestic and wildlife); and 5) economic. A subroutine is available to simulate the impacts of either grasshopper destruction or control, but at present this is an option and is not triggered by any model component. A soil frost subroutine is also included in SPUR. It predicts depth of frost penetration and thaw of the soil profile, frost type, and permeability (Bullen et al. 1982). Simulation is generally on a daily basis.

MODEL DESCRIPTION

SPUR is driven by daily inputs of rainfall, maximum and minimum temperatures, solar radiation, and wind run. These can be obtained from weather records or generated

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[1]The authors are, respectively, range scientist, hydrologist, and research hydraulic engineer, at the USDA-ARS, Northwest Watershed Research Center, 1175 South Orchard, Suite 116, Boise, Idaho.

[2]The author's name followed by the year underlined, refers to Literature Cited, p. 4.

stochastically within the climatic component. The stochastic generation of the climatic variables or parameters enhances the utilization of the SPUR model for long-term simulation runs and enables the model to be applied to areas where climatic data are limited.

The hydrology component calculates upland surface runoff volumes, peakflow, snowmelt, upland sediment yield, channel streamflow and sediment. It also calculates a daily soil water balance that is used to generate soil water suction pressures that control plant growth. Surface runoff is estimated by the Soil Conservation Service (SCS) curve number procedure, and soil loss is computed by the Modified Universal Soil Loss Equation (MUSLE). The hydrology component also includes a snowmelt routine which employs an empirical relationship between air temperature and each flux in the energy budget of a dynamic snowpack.

Net photosynthesis is the basis for predicting forage production. Carbon and nitrogen are cycled through several compartments including standing green, standing dead, live roots, dead roots, seeds, litter, and soil organic matter. Inorganic nitrogen is also considered. Photosynthesis is controlled by temperature and soil water availability. The model simulates competition between species and grazing impacts on vegetation. Inputs required include the initial biomass content of each compartment and parameters that describe species photosynthesis, respiration, and nitrogen utilization.

The animal component considers both domestic livestock and wildlife as consumers. Detailed growth information is available for cattle on a steer equivalent basis. Forage consumption is calculated for all classes of animals. Steer growth is computed by an adaptation of the Texas A & M Beef Model. The development of preference vectors based on forage palitability, abundance, and location to control plant utilization by animals is a unique feature of the model. Wildlife and insects are considered as fixed consumers and are allowed to have first access to the available forage.

Animal production or pounds of beef gain are used by the economic component to estimate benefits and costs of alternative grazing practices, range improvements, and animal management options.

MODEL SCALE

Two versions of SPUR have been developed and a third version contemplated. The first version is a grazing unit or pasture scale version that is relatively easy to operate and accommodates the resolution of the animal component to differentially graze a grazing unit according to the various preference vectors. The second version is a basin scale version that requires considerable lumping and averaging of animal and plant parameters but provides good resolution in terms of runoff, peakflow, sediment yield, and channel hydrology. A projected third version is a comprehensive basin scale model that retains the resolution of both the pasture scale and the basin scale through complexity and scope of model programming.

The pasture scale version simulates the growth of up to seven species or species groups on up to nine range sites within a grazing unit. This version provides pasture or allotment level managers with a relatively accessible model to simulate growth and grazing of the major plant species and animal production. It also provides erosion, runoff, and peak flow indices for relative comparisions as related to range sites and to management options.

The basin scale version is somewhat more complex; it provides a means of predicting quantities of runoff and sediment yield for basins of up to 10 mi^2 with up to 27 hydrologic units (drainages adjacent to a channel). It retains the ability to grow and graze plants and produce beef, but the resolution of these components is diminished. The basin scale version uses the watershed as a management unit and is designed to answer the questions of the land manager. Erosion calculations are made and impacts can be determined.

CURRENT STATUS AND FUTURE DEVELOPMENT

The initial objectives of the modeling effort have been met with a reasonable degree of success. Development of the SPUR model has enhanced the application of modeling technology to ARS range research programs and has provided focus and direction for long-range research planning. A comprehensive rangeland model has been developed that can be used as both a research and management tool. Information gaps have been identified and a framework for conducting the needed research has been established.

Full realization of the management objectives has yet to be realized. A model has been developed that is relatively easy to operate in terms of inputs; it is reasonably accessible in terms of computer requirements; and it provides estimates of many of the parameters essential for effective range management. Two factors are of major concern: 1) accuracy of the model prediction, and 2) interactive relationships between the plant and animal components and the hydrology component such that the dynamics of grazing impacts can be simulated in terms of the hydrological characteristics.

Testing of the SPUR model has been and continues to be a major problem. Usable field data that includes plant and animal growth along with measurements of runoff and erosion are limited. Testing of individual components is similarly limited by lack of field data. To date, the plant component has been tested only for the growth of western wheatgrass (*Agropyron smithii* Rybd.) and blue gramma [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.]. Application of the model for the growth of other species and species groups needs further development and evaluation. The runoff and erosion sections of the hydrology component were based on southwest rangeland hydrologic conditions and will need further evaluation in snow climates.

A specific objective of the SPUR model was to simulate management impacts, including impacts on rangeland hydrology. This requires dynamic linkages between the plant and animal components and the hydrology component that reflect changes in plant cover and infiltration induced by livestock management and climate. Specific problems are in relating the effects of animal grazing and vegetation to SCS curve numbers and the C-factor of the MUSLE. How do livestock trampling and species composition affect SCS curve numbers? What are the relationships of plant biomass (live and dead) as output by the plant component of the model to ground cover as utilized in soil loss calculations? The initial estimates of these relationships will need more research and evaluation.

Model accessibility in terms of FORTRAN programs, documentation, and user manuals will have a profound effect on the application of the SPUR model to problems of management and research. Procedures will be needed for maintaining, testing, and updating the model and for the distribution of the model and supporting documentation to potential users.

SUMMARY

An initial version of the SPUR model has been completed and is reported herein. The model, along with its supporting documentation, will be available for distribution sometime in late 1983. It has been and will continue to be effective as a research tool. It functions limitedly as a management tool but will require further refinement

and evaluation before its full management potential is realized. Such refinements and evaluations will be an ongoing process for the next several years.

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SPUR CLIMATE COMPONENT

By C. L. Hanson and C. W. Richardson[1]

INTRODUCTION

Climate and day-to-day variations in weather have major influences on range processes such as forage production, livestock water, insect dynamics, erosion, and many others. The climate of a range site determines in large measure the forage species and quality, type of grazing animals, and management systems for the site. Weather data are needed to assess the effects of climate on range processes and as inputs to range models.

For many range sites, weather data of sufficient length are not available to make the desired assessments. Therefore, it is desirable to have the capability of either generating weather data with the same statistical characteristics as the actual weather at the location or of using weather records when they are available.

INPUT DATA

The climate subroutine described herein contains three options for utilizing available climatic data or generating a climatic record. The following options are available:

1) Read in daily precipitation, maximum and minimum air temperature, and solar radiation from a location record.

2) Read in daily precipitation and generate daily maximum and minimum air temperature and solar radiation.

3) Generate daily precipitation, maximum and minimum air temperature, and solar radiation.

The subroutines in SPUR can utilize climatic data for only one location on a field or watershed. Daily wind is always generated.

WEATHER GENERATION MODEL DESCRIPTION

A model called WGEN (Weather Generator) has been developed for generating daily values of precipitation, maximum temperature, minimum temperature, solar radiation, and wind. The model is based on the procedure described by Richardson (1981a);[2]

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[2]The author's name followed by the year underlined, refers to Literature Cited, p. 15 .

however, several assumptions have been made that simplify the use of the model, and a wind component has been added. Model parameters required to generate new sequences of weather variables have been determined for many locations in the United States and will be listed in the SPUR Users Manual. A program is also available to compute the required precipitation generating parameters.

WGEN provides daily generated values of precipitation (p), maximum temperature (t_{max}), minimum temperature (t_{min}), solar radiation (r), and windspeed (v) for an n-year period at a given location. The model is designed to preserve the dependence in time, the internal correlation, and the seasonal characteristics that exist in actual weather data for the location. Precipitation and wind are generated independently of the other variables. Maximum temperature, minimum temperature, and solar radiation are generated conditioned on whether the day is wet or dry.

Precipitation

The precipitation component of WGEN is a Markov chain-gamma model. A first-order Markov chain is used to generate the occurrence of wet or dry days. When a wet day is generated, the two-parameter gamma distribution is used to generate the precipitation amount.

With the first-order Markov chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with 0.01 inch of rain or more. Let P_i (W/W) be the probability of a wet day on day i given a wet day on day i-1, and let P_i (W/D) be the probability of a wet day on day i given a dry day on day i-1. Then

$$P_i(D/W) = 1 - P_i(W/W) \qquad [1]$$

$$P_i(D/D) = 1 - P_i(W/D)$$

where P_i(D/W) and P_i(D/D) are the probabilities of a dry day given a wet day on day i-1 and the probability of a dry day given a dry day on day i-1, respectively. Therefore, the transition probabilities are fully defined given P_i(W/W) and P_i(W/D).

The density function of the two-parameter gamma distribution is given by

$$f(p) = \frac{\beta^{\alpha} p^{\alpha-1} e^{-\beta p}}{\Gamma(\alpha)}, \qquad p > 0 \qquad [2]$$

where α and β are distribution parameters and $\Gamma(\alpha)$ is the gamma function of α. The α and β are shape and scale parameters, respectively. For $0 < \alpha < 1$, the distribution has a reverse "J" shape. This shape is appropriate for precipitation amounts since small amounts occur more frequently than larger amounts. The gamma distribution was shown by Richardson (1981b) to be better for describing precipitation amounts than the simple exponential distribution.

The values of P(W/W), P(W/D), α, and β vary continuously during the year for most locations. In WGEN, each of the four precipitation parameters are held constant for a given month but are varied from month to month. The values of each of the four parameters have been determined by month for numerous locations in the United States. An example of the parameters for 10 locations in the western part of the United States is given in table 1. The parameters are used with a Markov chain generation procedure and the gamma generation procedure described by Haan (1977) to generate daily precipitation values.

Temperature and Solar Radiation

The procedure that is used in WGEN for generating daily values of t_{max}, t_{min}, and r is that described by Richardson (1981a). The procedure is based on the weakly stationary generating process given by Matalas (1967). The equation is

$$\chi_i(j) = A\chi_{i-1}(j) + B\epsilon_i(j) \tag{3}$$

where $\chi_i(j)$ is a 3X1 matrix for day i whose elements are residuals of t_{max} (j = 1), t_{min} (j = 2), and r (j = 3); ϵ_i is a 3X1 matrix of independent random components; and A and B are 3X3 matrices whose elements are defined such that the new sequences have the desired serial correlation and cross correlation coefficients. The A and B matrices are given by

$$A = M_1 M_o^{-1} \tag{4}$$

$$BB^T = M_o - M_1 M_o^{-1} M_1^T \tag{5}$$

where the superscripts -1 and T denote the inverse and transpose of the matrix. M_o and M_1 are matrices containing the lag-zero cross correlation coefficients and the lag-one serial correlation coefficients, respectively.

The seasonal and regional patterns of the correlation coefficients were described by Richardson (1982). The seasonal and spatial variation in the correlation coefficients were relatively small. If the small variations are neglected and the average values of the correlation coefficients given by Richardson (1982) are used, the A and B matrices become

$$A = \begin{bmatrix} 0.567 & 0.086 & -0.002 \\ 0.253 & 0.504 & -0.050 \\ -0.006 & -0.039 & 0.244 \end{bmatrix} \tag{6}$$

$$B = \begin{bmatrix} 0.781 & 0 & 0 \\ 0.328 & 0.637 & 0 \\ 0.238 & -0.341 & 0.873 \end{bmatrix} \tag{7}$$

The A and B matrices given in equations [6] and [7] are used with equation [3] in WGEN to generate new sequences of the residuals of t_{max}, t_{min}, and r that are serially correlated and cross correlated.

The final daily generated values of t_{max}, t_{min}, and r are determined by adding a seasonal mean and standard deviation to the residual elements generated with equation [3] using the equation

$$t_i(j) = \chi_i(j) \cdot s_i(j) + m_i(j) \tag{8}$$

Table 1.--Precipitation generation parameters for locations in the western United States

STATION		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
PHOENIX,	P(W/W)	0.407	0.478	0.364	0.303	0.294	0.313	0.366	0.318	0.429	0.354	0.327	0.400
AZ	P(W/D)	0.085	0.077	0.070	0.042	0.018	0.022	0.099	0.147	0.057	0.054	0.060	0.078
	ALPHA	0.825	0.822	0.998	0.883	0.899	0.629	0.752	0.650	0.532	0.680	0.917	0.746
	BETA	0.225	0.182	0.242	0.199	0.140	0.271	0.233	0.335	0.462	0.310	0.220	0.323
GRAND JUNCTION,	P(W/W)	0.407	0.410	0.388	0.404	0.476	0.427	0.318	0.384	0.391	0.475	0.385	0.344
CO	P(W/D)	0.173	0.183	0.179	0.168	0.107	0.086	0.114	0.184	0.136	0.107	0.127	0.169
	ALPHA	0.947	0.994	0.998	0.849	0.821	0.835	0.764	0.794	0.840	0.983	0.918	0.973
	BETA	0.096	0.089	0.093	0.128	0.150	0.155	0.121	0.189	0.176	0.172	0.131	0.099
BOISE,	P(W/W)	0.595	0.559	0.459	0.406	0.476	0.464	0.250	0.353	0.370	0.389	0.534	0.543
ID	P(W/D)	0.317	0.235	0.223	0.211	0.196	0.150	0.053	0.063	0.083	0.152	0.213	0.271
	ALPHA	0.846	0.920	0.998	0.841	0.740	0.854	0.826	0.676	0.801	0.998	0.998	0.883
	BETA	0.148	0.115	0.101	0.180	0.211	0.176	0.113	0.202	0.159	0.115	0.139	0.128
RENO,	P(W/W)	0.496	0.454	0.380	0.349	0.414	0.386	0.294	0.420	0.297	0.250	0.500	0.484
NV	P(W/D)	0.138	0.113	0.135	0.101	0.101	0.074	0.067	0.049	0.044	0.046	0.093	0.138
	ALPHA	0.728	0.748	0.838	0.721	0.663	0.942	0.998	0.900	0.960	0.701	0.813	0.718
	BETA	0.275	0.258	0.150	0.182	0.253	0.138	0.095	0.107	0.158	0.233	0.166	0.265
ALBUQUERQUE,	P(W/W)	0.263	0.392	0.346	0.264	0.346	0.412	0.395	0.429	0.320	0.378	0.339	0.350
NM	P(W/D)	0.080	0.090	0.095	0.073	0.094	0.077	0.253	0.240	0.129	0.090	0.070	0.093
	ALPHA	0.840	0.998	0.964	0.712	0.699	0.718	0.744	0.804	0.836	0.739	0.998	0.858
	BETA	0.112	0.101	0.124	0.205	0.139	0.213	0.209	0.191	0.182	0.294	0.111	0.156
BURNS,	P(W/W)	0.566	0.519	0.545	0.438	0.468	0.433	0.255	0.352	0.339	0.508	0.596	0.606
OR	P(W/D)	0.353	0.223	0.233	0.178	0.180	0.157	0.067	0.082	0.072	0.127	0.201	0.243
	ALPHA	0.910	0.890	0.998	0.927	0.986	0.930	0.868	0.792	0.657	0.738	0.998	0.897
	BETA	0.152	0.142	0.096	0.107	0.126	0.139	0.148	0.164	0.263	0.203	0.146	0.168
RAPID CITY,	P(W/W)	0.370	0.503	0.444	0.518	0.519	0.557	0.394	0.338	0.362	0.360	0.382	0.411
SD	P(W/D)	0.156	0.200	0.222	0.233	0.306	0.317	0.239	0.208	0.167	0.103	0.157	0.155
	ALPHA	0.998	0.988	0.815	0.776	0.674	0.713	0.622	0.757	0.709	0.782	0.830	0.998
	BETA	0.064	0.088	0.130	0.263	0.346	0.378	0.390	0.251	0.250	0.201	0.098	0.070
AMARILLO,	P(W/W)	0.313	0.353	0.326	0.376	0.443	0.448	0.464	0.373	0.303	0.477	0.419	0.365
TX	P(W/D)	0.081	0.117	0.121	0.107	0.212	0.207	0.203	0.203	0.147	0.090	0.061	0.092
	ALPHA	0.654	0.748	0.748	0.687	0.575	0.582	0.615	0.639	0.572	0.664	0.834	0.645
	BETA	0.214	0.173	0.240	0.352	0.560	0.753	0.546	0.560	0.564	0.479	0.214	0.237
SALT LAKE CITY,	P(W/W)	0.479	0.397	0.463	0.525	0.487	0.500	0.315	0.373	0.389	0.461	0.434	0.497
UT	P(W/D)	0.226	0.263	0.236	0.239	0.165	0.139	0.104	0.139	0.111	0.108	0.170	0.230
	ALPHA	0.854	0.881	0.911	0.799	0.853	0.734	0.635	0.638	0.696	0.702	0.821	0.879
	BETA	0.165	0.169	0.178	0.276	0.206	0.249	0.299	0.264	0.219	0.265	0.212	0.170
SPOKANE,	P(W/W)	0.648	0.600	0.542	0.409	0.469	0.400	0.240	0.388	0.395	0.479	0.584	0.621
WA	P(W/D)	0.361	0.269	0.239	0.225	0.202	0.200	0.099	0.121	0.154	0.184	0.278	0.386
	ALPHA	0.955	0.998	0.956	0.933	0.889	0.702	0.878	0.746	0.824	0.910	0.903	0.887
	BETA	0.181	0.143	0.139	0.135	0.161	0.242	0.131	0.173	0.135	0.168	0.199	0.178

where $t_i(j)$ is the daily value of t_{max} (j = 1), t_{min} (j = 2), and r (j = 3); $s_i(j)$ is the standard deviation and $m_i(j)$ is the mean for day i. The values of $m_i(j)$ and $s_i(j)$ are conditioned on the wet or dry status as determined from the precipitation component of the model. By expressing equation [8] in terms of the coefficient of variation (c = s/m) rather than the standard deviation, the equation becomes

$$t_i(j) = m_i(j) \left[\chi_i(j) \cdot c_i(j) + 1\right] \qquad [9]$$

The seasonal change in the means and coefficients of variation may be described by

$$u_i = \bar{u} + C \cos(0.0172 (i - T)), \; i = 1, \ldots, 365 \qquad [10]$$

where u_i is the value of the $m_i(j)$ or $c_i(j)$ on day i, $\bar{u}$ is mean of u_i, C is the amplitude of the harmonic, and T is the position of the harmonic in days. Values of $\bar{u}$, C, and T have been determined for the mean and coefficient of variation for each weather variable (t_{max}, t_{min}, r) and for the wet or dry condition. These values were determined from daily weather data for many locations. There were no detectable differences in the means and coefficients of variation for t_{min} on wet or dry days.

Some of the parameters were strongly location dependent while other parameters did not change significantly with location. The values of T for all of the descriptors of temperature (means and coefficients of variation of t_{max} and t_{min}) were near 200 days for all locations. Similarly, the T values for r were about 172 days (summer solstice) for all locations. Therefore, in WGEN all of the T values for temperature are assumed to be 200 days and all the T values for solar radiation are assumed to be 172 days.

The $\bar{u}$ and C values for t_{max} vary with location. The values for each parameter were plotted on a map and contours of the parameters were drawn. An example of one of the maps is given in figure 1. Maps of the other parameters will be included in the SPUR Model Users Manual. An algorithm is included in SPUR to adjust daily solar radiation for slope and aspect.

Wind

The wind component of WGEN provides for the generation of daily values of windspeed. Windspeed is generated using a two-parameter gamma distribution expressed as

$$f(v) = \frac{\gamma_j^{\lambda_j} \; v^{\lambda_j - 1} \; e^{-\gamma_j v}}{\Gamma(\lambda_j)} \qquad [11]$$

where λ_j and γ_j are distribution parameters for month j and v is daily wind speed. The values of λ_j and γ_j are estimated using the method of moments by

$$\lambda_j = \bar{v}_j \; / \; s_j^2 \qquad [12]$$

and

$$\gamma_j = \bar{v}_j \; / \; s_j^2 \qquad [13]$$

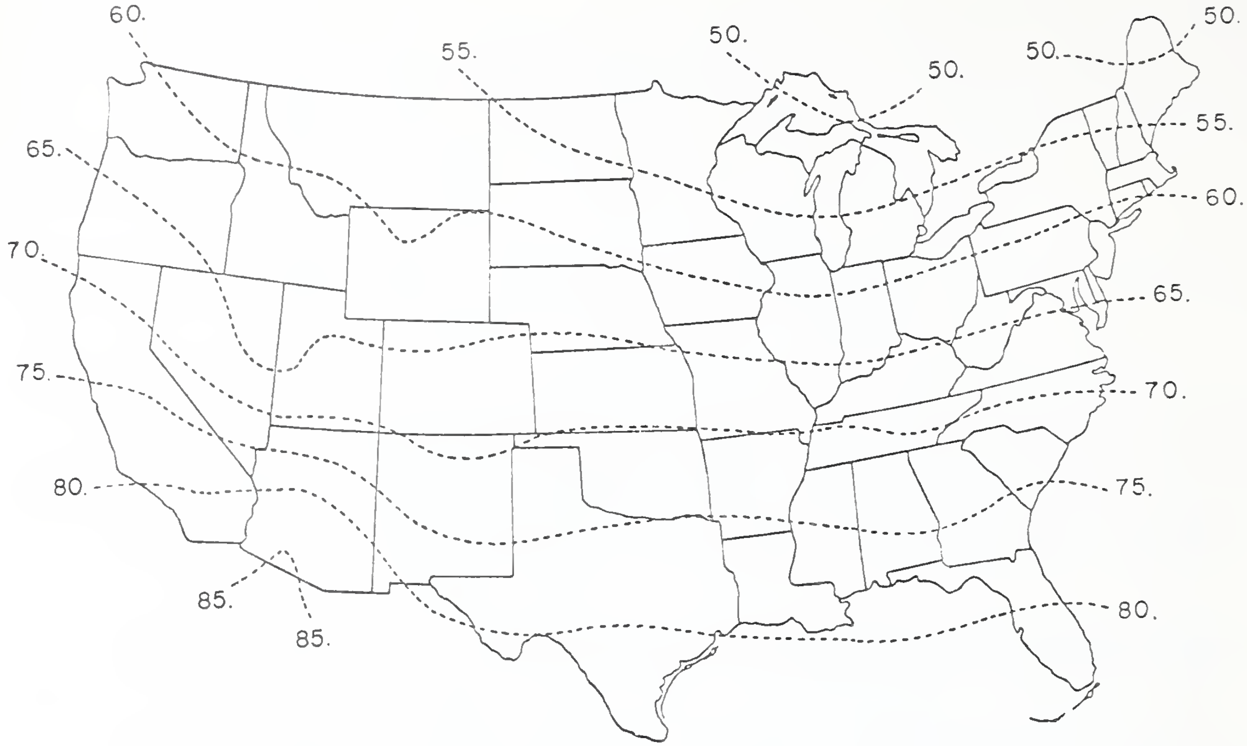

Figure 1.--Values of $\overline{u}$ for maximum temperature on dry days (°F).

where $\bar{v}_j$ is the mean daily windspeed and s_j is the standard deviation of daily windspeed. The Climatic Atlas of the United States (U.S. Department of Commerce, 1968) contains values of $\bar{v}_j$ for many locations. The mean annual wind speed ($\bar{v}_y$) and the standard deviation of hourly wind speed on an annual basis (s_h) are also available in the Climatic Atlas. By experimenting with the standard deviation of hourly and daily wind speeds for several locations, a correction factor of 0.7 was found to be appropriate for converting the standard deviation of hourly wind speed to the standard deviaton of daily wind speed.

If the coefficient of variation of daily wind speed (c_v) for a location is assumed to be constant over the year, c_v may be estimated by

$$c_v = 0.7\ s_h\ /\ \bar{v}_y \qquad [14]$$

The s_j values may be calculated by

$$s_j = c_v \cdot \bar{v}_j \qquad [15]$$

The $\bar{v}_j$ and s_j values are used with the gamma generation procedure (Haan 1977) to generate daily windspeeds.

APPLICATION OF THE MODEL

WGEN was used to generate a 30-year sample of weather data for Boise, Idaho, as an example of the application of the weather generation procedure. The precipitation parameters that were required for WGEN were obtained from table 1. The temperature and solar radiation parameters were obtained from a set of maps similar to that shown in figure 1. The wind parameters were obtained from the Climatic Atlas (U.S. Department of Commerce 1968). The statistical characteristics of the generated data were determined and compared with the characteristics of the actual weather data for Boise. The comparisons are illustrated in tables 2 to 5.

Table 2.--Average precipitation amount and number of wet days by month from data generated with WGEN and from observed data, Boise, Idaho

Month	Precipitation		Number of wet days	
	Observed	Generated	Observed	Generated
	Inches	Inches		
Jan.	1.69	1.63	13.5	11.9
Feb.	1.05	1.28	9.9	11.7
Mar.	.91	.96	9.1	8.8
Apr.	1.20	1.16	7.9	7.8
May	1.31	1.36	8.4	8.4
June	1.01	.88	6.7	6.1
July	.19	.20	2.1	1.7
Aug.	.36	.53	2.8	3.1
Sept.	.45	.33	3.5	3.0
Oct.	.71	.65	6.2	5.9
Nov.	1.29	1.32	9.3	8.7
Dec.	1.30	1.32	11.6	12.0
Annual	11.47	11.63	90.8	89.0

Table 3.--Mean daily maximum temperature, minimum temperature, and solar radiation by month and for the year data generated with WGEN and from observed data, Boise, Idaho

Month	Maximum temperature		Minimum temperature		Solar radiation	
	Observed	Generated	Observed	Generated	Observed	Generated
	°F	°F	°F	°F	Langleys	Langleys
Jan.	37.7	34.6	23.1	21.7	141	119
Feb.	44.0	38.0	27.3	24.6	231	200
Mar.	51.6	47.1	30.4	29.6	351	351
Apr.	60.8	60.5	35.9	37.5	485	499
May	70.8	73.8	44.0	46.4	588	595
June	79.3	84.3	51.8	52.9	634	663
July	90.8	88.4	58.7	54.9	672	660
Aug.	87.5	85.4	58.2	53.7	579	550
Sept.	77.7	76.8	48.8	48.2	457	419
Oct.	64.5	63.3	39.0	39.3	308	265
Nov.	49.2	49.1	30.5	30.9	172	148
Dec.	39.2	39.8	24.9	25.7	124	99
Year	62.9	61.7	39.4	38.8	400	381

Table 4.--Mean annual maximum temperature, minimum temperature, number of days per year with temperature greter than 95°F, and number of days per year with temperature less than 32°F from data generated with WGEN and from observed data, Boise, Idaho

Variable	Observed	Generated
Maximum temperature, °F	103.8	101.3
Minimum temperature, °F	1.3	3.4
Days $\geq$ 95°F	18.7	9.1
Days $\leq$ 32°F	128.0	129.3

Table 5.--Mean daily windspeed by month and for the year from data generated with WGEN and from observed data, Boise, Idaho

Month	Windspeed	
	Observed	Generated
	----------Mi/hr----------	
Jan.	8.9	9.1
Feb.	8.9	10.5
Mar.	10.0	10.9
Apr.	11.2	10.1
May	9.5	10.8
June	9.2	8.7
July	8.7	8.6
Aug.	8.6	8.1
Sept.	8.7	8.4
Oct.	8.2	9.3
Nov.	9.1	8.7
Dec.	9.5	9.0
Yearly average	9.2	9.3

The mean precipitation amounts and the mean number of wet days for each month and for a year are shown in table 2 for the generated and observed data. The mean precipitation amount for each month from the generated data was very close to that obtained from the observed data. The average number of wet days generated for each month was also a close approximation of that obtained from the observed data.

The maximum and minimum temperature and solar radiation data generated with the model are compared with the observed data in table 3. The mean daily maximum temperature from the generated data compared favorably with the observed data for most months. The largest difference was 6°F for February. On an annual basis, the average daily maximum temperature from the generated data was 1.2°F less than from the observed data. The mean daily minimum temperatures and the mean daily solar radiation from the generated data compared favorably with the observed means.

The mean annual extreme temperatures and the number of days with extreme temperatures are compared in table 4. The average annual maximum temperature from the Boise data was 103.8°F. The generated data had an average annual maximum temperature of 101.3°F. The average annual minimum temperatures were 1.3°F for the observed data and 3.4°F for the generated data. The average number of days with temperatures greater than 95°F was 18.7 for the observed and 9.1 for the generated data. The average number of days with temperatures below freezing was 128.0 and 129.3 for the observed and generated, respectively.

The generated windspeed was compared with the observed wind data in table 5. The generated mean windspeed for each month is about the same as that from the observed data.

DISCUSSION

The WGEN model can be used to generate daily weather variables that are essential for rangeland modeling applications where long term weather records are seldom available. WGEN produces daily values of precipitation, maximum temperature, minimum temperature, solar radiation, and windspeed that closely resemble the actual weather for a site, provided the parameters are properly defined.

Application of WGEN to a particular site requires that 48 precipitation parameters and 12 temperature and radiation parameters be defined. The precipitation parameters have been defined for many locations and the temperature and radiation parameters have been mapped for the United States. The windspeed parameters may be obtained from the Climatic Atlas of the United States (U.S. Department of Commerce 1968).

Parameter values for sites not given in the table of precipitation parameters or the Climatic Atlas may be estimated by interpolating between sites where the values have been defined. Careful judgment should be used in making interpolations in areas where the local climate may be affected by physiographic features such as high elevations or orientation of mountain ranges. If weather data of relatively short length are available for the site, the parameters can be defined from the data and used to generate a weather sequence of greater length.

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SPUR HYDROLOGY COMPONENT: UPLAND PHASES

By K. G. Renard, E. D. Shirley, J. R. Williams, and A. D. Nicks[1]

INTRODUCTION

The hydrology component of the model is designed to use inputs from the climate component and produce outputs unto its own (for example, runoff and sediment yield) or inputs for other components of the model (for example, estimates of available soil moisture for forage production and water for grazing animals). The hydrology component is divided into three parts: an upland phase, a snowmelt phase, and a channel phase. This portion of the report is for the upland phase.

In the streams draining the rangeland areas of the western United States, extreme spatial and temporal variability in physiographic and climatic conditions require that a hydrologic model consider such conditions. For example, it is very possible to have an individual storm event occurring as rain at low elevations and snow at high elevations. Airmass thunderstorms dominating the rainfall-runoff process in the semiarid Southwest have extreme variations in precipitaton depth in short distances (1 in/mi is not rare).

A hydrologic model component should be capable of simulating the effects of management changes on streamflow for streams that may have influent or effluent characteristics; have flow conditions that are subcritical or supercritical; and have a wide variety of slopes up to steep, rocky, pool-riffle systems.

The objectives of the upland phase of the hydrologic model are: 1) be capable of predicting changes in water quantity and quality resulting from management changes; 2) be physically based, so that model parameters can be evaluated from available data for ungaged areas; 3) have sufficient detail to allow simulation on subdivided watersheds to coincide more or less with ranch and pasture boundaries; 4) be computationally efficient to enable long-term simulation for frequency analyses; 5) be capable of providing input to other SPUR model components, such as soil moisture for plant forage yield estimates and water for domestic animals and wildlife; and 6) be used for environmental impact analysis, nonpoint pollution assessment, and other types of resource utilization and environmental protection problem solutions.

Although these objectives may seem overly ambitious, there have been significant improvements of water resource models in recent years (Crawford and Donigian 1976;[2] Williams and LaSeur 1976; Beasley et al. 1977; Simons et al. 1977; Knisel 1980a, 1980b), which facilitate such a development.

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[2]The author's name followed by the year underlined, refers to Literature Cited, p. 38.

The upland phases of the hydrology model for SPUR draw heavily from a model called SWRRB (Simulation for Water Resources in Rural Basins),[3] which has been modified and improved to consider the essential features known to affect the hydrologic response from rangelands. The SWRRB model includes the major processes of surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and erosion and sedimentation. The well known curve number technique (USDA 1972) is used to predict surface runoff for any given precipitation event because 1) many years of use have given confidence in its validity, 2) it relates runoff, soil type, vegetation, land use, and management, and 3) it is computationally efficient. The use of rainfall data for short time increments (minutes and/or hours), which are required with infiltration equations to compute precipitation excess, are not generally available for most areas of the United States, and especially not on the rangelands with the orographic precipitation effects, sparsity of recording rain gages, etc. Finally, daily rainfall estimates are computationally more efficient than similar operations with shorter time increments.

MODEL DESCRIPTION

Water Balance

The SPUR model maintains a continuous water balance on a daily computational basis using the equation

$$SW = SW_o + P - Q - ET - PL - QR \qquad [1]$$

where

SW = current soil water content (in),

SW_o = initial soil water content (in),

P = cumulative rainfall (in),

Q = cumulative amount of surface runoff (in),

ET = cumulative amount of evapotranspiration (in),

PL = cumulative amount of percolation loss to ground water storage (in), and

QR = cumulative amount of return flow (in).

In maintaining the continuous water balance, complex watersheds are subdivided to reflect different vegetation or soils, topography, stream morphology, etc. In other words, runoff is computed for each subarea and the water routed to the outlet of the basin to obtain the total runoff. This accounting allows changing management practices of only a portion of the area and should improve the model's accuracy, yet provide a more detailed physical preservation of the watershed details.

Soil Layer Water Storage

The soil in each subarea of the watershed is divided into layers (user specified number of layers (up to eight) and layer thickness for each subarea). Water balance

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[3]Mimeograph handout by J. R. Williams and A. D. Nicks.

is done on a daily basis using rainfall excess, evapotranspiration, percolation, and return flow as described in equation [1]. Total storage, field capacity, and initial water storage in the various layers are computed from input parameters as follows:

$$Ul_i = (SMO_i - SM15_i)THK_i \qquad [2]$$

$$FC_i = (SM3_i - SM15_i)THK_i \qquad [3]$$

$$SW_{oi} = (FC_i)(STF) \qquad [4]$$

where

Ul_i = upper limit of water storage in layer i (in),
FC_i = field capacity in layer i (in),
SW_{oi} = initial soil water in layer i (in),
SMO_i = soil porosity for layer i (in/in),
$SM3_i$ = 0.3 bar water content for layer i (in/in),
$SM15_i$ = 15 bar water content for layer i (in/in),
THK_i = soil layer thickness for layer i (in), and
STF = initial soil water content as a fraction of field capacity.

Runoff

The traditional three antecedent moisture levels (I -dry, II - normal, III - wet), as used by SCS, have been modified in the model by allowing soil moisture to be updated daily and by computing daily curve numbers based on soil water storage rather than using the three curve numbers associated with their moisture classes. Thus, each day has a curve number (Williams and LaSeur 1976), and the soil moisture changes between runoff events with estimates of evapotranspiration and percolation, using routines very similar to those used in CREAMS (Knisel 1980b). From the curve number method, surface runoff is estimated on a daily basis from

$$Q = \frac{(P - I_a)^2}{P + s - I_a} = \frac{(P - 0.2s)^2}{P + 0.8s} \qquad [5]$$

where

Q = daily runoff (in),

P = daily rainfall (in),

s = a retention parameter (in), and

I_a = 0.2s = initial abstraction.

The maximum value, s_{mx}, for the retention parameter, s, is computed with the following SCS curve number relationship (USDA 1972):

$$s_{mx} = \left(\frac{1000}{CN_I} - 10\right) \qquad [6]$$

where CN_I is the dry antecedent moisture condition curve number. If handbook curve numbers are available for the normal moisture condition, CN_{II}, the following polynomial may be used to estimate CN_I.

$$CN_I = - 16.91 + 1.348(CN_{II}) - 0.01379(CN_{II})^2 + 0.0001177(CN_{II})^3 \qquad [7]$$

The soil retention parameter is computed daily as a weighted average of the unused storage in the various soil layers scale from 0 to s_{mx}.

$$s = s_{mx}\left[\sum_{i=1}^{N} W_i \left(\frac{Ul_i - SW_i}{Ul_i}\right)\right] \qquad [8]$$

where

N = number of soil layers,

SW_i = current water storage in layer i (updated daily) (in), and

W_i = weighting factor.

The weighting factors decrease exponentially to give greater dependence of s on the upper soil layers.

$$W_i = a \exp(-4.16d_i) \qquad [9]$$

where

d_i = (depth to bottom of layer i)/(depth to bottom of last layer), and

a = constant adjusted so $\sum_{i=1}^{N} W_i = 1$.

Peak Flow Calculation

Peak discharge for daily runoff events is calculated using some relationships discussed in the channel routing process (SPUR Hydrology Component: Water Routing and Sedimentation) for SPUR.

$$Q_p = C_5Q/D \qquad [10]$$

where

Q_p = peak flow rate (in/hr),

Q = daily runoff volume (in),

D = duration of runoff (hr), and

C_5 = a constant.

Runoff duration (D is in hr) is obtained from

$$D = C_1 A^{C_2} \text{ (hr)} \qquad [11]$$

where

A = watershed area (acres); and C_1 and C_2 are constants.

Combining equations and converting units gives

$$Q_p = (1.00833) \frac{C_5}{C_1} QA^{(1-C_2)} \qquad [12]$$

where the constant (1.00833) allows conversion to give Q_p in cubic feet per second. The constants C_1, C_2, and C_5 are data input to the program.

Percolation

The percolation component of SPUR uses a storage routing model combined with a crack-flow model to predict flow through the root zone. These models are similar to those used in CREAMS (Knisel 1980b) and SWRRB. Water moving below the root zone becomes ground water, or appears as return flow that is routed into the channel network.

In the following, $PL1_i$ is percolation flow out of the bottom of layer i from the storage routing model. $PL2_i$ is the crack flow out of the same layer. $PL_i = PL1_i + PL2_i$ is the total flow out of layer i (ignoring return flow). PL_o is computed as equal to precipitation minus rainfall excess--the amount of water flowing into the first layer.

Flow through a soil layer may be restricted by a lower layer which is saturated or nearly saturated. PL_i, as subsequently computed, may exceed the projected available storage in the next layer ($UL_{i+1} - SW_{i+1}$ + projected evapotranspiration losses from layer i + 1), in which case, PL_i is set to this projected value. There is no "succeeding" layer to the bottom layer. Crack-flow computations use bottom layer values where the bottom layer needs succeeding layer values. PL2 is not limited by the succeeding layer.

Storage Routing

The storage routing model uses an exponential function with the percolation computed by subtracting the soil water in excess of field capacity at the end of the day from that at the beginning of the day

$$PL1_i = \begin{cases} (SW_i - FC_i)\left(1 - \exp(-\Delta t/T_i)\right), & SW_i > FC_i \\ 0, & SW_i \leq FC_i \end{cases} \qquad [13]$$

where

$PL1_i$ = amount of percolate (in),

SW_i = the soil water content at the beginning of the day for layer i (in),

Δt = time interval (24 hr),

T_i = travel time through a particular layer (hr),

FC_i = the field capacity water content for layer i, (in), and

i = soil layer number increasing with depth.

The travel time through each soil layer is computed with the linear storage equation

$$T_i = \frac{SW_i - FC_i}{H_i} \qquad [14]$$

where

H_i = the hydraulic conductivity of layer (in/hr).

Hydraulic conductivity is varied from the specified saturated conductivity value by

$$H_i = SC_i \left(\frac{SW_i}{UL_i}\right)^{\beta_i} \qquad [15]$$

where

SC_i = saturated conductivity for layer i (in/hr), and

β_i = parameter that causes $H_i \rightarrow 0.0022$ SC as $SW_i \rightarrow FC_i$.

The equation for estimating β_i is

$$\beta_i = \frac{-2.655}{\log(FC_i/UL_i)} \qquad [16]$$

where the constant (-2.655) assures that $H_i = 0.0022\ SC_i$ at field capacity.

Crack Flow

The crack-flow routine is used in the model to allow percolation of infiltrated precipitation even though the soil water content may be less than field capacity. Given a dry soil with cracks, infiltration can move through the cracks of a layer without becoming part of the soil water in the layer, while the portion that becomes part of a layer's stored water cannot percolate by the storage routing model until the storage exceeds field capacity. Crack flow percolation uses the equation

$$PL2_i = (d_c)(PL_{i-1})\left(1 - \frac{SW_{i+1}}{UL_{i+1}}\right)^2 \qquad [17]$$

where d_c is a soil parameter that expresses degree of cracking. Crack flow occurs only on days when water enters the layer (PL_{i-1}) and is greatest when the next layer down is dry.

Since the daily time increment is relatively long for routing the flow through soils, it is desirable to route the water in volume increments. The increments to be routed are variable and are a function of the difference between the $UL_i - FC_i$ and the total amount to be routed. By dividing the layer inflow into several "slugs," each slug may be routed through the layer, thus allowing SW_i to be updated during the calculation.

Return Flow

Return flow is calculated as coming from the bottom soil layer, N. The return flow function used for SWRRB is also used in SPUR (note the similarity to eq. [13])

$$QR = \left(SW_N - FC_N\right)\left(1 - \exp(1/T_R)\right) \qquad [18]$$

where

QR = return flow (in),

T_R = return flow travel time (days), and

N = last soil layer.

Return flow time, T_R, is the time required for subsurface flow from the centroid of the basin to the basin outlet. The value of T_R is input for each subarea by the SPUR user instead of being calculated form soil hydraulic properties. Experienced hydrologists familiar with the base flow characteristics of watersheds within a region should have little problem in assigning reasonable values to T_R.

Evapotranspiration

The evapotranspiration (ET) component in SPUR is the same as is used in CREAMS and SWRRB, and is based on work by Ritchie (1972). Potential evaporation is computed with the equation

$$E_o = \frac{0.0504 \Delta H_o}{\Delta + \gamma} \qquad [19]$$

where

E_o = potential evaporation (in),

Δ = slope of the saturation vapor pressure curve at the mean air temperature,

H_o = net solar radiation (Langleys), and

γ = a psychometric constant.

is computed with the equation

$$\Delta = \frac{5304}{(T_K)^2} \exp(21.255 - 5304/T_k) \qquad [20]$$

where

T_k = daily temperature (degrees Kelvin).

H_o is calculated with the equation

$$H_o = \frac{(1 - \lambda) R}{58.3} \qquad [21]$$

where

R = daily solar radiation (Langleys), and

λ = albedo.

Soil Evaporation

The model computes soil evaporation and plant transpiration separately. Potential soil evaporation is computed with the equation

$$E_{so} = \min \begin{cases} E_o \exp(-0.4 \text{ LAI}) \\ E_o \text{ GR} \end{cases} \qquad [22]$$

where

E_{so} = potential evaporation at the soil surface (in),

LAI = leaf area index defined as the area of plant leaves relative to the soil surface, and

GR = mulch (residue) cover factor (in).

Actual soil evaporation (E_s) is computed in two stages based on the soil moisture status in the upper soil profile. In stage 1, soil evaporation is limited only by the energy available at the surface, and thus, is equal to the potential (equation [22]). When the accumulated soil evaporation exceeds the first stage upper limit, the stage 2 evaporation begins. (The reader is referred to Ritchie (1972) for additional explanation of the procedure). The first stage upper limit is estimated from

$$U = 1.38\ (\alpha - .118)^{.42} \qquad [23]$$

where

U = stage 1 upper limit (in), and

α = soil evaporation parameter dependent on soil water transmission characteristics (ranges from 0.13 to 0.22 in/day$^{1/2}$).

Ritchie (1972) suggests using α = 0.14 for clay soils, 0.18 for loamy soils, and 0.13 for sandy soils. Similar values were obtained for data from Jackson et al. (1976).

Stage 2 soil evaporation is predicted by

$$E_s = \alpha \left(t^{1/2} - (t-1)^{1/2}\right) \qquad [24]$$

where

E_s = soil evaporation for day t (in), and

t = days since stage 2 evaporation began.

Plant Transpiration

Potential transpiration (E_{po}) from plants is computed with the equations

$$E_{po} = \frac{(E_o)(LAI)}{3}, \qquad 0 \leq LAI \leq 3 \qquad [25]$$

$$Epo = E_o - E_s, \qquad LAI > 3 \qquad [26]$$

(NOTE: If $E_{po} + E_s > E_o$, E_s is reduced so $E_{po} + E_s = E_o$.)

Because the LAI is generally considerably less than 3 in rangeland plant communities, such as SPUR is intended to consider, equation [25] will be used most of the time. If soil water is limited, plant transcription is reduced with the equation

$$E_p = \frac{(E_{po})(SW)}{0.25(UL)}, \qquad SW \leq 0.25(UL) \tag{27}$$

(NOTE: If $E_p + E_s$ exceeds available water, E_s is reduced so $E_p + E_s$ = available water.)

where

E_p = plant transpiration reduced by limited soil moisture (in),

SW = current soil water in the root zone (in), and

UL = total soil water storage capacity (in).

Evapotranspiration (ET) then is the sum of plant transpiration (equation [25], [26], or [27]) plus soil evaporation (equation [23] and/or [24]), and cannot exceed available soil water.

Distribution of ET in Soil Profile

Given the computed ET for a particular day, it must be distributed properly in the soil layers based on the rooting depth. The rate of soil water use by evapotranspiration as a function of root depth is computed with the equation

$$v = v_o \exp(-v_1 D) \tag{28}$$

where

v = water use rate by crop at depth D (in/day),

v_o = water use rate at the surface (in/day).

v_1 = 3.065, and

D = Soil depth/depth to bottom of last soil layer with roots.

The total water use within any depth can be computed by integrating equation [28]. The value of v_o is determined for the root depth each day, and the water use in each soil layer is computed with the equation

$$v_o = (v_1)(ET)/(1.0 - \exp(-v_1)) \tag{29}$$

$$UW_i = \frac{v_o}{v_1} \left(\exp(-v_1 D_{i-1}) - \exp(-v_1 D_i)\right) \tag{30}$$

where

UW_i = water use in layer i (in), and

D_{i-1} and D_i = the fractional depths at the top and bottom of layer i.

(NOTE: The UW_i are the initial estimates of ET to subtract from the various soil layers. If a layer has insufficient water, the excess ET is taken out of the first layer containing available water and having roots present.)

Water Balance for Ponds

Water for grazing animals in rangeland watersheds is often supplied by small earth dams, which create small ponds. These ponds can hold a considerable portion of the runoff from the contributing watershed, depending upon how full the pond is when runoff begins. In addition, the retention of water in such ponds can result in a significant delay or reduction in the downstream runoff and a distortion of the time-flow rate relationship. The SPUR model uses a component of SWRRB which was designed to account for the effects of farm/ranch ponds on water yield. The water balance equation is

$$VM = VM_o + QI - QO - EV - SP \qquad [31]$$

where

VM = volume of water stored in pond at end of day (ac-ft),

VM_o = volume of water in pond at beginning of day (ac-ft),

QI = inflow to the pond during the day (ac-ft),

QO = outflow from the pond during the day (ac-ft),

EV = evaporation from pond (ac-ft), and

SP = seepage from pond (ac-ft).

(Note: The amount of water consumed by grazing animals is assumed to be negligible compared to seepage and evaporation losses.)

Inflow, QI, is considered to be surface runoff from the watershed area draining into the pond plus precipitation on the pond's water surface. Outflow from the pond occurs from either an emergency spillway or a principle spillway and occurs when the permanent pool storage capacity is exceeded.

Evaporation from the pond is computed with the equation

$$EV = \frac{1}{12} (\alpha) (E_o) (SA) \qquad [32]$$

where

α = evaporation coefficient ($\simeq 0.6$), and

SA = surface area of the pond (acres).

Seepage from the pond is computed with the equation

$$SP = 2(SC)\ (SA) \tag{33}$$

where

SC = saturated conductivity of the pond bottom (in/hr).

No effort was made to make SC vary with water depth in the pond and other factors, like soil stratification or sediment distribution, in the pond. These modifications were not felt to be warranted because of the need for additional detailed information to implement them.

Since pond surface area is required for computing evaporation (equation [32]) and seepage (equation [33]), a relationship between pond volume and surface area is necessary. Data from a large number of stock ponds and small reservoirs in Texas and Oklahoma (USDA 1957) indicate that surface area can be calculated with the equation

$$SA = SA_{max}\ (VM/VM_{max})^{\delta} \tag{34}$$

where

δ = a parameter determined to be 0.9,

VM_{max} = maximum pond volume (ac-ft), and

SA_{max} = maximum pond surface area (ac).

Other research by Hanson et al. (1975) has indicated that, in Montana and South Dakota, the exponent δ should be about 0.7.

Sediment Yield

Estimating soil loss from the upland areas of rangelands is a difficult problem (Renard 1980) because most of the technology currently in use was developed for cultivated cropland areas. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and the modification to this equation (MUSLE) (Williams and Berndt 1977) are used in SPUR. The equation used is

$$Y = \eta (Q * Q_p)^{0.56}\ (K)\ (C)\ (P)\ (LS) \tag{35}$$

where

Y = sediment yield from upland area (tons/ac),

η = coefficient = 95

Q = upland runoff volume (in),

Q_p = peak flow rate (cfs),

K = soil erodibility factor,

C = cover/management factor,

P = erosion control practice factor, and

LS = slope length and steepness factor.

The determination of the LS factor in this equation is quite critical to the sediment yield calculation. Care must be taken when selecting the model elements to describe prototype configuration. As the model is used to describe larger and larger elements, some detail is lost. Thus, the way the LS term is evaluated may change with the size of the area to be simulated. The average land slope of any subarea or subwatershed can be estimated by field measurements or by measurements from a topographic map with the Grid-Contour Method (Williams and Berndt 1976) using the equations

$$S_d = N_d \, H/D_d \tag{36}$$

$$S = (S_\ell^{\,2} + S_w^{\,2})^{1/2} \tag{37}$$

where

S_d = slope in one grid direction,

S = average land slope of a subarea or subwatershed,

N_d = total number of contour crossings from all grid lines in direction d,

H = contour interval,

D_d = total length of all grid lines within the subarea in direction d,

S_ℓ = slope in the length grid direction obtained from equation [36] and,

S_w = slope in the width direction obtained from equation [36].

The average slope length can be estimated for each subarea or subwatershed by field measurements or with the Contour-Extreme Point Method (Williams and Berndt 1976) by using the equation

$$L = \frac{LC}{2EP} \tag{38}$$

where

EP = number of extreme points (channel crossings) on the contours of a topographic map,

LC = total length of all contours within the subarea or subwatershed, and,

L = average slope length (ft).

The LS factor is computed with the equation

$$LS = \left(\frac{L}{72.6}\right)^M (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065) \qquad [39]$$

where

θ = angle of slope (note S is often substituted for sin θ), and

M = exponent proportional to steepness.

The exponent, M, varies with slope and is computed with the equation

$$M = 0.6\left(1\text{-}\exp\left(-35.835(S)\right)\right) . \qquad [40]$$

The value of the C factor for each crop is determined from the tables in Agriculture Handbook 537 (Wischmeier and Smith 1978). In many rangeland areas, erosion pavement (rocks larger than one-half in) on the surface are very effective in absorbing the kinetic energy of rainfall. We recommend including an estimate of the percentage of the soil surface covered by the erosion pavement and including it with the plant basal area to arrive at a C factor (for example, by using table 10 of Handbook 537). Values of K and P can be obtained for each subwatershed using Handbook 537 or using the conservation reports of SCS for each State.

Sediment Routing in Ponds

The SPUR model assumes that the sediment coming into the pond with the inflow is retained there. Thus, the outflow from the pond is assumed to be clear, and any water leaving the pond thus picks up sediment again from the channel boundaries below the pond.

APPLICATION OF SPUR UPLAND HYDROLOGY MODEL

The hydrology portion of the SPUR model is designed to operate with the climatic portion of the SPUR model providing the input and with the channel routing portions for both the runoff and sediment transport. Thus, the user of the technology must be familiar with considerations in this part of the program as well.

Figure 1 is a flow chart of the upland hydrology model in SPUR. Examination of the chart shows that the main program consists of a series of loops to handle individual computations as well as those for each month and year. Loops are also used to handle the channel routing calculations. Finally, depending upon the needs of the user, summaries of the calculations can be made on a daily or monthly (tables for year) basis.

The conceptual configuration of a surface topography for input to the model is given in figure 2. In this conceptualization, there were 4 channel reaches (C1. . . .C4), 11 lateral inputs (L1, L2. . . .L11), 2 upland regions (U1 and U2), plus 1 pond (P1). The constraints shown at the bottom of the figure illustrate requirements for the computer model. These constraints allow simulation of almost any topographic or land use variation patterns into a fairly rigorous reproduction of the prototype.

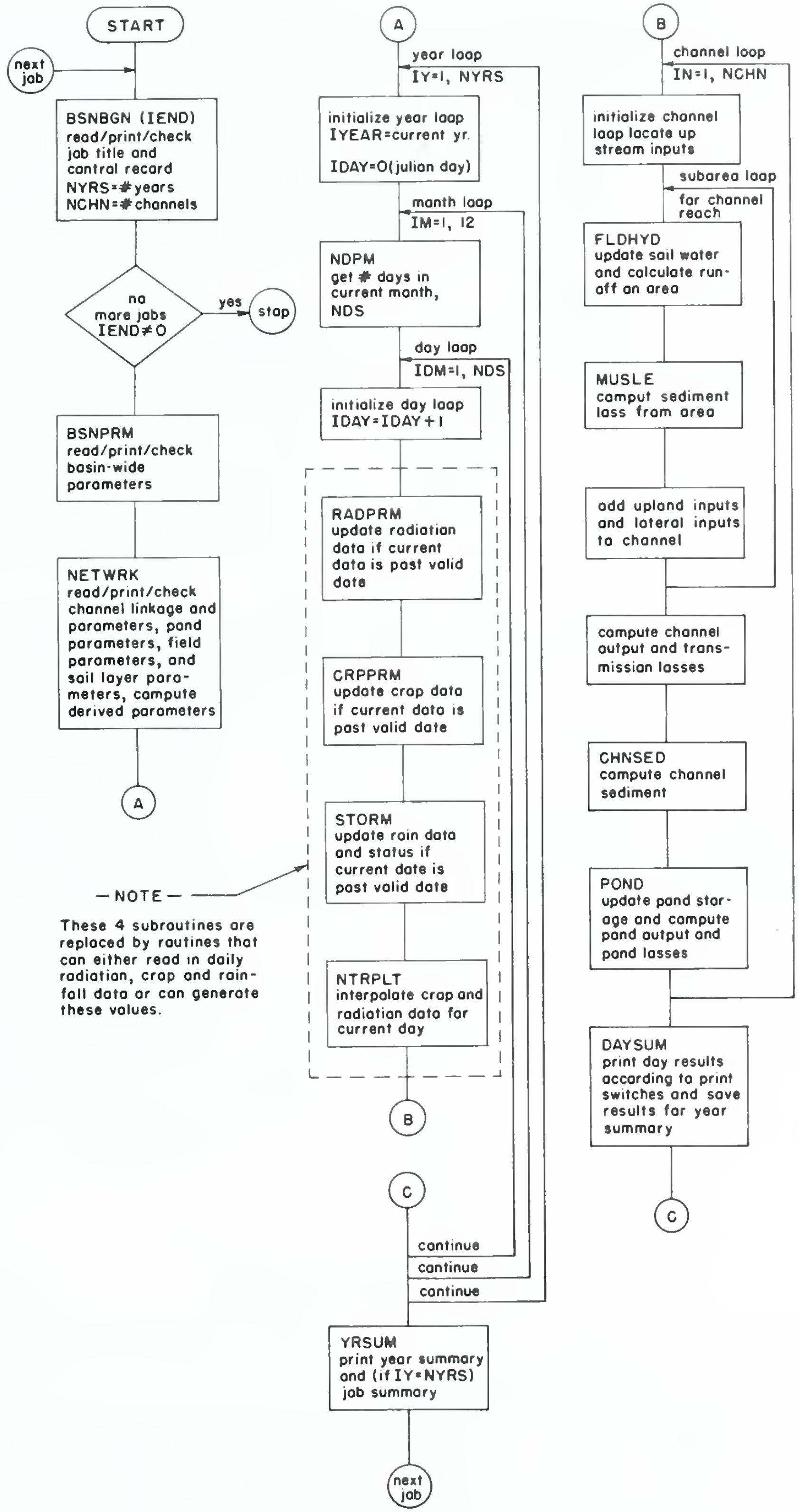
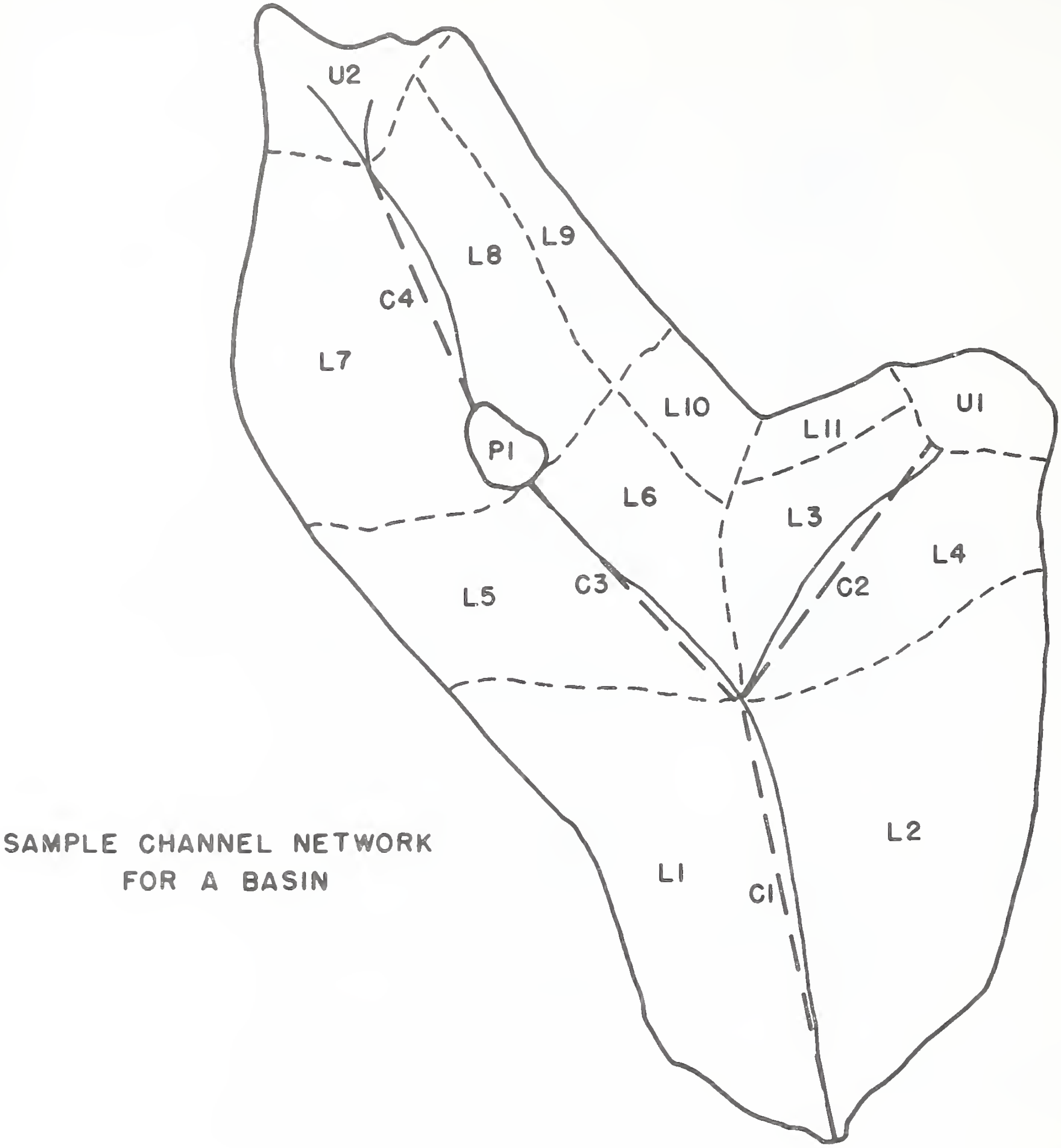


Figure 1.--Hydrology component. This flowchart of the upland and channel phases includes everything but the snowmelt.



MODEL CONSTRAINTS

1. EACH CHANNEL MUST HAVE AN INPUT ; EITHER AN UPLAND REGION OR UP TO TWO CHANNELS.
2. EACH CHANNEL MUST HAVE ONE OR MORE LATERAL INPUTS.
3. EACH CHANNEL MAY OUTPUT THROUGH A POND.

Figure 2.--Conceptualization of a watershed into upland ares (U1-U2), lateral areas (L1-L11), stream channel reaches (C1-C4), and ponds (P1).

Illustrations of the model application to a small watershed on Walnut Gulch follow. Walnut Gulch is an ephemeral tributary of the San Pedro River in southeastern Arizona. The watershed is an intermountain alluvial basin typical of mixed grass-brush areas encountered in Major Land Resource Area 41, the Southeastern Arizona Basin and Range. Figure 3 illustrates the features of stock pond watershed 23 (known locally as the Lucky Hills Watersheds) on Walnut Gulch. The watershed was conceptualized for the model as one 9.1-acre upland area discharging to a 4,000-ft long channel (C1 and C2) having lateral contributing areas L1 (49.2 acres) and L2 (49.7 acres) or a total drainage of 108.0 acres into the pond (P1).

Tables 1, 2, and 3 contain the input data used in the upland hydrology portion of the SPUR model for the 108-acre watershed used in the test application for the hydrology component only. The 100-day return flow travel time was used to ensure that there was no base flow. Similarly, the use of 0 for the crack-flow factor means that the model in the test application did not consider this type of flow situation (table 1).

The soils data in Table 2 are for a Rillito-Laveen gravelly loam soil. Gelderman (1970) described this association as occurring on moderately sloping ridges formed by the deep dissection of old alluvial fans and valley plains.

Table 1.--Parametric values input for upland areas in the SPUR hydrology model

Parameter	Units	Field identification		
		1	2	3
Field type		Upland	Lateral	Lateral
Soil layers	number	8	8	8
Field area	acres	9.1	49.2	49.7
Curve number		86	86	86
Return flow time	days	100	100	100
MUSLE Parameters				
K		0.10	0.10	0.10
C		0.10	0.13	0.13
P		1.00	1.00	1.00
LS		1.30	1.30	1.30
Soil evaporation	$in/(day)^{1/2}$	0.122	0.122	0.122
Crack-flow factor		0	0	0

These soils generally consist of deep, well-drained, medium and moderately coarse-textured gravelly soils. Because the same soil occurred in each of the three field elements simulated in the model, only one data set is included in table 2. The seventh layer of the model was assumed to have zero saturated hydraulic conductivity to simulate the caliche layer, which persists throughout the area. This layer is synonymous with the limit of the most active root layers. In our experience, using a

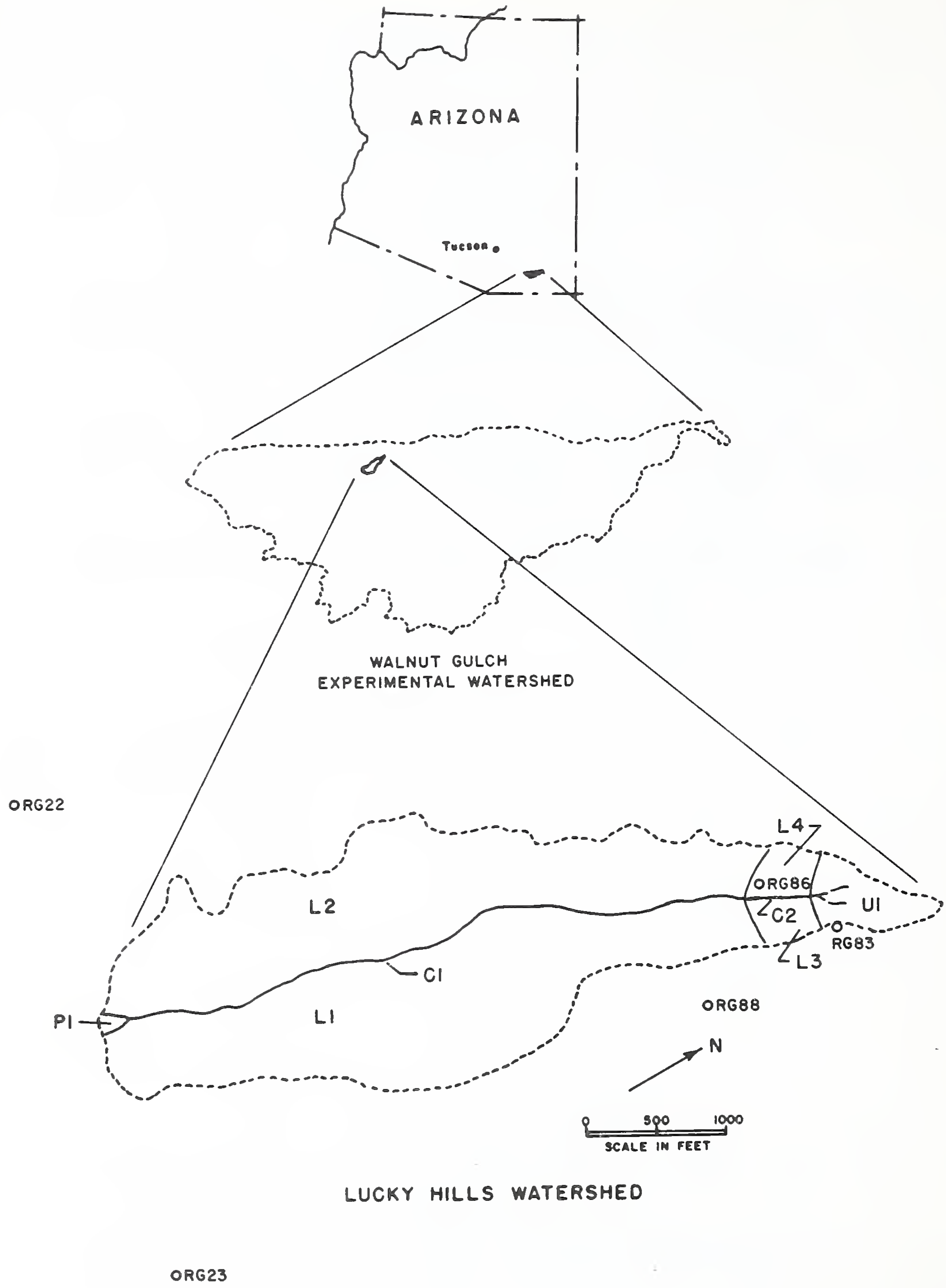


Figure 3.--Location map of the Lucky Hills watershed used in the model evaluation. There are two lateral areas (L1-L2), one upland area (U1), one pond (P1), and a single channel reach.

Table 2.--Soil data for upland areas in SPUR hydrology model

	Soil layer parameters							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Soil porosity (in/in)	0.440	0.440	0.440	0.400	0.400	0.400	0.400	0.400
Water at .3 bar (in/in)	.120	.120	.120	.120	.120	.120	.120	.120
Water at 15 bar (in/in)	.045	.045	.045	.056	.056	.056	.056	.056
Saturated condition (in/hr)	.500	.450	.300	.300	.300	.300	.000	.300
Soil depth, accumulative (in)	.500	5.000	10.000	15.000	20.000	22.500	25.000	27.000
Field capacity (in)	.037	.337	.375	.320	.320	.160	.160	.128
Maximum storage (in)	.197	1.777	1.975	1.720	1.720	.860	.860	.688

greater soil depth results in the creation of an artificially large soil moisture reservoir, and, in turn, a low curve number which, therefore, simulates lower runoff than the prototype records indicate.

A sample of the output from the hydrology portion of the SPUR model is given in table 4 for 1965. The 11.39 inches of precipitation is very near the average annual for the period of record, but below the normal for the long-term record at the Tombstone, Arizona gage about three miles from the watershed. Monthly values of infiltration, evaporation, and plant transpiration are very representative of those for normal conditions in this environment. The table summarizes what the model predicts will happen from the fields (upland and lateral areas), from the soil profile, in the channels, and, finally, the net yield of sediment from the fields as well as the fine material (silt and clay) and coarse material (bedload) from the channels.

Table 3.--Input data for calculating potential evapotranspiration in Spur hydrology model

Julian date	Temperature (°F)	Radiation (L)
1	46.9	327
12	46.0	341
22	45.8	359
35	46.1	390
46	47.0	420
56	48.5	451
66	50.1	484
110	61.3	628
175	76.7	714
185	77.8	707
195	78.5	694
205	78.7	676
215	78.7	653
225	78.0	626
235	76.7	596
245	75.1	564
300	61.4	388
350	49.2	319
360	47.8	322
365	47.0	325

Table 4.--Sample output from the simulation with the SPUR hydrology model for 1965 on the 108-acre Lucky Hills watershed using measured daily precipitation

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						FIELDS							
Rainfall	0.580	0.078	0.231	0.032	0.039	0.241	3.299	1.904	1.134	0.000	0.247	3.609	11.392
Infiltration	.580	.078	.231	.032	.039	.241	3.069	1.480	1.109	.000	.247	3.237	10.340
Runoff	.000	.000	.005	.000	.000	.000	.231	.424	.025	.000	.000	.372	1.052
						SOIL							
Return flow	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Soil evap	.913	.077	.224	.032	.039	.031	1.794	1.292	1.066	.000	.154	1.382	7.204
Plant evap	.009	.000	.007	.000	.000	.010	.587	.696	.222	.000	.004	.105	1.640
Deep perc	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Storage	.000	.000	.000	.000	.000	.000	.688	.179	.000	.000	.089	1.838	1.838
						CHANNEL							
Losses	.000	.000	.005	.000	.000	.000	.057	.058	.016	.000	.000	.077	.208
Runoff	.000	.000	.000	.000	.000	.000	.173	.366	.009	.000	.000	.295	.844
Peak	.0	.0	.0	.0	.0	.0	32.6	76.2	2.0	.0	.0	31.6	76.2
Minimum CN*	100.00	100.00	100.00	100.00	100.00	100.00	84.07	84.65	84.25	100.00	100.00	85.09	84.07
Average CN*	.00	.00	.00	.00	.00	.00	84.73	84.65	84.25	.00	.00	85.88	85.02
Maximum CN*	.00	.00	.00	.00	.00	.00	85.38	84.65	84.25	.00	.00	85.67	86.67
						SEDIMENT							
Field Sediment	.00	.00	.03	.00	.00	.00	19.37	40.66	1.75	.00	.00	32.07	93.85
Silt-clay	.00	.00	.00	.00	.00	.00	4.06	12.36	.08	.00	.00	7.17	23.68
Bedload	.00	.00	.00	.00	.00	.00	15.75	42.73	.29	.00	.00	27.89	86.66

Note: Water = inches peak flow = cfs; sedimentation = tons. 1 acre-ft of water is 0.1111 inches over the watershed.

*When there is no runoff for the month in question, the computer program produces the indicated values.

The output from the channel routing is that documented by L. J. Lane in the subsequent section titled, "SPUR Hydrology Component: Water Routing and Sedimentation."

A 17-year simulation with the SPUR hydrology component was performed to compare with actual data from the Lucky Hills watershed for 1965-81. Figures 4 and 5 illustrate the agreement between the predicted and observed runoff for the upland area and that of the entire area. The relatively poor agreement between the observed and predicted data, as evidenced by the regression statistics in figure 4b, results largely from the 1975 data where the 2.10-inch simulation seriously underestimates the 2.96 inches of observed runoff. Without this one year, the slope of the regression line is much closer to unity.

In figure 6, the cumulative observed and predicted runoff are shown for the annual runoff as predicted with two different curve numbers. Again, the problem of the 1975 data shows with the large departure from the one-to-one line. With the curve number equal to 87, the cumulative runoff at the end of the 17 years overpredicted the observed results. The sensitivity of the curve number model is illustrated with this figure.

Figure 7 illustrates the annual variability of precipitation, evapotranspiration, and transmission losses from the upland area and the entire 108 acre Lucky Hills watershed. As would be expected, the ET follows the precipitation fairly closely, with some noticeable exceptions like that in 1966. In 1966, the computed ET actually exceeds the precipitation because of some soil moisture carryover from the fall of 1965. In addition, the underestimation of the runoff meant there was additional soil moisture for evaporation and transpiration in 1966. Transmission losses are notably larger on the larger watershed as would be expected.

To test agreement of simulated and actual sediment yield with the MUSLE relationship in SPUR, data was available from the upland area (9.1 acres) (fig. 3) for 1965-81. Correlation coefficient of 0.92 and an intercept near zero with a slope of 1.1 indicates a close relationship between field-measured and simulated values.

CONCLUSIONS

A model has been developed which facilitates describing the spatial variability of soils, vegetation, and topography. By allowing such spatial physiographic variability, differences in hydrologic process magnitudes can be accommodated, including those which are restricted to the upland areas as contrasted from those that happen in stream channels. Although testing of the model must be expected to continue, the fundamental precepts behind the development are felt to be in sufficient detail to facilitate describing the heterogeneity encountered in most rangeland conditions.

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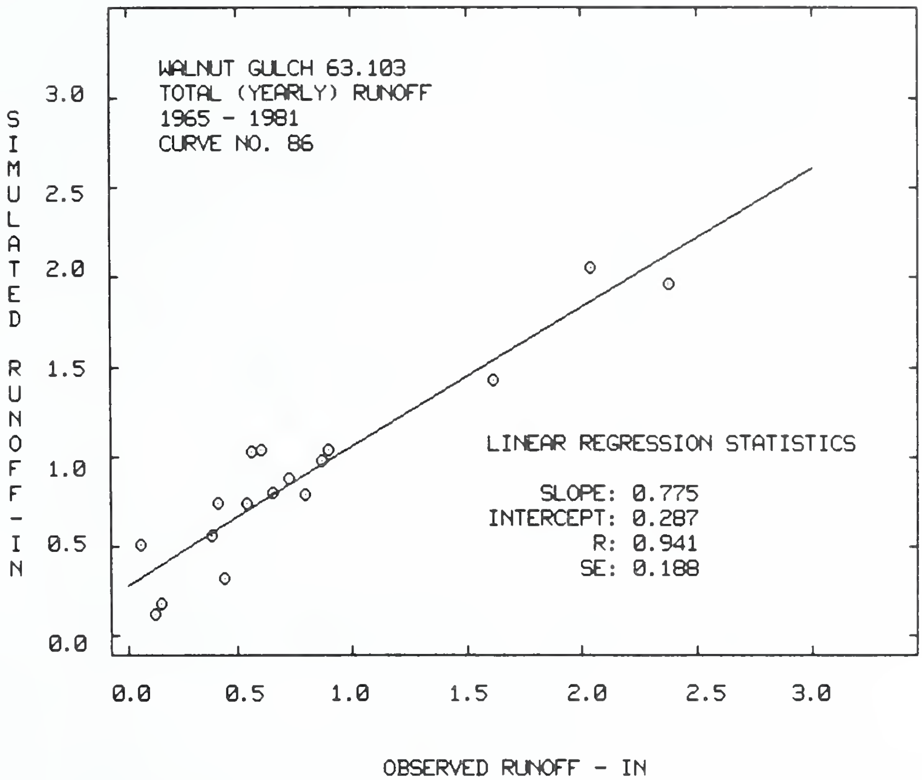

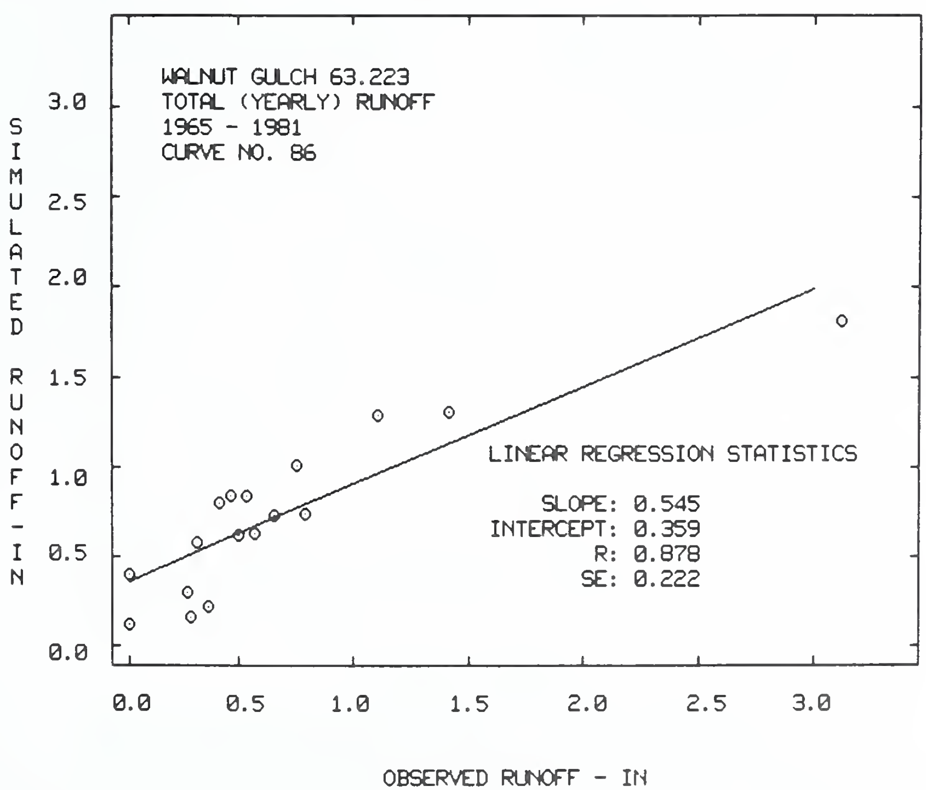

Figure 4.--Simulated versus observed runoff for the upland area and the entire 108-acre Lucky Hills watershed.

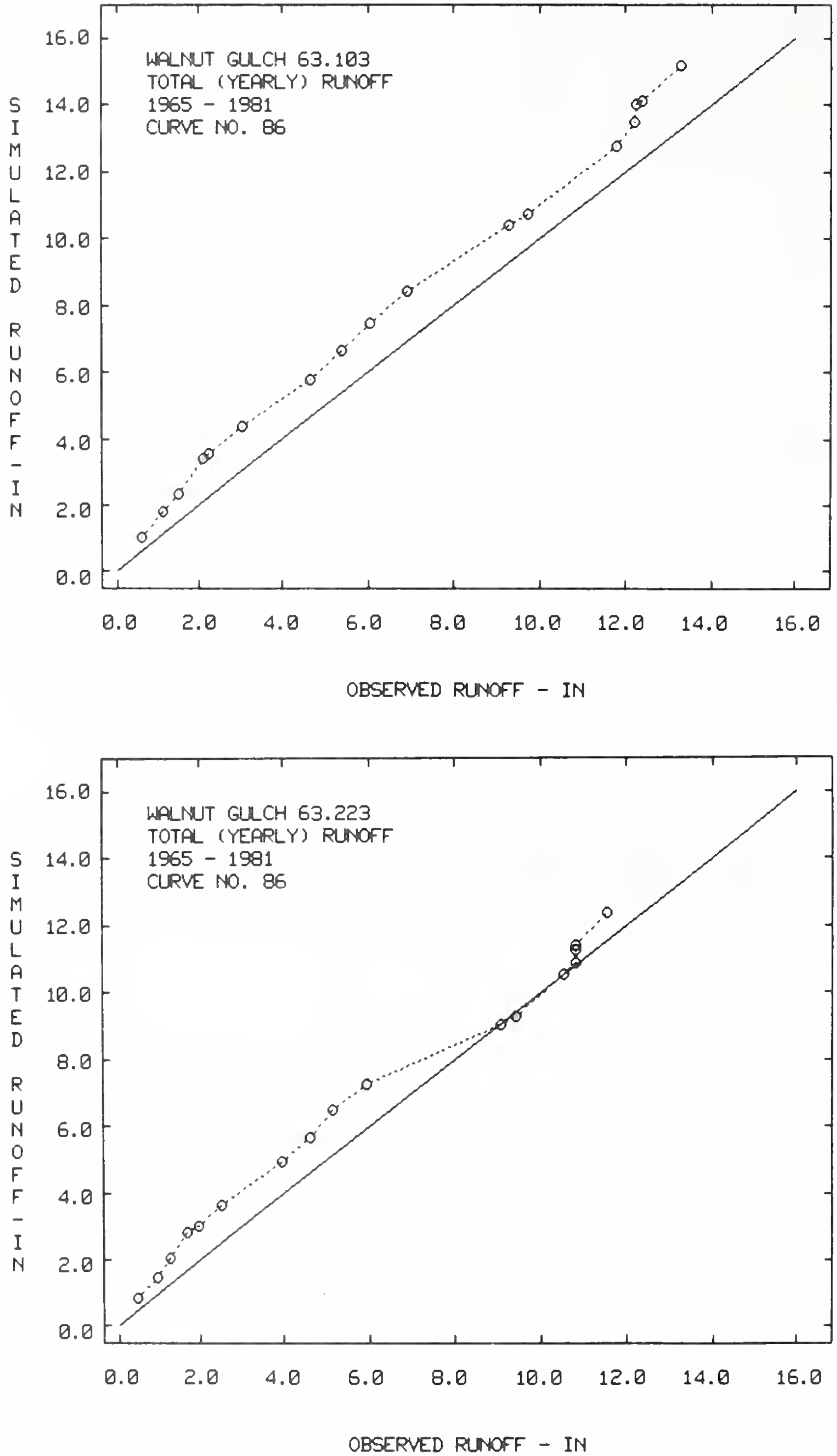

Figure 5.--Cumulative predicted versus actual runoff from the 9.1-acre upland area and for the entire 108-acre Lucky Hills watershed.

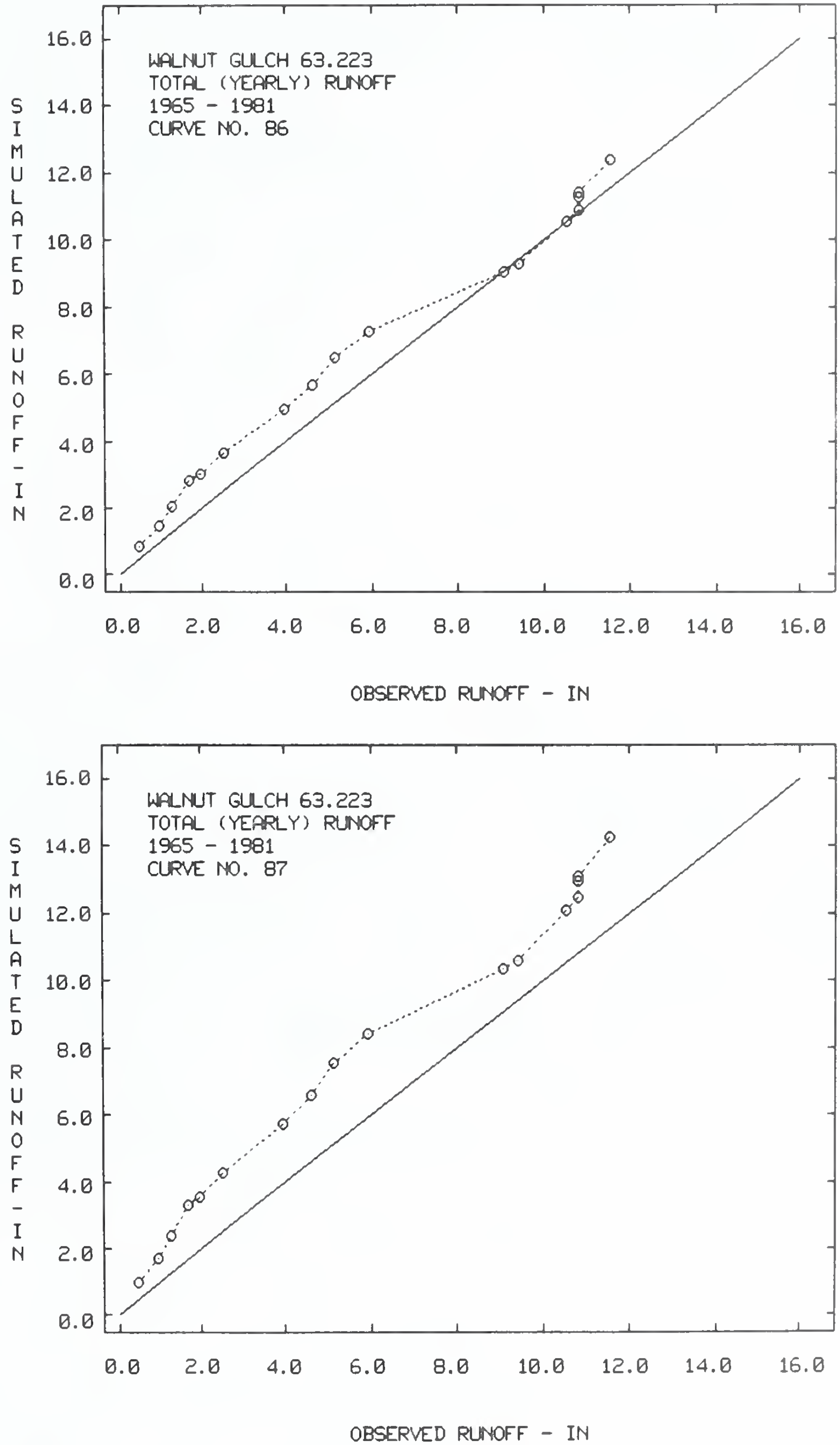

Figure 6.--Cumulative predicted versus actual runoff for the 108-acre Lucky Hills watershed for two different curve numbers.

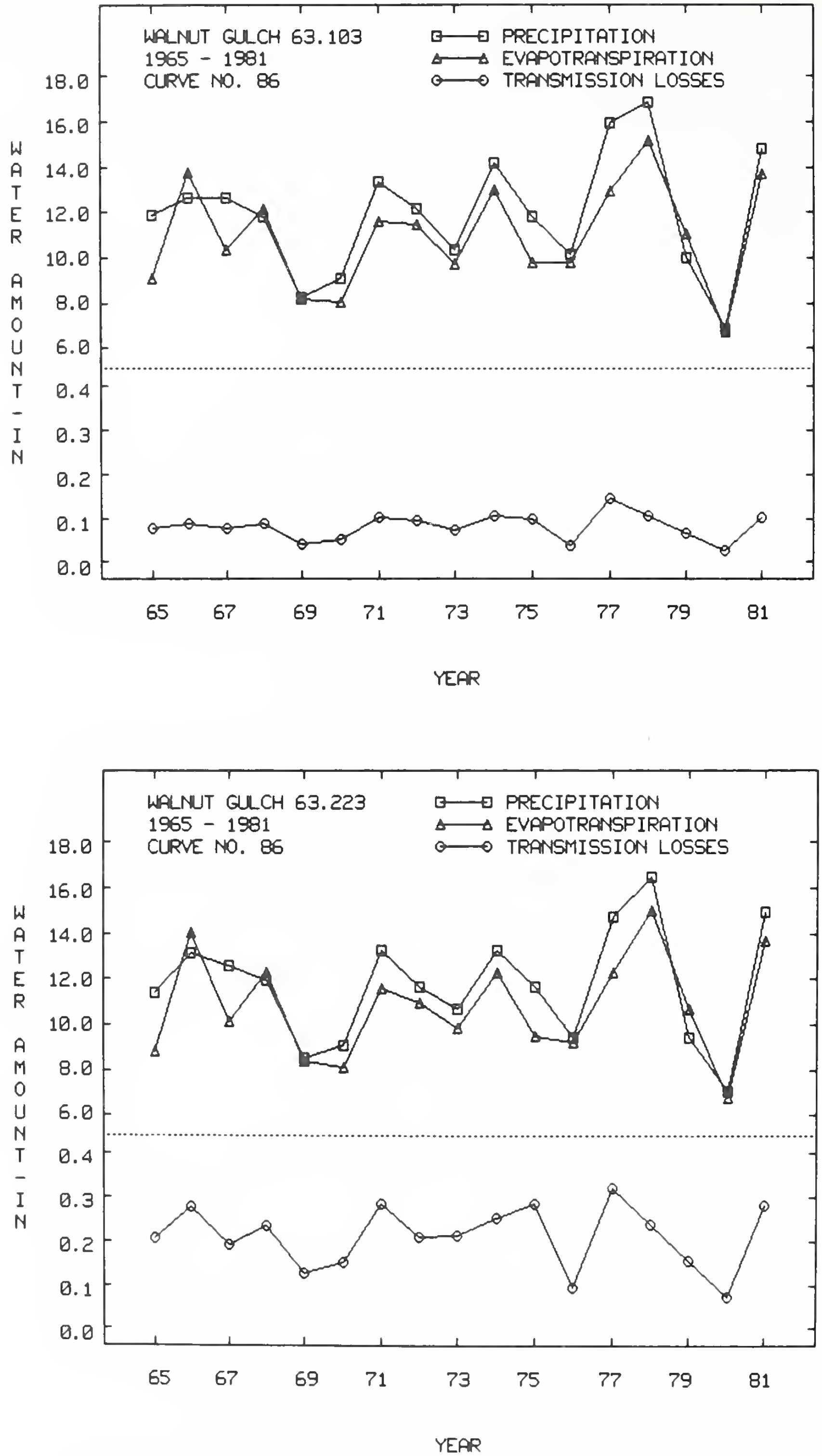

Figure 7.--Precipitation, evapotranspiration, and transmission losses are simulated daily and summed annually. The variability is appreciable from year to year and the transmission losses are much larger for the entire watershed (bottom) than for the 9.1-acre upland area (top).

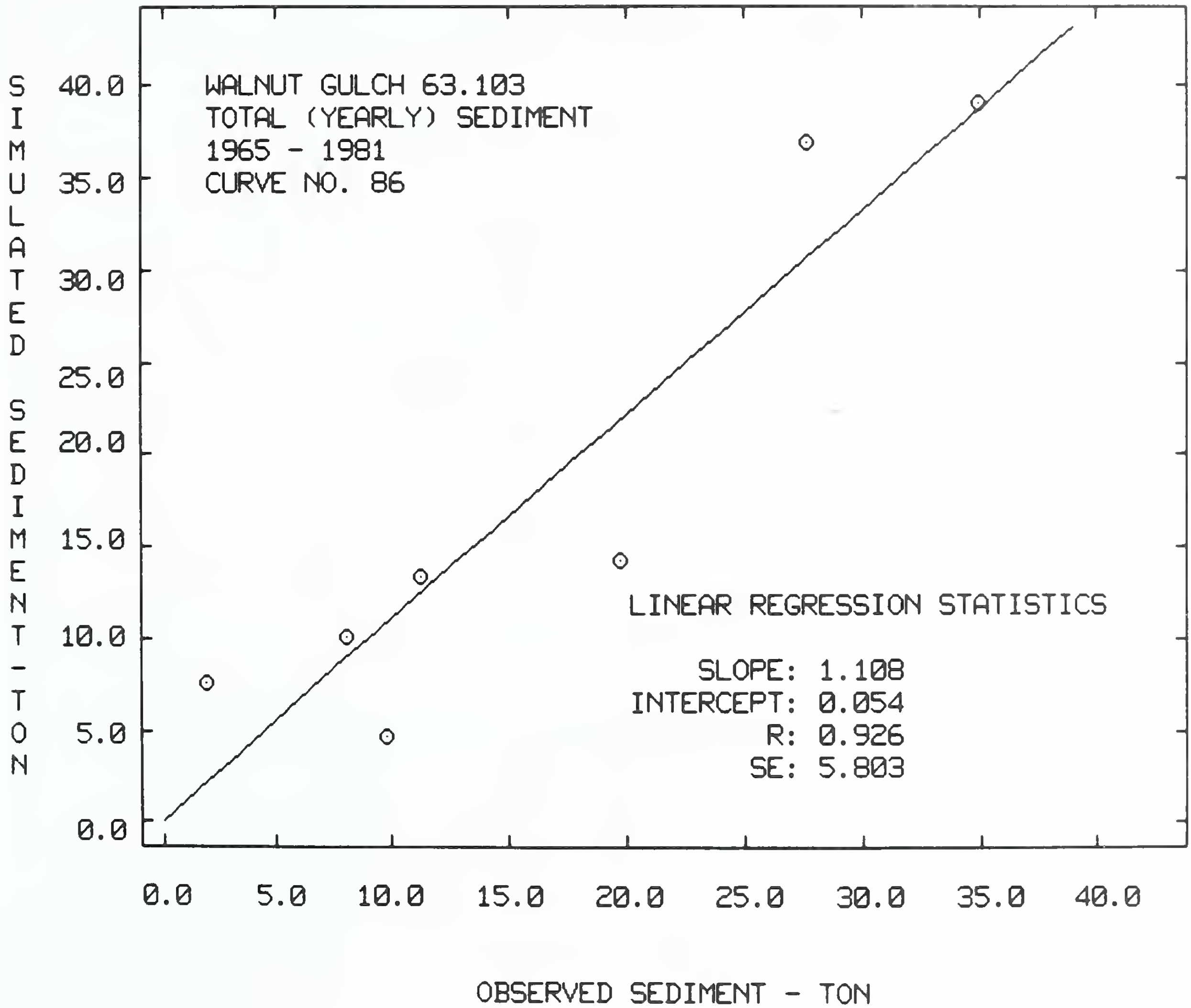

Figure 8.--Predicted versus simulated annual sediment yield using MUSLE for the 9.1-acre upland area of the Lucky Hills watershed.

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SPUR HYDROLOGY COMPONENT: SNOWMELT

By K. R. Cooley, E. P. Springer, and A. L. Huber[1]

INTRODUCTION

Several of the models used within the Agricultural Research Service (ARS) to predict soil water status, forage yield, or a complete water balance do not have adequate provision to take into account snow accumulation and melt. Some incorporate a simple constant times the average daily air temperature concept, which provides reasonable results under certain conditions. However, a more general model is needed that would provide adequate results under heavy continuous snow, isolated drifts, or intermittent light snow conditions in order to expand the use and flexibility of the existing and future hydrologic models.

A review of the literature indicated that three main types of snow accumulation and melt models have been developed. The first, and most numerous type, consists of a wide variety of empirical relationships generally requiring only one or two parameters, such as the constant times air temperature concept (Riley et al. 1972;[2] Stewart and others 1975). The second consists of the more technically sound partial or complete energy budget approach, which requires considerably more detailed data such as temperature, radiation, vapor pressure, and wind (Leaf and Brink 1973). The third type combines both by developing empirical relationships between readily available air temperature and each flux in the energy balance relation. The third type was selected for testing because 1) the air temperature data are readily available, 2) the approach appeared to be technically sound, 3) the model had been tested in a variety of U.S climatic regions, and 4) an expected range of values for the calibration parameters was provided for a variety of conditions. In contrast, most of the empirical models were developed for one set of conditions and seldom, if ever, used again.

DESCRIPTION OF THE MODEL

The model selected was developed by Eric Anderson at the National Weather Service (NWS) Hydrologic Research Laboratory (Anderson 1973). After considerable experience and effort in developing complete energy balance models of snow surfaces, he determined that for most cases a user oriented model would require drastic simplification and reduction in data needs. This model, referred to as HYDRO-17, meets those criteria. It is a conceptual model of the physical processes affecting snow accumulation and snowmelt which Anderson considers mathematically significant. Air temperature is used to index energy exchange across the snow-air interface. This is not the same as the degree-day method, which uses air temperature as an index to snow cover outflow. The degree-day method does not explicitly account for freezing of

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[2]The author's name followed by the year underlined, refers to Literature Cited, p. 61.

the melt water due to a heat deficit and the retention and transmission of liquid-water, both of which cause snow cover outflow to differ from snowmelt. Figure 1 is a flow chart of the model showing each of the physical processes included. The following description of the model and its parameters is a summary of Anderson's work and the reader is referred to the report describing the current model for more detail (Anderson 1973).

Data Requirements

As previously noted, one reason for selecting the NWS model was the availability of required data. The original HYDRO-17 model used 6-hour mean air temperature estimates as the index; however, the current version is programmed so that the time interval is variable. A daily time step was chosen for the present study since mean daily values of air temperature and precipitation are more generally available. Elevation of the study site or area is also needed to make an atmospheric pressure estimate.

Model Parameters

In addition to the data requirements, there are six major and six minor parameters for which values must be set in order to use the model. The six major parameters are those which generally have the greatest effect on the simulation results and, therefore, require the most care in determining the proper value. The six major parameters are:

1) SCF -- A snow correction factor which adjusts precipitation for gage catch errors during periods of snowfall and implicitly accounts for net vapor transfer and interception losses. This parameter depends mainly on the windspeed at the gage site and whether the gage is shielded.

2) MFMAX -- Maximum melt factor during nonrain periods. This factor is affected by many climatic and physiographic variables such as radiation intensity, wind, forest cover, and aspect.

3) MFMIN -- Minimum melt factor during nonrain periods. The same climatic and physiographic variables that affect MFMAX also affect MFMIN, and in essentially the same way.

4) UADJ -- The average wind function during rain-on-snow periods. Affected most by density and height of vegetation, and terrain.

5) SI -- The mean areal water-equivalent above which there is always 100 percent areal snow cover. This value is affected by the snowfall characteristics of the area. If the snow cover is uniform and melts at a uniform rate, the area will remain at 100 percent cover until just before the snow disappears. In contrast, especially where drifting occurs, the snow cover in some areas is so variable that bare ground appears as soon as melt begins.

6) Areal Depletion Curve -- Curve which defines the areal extent of the snow cover as a function of how much of the original snow cover remains. It also implicitly accounts for the reduction in the melt rate that occurs with a decrease in the areal extent of the snow cover, and is closely related to the SI parameter (fig. 2).

The six minor parameters can normally be determined in advance, based on a knowledge of the typical climatic and snow cover conditions for the area. The six minor parameters are:

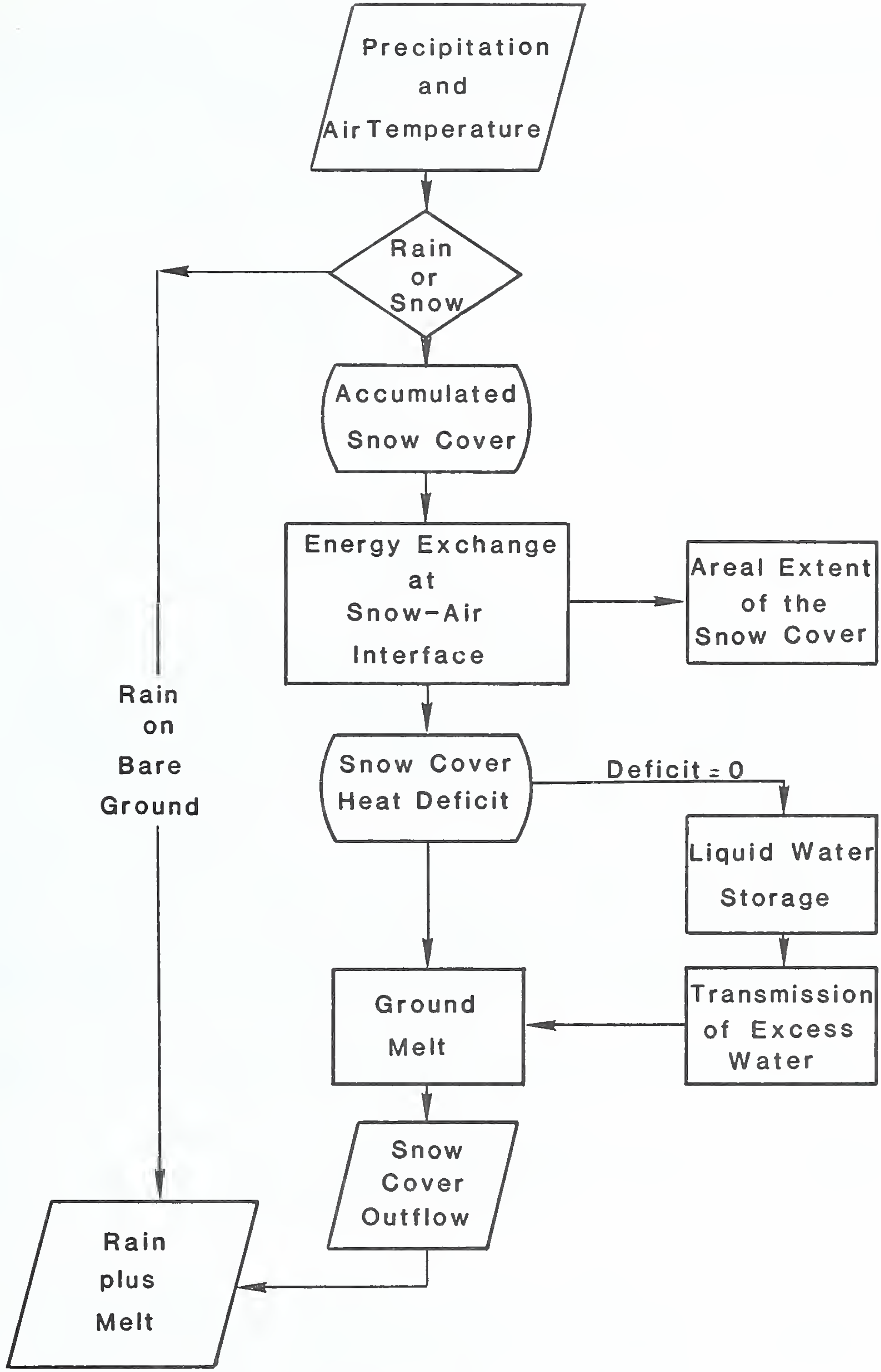

Figure 1.--Flowchart of the snow accumulation and ablation model from Anderson (1973).

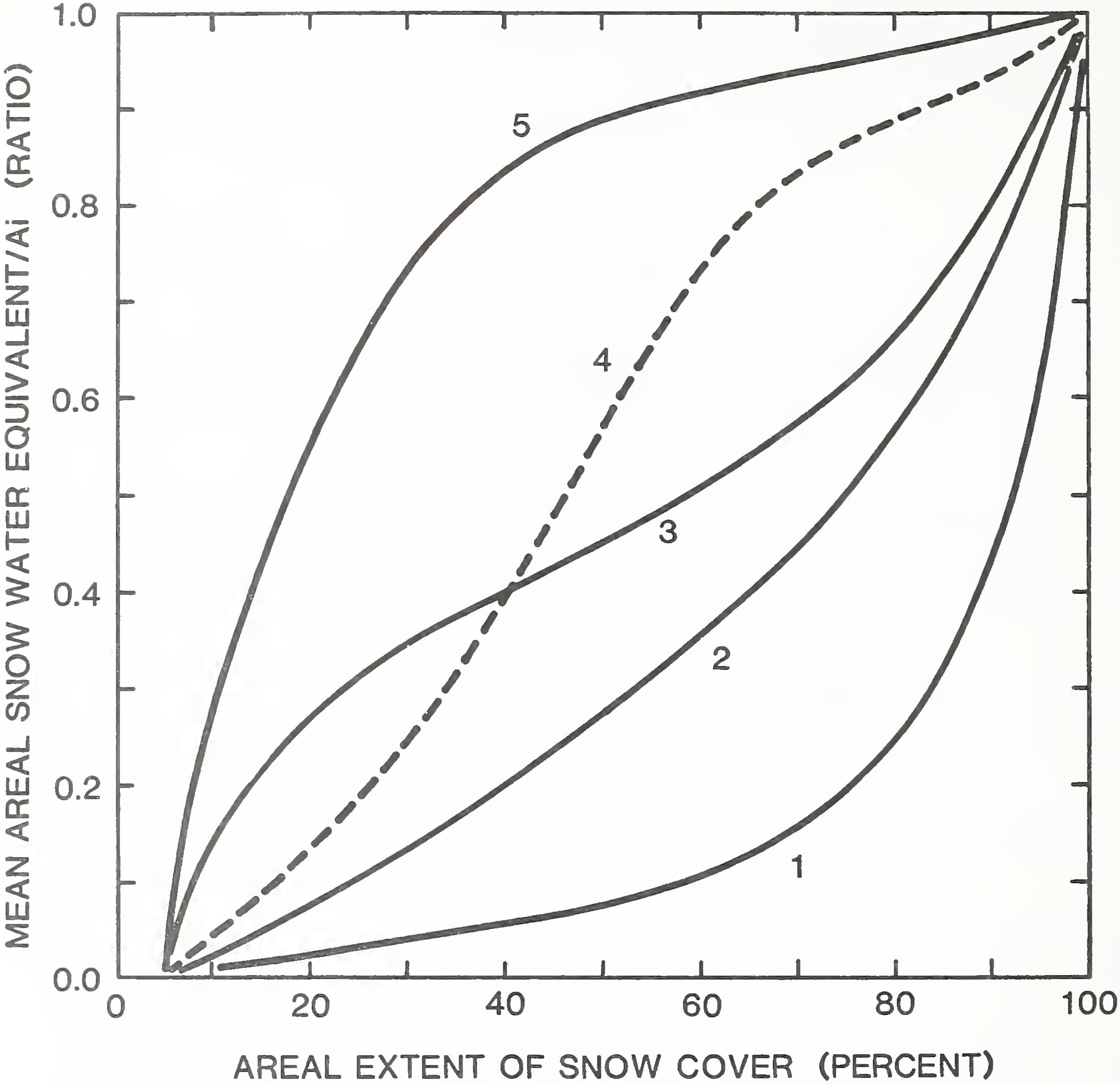

Figure 2.--Snow cover areal depletion curve types corresponding to ADPT values of 1, 2, 3, 4, and 5 (modified from Anderson 1973).

1) TIPM -- A factor that determines how much weight is placed on the air temperature for each of the prior periods. A small value corresponds to deep snowpacks and longer waiting periods, while a larger value corresponds to shallow snowpacks and short periods of only a few hours.

2) NMF -- The maximum negative melt factor. This factor is assumed to have the same seasonal variability as the surface melt factor. It is affected mostly by snow density, though climate and physiographic variables also affect heat exchange during nonmelt periods.

3) MBASE -- Base temperature (normally 0°C) for snowmelt computations during nonrain periods.

4) PXTEMP -- The temperature which delineates rain from snow (normally 0° to 2°C).

5) PLWHC -- Percent liquid water holding capacity expressed as a decimal. Represents the maximum amount of liquid water in the snowpack that can be held against gravity drainage.

6) DAYGM -- Constant rate of melt which occurs at the snow-soil interface whenever the soil is not frozen and snow is present.

Accumulation Process

The accumulation of snow in the model is simply based on the air temperature and the temperature selected to delineate rain from snow (PXTEMP). Precipitation is considered to be snow if the air temperature is less than or equal to PXTEMP, and rain if the air temperature is greater than PXTEMP. The amount of new snow is added to the existing snowpack to establish a new total snowpack.

Melt Processes

The snowmelt processes are divided into two categories, snowmelt during rain-on-snow and snowmelt during nonrain periods. Snowmelt during rain-on-snow periods is separated from melt during nonrain periods because 1) of the difference in magnitude of the various energy transfer processes, 2) the dominant energy transfer processes during rain-on-snow periods are known, and 3) the seasonal variation in melt rates is generally quite different for the two processes.

Rain-on-snow: During rain-on-snow, melt is assumed to occur at the snow surface. It is also assumed that 1) incoming solar radiation is negligible because it is overcast, 2) incoming longwave radiation is equal to blackbody radiation at the temperature of the bottom of the clouds, which is close to air temperature, and 3) the wet bulb temperature is essentially the same as the air temperature. With these assumptions and the employment of a standard atmosphere, altitude-pressure relationship, the energy balance equation can be determined for computing melt during rain-on-snow (Anderson 1973).

Ablation (non-rain periods): Because such a wide variety of meteorological conditions can occur during nonrain periods, the energy balance equations are not used as a basis for estimating snowmelt from air temperature. Rather, an empirical air temperature based relationship is employed in which snowmelt is determined by

$$M = M_f \cdot (T_a - \text{MBASE})$$

where M_f is a melt factor, MBASE is the base temperature below which no melt is produced, and T_a is the air temperature. The melt factor exhibits a seasonal variation due partly to the variation in incoming solar radiation, and partly to a decrease in the albedo of the snow cover with time since the last snowstorm. Seasonal variations in other meteorological factors, like vapor pressure, wind, and cloud cover, also influence the melt factor. A sinusoidal relationship between melt factor and season has been developed within the model to account for this variation. This relationship has been found to be adequate for use throughout the contiguous United States.

Groundmelt: In some watersheds, a small amount of melt takes place continuously at the bottom of the snowpack. This melt is small on a daily basis, but it can amount to a significant quantity of water when accumulated over an entire snow season. Groundmelt adds to soil moisture storage, and helps sustain baseflow throughout the winter. It is added to the snow cover outflow and to rain which falls on bare ground to obtain total rain plus melt.

MODIFICATION TO HYDRO-17 SNOWMELT MODEL

Areal Extent of Snow Cover

We have modified the input of the snow cover depletion curve by defining a new parameter, the areal snow cover depletion curve type (ADPT), which defines the specific curve for the site being modeled by a table lookup and interpolation procedure. Figure 2 shows the five curves covering the feasible range of types which provide the basis for the procedure. Curves 2 through 5 correspond to curves A through D presented by Anderson (1973). Each of the five curves is represented by 11 discrete points giving the percent snow cover corresponding to each one-tenth increment in the ratio of the mean areal snow water equivalent (SWE) to the areal index (A_i). The values representing each curve are given in table 1.

Table 1.--Snow cover area depletion curve values (percent snow cover)

Curve type (ADPT)	Mean areal water equivalent/A_i (ratio)										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	5	58	76	84	89	93	95	97	98	99	100
2	5	24	40	53	65	75	82	88	93	97	100
3	5	8	14	23	40	59	73	83	90	95	100
4	5	16	26	34	40	46	52	58	66	82	100
5	5	6	8	10	14	18	22	27	35	54	100

The range of values for ADPT is 1.0 to 5.0. Values that have fractional parts result in depletion curves defined by linear interpolation between the two curves which bracket the specified ADPT value; for example, an ADPT value of 2.5 specifies a depletion curve half way between curve types 2 and 3. A value less than 1 selects curve 1 and a value greater than 5 selects curve 5.

VALIDATION OF THE MODEL

Reynolds Creek Snow Course Test

The National Weather Service snow accumulation and ablation model (Anderson 1973) was tested at the USDA-ARS Reynolds Creek Experimental Watershed in southwest Idaho. Data used in the testing included daily maximum and minimum temperatures recorded at the Reynolds Mountain weather station and daily precipitation measured at the weather station and the snow course site. The model was evaluated using the accumulated absolute deviations of the simulated from the observed SWE. The bias of the fit was also determined, which consists of the algebraic sum of the deviations between simulated and measured SWE. The model was first calibrated with the 1980 water year data. The simulated snowpack for the snow course survey date was used to compute the objective and bias functions defined above. A minimum objective function value of 144 mm with a bias of -26 SWE was obtained. Figure 3 graphically depicts the fit obtained with the 1980 data. The correlation between the simulated and observed SWE was 0.998. Figure 4 shows the computer output for the calibration period, water year 1980, as well as for one of the test years, 1970.

A 4-year test period, including the high and low years of record, was assembled to test the validity of the calibration coefficients. The test results are shown in figure 5. The correlation between computed and observed SWE was 0.905, which indicates that the model represents about 82 percent of the variance between the computed and observed SWE values.

The 4-year simulation shown in figure 5 illustrates a problem common to all of the temperature driven snowmelt models. The model, which uses the ambient temperature as an index of the physical processes causing the snowpack to accumulate and melt, worked very well for the winter years 1971 and 1980, but caused the snowpack to melt prematurely during three of the test years. This observation may be verified from figure 4, where the poor performance of the model is caused primarily by the premature melt early in the snow season and continuing throughout the snow accumulation period. This same phenomenon also prevailed during the test years 1972 and 1977, which suggests that under certain conditions, the ambient temperature fails as an index of the physical processes that cause the snow to accumulate and melt, and the inclusion of additional variables such as solar radiation, wind run, and vapor pressure would be necessary to improve the model. Since these data are not usually available at the sites requiring simulation, the temperature data must suffice.

A summary of the results of testing the HYDRO-17 snow model is given in table 2.

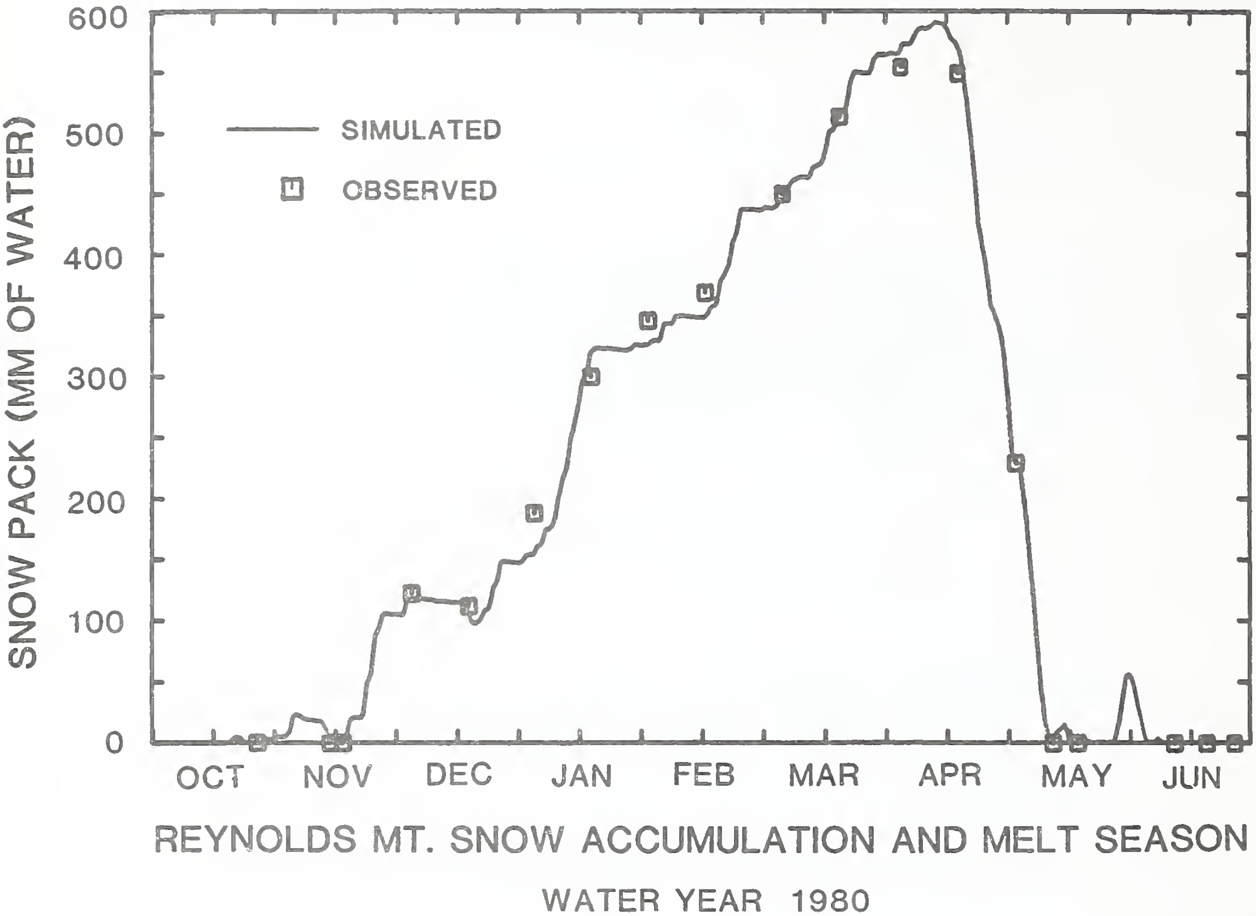

Figure 3.--Snow water equivalent at the Reynolds Mountain snow course during the water year 1980 accumulation ablation period. Simulated by HYDRO-17 versus observed.

REYNOLDS MOUNTAIN SNOW COURSE WY 1980 SWE SIMULATED BY DAILY HYDRO-17

MODEL PARAMETERS ARE AS FOLLOWS:

PAR NAME	VALUE	PAR NAME	VALUE
1 SCF	1.000	7 NMF	0.300
2 MFMAX	4.800	8 TIPM	0.120
3 MFMIN	2.000	9 MBASE	0.000
4 UADJ	0.340	10 PXTEMP	0.000
5 SI	0.000	11 PLWHC	0.010
6 ADPT	3.000	12 DAYGM	0.300

SNOW COVER DEPLETION CURVE PERCENT COVER VALUES

WE/AI	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
ADC	5.0	8.0	14.0	23.0	40.0	59.0	73.0	83.0	90.0	95.0	100.0

SEQ	DAY	MO-DA-YR	TMAX	TMIN	TAVE	P	MELT	RPSM	COVER	TWE	SWEOBS	DIFF
1	274	10- 1-79	21.83	10.16	15.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	288	10-15-79	22.38	2.38	12.38	7.32	0.00	7.32	0.00	0.00	0.00	0.00
24	297	10-24-79	14.05	-4.29	4.88	61.98	5.84	61.98	0.00	0.00	0.00	0.00
64	337	12- 3-79	11.83	-15.95	-2.06	160.93	32.20	42.77	100.00	118.17	121.92	-3.75
78	351	12-17-79	6.27	-14.84	-4.29	1.27	11.62	12.13	100.00	107.31	111.76	-4.45
94	2	1- 2-80	6.83	-15.40	-4.29	62.53	14.96	15.22	100.00	154.62	187.96	-33.34
108	16	1-16-80	0.71	-17.06	-8.17	170.56	4.22	4.22	100.00	320.97	299.72	21.25
122	30	1-30-80	0.16	-23.73	-11.79	9.30	4.21	4.21	100.00	326.05	345.44	-19.39
136	44	2-13-80	2.94	-10.40	-3.73	26.39	4.21	4.21	100.00	348.23	368.30	-20.07
155	63	3- 3-80	4.60	-9.29	-2.34	103.07	5.71	5.71	100.00	445.59	449.58	-3.99
169	77	3-17-80	1.27	-15.40	-7.06	71.53	4.21	4.21	100.00	512.91	513.08	-0.17
184	92	4- 1-80	-0.95	-14.29	-7.62	56.46	4.25	4.51	100.00	564.87	553.72	11.15
198	106	4-15-80	10.16	-12.06	-0.95	28.68	18.57	18.57	100.00	574.98	548.64	26.34
212	120	4-29-80	15.16	-4.29	5.44	12.95	346.02	358.98	100.00	228.95	228.60	0.35
226	134	5-13-80	12.94	-5.95	3.49	30.12	244.96	259.08	0.00	0.00	0.00	0.00
231	139	5-18-80	12.94	-4.84	4.05	10.34	1.70	10.34	0.00	0.00	0.00	0.00
252	160	6- 8-80	20.16	-5.40	7.38	109.63	61.42	109.63	0.00	0.00	0.00	0.00
260	168	6-16-80	17.38	-1.51	7.94	8.38	0.00	8.38	0.00	0.00	0.00	0.00
273	181	6-29-80	20.71	-1.51	9.60	9.91	0.00	9.91	0.00	0.00	0.00	0.00

OBJ = 144.2351 OAJ = -26.0613

REYNOLDS MOUNTAIN SNOW COURSE WY 70 SWE SIMULATED BY DAILY HYDRO-17
USING MODEL PARAMETERS DERIVED FROM WY 1980 CALIBRATION

SEQ	DAY	MO-DA-YR	TMAX	TMIN	TAVE	P	MELT	RPSM	COVER	TWE	SWEOBS	DIFF
63	335	12- 1-69	14.60	-17.62	-1.51	86.08	54.33	86.08	0.00	0.00	55.88	-55.88
95	2	1- 2-70	7.94	-13.17	-2.62	138.73	32.31	59.85	100.00	78.89	172.72	-93.83
108	15	1-15-70	0.71	-15.95	-7.62	101.73	3.91	3.91	100.00	176.71	213.36	-36.65
120	27	1-27-70	4.05	-10.95	-3.45	268.20	27.93	50.76	100.00	394.14	487.68	-93.54
134	41	2-10-70	8.49	-10.95	-1.23	10.13	19.78	19.78	100.00	384.50	477.52	-93.02
140	47	2-16-70	6.83	-4.84	0.99	17.35	22.40	30.17	100.00	371.68	508.00	-136.32
149	56	2-25-70	5.71	-8.73	-1.51	15.42	7.98	7.98	100.00	379.12	528.32	-149.20
162	69	3-10-70	7.38	-9.84	-1.23	45.90	31.28	31.28	100.00	393.74	609.60	-215.86
176	83	3-24-70	7.94	-8.17	-0.12	30.71	30.04	49.85	100.00	374.60	594.36	-219.76
190	97	4- 7-70	8.49	-11.51	-1.51	17.91	21.84	21.84	100.00	370.67	660.40	-289.73
204	111	4-21-70	6.83	-12.62	-2.90	82.12	14.66	14.66	100.00	438.12	716.28	-278.16
218	125	5- 5-70	16.27	-11.51	2.38	17.35	165.37	165.37	100.00	290.10	635.00	-344.90
232	139	5-19-70	19.60	-7.62	5.99	38.13	309.35	328.22	0.00	0.00	391.16	-391.16
241	148	5-28-70	19.05	1.27	10.16	17.02	0.00	17.02	0.00	0.00	0.00	0.00
246	153	6- 2-70	20.71	-0.40	10.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
252	159	6- 8-70	22.94	1.83	12.38	11.02	0.00	11.02	0.00	0.00	0.00	0.00
259	166	6-15-70	10.16	-0.40	4.88	18.01	0.00	18.01	0.00	0.00	0.00	0.00
266	173	6-22-70	25.16	4.05	14.60	2.54	0.00	2.54	0.00	0.00	0.00	0.00

OBJ = 2398.0308 OAJ = -2398.0308

Figure 4.--Computer output from HYDRO-17 simulating the Reynolds Mountain snow course water equivalent (SWE) for the water years 1970 and 1980 snow accumulation and ablation period.

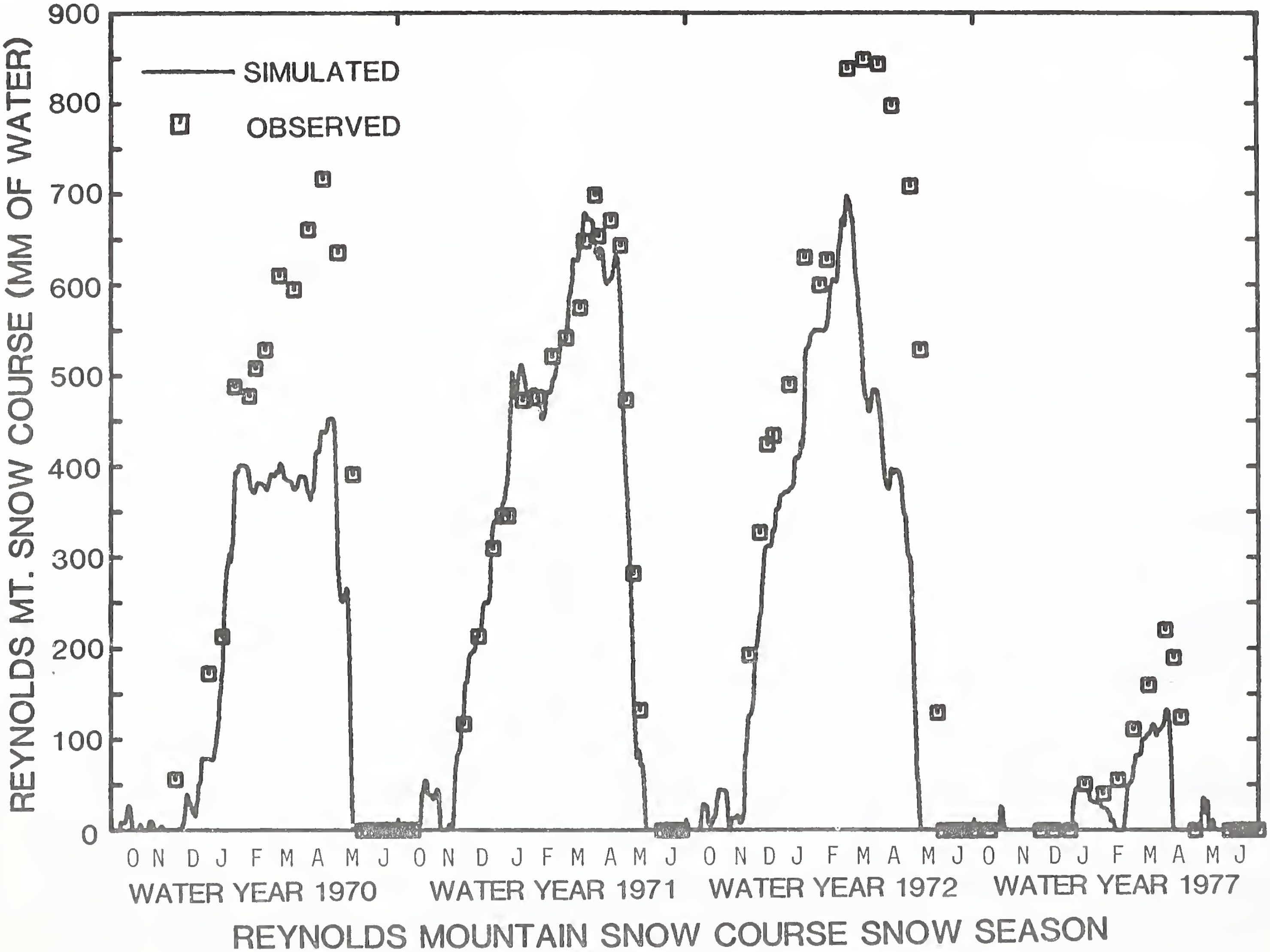

Figure 5.--Snow water equivalent at the Reynolds Mountain snow course during the water years 1970, 1971, and 1977 snow accumulation and ablation period. Simulated SWE by HYDRO-17 using water year 1980 calibration parameters versus observed values.

Table 2.--Results of testing the National Weather Service snow accumulation and ablation model (HYDRO-17) on Reynolds Creek Experimental Watershed - Reynolds Mountain snow course site with parameter values obtained from the water year 1980 calibration

Water Year	Objective function	Bias function	Correlation coefficient	Observations
	mm of water	mm of water	R	Number
1980 (calib.)	144	-26	0.998	19
1970	398	-2398	0.914	18
1971	775	-280	0.985	25
1972	3074	-3074	0.866	20
1977	577	-577	0.720	19
(4-yr total) 1970, 71, 72, 77	6824	-6329	0.905	82

Calibration on runoff response at Upper Sheep Creek Watershed

The process of calibrating a model attempts to obtain the set of parameters that will best reproduce the observed data through minimization of a selected objective function. Next in the modeling process is the validation phase in which a totally different data set is used to compare observed and predicted values.

When calibrating or validating a snow accumulation and melt model such as HYDRO-17 and the SPUR hydrology component, the ideal situation would be to calibrate the HYDRO-17 model on observed snowpack data, like areal coverage and water content, and use runoff data to determine parameters for the hydrology model. If parameters for both models are lumped and calibration is conducted on a single variable such as runoff, then interaction between parameters would lead to fewer physically based values and the transfer of these values to other basins would be more difficult. Unfortunately, little rangeland watershed data are available, which include the snowpack, runoff, and soil moisture information required to independently check the separate components.

The closest data set that could be found was collected in an intensive study of snowmelt contribution to runoff at the Reynolds Creek Experimental Watershed in southwest Idaho and reported by Stephenson and Freeze (1974). The hydrology of the Upper Sheep Creek watershed (fig. 6) is dominated by deep, late-laying snowdrifts on its northeast facing slope. During 1971, an intensive study of a section of this slope involved measurement of the snowdrift water content for the outlined zone, as well as runoff, soil moisture, and water table elevation. Since only a portion of the slope was sampled, these data were extrapolated to the entire field. It must be remembered that the snow survey was not conducted to sample the entire drift, but only the portion of interest.

The Upper Sheep Creek watershed was divided into three fields for simulation (fig. 6). Soil and crop type were the same for fields 1 and 3. There was only one season of snowpack data, and the HYDRO-17 model was calibrated on these data. Initial estimates of the parameters for the HYDRO-17 model came from the snow course parameter estimates

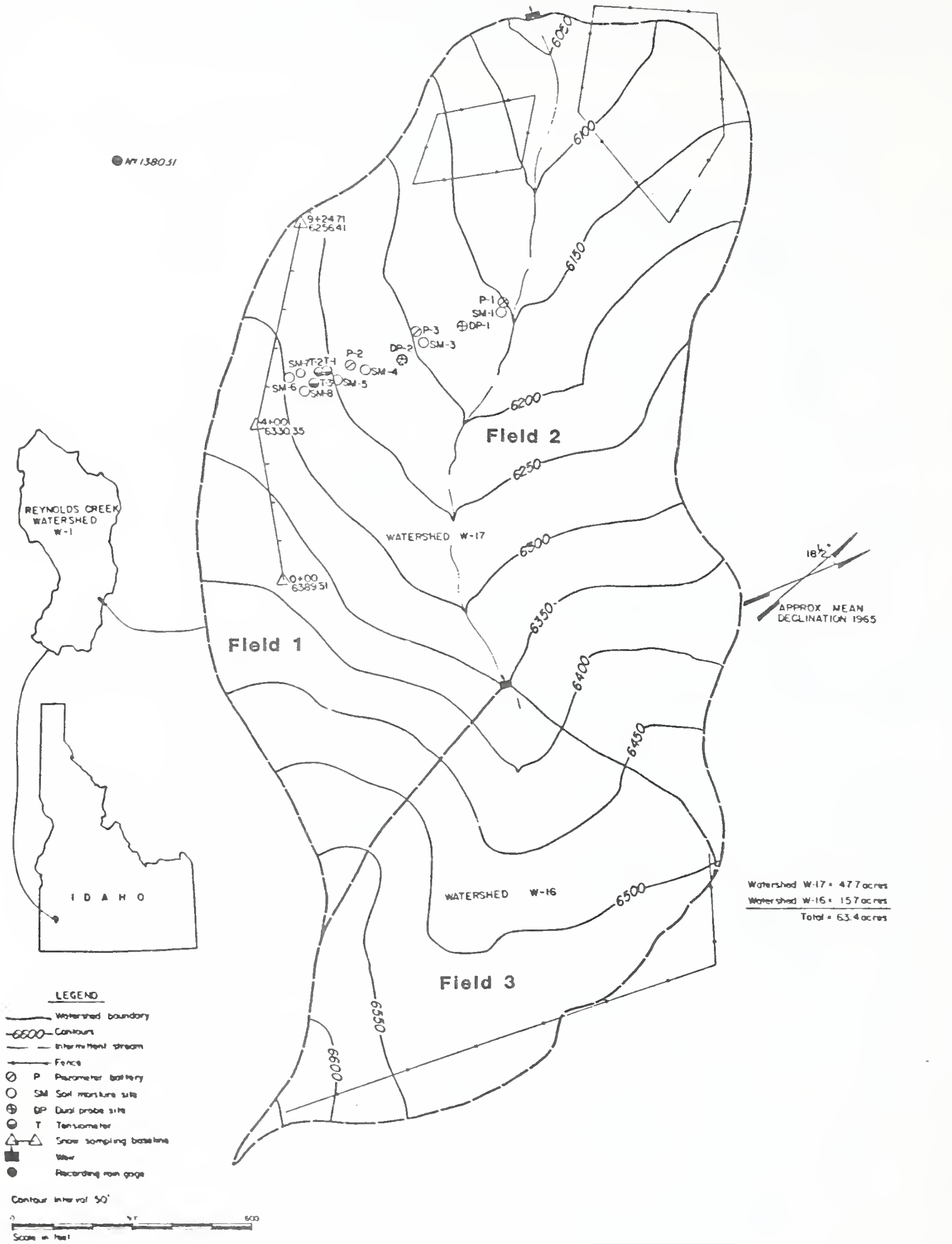

Figure 6.--Instrumentation and topography map of Upper Sheep Creek Watershed with field site locations (Stephenson and Freeze 1974).

previously reported. The point data represented by the snow course does not depend on the areal depletion curve as much as the watershed data, and different estimates for SI and ADPT were required.

The hydrology parameters were calibrated over the entire period of record (October 1970 to December 1975). The parameters that varied were the condition I curve number, the return flow time, and the hydraulic conductivity of the soil layers.

The calibrated HYDRO-17 parameters are listed in table 3 for each field. Fields 2 and 3 were considered to be warmer due to more southerly exposures. The observed and predicted snow water contents for field 1 during 1971 are presented in table 4, and the root error sums of squares are in table 5.

Table 3.--Snow accumulation and melt model (HYDRO-17) parameters calibrated by fields

	Field Number		
	1	2	3
SCF	1.0	1.0	1.0
MFMAX (mm/day)	5.0	5.5	5.0
MFMIN (mm/day)	3.00	3.50	3.25
UADJ	0.20	0.20	0.20
SI (mm)	800.00	500.00	800.00
ADPT	5.0	5.0	5.0
TIPM	0.5	0.6	0.5
NMF	0.9	0.9	0.9
MBASE (°C)	0.0	0.0	0.0
PXTEMP (°C)	0.0	0.0	0.0
PLWHC	0.02	0.02	0.02
DAYGM (mm/day)	0.30	0.30	0.30

Table 4.--Observed and predicted snow water equivalent (SWE) from field 1 for Upper Sheep Creek in 1971

Date	Observed SWE (mm)	Predicted SWE (mm)
March 1	71	90
April 8	218	110
April 22	233	85
May 6	186	43
May 13	37	24
May 19	11	14
May 26	0	0

Table 5.--Root error sum of squares for 1971 field 1 snow water content, daily runoff, and monthly runoff for the period 1971-75 for Upper Sheep Creek

	$\left(\sum(\text{obs}-\text{pre})^2\right)^{1/2}$ (mm)
Snow water content	233
Daily runof	93
Monthly runoff	20

It is apparent from table 4 that the predicted accumulation is about half the observed. The accumulated values could be increased by multiplying the precipitation by an increased SCF value. This was not done because 1) the dual-gage network used at Reynolds Creek is designed to obtain an accurate value of snowfall, and 2), as stated, the sampling procedure for the water content data was not designed to sample the entire drift, hence the water equivalent values are biased. The values for SI and ADPT reflect the shallow transient snowpacks that generally exist at these elevations. A type 5 area depletion curve (ADC) initially has a rapid decrease in area with a small decrease in water content (fig. 2). The high values for SI allow the maximum accumulated water content to control the ADC.

Aerial photographs of the site on 22 April, 1971, and 11 May, 1971 allowed, a qualitative check on the areal coverage calculations by the model. The photograph on 22 April indicated that the snowdrift covered 33 percent of field 1, but the model predicted a snowfall that day so coverage was 100 percent. Two days prior to 22 April, the model predicted an areal coverage of 20 percent. On the 11 May photograph, the areal coverage was found to be approximately 13 percent and the model predicted 7 percent.

After calibrating the snow model and determining the best fit parameters, a calibration of the streamflow model was conducted for the entire period of record (1970-75). As noted by Stephenson and Freeze (1974), overland flow is rarely observed on the Upper Sheep Creek watershed. This is reflected in the low value of the condition I curve number, CNI = 55, which was assigned to each field. Basically, the return flow function was adjusted for each field until the best fit was achieved. From figure 7, it can be seen that the timing of the runoff is reasonable, but the magnitudes are variable. The coefficient of determination, r-squared, for this calibration was 0.35.

A more complete and thorough calibration and validation of the HYDRO-17 routines will require watershed data collected for these purposes. From Figure 7, it appears that the model is melting the snow at the right time intervals. Obviously, the peaks are not reproduced all that well, but this would require further work with both components. Without similar data available for other watersheds, it is impossible to calibrate and compare the parameters.

DISCUSSION AND CONCLUSIONS

The NWS snow accumulation and melt model (HYDRO-17) (Anderson 1973) was chosen for testing and possible use in the ARS range model for Simulation of Production and Utilization of Rangelands (SPUR), because of its minimal data requirements, program size, theoretical basis, parameter guidelines, and previous use in many areas.

The model was tested at a snow course site and on a subwatershed of the Reynolds Creek Experimental Watershed near Boise, Idaho. In both of these situations, adequate results were obtained with a minimum of calibration and parameter adjustment. The range of parameter values presented in the users guide proved adequate for both the point and basin tests at this location.

Use of this model should provide better results over a wider range of snow accumulation and melt conditions than those provided by the simple relation used in the CREAMS model (Knisel 1980). However, as stated in the users guide, there will still be situations where model results will not match actual snow conditions. In these cases only a complete energy balance method would provide good results, and at the expense of considerably more data than is normally available, in addition to greater program complexity.

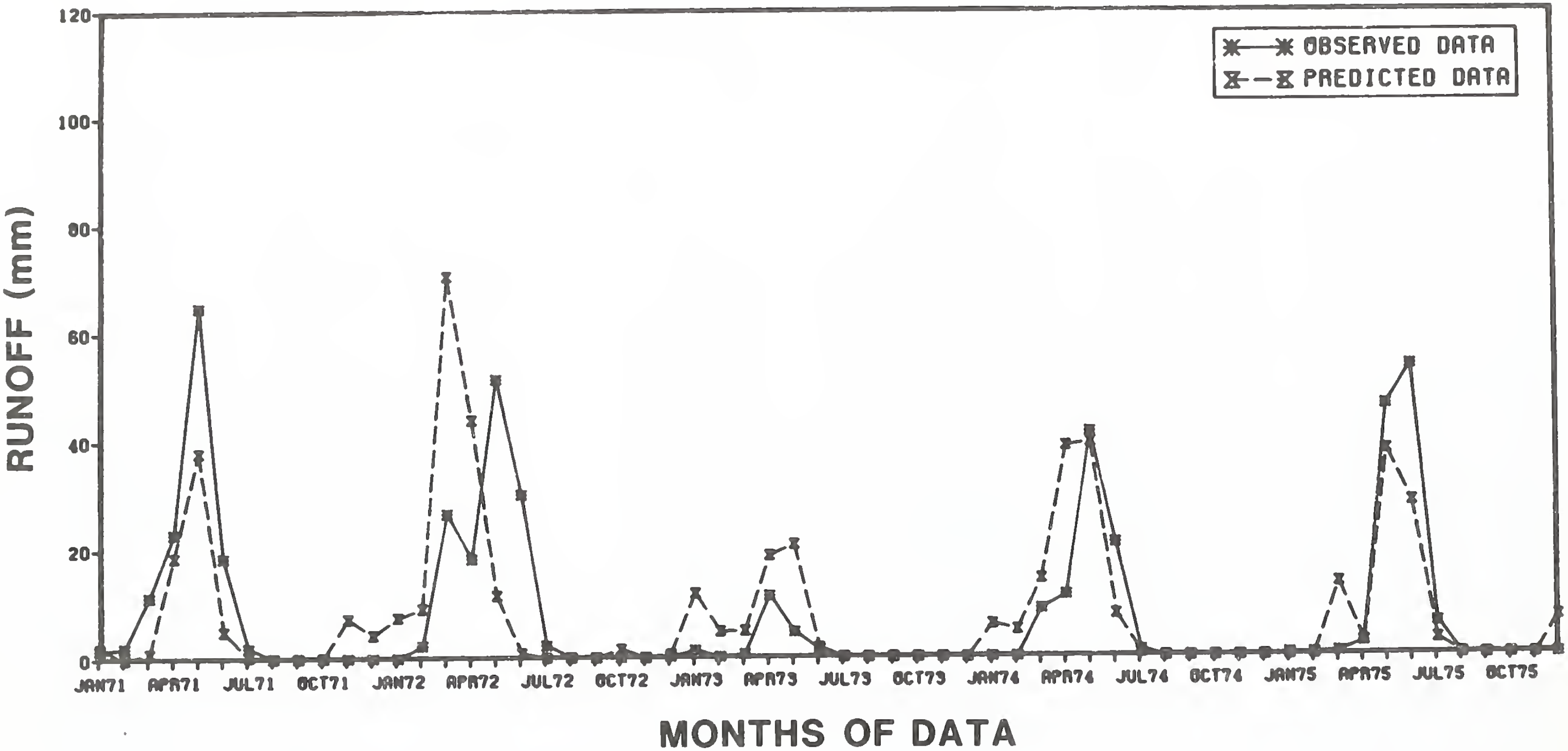

Figure 7.--Observed and predicted monthly runoff from Upper Sheep Creek, 1971-75.

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SPUR HYDROLOGY COMPONENT: WATER ROUTING AND SEDIMENTATION

By L. J. Lane[1]

INTRODUCTION

Stream channels, and thus watersheds, combine in complex patterns to produce upland areas, channel networks, and interchannel areas. These features control the routes and rates of water and sediment movement as runoff occurs in response to precipitation. While many of the physical processes controlling water and sediment movement are common to the upland areas and the stream channels, channel processes are sufficiently complex and important to require special attention in formulating a simulation model. Of particular concern are the relationships among hydrologic processes, flow hydraulics, and sedimentation processes occurring in stream channels.

The objectives of this paper are to describe the development of simplified procedures to estimate runoff and sediment yield from rangeland watersheds by modeling streamflow and sediment transport in channels, to link these processes with the upland phase, and to identify future directions and research needs.

The models described herein are intended for application on small rangeland watersheds with well-defined channel systems where streamflow is ephemeral or intermittent. The procedures can also be applied to streams with base flow under conditions where the time constant in the subsurface flow component is known or can be estimated. Because the sediment yield calculations are based on computed transport capacity, the procedures are designed to compute transport capacity in alluvial stream channels composed of noncohesive sediments.

STRUCTURE OF THE MODEL

The logical and computational structure of the model follows the stream channel network from upland areas to the watershed outlet. Each exterior or primary channel receives runoff and sediment from any combination of an upland and two lateral flow areas. Interior or higher order channels can receive water and sediment from one or two upstream channels and from one or two interchannel or lateral flow areas. Computations proceed in the downstream direction until the watershed outlet is reached.

Linkage with the upland phase is accomplished by taking runoff and sediment yield from the upland and lateral flow areas as input to the channel system. (See the section on "SPUR Hydrology Component: Upland Phases.")

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Water Routing Component

The water routing component is based on a distributed hydrologic model (Lane 1982a),[2] and can include the influence of channel abstractions or transmission losses upon the volume and peak rate of runoff. Mean duration of flow is estimated using watershed characteristics following procedures developed by Murphey et al. (1977). Given estimates of runoff volume and flow duration, peak discharge, and hydrograph shape are estimated using a double-triangle hydrograph approximation (Ardis 1972, 1973; Diskin and Lane 1976).

When the stream channels are ephemeral, the model includes procedures to account for infiltration or transmission losses into the channel beds and banks. Under these conditions, runoff volumes and peak flow estimates include the influence of transmission losses in reducing runoff volumes and attenuating peak flow in the downstream direction. In the absence of significant transmission losses, peak runoff rates are also attenuated in the downstream direction, because hydrograph characteristics, such as time to the peak rate of runoff, increase with increasing drainage area.

The double-triangle hydrograph is broken into N intervals for the period [0, D], where D is the flow duration. This results in a piecewise-normal approximation where normal flow is assumed within each of the N time intervals, and the Manning equation is used to compute flow depth, velocity, and hydraulic radius throughout the duration of flow. The assumption of normal flow within each time interval, but changing flow rates between intervals, allows an approximation of unsteady flow. By changing the piecewise-normal hydrograph in the downstream direction, we approximate spatial variability. The combined results of these assumptions is an approximation to spatially varied and unsteady flow in the stream channels (Lane 1982b).

The water routing component was developed and tested using hydrologic data from Arizona, Kansas, Nebraska, and Texas. The transmission loss equations are based on analysis of runoff data from 14 channel reaches in Arizona, Kansas, Nebraska, and Texas, and have been tested using data from 14 other channel reaches in Arizona and seepage rates in unlined canals. The computations for runoff volume, time to peak, and peak discharge were evaluated using data from 260 rainfall-runoff events on 10 experimental watersheds in Arizona. The model reproduces trends in runoff rates and amounts and has been used to compute flood frequency distributions on small watersheds.

Additional research is underway to improve parameter estimation techniques and to improve individual components of the water routing model. However, based on available information contained in soils and topographic maps, and from channel characteristics based on field observations, the procedures outlined here can be used to estimate runoff rates and amounts from rangeland watersheds.

Sediment Routing Component

Based on flow hydraulics and sediment transport mechanics, the larger sediment particles are assumed to travel as bedload, with the smaller particles traveling as suspended sediment. The distribution of sediment is represented by up to 10 particle-size classes greater than 0.062 mm representing bedload, and one class of particles smaller than 0.062 mm representing suspended sediment. Transport capacity of bedload is computed using a modified form of Duboys' equation, and suspended

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[2] The author's name followed by the year underlined, refers to Literature Cited, p. 66.

sediment transport capacity is computed using a modified version of Bagnold's equation (Lane 1982b).

Sediment yield is computed by integrating water flow rates and sediment transport capacity through the N time intervals on the approximating hydrograph. Sediment yield calculations are made at channel cross sections representing each channel reach, so that net deposition or erosion in the reach can be computed with a continuity of mass equation.

The sediment transport capacity equations were evaluated using data from the Niobrara River in Nebraska. These data were used to assess the steady-state performance of the sediment transport equations, which explained over 90 percent of the variance in the observed data from the Niobrara River. The sediment yield model, using the piecewise-normal approximating hydrograph, was tested using data from 47 runoff events on five small watersheds in Arizona. The sediment yield model explained about 80 percent of the variance in these observed sediment yield data. Additional research is needed to test the combined hydrologic and sediment yield model using experimental data and to improve the parameter estimation techniques.

Selected References

Background material on hydrologic processes, model development, water routing, and sediment routing are summarized in table 1. While these references do not provide a complete picture, they do describe the processes and provide further reference material.

Table 1.--Selected references providing background information

Process or component	Comments	
Hydrology of rangelands	Basic source material and technical overview	Branson et al. (1981)
Hydrologic modeling	Emphasis on agricultural watersheds	Haan et al. (1982)
Upland processes	Hydrologic models for upland phase	Knisel (1980); SCS (1972); Murphey et al. (1977)
Channel processes	Open channel flow Sediment transport Basic source material	Chow (1959) ASCE (1975) Graf (1971)
Water routing	Distributed model Transmission losses	Lane (1982a) Babcock and Cushing (1941) Lane (1980)
Sediment routing	Development of procedure	Lane (1982b)

APPLICATIONS

Typical applications of the model include simulating flood frequency and predicting sediment yield for rangeland watersheds. The section "SPUR Hydrology Component: Upland Phases" discusses application on a small watershed in southeastern Arizona, including the influence of transmission losses on runoff and the importance of channel processes on sediment yield. Lane (1982a) describes the hydrologic model and presents examples of flood frequency estimation. Lane (1982b) presents results for flood estimation and sediment yield estimation for a number of small watersheds in Arizona. Lane and Hakonson (1982) describe applications in predicting sediment transport in alluvial stream channels in New Mexico and discuss the significance of differential sediment transport and particle sorting.

Important applications of the model include using it to evaluate the influence of land use and conservation measures upon water and sediment yield. The upland component of the hydrologic model contains infiltration and erosion parameters (for example, runoff curve numbers and Universal Soil Loss Equation factors) which are affected by land use and management practices. Given changes in runoff and sediment yield from the upland areas, as reflected in these parameters, the model can be used to estimate the response of the channel system to these changing inputs. By routing runoff and sediment through the channel network, it is possible to assess the influence of land use and management on the upland areas on runoff and sediment yield from complex watersheds. Without a component to represent the stream channel system, it is difficult to integrate the influence of land use and management practices upon water and sediment yield from areas larger than plots or individual pastures.

Taken together, the references cited earlier document development and applications of the water and sediment routing components of the SPUR Model. Additional testing, evaluation, and model applications are continuing, and will represent more broad-based applications with respect to climate, topography, soils, vegetation, land use, and watershed size.

FUTURE DIRECTIONS AND RESEARCH NEEDS

The channel component of the SPUR Model represents a simplified approximation to hydrologic, hydraulic, and erosion and sedimentation processes occurring in stream channel systems. As research continues to improve our knowledge and existing data, significant improvements can be anticipated. These include the dynamic relationship among hydraulic processes, channel erosion rates, and sediment deposition rates, and how they are affected by conservation measures, land use, and range management practices.

Future Directions

Improved linkage between the upland and channel phases will more accurately reflect the influence of range management practices on runoff and erosion from rangelands. Complex watersheds represent systems which exhibit complex interactions and feedback. For example, increases in sediment yield from the upland areas can be offset by increased sediment deposition in the stream channels. This can result in delayed or reduced increases in sediment yield at downstream locations. On the other hand, decreases in sediment yield from the uplands can result in increased channel erosion, which might delay or reduce decreases in sediment yield at downstream locations. Improved linkage between the upland and channel phases will allow more accurate representation of these interactions. Improved parameter estimation techniques are also needed to allow wider application of the model under varied climatic conditions.

Selected Research Needs

A recent report (ASCE 1982) discusses relationships between channel morphology and sediment yield and includes a statement of research needs. This state-of-the-art assessment documents research needed to improve the water and sediment routing component of the SPUR Model. Additional research needs are documented in the proceedings of a recent workshop on estimating erosion and sediment yields from rangelands (ARS 1982).

Research is needed to improve methods of modeling channel erosion and sediment deposition processes, especially as they are affected by land use and management practices. Research is needed to quantify channel bank erosion and erosion of cohesive sediments, including gully development. Improved models are needed for hydraulics of out-of-bank flow and the associated sediment deposition processes occurring in floodplains.

Hydrograph characteristics are estimated using geomorphic features of the watersheds and stream channel systems. These relationships need to be developed and tested in several land resource regions representing a wider range of climate, soils, vegetation, topography, and land use. Moreover, objective methods are needed to select the number of stream channel segments and upland areas required to accurately represent complex watersheds. The appropriate degree of lumping or simplification will depend on the required accuracy in water and sediment yield, which, in turn, depend upon the purpose of the model application. Objective criteria are needed to specify required accuracy of model predictions, and these specifications, in turn, need to be related to the degree of lumping or simplification assumed in formulating upland areas and channel segments in the hydrologic model.

SUMMARY STATEMENT

The water and sediment routing component of the SPUR model approximates hydrologic, hydraulic, and sedimentation processes controlling runoff and sediment yield from ephemeral and intermittent stream channels on rangeland watersheds. Background information for the model is summarized in table 1 and in the references cited earlier. Specific details, such as formulation of the equations, testing and evaluation, and applications have been published in the references cited. Additional details on parameter estimation and applications will be documented in subsequent publications, such as user manuals.

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SPUR PLANT GROWTH COMPONENT

By J. D. Hanson, W. J. Parton, and J. W. Skiles[1]

INTRODUCTION

Many simulation and mathematical models describing plant growth and development have been produced in the past decade. These models range in complexity from simple predictive models (Wight and Hanks 1981)[2] to extremely complex process oriented models. Two rather complex plant growth models have been presented by Reynolds et al. (1980) and Jones et al. (1980). Both models present similar philosophies in that they are driven by photosynthesis and subsequently partition assimilated carbon in some manner.

Hesketh and Jones (1980) stated the importance of crop growth and yield models based on photosynthetic predictions in order to study effects of various policies on agricultural production, the economy, and the environment. The debate continues, however, concerning the relevancy of using net photosynthetic activity as the starting point of plant growth models (Elmore 1980). This model, based on the intricacies of plant physiology, was developed to link various environmental variables with rangeland plant growth and to serve as a management tool.

Extant models were reviewed during the construction of the primary producer model. Of particular interest were the Ecosystem Level Model (ELM), developed for the shortgrass prairie by the International Biome Project, U.S. Grassland Biome Study, and grassland models developed by Parton et al. (1978), Detling et al. (1978), and Detling (1979). The model described herein differs in many respects from these previous models, but information from them was used extensively during model development.

BRIEF MODEL DESCRIPTION

The primary producer model simulates the flow of phytomass (plant biomass) and nitrogen through the soil-plant-animal interface. There are seven phytomass and eight nitrogen state variables in the model (fig. 1). In the flow diagram, seven of the compartments are divided into two separate components to emphasize the concomitant existence of phytomass and nitrogen within the state variables. If nitrogen and phytomass flow between two state variables, the arrow points to the box title; however, if either phytomass or nitrogen flow independently, the arrow points to the phytomass or nitrogen subcompartment, respectively. Nitrogen and phytomass are calculated in different subroutines; thus each compartment represents two different state variables. The model is designed to run on daily time steps in order to be

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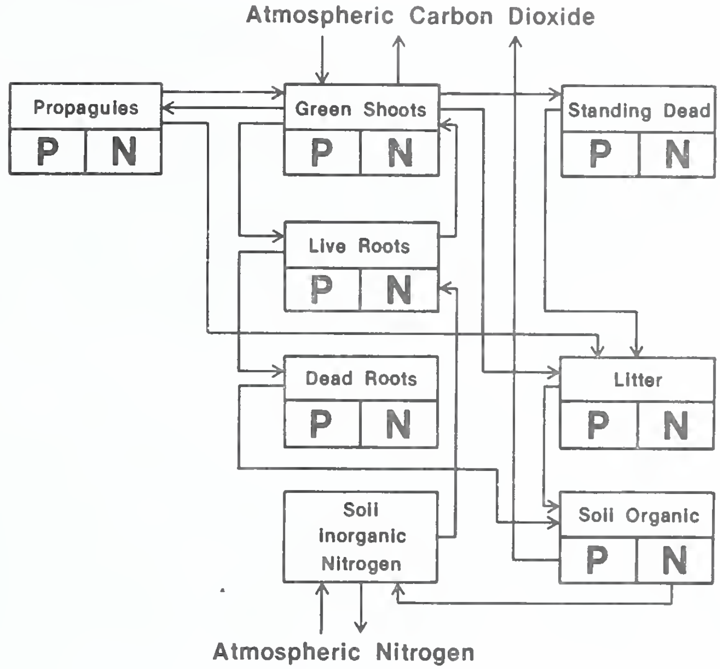

Figure 1.--Flow diagram of primary production simulation model.

consistent with SPUR (Simulation of Production and Utilization of Rangelands). The model in its present form is also dimensioned to handle up to seven species/species groups existing on up to nine range sites.

Abiotic variables are used to drive the plant growth processes. In a few instances, biological feedbacks are also included. Abiotic driving variables used by the primary producer model include air temperature, precipitation, soil water potential, solar radiation, and daily windrun. Bulk density of the soil is also used by the model.

For the SPUR model, amount of phytomass on each day is required output from the primary producer model. Conversion from phytomass to carbon is accomplished by multiplying phytomass by 0.4. All compartments and flow rates are dimensioned in grams per square meter. Species dependent state variables in the phytomass and nitrogen submodels are green shoots, live roots, propagules, and standing dead. Dead roots, litter, soil inorganic nitrogen, and soil organic matter have no species identity.

The ability of this model to simulate rangeland production has been investigated in single and multiple species runs of the model (Skiles et al. 1982). The model produced generally good phytomass and nitrogen simulations, typical of blue grama phytomass dynamics in northeastern Colorado. Two species runs, using blue grama and western wheatgrass, mimicked the expected dynamics of production and nitrogen flow. The model showed greatest sensitivity to processes controlled by temperature.

Phytomass Flow

Change in green shoot phytomass (S) over time is calculated as

$$dS/dt = PN-TSR-SC-DS-TSP+TRS+GERM-RESP \quad [1]$$

PN is daytime net carbon dioxide assimilation rate and is controlled by ambient temperature, soil water potential, nitrogen content of green shoots, leaf area of live shoots, and solar radiation (Detling et al. 1978). Diurnal patterns of PN are simulated for each day using a modified Michaelis-Menton function and subsequently integrated for total daily net assimilation. Translocation from shoots to roots (TSR) is calculated as a proportion of PN. The proportion is based on shoot/root phytomass ratios until senescense begins. Then a species-dependent constant fraction of the photosynthate produced is translocated to the roots. SC is trampling by herbivores and is a function of the stocking density. Mortality of live shoots (DS) accounts for death from frost, water stress, natural mortality, and excessive leaf area (Parton et al. 1978). Photosynthate is also transported to propagules (TSP) as a direct proportion of PN at maturity. Translocation form roots to shoots (TRS) occurs when water conditions are adequate, average 10-day temperature is high enough, and amounts of standing green phytomass are low. This mechanism initiates spring growth and regrowth after grazing. Biomass can also be added to standing green through seed germination (GERM). GERM is a function of soil water potential at the surface and average 10-day ambient temperature. RESP is nightime respiration rate and utilizes soil water potential and average nighttime temperature.

The dynamics of live roots (R) are expressed as

$$dR/dt = TSR-TRS-ROOTR-ROOTM \quad [2]$$

Root respiration rate (ROOTR) and root mortality rate (ROOTM) are temperature and water stress dependent, respectively. Information concerning these processes was extracted from Parton et al. (1978).

Propagule (P) dynamics in the model are expressed as

$$dP/dt = TSP-GERM-SEEDM \quad [3]$$

where SEEDM is seed mortality. SEEDM is calculated as a proportion of total propagule phytomass present. The facility exists to include granivory in the model, thereby reducing seed viability.

Standing dead phytomass (D) is simply

$$dD/dt = DS-TDSL \quad [4]$$

Standing dead is transferred to the litter compartment (TDSL) at rates dependent on wind speed, precipitation, and herbivore trampling.

As material moves through the system and decomposition occurs, it becomes impossible to maintain species identity. Consequently, dead roots, litter, and soil organic matter compartments no longer contain information concerning individual species but represent carbon and nitrogen pools. The following three equations represent the dynamics of these compartments

$$dS1/dt = ROOTM(i)-TDRO \quad [5]$$

$$dS2/dt = SC(i)+TDSL(i)+SEEDM(i)-TLO \quad [6]$$

$$dS3/dt = 0.4*TDRO+0.4*TLO-TOA \qquad [7]$$

Equations [5], [6], and [7] represent expressions for dead roots (S1), litter (S2), and soil organic (S3) compartments. TDRO, TLO, and TOA are transfers from dead roots to organic, litter to organic, and organic to atmosphere, respectively. All three of these transfers are functions of water stress and temperature. The subscripted variables represent terms which reflect species identity and have the numeric value as previously defined. It is assumed that only 40 percent of the phytomass is retained following decomposition (60 percent is released as carbon dioxide through respiration) into the organic pool (equation [7]).

Nitrogen Flows

As can be seen from the flow diagram (fig. 1), the nitrogen flows, for the most part, parallel the phytomass flows. Amounts of nitrogen moving between compartments are calculated by multiplying the carbon flow rate times the N/C ratio of the donor compartment. This allows the N/C ratio of the state variable to change with time. The C/N ratio for soil organic matter is assumed to be constant, and the flow of N into soil organic matter is equal to the amount of N needed to form soil organic matter with a C/N of 10. Decomposition of dead roots and litter form soil organic matter. Generally, the N content of litter and dead roots is fairly low and C/N ratios of phytomass flowing into soil organic matter is greater than 10. The model assumes that N from the mineral N pool is immobilized during decomposition and the amount needed to create soil organic matter with a C/N ratio of 10 is transferred to the soil organic pool. When soil organic matter decomposes, the nitrogen contained in the phytomass compartment is released into the mineral N compartment.

Several processes of the nitrogen portion of the model deserve some discussion. Nitrogen uptake is calculated by the use of a Michaelis-Menton type equation with soil inorganic nitrogen as the substrate. Rate of uptake is subsequently modified depending on root biomass, soil moisture, and temperature. Movement of nitrogen from roots to shoots or shoots to roots is calculated by the methods of Reuss and Innis (1977). Also, nitrogen fixation rates are calculated as a linear function of precipitation. Finally, plants tend to retain nitrogen during the death process. Thus, instead of transferring nitrogen from green shoots to standing dead at the present C/N ratio it is transferred at a ratio of C/N + 10.0 (McGill et al. 1981).

MODEL APPLICATION

This model was designed to be used as a tool for management and research. As a research tool, the model can be used, for example, to test the effect of environmental stress (temperature, nitrogen, or water) on total rangeland production. This would be particularly interesting if net carbon assimilation was output along with total plant production. The model is designed to simulate seven species or species groups simultaneously; thus, one could investigate the interrelationships and competitive behavior of several species. Another use of the model could be to investigate the impact of various perturbations on the total range system. Such factors as extreme drought or below average temperatures affect total plant activity and would be reflected through the photosynthetic process and mortality rates. Through computer experimentation, the investigator can possibly determine research needs and direction. Much of the experimentation on the model would be done by changing its parameters. For this model, information describing the physiological behavior of each simulated species is required input from the user.

The number of parameters required as input by the user poses no real problem to the researcher, but can severely hinder a manager who wishes to use the model. At this time, we have not totally solved this problem, but to make the model more useful to managers an algorithm is being developed so that the model will be self-parameterizing. In this way, the manager will be able to input what information is available for a particular species and location and the model will determine the necessary parameters. Thus, the model will be able to simulate production for many species and species groups across a broad range of environments.

The model can easily be linked to various waterflow and animal production models; thus, the model will aid in the management decision making process. The model, when linked with other submodels, can test grazing strategies, the effect of policies on range condition, or make predictions which can be used to make short-term planning decisions. These are just a few of the possible applications of this type of model. The most important thing to keep in mind is that the model is only a tool. As such it can be used to predict, but any prediction must be carefully scrutinized. Overall, the model works well and is able to return reasonable estimates of above and below ground plant production.

SUMMARY

A plant production model has been developed which simulates above- and belowground plant production. The model is capable of simultaneously simulating up to seven species or species groups on nine sites at daily time intervals. The model uses net carbon assimilation as the entry point of carbon dioxide into the plant. Subsequently, carbon and nitrogen contents of standing green, live roots, propagules, standing dead, litter, dead roots, and soil organic matter are simulated. Soil inorganic nitrogen is also included in the model. The model has been successfully used to simulate a two species system and shows promise when expanded to entire plant communities.

The model will be useful subsequent to validation for research and management applications. For both types of applications the model can produce output which will aid in gleaning information at costs significantly lower than direct experimentation. The model ultimately should be able to aid managers in making evaluations such as the effect of grazing on range forage production and range condition.

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SPUR LIVESTOCK COMPONENT

By R. W. Rice, M. D. MacNeil, T. G. Jenkins, and L. J. Koong[1]

INTRODUCTION

Livestock are an integral part of rangeland systems. Their control and management is a primary management tool, and they provide the principle economic output. Livestock response and productivity are important factors for comparison and evaluation of management options. Livestock affect rangelands principally through their activities in obtaining food and water. They travel and graze nonrandomly and exhibit preference for herbage species and for location or site within a rangeland. Livestock grazing behavior is a dynamic, highly interactive process which affects watershed behavior, herbage species composition, rangeland condition, and productivity. The livestock component of SPUR was designed to simulate the dynamic impact of grazing on rangelands and livestock response.

PROCEDURES

The dynamic functions and operational requirements for the livestock component were specified as:

1) Applicability to many different rangelands;

2) Representative of livestock impact upon vegetation;

3) Livestock response will be an output;

4) Data input requirements define the specific case to be simulated and are readily available for most rangelands;

5) Rangeland and livestock management options can be compared or evaluated; and

6) The resolution or scale will be consistent with typical management units such as pasture, grazing allotment, or ranch.

The major concepts included in the component development were: 1) the effects of livestock grazing on herbage composition and production are the result of the selective removal of herbage by livestock and the amount and distribution of excretal return of nutrients; and 2) livestock response to a rangeland is the function of herbage quantity and nutrient quality, herbage species, and the site or location within a grazing area.

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MODEL STRUCTURE AND FLOW

The structure and flow diagram for the animal component of the model is illustrated in figure 1. Herbage supply from the plant growth component is defined according to plant species or species groups and site. The definition of species and location is coordinated with the plant component and is representative of the rangeland to be simulated. The herbage supply provides two elements, standing biomass and nitrogen content, for the green and dry herbage classes.

The sequence of model flow calculations is as shown. Insect consumers exercise their demand followed by wildlife (noncattle) consumers. The livestock demand is computed based upon growing cattle or their equivalent, the number of animals, average weight, and their physical condition.

Demand for herbage is partitioned over the herbage supply categories. The quantity demanded from the supply is derived from plant species preference and site preference data inputs. Each cell of the herbage demand matrix is compared with the corresponding cell of the supply matrix. If no cell of the demand matrix exceeds the corresponding cell in the supply matrix, animal demand is met. If any of the herbage supply matrix cells are less than demand, cattle demand is recalculated and the computer simulated consumers search for herbage from less desirable plant species and from less desirable grazing sites. The search by the computer grazer to satisfy dietary demand continues until the demand is met or available vegetation is exhausted. The realized diet and its nitrogen content are used to compute digestible dry matter intake. Digestible dry matter intake provides for the calculation of animal response in a modified version of the model of Sanders and Cartwright (1979).[2] Excretal nitrogen return to the rangeland is determined from the amount of nitrogen consumed which is not digested and urinary nitrogen excretion.

DATA INPUT REQUIREMENTS

The plant growth component of SPUR generates forage and nitrogren matrices for aboveground biomass in grams per meter squared. Herbage supply is classified according to the major plant species or species groups and sites within the grazed area as they affect animal selectivity for plant species and preference for sites. The model provides space for up to nine sites and up to seven herbage species at two maturity states, green or dry vegetation.

For simulation of specific rangeland, the livestock component requires the following data inputs which are provided by the user:

1) Area of each site (ha) as defined in the plant growth component;

2) Animal preference (0.0 - 1.0) for site or location;

3) Animal preference (0.0 -1.0) for forage species or species group;

4) Forage physical availability (0.0 - 1.0);

5) Number of cattle on a yearling steer equivalent basis;

6) The mature weight (kg) of a typical cow representing the breed or type of animal

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[2] The author's name followed by the year underlined, refers to Literature Cited, p. 86.

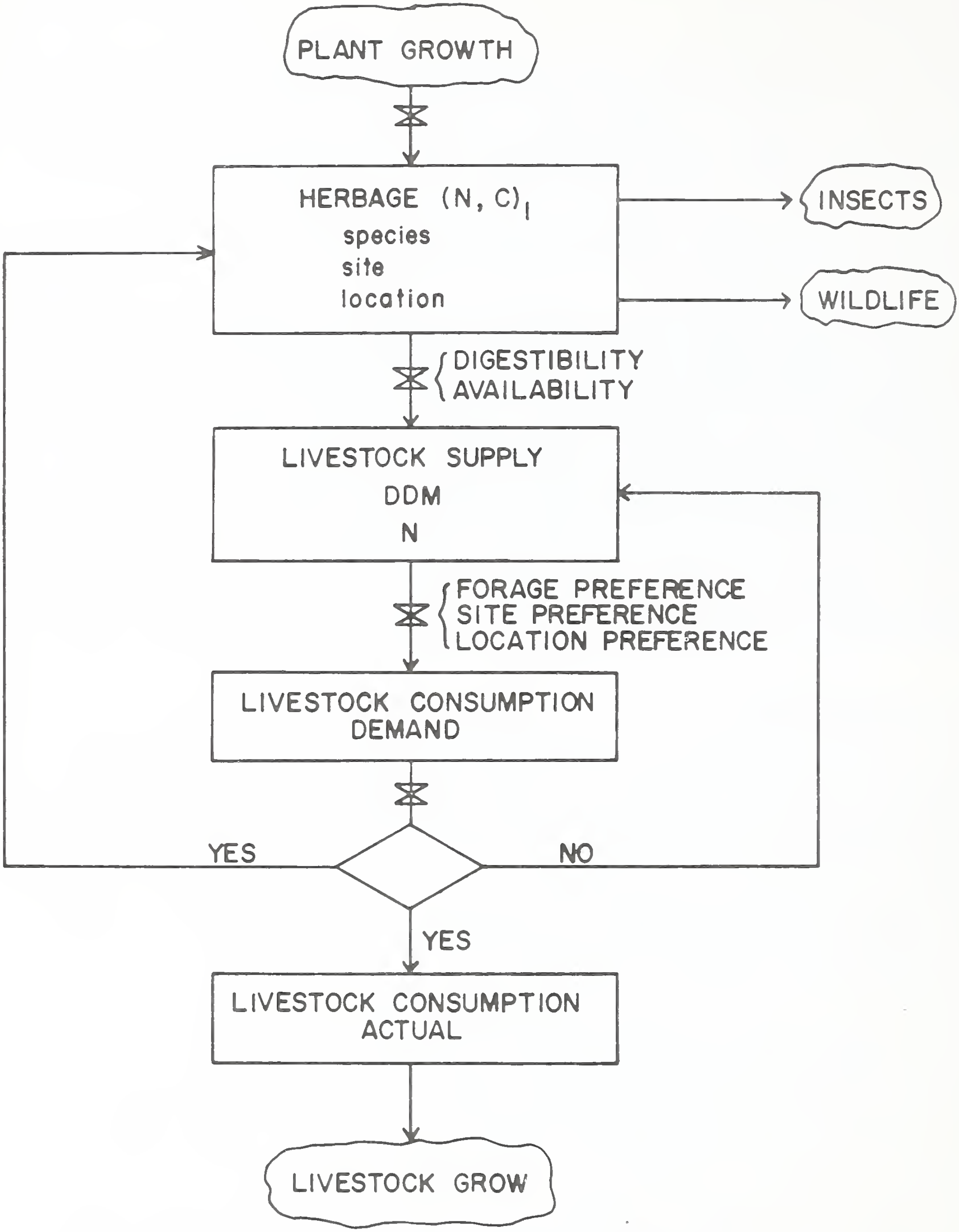

Figure 1.--Structure and flow chart for animal subsystem component. N = nitrogen (%); C = carbon (g/m^2) aboveground biomass; and DDM = digestible dry matter.

7) Age (days) and weight (kg) of cattle at turnout on rangeland;

8) Turnout day and removal day from rangeland; and

9) Supplements to be allocated (kg/hd/da), supplement digestibility (percent), day of the year to begin feeding, and day of year to end feeding supplement.

LIVESTOCK COMPONENT OPERATION

To illustrate the concepts and procedures for simulation, a theoretical rangeland will be used as an example. The example rangeland was defined as a shortgrass prairie producing six plant species groups which affect animal preference. Within each plant group, green and dry standing vegetation is monitored as the simulation will normally run over a number of years and the growth cycles of plant classes within each year proceeds from initiation of growth through maturity and dormancy. The plant species classes determined for this rangeland are described in table 1.

Preference for Plant Species Groups

The model accommodates up to seven vegetation classes at two maturities (green or dry). The bases for vegetation preference are twofold: 1) cattle prefer green vegetation; and 2) plant species in a mixed vegetation type are consumed selectively. A summary of research on vegetation preference is available from a recent comprehensive publication by Van Dyne et al. (1980).

The short grass prairie forming this example produces six plant species groups, which have been identified as determinants of animal preference. Within each group, both green and dry vegetation are normally available. The plant species classes are described in table 2. The model will accommodate up to 14 vegetation classes; however, it is not necessary to provide data for all available spaces in the model. For cattle, it was determined that given unlimited availablility, green vegetation would make up 90 percent and dry vegetation 10 percent of the diet. Preference for cool-season grass (CSG) was estimated at 0.30; warm-season grass (WSG) 0.25; cool-season forbs (CSF) 0.15; warm season forbs (WSF), 0.10; palatable browse (PB), 0.15; and unpalatable browse (UPB), 0.05. A zero value indicates that no vegetation is available. The two vegetation preference concepts are combined to form a 14-element composite vector of decimal proportions, summing to 1.00 (table 1).

Table 1.--Composite plant group preference vector

Vector element	Species group[1]	Species preference	G/D preference	Composite vector
1	CSG G	0.30	0.90	0.270
2	CSG D	.30	.10	.030
3	WSG G	.25	.90	.225
4	WSG D	.25	.10	.025
5	CSF G	.15	.90	.135
6	CSF D	.15	.10	.015
7	WSF G	.10	.90	.090
8	WSF D	.10	.10	.010
9	PB G	.15	.90	.135
10	PB D	.15	.10	.015
11	UPB G	.05	.90	.045
12	UPB D	.05	.10	.005
13	empty	-0-	-0-	-0-
14	empty	-0-	-0-	-0-
Total				1.000

[1] CSG = cool season grass; WSG = warm season grass;
CSF = cool season forbs; WSF = warm season forbs;
PB = palatable browse; UPB = unpalatable browse;
G = green vegetation; and D = dry vegetation.

Grazing Site or Location

The grazing sites for this rangeland were defined with regard to relative animal preference for location (fig. 2). Cattle grazing use on shortgrass prairie is known to be influenced by terrain and water location (Senft et al. 1980). Terrain was divided into three classifications--lowland, sidehill, and upland. Cattle are known to prefer lowlands with uplands and sidehills receiving less grazing use, provided adequate vegetation is available (Cook 1966; Senft et al. 1980).

Water Location

Grazing near water is usually more intense and varies inversely with distance from water. Voluntary daily travel by cattle is highly variable; however, their grazing strategy appears to be to minimize effort and to utilize readily accessible areas first, then extending grazing to locations more distant from water (Squires 1970; Valentine 1974). Under rangeland conditions, cattle daily travel of 5.8 km was reported by Malachek and Smith (1976), 5.0 km by Anderson and Kothman (1980) and from 7 to 15 km by Herbel and Nelson (1966). Sneva et al. (1973) reported that a distance of over 1.5 km from water to forage was detrimental to grazing success and cattle performance. For the example, it was determined that given unlimited vegetation and level terrain, cattle would prefer to graze within 1 km of water; however, within a population or herd, a certain proportion of time spent grazing would be in the zone

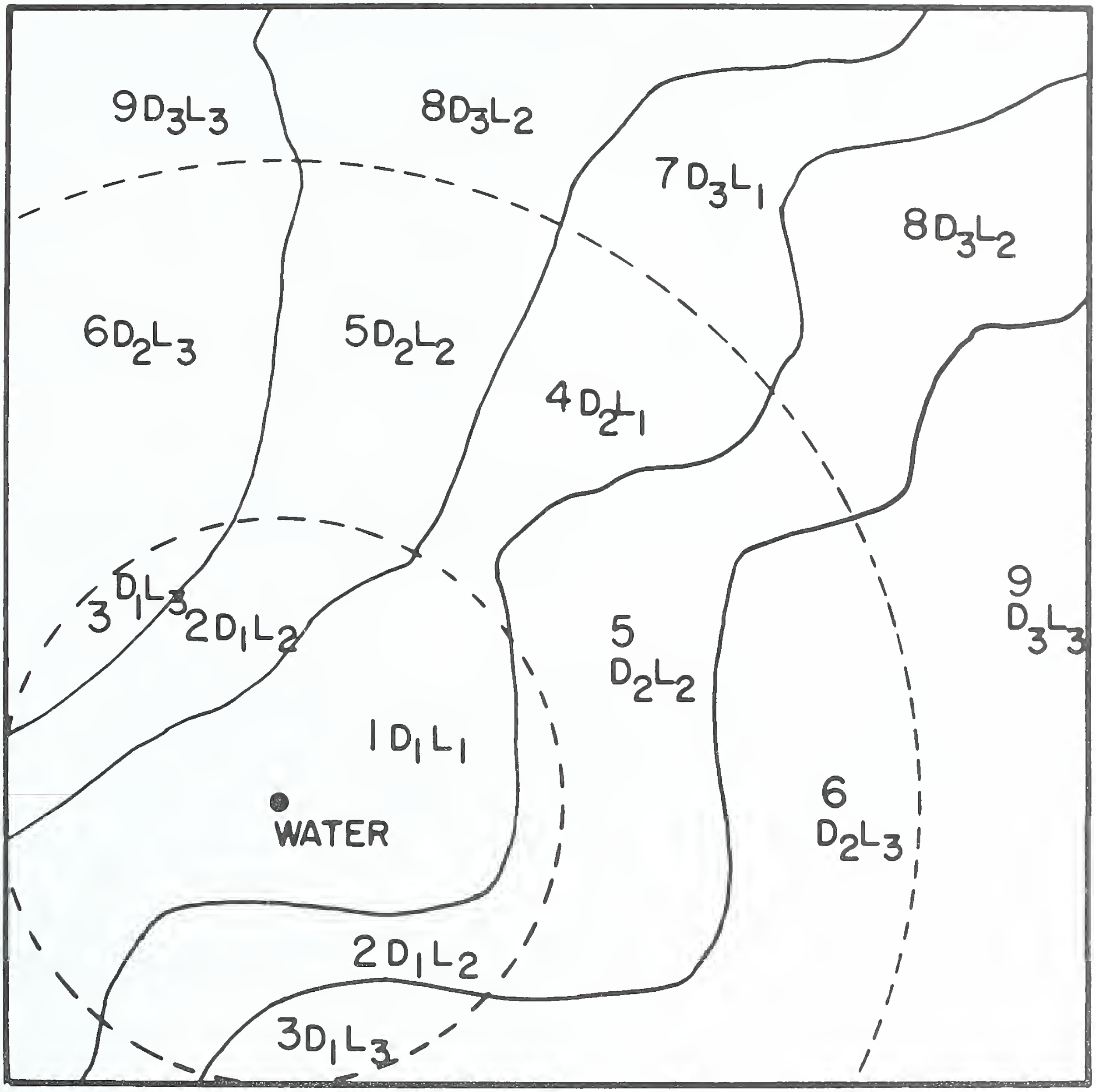

Figure 2.--Site designation of a theoretical range with three terrain (L_1 = lowland, L_2 = sidehill, and L_3 = upland) and distance classes (D_1 = 0-1 km, D_2 = 1-2 km, and D_3 = >2 km).

from 1 to 2 km while a small amount of use would be expected at distances over 2 km from water.

The data input required for site preference is in the form of a vector of proportions, summing to 1.0. For preferred areas, a high value is input. Lower values are given for less preferred locations. All locations must receive a value for proper operation of the model component. For this illustration, it was estimated that 0.75 of cattle use would be in the zone nearest water (0 to 1 km), 0.18 would occur in zone 2 (1 to 2 km), and 0.07 in distance zone 3 (>2 km). The distance zones are identified in figure 2 by the dash lines forming arcs at designated distances from water.

Terrain

When vegetation is equivalent on all terrain types and equal distant from water, a population of cattle prefer to graze lowlands, however, some occasionally use slopes and uplands with uplands being preferred to slopes (sidehills). Cattle were predicted to obtain 60 percent of their food from lowland sites, 25 percent from upland sites, and 15 percent from slopes or sidehills in the shortgrass prairie under consideration (Cook 1966; Senft et al. 1980).

The estimates for terrain preference are formulated into a three-component vector summing to 1.00 [lowlands (1) = 0.6, slopes (2) = 0.15, and uplands (3) = 0.25]. A nine-element vector, representing the two factors of distance from water and terrain, is constructed and is shown in table 2. This nine-element vector is the data input describing site preferences for cattle, assuming that vegetation is the same for all sites.

Table 2.--Composite preference vector for site

Site	Distance zone		Terrain[1]		Composite vector[2]
	Zone	preference	Class	preference	D x T
1	1	0.75	1	0.60	0.45
2	1	.75	2	.15	.11
3	1	.75	3	.25	.19
4	2	.18	1	.60	.11
5	2	.18	2	.15	.02
6	2	.18	3	.25	.05
7	3	.07	1	.60	.04
8	3	.07	2	.15	.01
9	3	.07	3	.25	.02
Total					1.00

[1] 1 = lowland; 2 = sidehill; and 3 = upland.

[2] D = distance; and T = terrain.

The two vectors, preference for sites and preference for plant species groups, form the central bases for operation of the model. They must be constructed carefully in order for grazing behavior to be representative of the area to be simulated. The concepts under which they are constructed are very important to proper operation of the model and are:

1) All vegetation types and locations which may provide food must be represented. The values are in decimal proportions, summing to 1.00. Those locations and species which are most desirable should receive a high value. Areas or species which are not expected to be grazed receive a low value; however, for proper operation of the model they must receive a value which is greater than zero.

2) The preferences for site are entered as if there were no differences in available vegetation and for vegetation as if there were no differences in site.

3) Vegetation preference is that proportion which would be expected to be consumed when all vegetation classes are available in unlimited amounts.

The model calculation procedure is to combine these vectors into a matrix which represents both concepts. The quantity of vegetation available is derived from the plant supply matrix as modified by the relative area of each site available for grazing.

Forage Physical Availability

The forage physical availability is the proportion of the total aboveground biomass of a plant species group which is readily consumed by a single grazing event. This is primarily a function of the growth form of the plant. Tall, erect grass species have a greater proportion of their weight accessible for grazing, while low growing grasses have a large proportion of their weight in the basal area and a low proportion of the total weight is removed by a single grazing bite. The green portion of shrubs is considered to be the current annual growth. A low proportion of a shrub is usually removed when grazed once.

The cool-season grass in shortgrass prairie is primarily western wheatgrass (*Agropyron smithii* Rybd.). This plant is readily accessible and a large proportion of the weight can be removed by grazing. The warm-season grass is primarily bluegrama [*Bouteloua gracilii* (H.B.K.) Lag. ex Steud.] which is a low-growing plant with a high proportion of its weight in the basal area. Grazers do not eat a large proportion of its weight in one bite. The forb and the browse components are readily accessible for shortgrass prairie. The data input for physical limits to utilization for shortgrass prairie is shown in table 3. The physical limit vector is not required to sum to 1.00 as is essential for the site and species preference vectors.

Table 3.--Herbage species class physical limits to utilization

Vector element	Species group [1]	Physical limitation
1	CSG G	0.60
2	CSG D	.60
3	WSG G	.40
4	WSG D	.40
5	CSF G	.60
6	CSF D	.60
7	WSF G	.60
8	WSF D	.60
9	PB G	.50
10	PB D	.25
11	UPB G	.40
12	UPB D	.20
13	empty	-0-
14	empty	-0-

[1] CSG = cool season grass; WSG = warm season grass, CSF = cool season forbs; WSF = warm season forbs; PB = palatable browse; UPB = unpalatable browse; G = green vegetation; and D = dry vegetation.

Dietary Digestibility

The digestibility of the realized diet drives the cattle performance component of the model and is derived by calculation of the nitrogen content of the animal diet and prediction of digestibility by equation [1].

$$DMD = 37.1 + 2.4\ X \qquad [1]$$

X = percent protein of the diet

$r^2 = 0.33$, $n = 143$

This equation was derived from data summarized by Cook et al. (1977) who reported protein content and dry matter digestibility values for 143 typical rangeland grasses. The coefficient of determination of this prediction ($r^2 = 0.33$) is not as high as has been reported by others (Bredon et al. 1963; Horton et al. 1980) who derived their regressions from much more discreet data sets, for example, a single species of grass at varying maturity. However, it represents the range of digestibilities typically encountered with rangeland plant species. Digestibility estimates for the diets of grazing herbivores are highly variable because of the difficulty of obtaining representative dietary samples.

Excretion

The excretion component of the model distributes organic material and nitrogen to sites in proportion to herbage removal by grazing. The model accommodates the nonrandom distribution for excreta according to grazing use, but does not account for concentrations of excreta in loafing or resting areas, which make up a low proportion of the rangelands area. Excretal distribution has been shown by Senft et al. (1980) to be related to grazing use. Fecal nitrogen is determined by using a constant average protein digestibility for range forages of 65 percent. Apparent protein digestibilities of forages are variable; however, except for mature, weathered forage are not greatly different from the constant value used in the model (NRC 1972). Data for urinary nitrogen excretion by grazing livestock is limited. Currently, the model estimates urinary nitrogen excretion at two times the endogenous urinary nitrogen. Endogenous urinary nitrogen values are derived from data summarized by the Agricultural Research Council Publication (ARC 1965). The functions utilized for cattle growth are described by Sanders and Cartwright (1979).

MODEL BEHAVIOR

A simplified example of the behavior of herbage/animal interface is presented to illustrate the calculation procedures followed by the computer in simulation of vegetation and site grazing preference behavior for cattle. Plant supply consists of two species groups and two sites. The computer plant growth component provides a 2 by 4 matrix of plant supply with two site and four plant species groups (two species with a green or dry herbage class).

The aboveground biomass is expressed as kilograms of vegetation per cell available for grazing. The matrix shown has already been adjusted for area and for physical availability of aboveground biomass (fig. 3). The vectors for site preference and for species preference were determined to be 0.80 for location 1; 0.20 for location 2; .050 for species 1, green (S1G); 0.05 species 1, dry (S1D); 0.40 for species 2, green (S2G); and 0.05 for species 2, dry (S2D) (fig. 4). From these values, which are provided by the model user, the computer calculates a preference matrix with the expected proportion of dietary consumption for cattle of each matrix component when there are no limitations of herbage supply (fig. 4). This preference matrix (in dietary proportions) is used to produce the animal demand in kilograms of forage per cell by multiplying the proportions times the total dietary demand (kilograms per day) of the cattle population. Supply and demand amounts are compared cell by cell. If all supply cells equal or exceed demand, cattle dietary demand is met, the digestible dry matter intake calculated, and the intake is used to predict cattle growth for that day (fig. 5). The diet realized (kilograms per cell) is deducted from the plant supply, and the updated supply is returned to the plant growth component.

If any of the individual cells of cattle demand exceeds a corresponding supply cell (as in fig. 6), a modified preference is calculated based upon the limitation of supply and a new demand is calculated. The supply and demand matrices are compared again. If all supply components equal or exceed demand, a realized diet is calculated. The supply matrix is reduced by the dietary intake, and the next daily procedure continues. If all components of supply do not meet demand, the preference vector is recalculated and the process continues until a realized diet is determined or available vegetation is exhausted.

A case where the demand was met by one revision of preference is illustrated in figure 6, which compares the recalculated preference with the most preferred preference. A failure of supply to meet demand (cell 1 is less than demand) resulted in a reduction of the dietary proportion derived from cell 1 (0.40 demanded versus 0.25 realized). The proportion realized from all other cells was increased. The increase per cell is related to the relative preferences for the vegetation in the remaining cells.

The magnitude and direction of the search for food when certain cells are limiting are controlled by the relative preferences for sites and species, which are required input

	L1	L2
S1G	100	100
S1D	50	50
S2G	200	200
S2D	100	100

Figure 3.--Forage supply matric (kg/cell) for two species both green (G) and dry (D) vegetation classes and two locations (L).

	L1 0.80	L2 0.20
S1G 0.50	.40	.10
S1D 0.05	.04	.01
S2G 0.40	.32	.08
S2D 0.05	.04	.01

Figure 4.--Species and location preference matrix.

	L1	L2
S1G	100 40	100 10
S1D	50 4	50 1
S2G	200 32	200 8
S2D	100 4	100 1

Figure 5.--Preferred diet versus available forage with a total demand of 100 kg/day.

		L1 PREFERRED 0.80	L1 REALIZED	L2 PREFERRED 0.20	L2 REALIZED	
S1G	0.50	.40	.25	.10	.13	0.38
S1D	0.05	.04	.05	.01	.02	0.07
S2G	0.40	.32	.40	.08	.10	0.50
S2D	0.05	.04	.05	.01	.01	0.06
			0.75		0.25	

Figure 6.--Preferred realized dietary proportions with a total demand of 400 kg and with cell 1 limiting.

data. In this case, the cattle desired 50 percent of their diet as S1G and realized 38 percent and consumed 10 percent more S2G (50 percent versus 40 percent), 2 percent more of S1D (7 percent versus 5 percent) and 1 percent more S2D (6 percent versus 5 percent). They also consumed more vegetation in location 2 than preferred (25 percent versus 20 percent).

The simultaneous extension of grazing effort to other locations and species from those most desired simulates the biological response of animals to limiting quantities of preferred vegetation in preferred areas. The calculation procedure is simple, and the direction and magnitude of the search of the grazer to satisfy dietary demand are determined by the data input vectors for location and species preference.

SUMMARY AND CONCLUSIONS

The purpose of SPUR is to evaluate the short and long term effects of rangeland management. Since the impact of grazing livestock is site or location specific, the model must simulate the effects of nonrandom grazing at the pasture level. Management for rangelands is applied principally to livestock through control of stock density, season and duration of use, and by the implementation of control of animal behavior through fencing, stock water location, and grazing systems. The primary purpose of management practices is to override the tendency for livestock to graze selectively or to minimize the impact of that selectivity upon the rangeland.

The animal component of SPUR operates upon three key concepts which describe the grazing strategy of the herbivores. These concepts, plant species coupled with stock density or animal demand, are central controlling factors for the simulation of short- and longterm grazing effects on herbage species production, plant succession or survival, herbivore competition, livestock production, and grazing efficiency.

The applicability of the component to a wide variety of rangelands is based upon input data required which define the key concepts for a specific case. The concepts governing grazing behavior are based upon information available in the literature; however, testing, validating, and evaluating the behavior of the animal component of SPUR in specific situations has not been accomplished. Experimental information defining daily location and plant species preferences is not available; however, season-long or longer term information is available and will be used for testing and validation. The search strategy which herbivores use for food when preferred plant species and locations are limiting has not been well defined experimentally. Computer simulation experiments and research efforts will be utilized to validate and test this concept. The process of model development has identified animal grazing behavior as an important research area.

The livestock component of SPUR is unique because it considers spatial behavior as well as food habits in the simulation. The structure is simple mathematically and requires no complex functions or constraints for operation. The evaluation of simulation is based primarily upon domestic cattle performance for which adequate data are available in practical situations.

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SPUR WILDLIFE CONSUMERS

By M. Vavra and R. J. Raleigh[1]

INTRODUCTION

The development of a herbage/animal interface simulation model applicable to rangelands must include the potential for impact by wild, free roaming herbivores. Many areas in the western United States grazed by domestic livestock may also support several other species of herbivore for at least a portion of a year (Olsen and Hansen 1977;[2] Hansen and Clark 1977; Vavra and Sneva 1978). For example, the potential impact of elk can be great since they may attain an average weight of 180 kilograms for cows and 335 kilograms for bulls (Kirsch and Greer 1968), and populations of over 40,000 are known in some western States (Bryant and Maser 1982). Also, the more subtle impact of wildlife grazing on plant physiology and production may decrease forage available to livestock. Livestock also have the potential to significantly decrease forage availability to wildlife and change the composition of plant communities. Public land managers have to consider the impacts of wild herbivores when they allocate forage as part of their planning processes. The extent of competition among herbivores is dependent on many factors (Cooperrider and Bailey 1982). In the model subcomponent, forage consumption by wild herbivores is simulated.

FORAGE SELECTION AND INTAKE

The most common form of expressing competition and complimentary relationships among herbivores in the literature has been comparative food habits (Hansen and Clark 1977; Hansen and Reid 1975; Johnson 1979; Lesperance et al. 1970, McMahan 1964; Vavra et al. 1982; and others). A review of the literature pertaining to the food habits of herbivores in the western United States generally indicates that most can be classified as intermediate feeders, a term used by Wallmo (1978) to describe the foraging habits of mule deer. Intermediate feeders are those that are capable of adapting to a wide range of forage types and phenological conditions. Reviews of food habits studies by Kufeld (1973) and Leege et al. (1976) for elk and Kufeld et al. (1973) for mule deer serve as examples. Generalizations that categorize specific herbivores as browse, forb, or shrub consumers are misleading, since most are adaptable and opportunistic grazers.

Factors that influence diet selection and quantity consumed by a specific herbivore include availability of forage (both species and plant part diversity), physiological state of the animal, type of digestive system, body size, rumino-reticular volume to body weight ratio, mouth size, and other factors. Type of digestive system, body

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[2]The author's name followed by the year underlined, refers to Literature Cited, p. 91.

size, rumino-reticular volume to to weight ratio, and mouth size determine if an animal's eating strategy is for quality or quantity (Hanley 1982; Bell 1971). Large bodied, cecal or ruminant digestors, ruminants with a large rumino-reticular volume to body size ratio, and large-mouthed animals (cattle, horses, and elk) are primarily quantity oriented in food selection. Ruminant animals that are small in body size possess a small rumino-reticular volume to body size ratio, and have small mouths, select for quality in their diet (mule and white-tailed deer and pronghorn antelope). Divergence from specific strategies due to forage availability or quality may lead to declining body condition, decreased production, and possibly death.

Availability of forage, then, may be influenced by the aforementioned. Because the large animal is quantity oriented, it may not have the time to consume a highly nutritious forage that is limited in kilograms per hectare or a forage that has small portions that are highly nutritious (small leaves and fruits). The availability of a forage may also be affected by its proximity to cover. Many wild herbivores are reluctant to venture more than about 180 m from cover (Thomas et al. 1979).

Physiological state of the animal also influences diet selection and daily intake. As in domestic animals, gestation and lactation place an increased need for nutrients on the female (Moen 1973). Wild herbivores breed primarily in the fall, and most breeding and secondary activity involved therein is by dominant males. Fat stores accumulated in summer are usually expended during breeding, which occurs just prior to winter; the period of nutritional limitation (Moen 1973).

Other factors influencing the herbivore's search for food include parasite load, environmental stress (heat or cold), and activity level (running, walking, and ruminating) (Moen 1973). Energy cost for the animal may double its basal metabolic rate (Moen 1973). The animal would respond to the increased need for energy by consuming a higher quality diet and/or increasing daily intake within the limits of the adaptability of the species.

The point of this brief discussion is that food selection and intake are complex animal responses influenced by factors from the animal and the environment (including forage supply). Use of literature values for food habits and daily dry matter intake must be carefully interpreted before being applied to specific forage allocation procedures.

HABITAT SELECTION

Wild herbivores exhibit totally different behavioral responses to their environment than do livestock. The need for solitude and escapement from predation are seldom behavioral concerns of cattle. Skovlin (1982) lists the following factors influencing habitat selection by elk; topograhic, meteorologic, food, cover, space, water, salt, and specialized (calving, wallows). Land area, climate, soils, water, vegetation, other animals, and man were listed by Yoakum (1980) as factors influencing habitat selection by pronghorn antelope.

Geist (1982a; 1982b) provided a general rule applicable to wild herbivores. The rule states that individuals are required to maintain homeostasis, which is obtained by the law of least effort. Necessary resources must be obtained with a minimum of effort to maximize benefits derived. He also provided some examples. Individuals must live frugally, stay in predictable social and physical environments that contain a minimum of costly surprises, communicate with minimum effort, and do these things in such a manner as to reduce the cost of direct competition.

Any application of habitat preference of a specific herbivore must be based on knowledge of that animal in the mix of habitats available for the specific case to be simulated. The literature serves as a guideline.

APPLICATION TO THE MODEL

The wildlife or noncattle consumer subcomponent of the model accounts only for forage removal per day; no estimation of animal production is made. The model will accommodate 10 noncattle consumers. The user may have one to 10 different species or he may elect to break down a species by age and sex. For example, elk bulls, cows, yearlings, and calves could constitute four separate consumer inputs. Therefore, the subcomponent will account for different forage preferences, intake rates, and location (habitat) preferences by various age and sex classes of an individual herbivore species, if the user desires. A herbivore species average over all sex and age classes is also a possibility and would constitute one consumer input. The decision as to important noncattle consumers and consumer classification is determined by the model user.

In the model, forage is allocated to wildlife prior to cattle demand; however, since the model runs on a daily time step, consumption of forage by cattle will affect forage available to wildlife on the next day if both cattle and wildlife are grazing the area during the same timespan. In the case of migratory wildlife, the timespan that the model runs is usually a full year, so the interim periods when forage is allowed to regrow and the competition between cattle and wildlife consumers where cattle are summer range users and wildlife winter and early spring users is accomplished. Facilitation between the two consumer groups is also expressed. Forage removed by one consumer often improves the availability and/or quality of the remaining forage for another consumer. Facilitative herbivory by a mix of animals has been identified on the grasslands of Africa (Bell 1971). Using cattle to change the growth form and, hence, palatability and nutritional quality of forage for wintering elk has been accomplished by Anderson and Scherzinger (1975) in Oregon. Urness (1982) reported on studies involving cattle, sheep, horses, goats, mule deer, and elk, whereby livestock were used as tools for managing big game winter range. Fulgham et al. (1982) reported a compatible grazing relationship between domestic sheep and mule deer.

Data inputs for wildlife consumers are under the control of the user. Requirements for operation of this subcomponent are:

1) Preference for location;

2) Preference for plant species and/or plant species groups;

3) Time animals are present on the site;

4) Estimated daily dry matter intake (kilograms per day) of each wildlife consumer (species or age, and sex class); and

5) Population size of each wildlife consumer. No animal production estimates like weight change or increasing population size changes are now possible.

As preferred forage supplies at preferred sites become limiting for the wildlife consumer, the model will simultaneously extend grazing to less preferred plant species and sites. Input data from the user controls the searching strategy process.

DEVELOPMENT OF USER INPUTS

The accuracy of data inputs is dependent on the user. Inputs for forage and site preference, time frame, and daily dry matter intake are particularly critical. The user must be familiar with habitat (location) availability and preference, food habits, daily dry matter intake, and, perhaps, herd composition of each wildlife species he inputs to the subcomponent. State-of-the-art publications are available for many species such as pronghorn antelope(Yoakum 1980, Salwasser 1980), elk (Thomas and Toweill 1982), mule and black-tailed deer (Wallmo 1981), and hares (Hansen and Flinders 1969). Publications that deal with specific species in specific areas are also available: Bighorn sheep (Todd 1975; Tilton and Willard 1981); mountain goat (Saunders 1955; Johnson et al. 1978); white-tailed deer (White 1961; Allen 1968); and Townsend ground squirrel (Rogers and Gano 1980) serve as examples. Dietary preferences and intake rates for many wildlife consumers for a variety of rangelands have been summarized by Van Dyne et al. (1980). The interpretation of literature values and their application by the user are critical to the successful simulation of the wildlife impact of the model.

SUMMARY

The wildlife subcomponent allows for up to 10 noncattle consumers. Species or various sex and age categories are possible. Food habits, daily forage intake, grazing time frame, site preference, and population size are user inputs. Users must be acquainted with local variability in the aforementioned.

Changes in wildlife population size and/or herd composition due to predation, hunting, drought, or winterkill are not expressed in the subcomponent. At this time, the user may change wildlife numbers only by stopping the model run at the expected time of population change and inputting new population and/or herd composition data and beginning a new run.

The wildlife subcomponent provides a necessary function in the model. Wildlife consumers are present on most western rangelands and comprise a significant force in forage removal. Users involved with forage allocation on public lands must by law provide, through the multiple use concept, forage for wildlife. The model in its present form does make this accommodation.

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SPUR INSECT CONSUMERS

By J. A. Onsager and George B. Hewitt[1]

Rangeland insects attack roots, stems, flowers, leaves, and seeds of grasses, forbs, and shrubs. Many insect species are rare or have limited distribution and are not of economical importance; however, others occur periodically in high densities and can cause economic losses. Such pests of grasses and forbs include grasshoppers, Mormon crickets, termites, leafhoppers, wireworms, white grubs, weevils, range caterpillars, webworms, cutworms, armyworms, crane flies, harvester ants, black grass bugs, stink bugs, thrips, stem maggots, gall midges, and stem borers. Most of these pests have a limited distribution. For example, Mormon crickets are found mainly in the mountains of some of the Western States, rangeland termites are pests in Texas and Mexico, the rangeland caterpillar is found primarily in New Mexico, and crane flies are especially important on the annual grasslands of California. Only a few pests are important over wide areas. These include three groups, harvester ants, black grass bugs, and grasshoppers.

Grasshoppers are the only major insect group that has been researched sufficiently to support inclusion in the SPUR model. They are the most destructive insects on western rangeland (Watts et al. 1982,[2] Hewitt and Onsager 1982b). About 26 species occur frequently in high numbers (Hewitt 1977). Some species feed on undesirable plants and may be considered beneficial, and many species serve as food for other animals such as birds and reptiles. However, the majority of grasshopper species destroy desirable grasses and forbs, and thereby compete with livestock and wildlife for the available forage. Most of the western rangeland is suitable habitat for grasshoppers, and it has been estimated that grasshoppers annually destroy an average of 21 to 23 percent of available range vegetation (Hewitt and Onsager 1982b).

Grasshoppers are more competitive and efficient grazers than livestock. They can drastically affect carrying capacity on late summer, fall, and winter range by consuming forage that otherwise would be available to livestock. They can contribute to severe overgrazing, especially on spring and early summer range, by continuing to graze long after optimum forage utilization has been achieved with livestock.

In general, the type of weather (hot and dry) that favors rapid development and high survival of grasshoppers is associated with low forage production. Therefore, grasshopper populations are likely to be highest when forage production is lowest, so their demand for forage is likely to be most severe when range managers can least afford to feed them.

If estimated or predicted forage production is near or below average, it is suggested that range managers assess the potential forage destruction by grasshoppers before they decide on a stocking rate. Failure to do so could result in complete destruction

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[2]The author's name followed by the year underlined, refers to Literature Cited, p. 96.

of forage that was intended for livestock. SPUR can estimate the seasonal distribution and total amount of forage destruction by typical populations of mixed grasshopper species. Required inputs are the average stage of grasshopper development and the average density per square yard. The former can be estimated from a sample of about 100 grasshoppers that is sorted into the different developmental stages (that is, into the five successive nymphal instars plus the adult stage). Each grasshopper is weighted by the number of its instar (adults are considered instar No. 6 for this purpose), and the sum of the weights divided by the number of grasshoppers equals the average stage of development. The average density per square yard can be estimated by several methods (Onsager 1977), but sampling procedures generally should continue until at least 20 subsamples have been examined and at least 100 grasshoppers have been counted in the process. SPUR then converts average development to average age, converts average density to average number of hatchlings per square yard, estimates total forage destruction to date, and estimates total potential forage destruction for the season. This information allows a manager to rationally assess various options, such as adjustment of stocking rates, overgrazing, or grasshopper control measures.

Grasshopper density and, consequently, the daily amount of grasshopper damage both decrease exponentially over time. Therefore, it is essential that any necessary control actions be taken as soon as possible after significant forage destruction begins. For example, a treatment may be efficacious against a light infestation if it is applied early enough that livestock can utilize the forage that is saved. On the other hand, the same treatment against a heavy infestation could be worthless if applied so late that the entire carrying capacity had already been utilized by grasshoppers. SPUR will estimate the relative efficacy of treatments with two useful insecticides, carbaryl and malathion, applied at times that are selected by the operator.

The two treatment options differ quite drastically. Carbaryl is a relatively persistent, slow acting chemical. It is an excellent stomach poison and can be applied over a long interval, even very early in the season, before significant damage occurs. Maximum efficacy is against fourth instar nymphs. Malathion is a nonpersistent chemical that kills primarily by contact. It is extremely effective under hot, dry conditions, but can provide little or no control if extended cool weather or precipitation follows application. The earliest treatments are potentially the more effective, but they also carry the highest risk of failure. Malathion, therefore, seldom is applied before grasshoppers approach the adult stage. During the interval when either chemical may be used with confidence, malathion is clearly most efficacious because almost identical control can be achieved for about half the cost.

The logic within SPUR's grasshopper component is as follows. It is assumed that grasshoppers require 10 days to develop through each of five nymphal instars and that the maximum adult life span does not exceed 90 days. The average daily rate of survival is set at 0.95, which is characteristic of a stable, moderate, but definitely economical infestation on the order of about 20 to 30 fourth instar nymphs that will produce about 8 to 12 adults per square yard (Onsager and Hewitt 1982). Only fourth and fifth instar nymphs plus adults are considered destructive, and they destroy an average of 43 mg (0.000095 lb) per grasshopper per day (Hewitt and Onsager 1982a). The number of destructive grasshoppers per unit area was plotted versus time in days, and the area under the curve (a product of grasshoppers times days) multiplied times 43 gave the estimated total seasonal destruction. The benefits of a contemplated treatment were estimated by adjusting the population curve according to anticipated effects of treatment, calculating forage destruction under the new curve, and attributing the differences to benefits of treatment (Onsager 1978). For economic analyses, it was assumed that a carbaryl treatment costs $2.71/acre, a malathion treatment costs $1.45/acre, and that an AUM is equivalent to 850 lb of forage worth $17.50. These data can easily be adjusted by users of SPUR.

SUMMARY

At present, grasshoppers are the only insect component in SPUR. Grasshoppers are more competitive grazers than livestock and can drastically reduce carrying capacity or affect total grazing intensity on rangeland. Their demand for forage is likely to be highest during seasons when forage production is lowest. Given an average density and stage of development, SPUR can estimate the total forage destruction by a typical population of mixed rangeland species as well as the seasonal distribution of damage. Grasshopper density and, consequently, grasshopper damage both decrease exponentially over time. Therefore, if control is necessary, action should be taken early in the season.

SPUR assumes that 43 mg of forage is destroyed per grasshopper per day during their most destructive stages, and estimates the potential forage destruction and potential benefits of treatment with two useful insecticides, carbaryl and malathion. Carbaryl is more expensive, slower acting, and more persistent, so it can be applied very early before significant forage loss occurs. Malathion is cheaper, faster acting, and less persistent, so it is best suited for late treatments. SPUR estimates the relative efficacy of the two, based on data available January 1, 1982.

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SPUR ECONOMIC COMPONENT

By E. Bruce Godfrey and L. Allen Torell[1]

The economic component of the SPUR model is one of the last portions to be developed because biological data from the other SPUR model components are necessary to perform economic anaylses. This illustrates an important feature of economic considerations that is commonly misunderstood by range managers. That is, the economic analysis of any range improvement project, management strategy, or grazing alternative is based on biological information. As a result, the economic analysis is no better than the biological information upon which it is based. Therefore, the discussion that follows must be tempered by certain factors. First, the economic component of SPUR is not complete. At this point, the economic component, like the other components, is being updated and improved continuously. As a result, changes in any of the other components such as the plant component and the livestock component will have a strong influence on the results obtained from the economic component of SPUR. Consequently, any weaknesses found in the other components will ultimately affect the results obtained by the economic component. Second, no work has been done on constructing an economic component for the basin scale version of SPUR. Therefore, the following discussion is based on computer simulations on the grazing unit or pasture scale version of SPUR. Furthermore, most of the following discussion is supposition at this time (November 1982) since it was not possible to complete the programming of the economic component until most of model biological components were completed and refined. All economic simulations discussed appear to be possible at this time, and it is anticipated that examples of each type will be developed and further tested before SPUR is released for general use.

THE ECONOMIC COMPONENT

The economic component is built primarily on the output of the animal component. The evaluation of all economic benefits is based on the response of animal gains and increased herd size from various alternative grazing and improvement strategies that may be considered. Necessary inputs for the economic component that must be provided by the user include the following: the value of the animal gains in dollars per hundred weight, the applicable discount/interest rate to be used for discounting, and the fee and nonfee costs of forage on a per animal, acre, or Animal Unit Month (AUM) basis. The primary outputs include the following: animal gains per day and per AUM of forage consumed, the value of these gains, and the costs of using the grazing management unit. These outputs are summarized monthly. These outputs are then discounted to derive the present value of the net benefits (value of animal gains less the fee and nonfee costs of grazing the grazing unit) over the planning horizon. The internal rate of return (IRR) and benefit/cost (B/C) ratio for the project being considered may also be calculated. In addition, we anticipate that eventually the model will be developed to enable livestock gains and returns to be plotted over time using one of the many available plot routines.

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SIMULATIONS

Almost every economic evaluation concerning the use of rangelands must be based on some status quo, existing base strategy, or management scheme. This provides the basis for a "with" versus "without" analysis common to all benefit/cost analyses. Therefore, one must make one base computer run that reflects the current situation. This base run provides the basis for comparing all other improvement and management schemes.

Numerous management alternatives and range improvement scenarios could be evaluated using the SPUR model--they are only limited by data availability and the user's imagination. Three alternatives are discussed below.

Grazing Strategies

Perhaps one of the most fruitful and popular evaluations that can be considered using SPUR involves various grazing strategies for a particular field or pasture. This may involve any or all of the following: changes in season of use, grazing intensity, or class of grazing animal. For example, one of the early runs made, and one that will be studied further, involves what happens to stand density and production over time as grazing intensity is increased. We are currently striving to determine what are the impacts, benefits, and costs of high intensity grazing followed by rest, deferment, and/or rehabilitation of a grazing unit (a crested wheatgrass pasture in our example) as opposed to lower levels of use with an associated longer-lived stand. This is analogous to short versus long rotation forest practices, but a practice that has not been extensively evaluated economically.

SPUR will estimate livestock gains, the grazing effect on forage production, and the economics of each grazing strategy considered. By considering many alternative grazing strategies with the SPUR model, the user can estimate the most profitable management scheme and can rank various grazing strategies according to predetermined goals and objectives. These goals may include providing forage for a given wildlife population while attempting to meet the primary goal of profit maximization.

RANGE IMPROVEMENTS

The economic benefits and costs of nearly any type of range improvement can conceptually be evaluated using SPUR. For example, management practices such as salting on water developments that alters animal distribution can be evaluated. In addition, stand alteration techniques (such as seeding and spraying) can be considered. These two types of improvements are especially adaptable to analysis by SPUR. As discussed in the paper on the SPUR livestock component, the livestock model considers explicitly the criterion of distance to water and livestock plant preferences. Therefore, any range improvement which establishes water, for example, in a previously "dry" location of the pasture, could: 1) increase available forage, or 2) alter plant species to more palatable and desirable species. These improvements are expected to significantly affect model results.

The discounted net present value of range improvements can be compared with the expected costs of the improvements to determine if the range improvement considered would be economical from a livestock production point of view.

Other Forage Users

Perhaps the most fruitful simulations that could be run (none have been run to date) involve other forage users and their impacts on livestock production levels. For example, wildlife, insects, or other users of herbage could be included in simulations to determine when, to what degree, and why some users compete with or complement livestock production. This could conceivably provide one means of estimating the opportunity cost (trade-off value) and thus provide a minimal necessary value for wildlife and/or other users of range forage.

While each of the above alternatives, or others that could be described, could be evaluated, one should recognize that the SPUR model is not a panacea. In fact, it has some weaknesses that may limit its use in some cases; however, it also has strengths that may make it a valuable tool for range managers.

STRENGTHS AND WEAKNESSES

Like any computer model, SPUR requires a certain amount of data. Fortunately, it has been developed with the user in mind so the data requirements are much less than many other simulation models of its size. This represents a virtue as well as a vice. For example, minimal data requirements make the model efficient for the user but may mask some important elements or results. Thus, the need for validation becomes an important consideration.

Perhaps the major economic weakness of SPUR stems from the model structure. First, it is a simulation model. As such, it does not provide much of the useful output that is associated with optimization modes (such as profit maximizing solution, limiting resources, and shadow prices). Second, SPUR does not and cannot evaluate the impact of a management scheme of one grazing unit on other resources (such as labor, other grazing units, ranch forage balance, other rangelands, and capital needs). This problem stems largely from the fact that the grazing unit version of SPUR does not consider all the forage that may be used by livestock and/or wildlife throughout the year. Given these limitations, simulations using SPUR must be evaluated, *ex post facto*, from a broader perspective. Part of this problem can be overcome if one has good data for the nonfee costs of grazing some management unit, but these data are rarely available. The need for this data, however, may stimulate some needed research on the nonfee costs of grazing public and private lands.

All of the possible simulations outlined above do not come freely. At Utah State University, we have found that an average computer run takes about 30 minutes and costs about $25. This suggests that SPUR may be a fairly expensive tool for some users.

Perhaps the greatest virtue of SPUR, however, stems from the very flexible nature of the model. Nearly any imaginable range management strategy could conceivably be evaluated. Surely, this is a less costly alternative than are some of the grazing studies being implemented on public and private rangelands. SPUR, therefore, represents the first generation of a range model that may be modified and improved for many years to come.

FUTURE POSSIBILITIES

While the total SPUR model is large, each of the components is relatively small. In fact, most of the components may be able to be put on modern microcomputers, which would make the model more available to some users and would reduce the cost of running the model significantly.

Perhaps the area where least is known, but where work is most needed will become more apparent as the economic component for the basin version of SPUR is developed. Almost nothing is known of the economic costs and benefits of watershed management practices. We hope the basin version of SPUR will provide some of the answers needed by range managers. Development of the basin model will also increase the economic questions that can be answered using SPUR.

SPUR MODEL EVALUATION

By E. P. Springer and J. R. Wight[1]

INTRODUCTION

The previous presentations have described the components that constitute SPUR. This paper will discuss those components as they are now linked in the SPUR model. A strategy for model sensitivity analysis and validation is also presented.

MODEL OPERATION

Model Structure

A simple diagram describing the order of operation of the major components is given in figure 1. Following initialization of the components, the model is set to either generate or read the climate data. The climate variables required on a daily basis are precipitation, maximum-minimum temperature, solar radiation, and wind run. Note, that the climate generator is outside the daily time loop that contains the other components. This allows the climate component to be removed, if so desired, for computer storage requirements or if observed data are available. The remaining components are within the daily simulation loop. The plant routines add and subtract biomass and nitrogen from various plant and soil compartments. The animal component is called from within the plant component, and a check is made to see if wildlife and/or livestock are present. The hydrology component maintains the daily water balance. Finally, a daily report can be written or results stored for writing of weekly, monthly, or annual reports.

This operating scheme is one of several possible and may not be the most efficient. Initially, it was desirable to maintain the individual components as near to their original code as possible. A simple and useful alteration would be to include the climatic generator inside the daily simulation loop and generate a value every day. This arrangement could reduce storage and code size, but would increase execution time.

Component Interactions

It is useful to describe the variables that form the link between the various components. This indicates what factors in each component will affect the other components. The relationships are presented schematically in figure 2.

The climate component affects the response of both the hydrology and plant components directly, but there is no interaction between these components and the climate.

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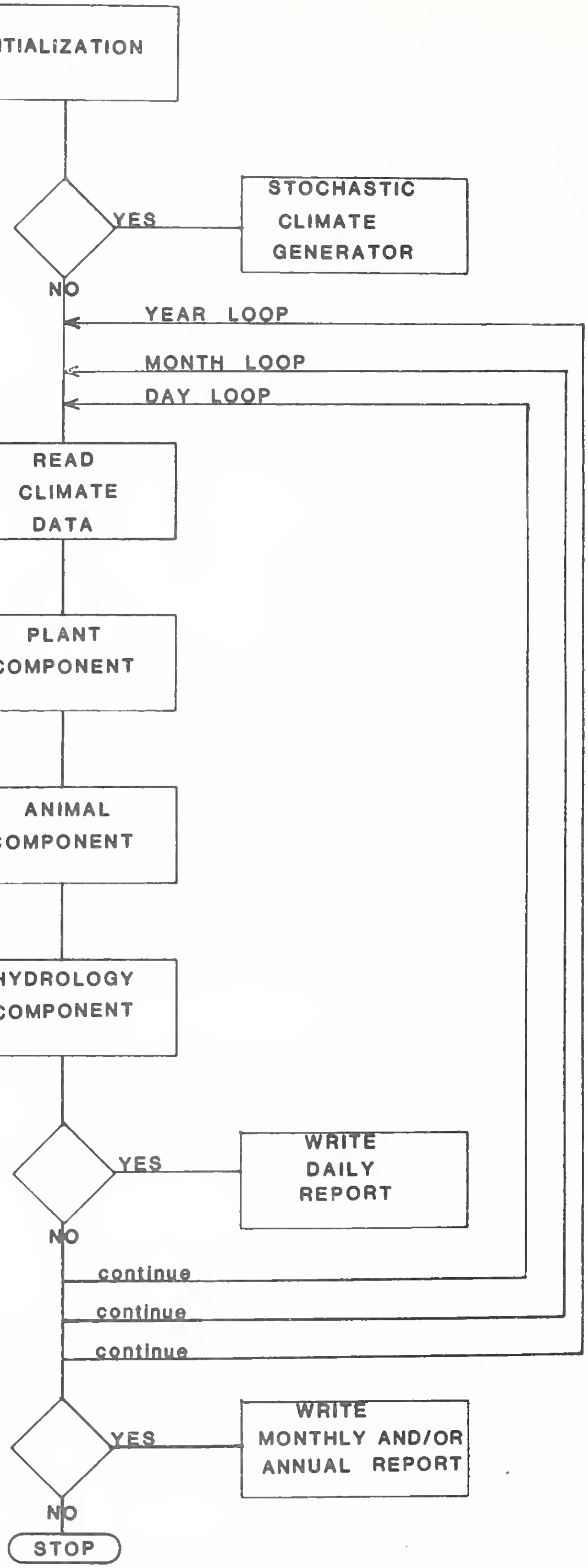

Figure 1.--Simple flow diagram of SPUR model.

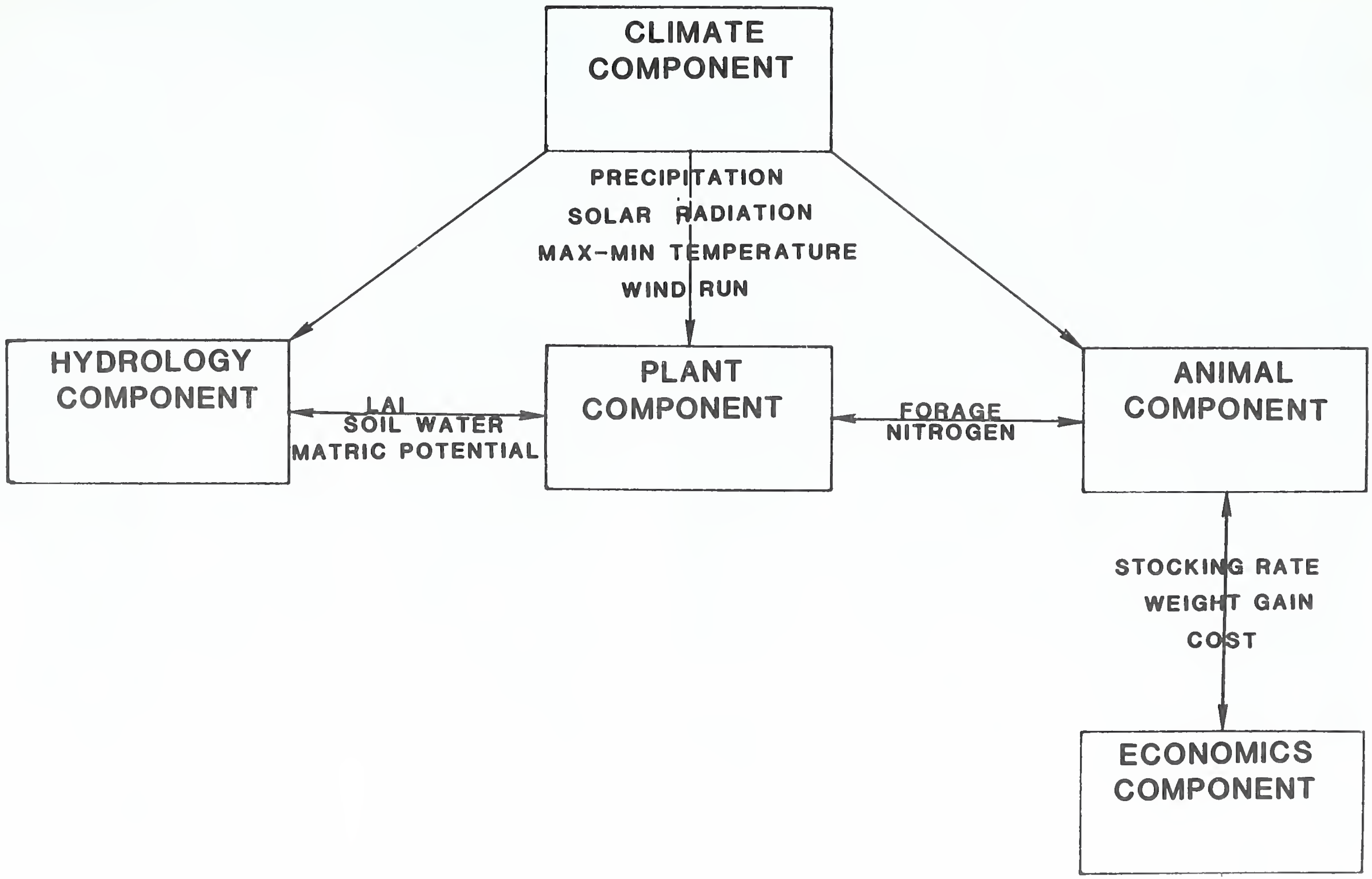

Figure 2.--Interaction between various components of SPUR.

Hence, the arrows point in only one direction. Currently, there is no interaction between the animal component, particularly livestock nutritional requirements, and the climate component. This interaction should be considered in future refinements.

The plant and animal components are linked through forage consumed or trampled (based on stocking rate), and biomass and nitrogen returned by animal excretion. Since only the growth dynamics of cattle are considered, forage consumed by the other consumers is lost to the system. The arrow points in both directions between the plant and animal components, indicating that these variables form an interaction in the model.

Another interaction occurs between the hydrology and plant components. The variables which define the interaction are soil water matric potential and leaf area index (LAI), which is used to calculate evapotranspiration. The LAI is a direct conversion of aboveground live plant biomass. The soil water matric potential is calculated by a relationship defined by input data and current soil water status. There is no direct linkage between the animal and hydrology components. The animals impact the water balance indirectly through reduction in LAI and its subsequent impact on evapotranspiration. Current efforts are being directed towards developing the linkages between the plant, animal, and hydrology components and the cover factor in the Modified Universal Soil Loss Equation (MUSLE) and the Soil Conservation Service curve numbers. These relationships will be crude, but will allow the model to simulate impact trends. Initially, these functional relationships will be based on the amount of live or dead plant biomass.

As stated in the previous paper on the economics component, the most available interaction is through the livestock component. This is based on management decisions, (for example the number of grazing animals) and is not automatically controlled by the model. Economic relationships for the other components, such as the impact of soil erosion and onsite water use will require additional effort.

Model Scale

As has been stated, there are two versions of SPUR differentiated by the scale of operation. The two versions were deemed necessary when interaction with potential users identified two distinct users groups. Production-oriented users are primarily interested in plant and animal responses and, often, their grazing units do not follow any topographic or physiographic boundaries. A pasture scale version has been constructed for these users. Another user group is interested in long-term impacts of range management practices. Their concerns are towards the environmental and ecological effects of range management practices. The watershed has been identified as their basic management unit, and their model is identified as the basin scale version.

Figures 3 and 4 are visual representations of the differences in the two scales. Figure 3 is the representation of a pasture with different sites identified. Sites within the pasture scale can be delineated based on differences in vegetation, soils, distance from water, and animal preference. Renard et al. (in this SPUR publication) described the basin scale version and the subdivision of the watershed into "fields" (hydrologically distinct units).

The pasture scale version will not calculate sediment yields or consider channel systems. It does maintain a daily water balance on each site, but any runoff generated is lost. An erosion and peakflow index will be calculated using a unit plot concept which will provide relative values between sites for comparison.

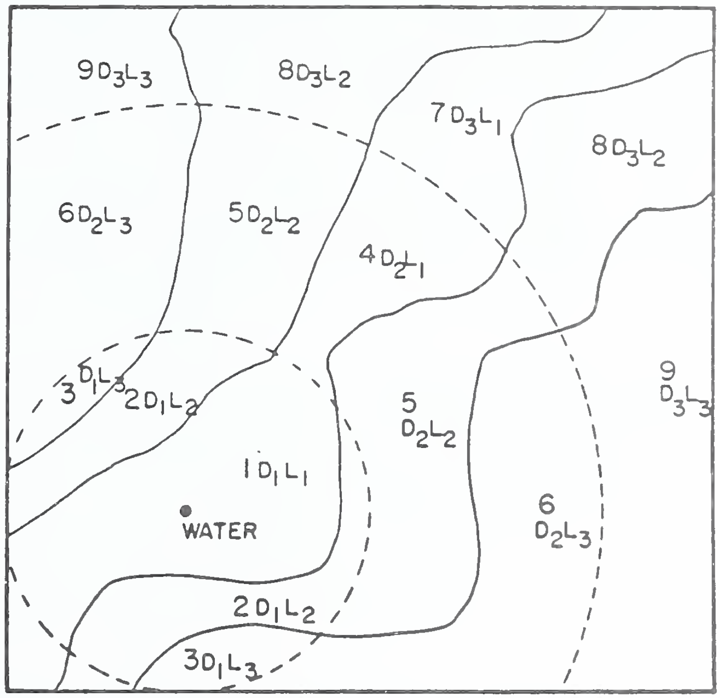

Figure 3.--Pasture representation for field scale version of SPUR (from Rice et al. this publication).

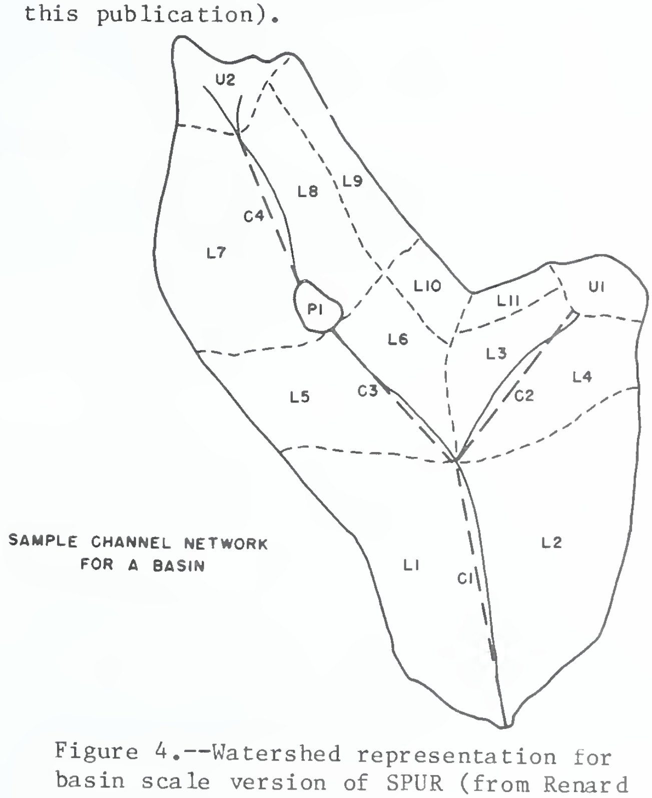

Figure 4.--Watershed representation for basin scale version of SPUR (from Renard et al. this publication).

The basin scale will not differentiate between sites within defined "fields". When the animals are grazing a "field", the forage consumed will be assumed to come off the "fields" uniformly, that is, the animals will be grazing the low, middle, and upper sites simultaneously. This results in a loss of resolution in both the plant and animal components. The primary advantage of the basin scale model is the routing of water and sediment from "fields" to the basin outlet. The structure of the model requires slope length and channel information to be input which is needed to perform the routing calculations.

A remedy to this dilemma is to include the site concept into the "fields" of the basin scale version. This can be done in later versions of SPUR. A major problem in such a version is that pasture boundaries seldom follow watershed boundaries. Another problem is that the size and complexity of the model would increase to such an extent as to become unwieldy.

In terms of model operation, both versions operate in the same manner if figure 1 is considered. The biggest differences are the inputs and operation of the hydrology routines in the basin scale model, where stream channel and sediment routing are done. Sites within the pasture scale version are modeled as a distributed system like the hydrologic fields in the basin scale version. Each version has its drawbacks, but their uses are defined so that the deficiencies are minimized.

MODEL EVALUATION

Model Test

A comprehensive test or evaluation of the SPUR model was not possible because the interactions between components were not sufficiently refined and data sets with the required response variables were not available. Perhaps, the only data set currently available which is capable of providing the information needed to validate this model is that collected for the International Biological Program (IBP) ELM model at the Pawnee site. Unfortunately, that data set was not ready for analysis at the time of this report.

As an alternative to evaluation with actual data, a qualitative test was used to demonstrate the model's ability to simulate plant competition. Since only two species, blue grama and western wheatgrass, were initially parameterized, competition between them was simulated for two sites in the Great Plains. The Pawnee site in north central Colorado was chosen because blue grama is the predominant species. In the northern Great Plains near Sidney, Montana, western wheatgrass is the dominant species. If the model responded correctly, the results, or at least the trend, at each site should point to the proper species becoming dominant.

The test scenario at both sites followed the same schemes. Ten years of climate data were generated, and the plant routines were initialized to the same values for each location. All simulations started on January 1 of the first year. Grazing was not imposed in this study. Therefore, differences between locations were limited to soils and climate. Descriptions of the two sites, Pawnee and Sidney, Montana, are reported by Van Haveren and Gailbraith (1971)[2] and Black and Wight (1972), respectively.

Results for Pawnee are presented in figure 5a and b. For the first year at Pawnee (figure 5a), it can be seen that the western wheatgrass made a substantial contribution to aboveground live biomass, but by the fifth year, western wheatgrass

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[2] The author's name followed by the year underlined, refers to Literature Cited, p. 110.

was almost completely removed from the system (fig. 5b). Obviously, this response was not correct from a quantitative standpoint; that is, western wheatgrass should remain in the system to some degree. Another cause for concern could be the reduction in total production during the simulation period. The latter was the result of the model attaining equilibrium with the given soil, climatic, and initial plant conditions. This equilibrium condition determined how much biomass the site can support, and if grazing was imposed or a soil condition was changed, a new equilibrium condition would be achieved. The seemingly complete removal of western wheatgrass was partially due to the attainment of equilibrium. Another reason was lack of calibration of the model to observed data. A calibration would have allowed sufficient parameter adjustment to maintain western wheatgrass in the system at observable levels.

Results for the Sidney location are presented in figure 6a-c. For the first year (fig. 6a), both species were present and their production was substantial. By the fifth year (fig. 6b), total production has decreased, and the blue gramma contribution was relatively less. Finally, blue gramma was almost entirely out of the system by the 10th year (fig. 6c). The same comments could be made about equilibrium conditions and model calibration for this location as were made about the Pawnee location.

One should not look at the absolute values in figures 5 and 6 to judge these results. We would like to stress that the trends which appear are correct. In no way, would we want to infer that this is a conclusive test of the SPUR model. Through the whole modeling process, calibration, validation, and sensitivity analysis, responses will be improved to better reflect onsite conditions.

This test provides some idea of the model's potential. For two locations which were different in soils and climates, the model simulated plant species dominance correctly at these locations. For initial applications of the model, the simulation of trends may be the most appropriate use until sufficient data are available to complete the modeling process for all range ecosystems.

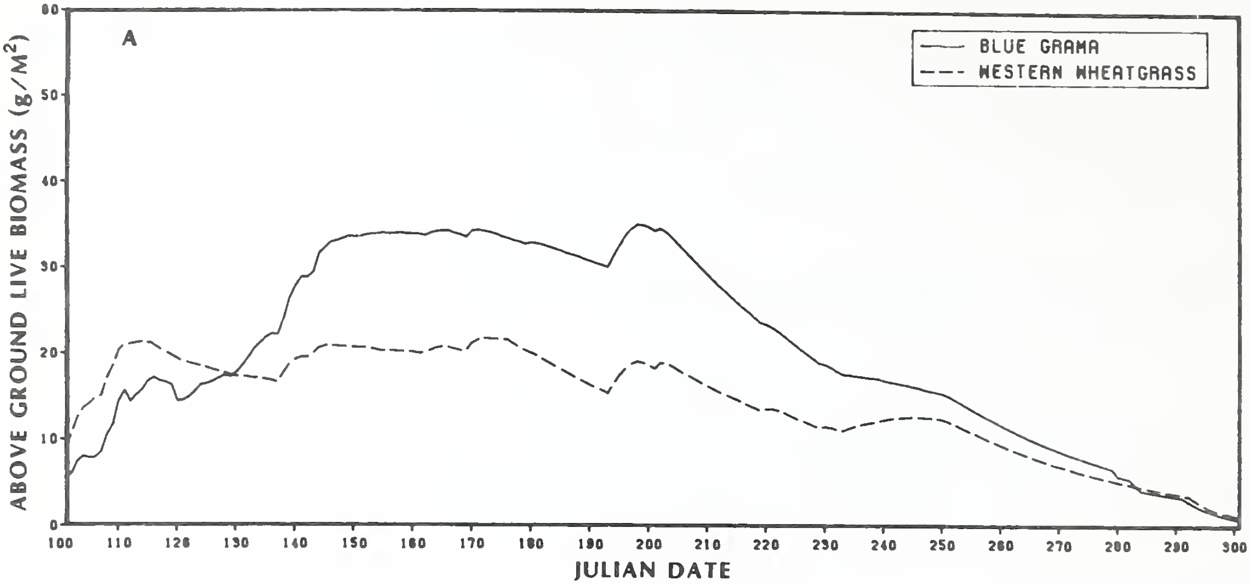
Sensitivity Analysis

A sensitivity analysis was not conducted prior to this report because the model was not yet sufficiently refined. A sensitivity analysis of SPUR will follow the same procedures as the analyses conducted for ELM (Steinhorst et al. 1978) and CREAMS (Lane and Ferreira 1980). Selected parameters will be altered or perturbed from calibrated values and the effects of the perturbation on output of key response variables will be examined.

SUMMARY

The operation of the SPUR model is presented, and the interactions between the various components are discussed. At present, the interactions are between the plant-animal and plant-hydrology components. Future efforts will be directed towards strengthening the interactions between these components and extending economic analysis.

Two versions of the model are being constructed for operation at two different scales. The field scale version is designed more for the production-oriented users and does not provide absolute runoff or erosion values, only relative indices. The basin scale version uses the watershed as the management unit and routes runoff and sediment to the basin outlet, but it loses resolution in terms of plant and animal production because of the definition of the hydrologic units.



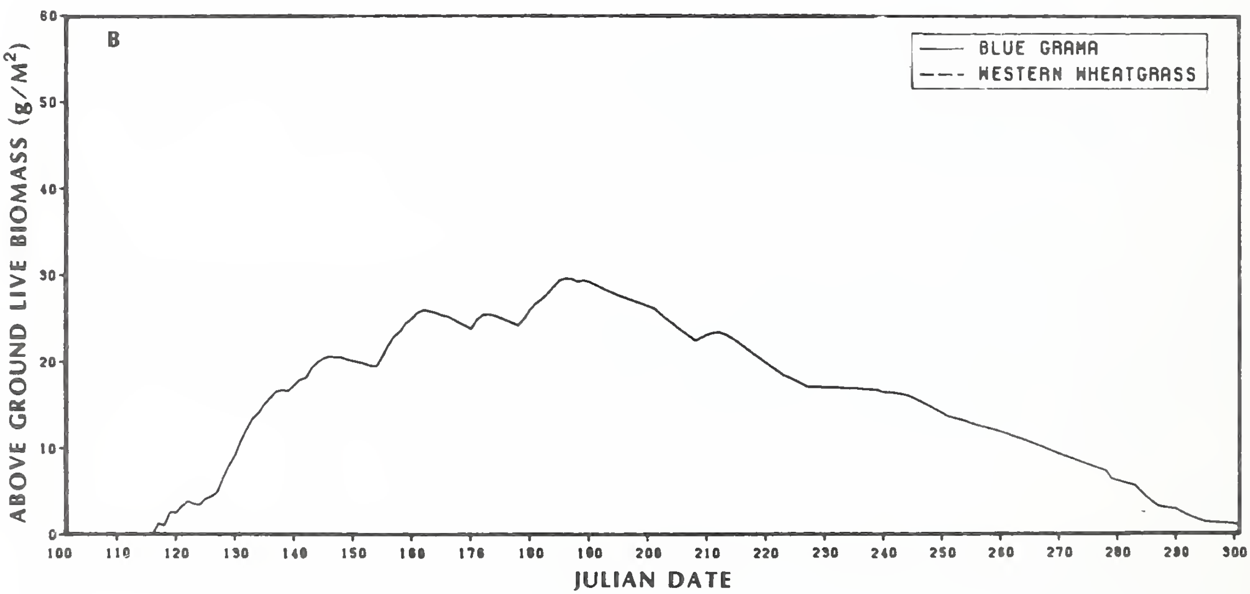


Figure 5.--Aboveground live biomass for the Pawnee site for first year of simulation (A) and fifth year of simulation (B).

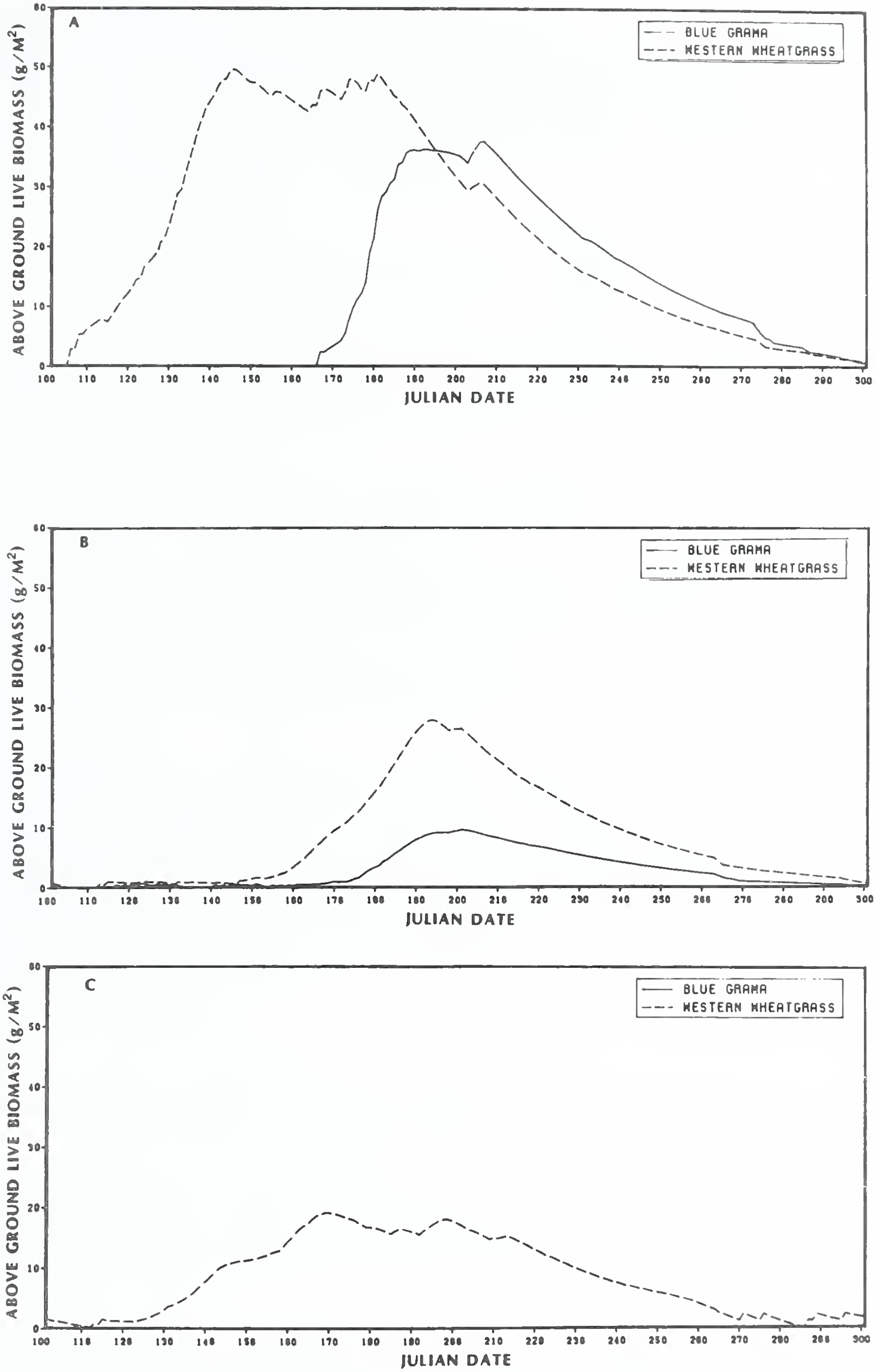


Figure 6.--Aboveground live biomass for Sidney, Mont., site for first year of simulation (A), fifth year of simulation (B), and tenth year (C).

A simple test was conducted to indicate the potential of the model to simulate plant dynamics in response to soil and climate. Ten-year simulations were conducted for sites in eastern Colorado and eastern Montana. The results were qualitative, but correctly reflected the actual conditions; blue grama became dominant at Pawnee and western wheatgrass became dominant at Sidney.

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SPUR APPLICATIONS AND LIMITATIONS - MANAGEMENT

By S. A. Loomis[1]

As manpower and operating costs continue to increase, computer modeling of rangeland ecosystems becomes an increasingly efficient tool for assisting land management agencies in the decision making process. Models that can simulate the effects of different management scenarios on the resource responses of an area will become extremely useful.

The SPUR model has the potential to be a useful management tool if applied with an understanding of its applications and limitations. It is a physically based model driven by daily inputs of precipitation, maximum and minimum air temperatures, solar radiation, and windrun. Most of the components of an ecosystem of interest to land managers can be incorporated, though to varying degrees of complexity. Generally, the more complex the component and the more physically based the component relationships, the greater the data requirements will be to adequately simulate the system. Presently, a large number of initial conditions and parameter values must be measured or estimated to run the model, but work is continuing on some of the components to allow them to calculate their own parameter values given a lesser amount of user information.

The model can operate on either a pasture or basin scale. Herbage yield, livestock production, runoff, and erosion can be predicted or indexed in either mode as a function of resource characteristics, climate, and livestock management. The pasture scale provides for better resolution of the plant and livestock processes, whereas the basin scale stresses the hydrologic component resolution and response.

A brief discussion of possible management applications and limitations for each component of the model is given.

CLIMATE

The SPUR model utilizes daily inputs of precipitation, maximum and minimum air temperatures, solar radiation, and windrun to drive the vegetation and hydrology components. Actual data from the site of interest can be used if they are available; otherwise, a routine can be used to generate the needed inputs based on the statistical characteristics of the actual weather at the location. The stochastic weather generator allows a short climate record to be extended to simulate long-term processes such as changes in vegetation species composition and range condition. Long-term hydrologic response information also requires an extended climate record.

VEGETATION

The vegetation component of the model simulates the flow of plant biomass and nitrogen through a system that may include up to seven species or species groups on nine sites.

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Monitoring

The Bureau of Land Management is moving into a monitoring mode in which methods are needed by which to evaluate, over time, the effects of a particular management scheme. A key question being asked is, "Will the implementation of a particular livestock management system result in an upward trend in range condition?" A model that adequately simulates the various key variables and interactions in a rangeland ecosystem may assist in determining which of these variables might be useful in an on-the-ground monitoring scheme and what the sampling procedure might entail.

To determine whether a particular variable should be measured in a monitoring program, two key factors must be addressed. First, is the variable an appropriate indicator of the response in question? For example, a change in range condition of a site over time may be reflected in a change in species frequency and production. Second, is the variable sufficiently sensitive to the management being applied? Annual vegetation production, for example, may be too strongly influenced by climate to allow an evaluation of livestock grazing effects. Other factors within a monitoring program are important, such as manpower and travel costs, and may in fact be the final determinants in what variables will be measured within the program.

The model can simulate several alternative management scenarios and track the trends of the various state variables. By evaluating the sensitivity of the variables with respect to the management applied, information useful to planning a monitoring scheme can be identified. If a variable appears to be sensitive to management, the model can provide information to aid in determining the frequency, duration, and precision to which the variable must be measured on the ground in order to adequately reflect the impacts occurring.

Range Condition

In its development, the model was limited to the growth simulation of only two species. As other species or species groups representing several vegetation types are parameterized, the potential for significant application is apparent. For example, the effects of range condition and cattle stocking rates on continued forage production and livestock weight gains can be simulated.

Simulation runs require initial conditions for above and belowground biomass for each species being modeled, which in essence corresponds to an initial ecological condition for the range site. The user then can simulate any number of cattle using the site, though presently they must graze at the same season each year. The forage production and relative species composition can then be tracked, and if the relationships in the model are functioning realistically, the range condition is implicitly simulated over time.

To evaluate the effects of a different stocking rate, the user need only change the initial number of cattle on the site and inspect the species composition and production through time. At stocking rates below a certain threshold, there may be a minimal effect on species composition beyond the ungrazed situation. Aboveground biomass and nitrogen would remain sufficient to permit adequate translocation back to root reserves for subsequent green-up or growth the following year. The plants would not be stressed sufficiently beyond their limit for soil water and nutrient uptake. At stocking rates above the threshold, the aboveground storages would be depleted year after year to a point where translocation to root reserves declines and subsequent aboveground growth is reduced. The ability to withstand environmental stresses is also reduced, and species composition changes may occur.

The model should eventually be able to simulate the effects of different initial range condition on the long-term condition under the influence of grazing. This would entail changing the initial conditions of relative species production to imply a difference in condition class. Superimposed livestock use at several stocking rates may help determine the level of grazing at which the range site can be utilized and still maintain a favorable condition.

LIVESTOCK

The livestock component of the model operates on a yearling steer equivalent basis, and, as such, the cattle weight is set back to its initial condition at the beginning of each season of use. The demand for consumption by livestock is a function of the number of animals and their weight and physical condition. The availability of forage for consumption is a function of species or species group preference, terrain location (lowland, sidehill, or upland), distance to water, and physical availability (upright or low-lying growth habit). The various combinations of these factors, which represent the site being modeled, allow for the simulated movement of livestock from one vegetation type to another. In essence, the selectivity for herbage species and location, with the subsequent differential species competition and production, is simulated.

With the appropriate spatial partitioning and accounting of herbage growth and livestock utilization, the possible effects of forced livestock moves can be investigated. For example, once the model indicates that the desirable lowland vegetation has been utilized to a given percentage of the current year's growth, the livestock demand could be automatically moved to the uplands to simulate a forced move away from the meadows. Through subsequent regrowth and competition on the lowland vegetation, the condition class can be monitored and compared tc a situation in which the lowlands are utilized to a much greater degree. The effects on livestock would have to include possible weight losses due to the distance and terrain over which they moved.

A useful, and relatively simple, improvement to the present model would be the ability to simulate livestock use at different seasons from year to year. In this way, the effects of more intensive management such as rest-rotation or deferment could be evaluated as to their effects on both the range vegetation and livestock production. As intensive management systems become more widely implemented, the need for this type of evaluation becomes even more important.

At present, with the model operating at the pasture scale, the livestock production cannot be simulated throughout the year, as only one pasture can be modeled at a time. Overwinter maintenance can be simulated through the operation of the supplemental feed functions in the model.

Another possible addition to the livestock component for management application would be the ability to simulate the effects of different classes of livestock. The forage species and terrain location preferences may change with class of stock, resulting in possible changes in site vegetation characteristics as well as livestock weight gains.

WILDLIFE

The wildlife component does not actually simulate any population dynamics, but rather it consists of a constant daily consumption demand for the period that the animals are determined to be on the site. A specified number of animals for each wildlife species is input along with the daily consumption demand on a unit animal basis. A set of herbage species preference and location preference characteristics for each wildlife species are input, similar to the format for livestock use. The model allows wildlife to meet their forage demand for a given day before the livestock can begin to meet their demand. Simulation of both wildlife and livestock demand can help focus attention on the potential problem of competition for forage.

HYDROLOGY

At present, the hydrology component of the model can produce estimates of upland runoff and soil loss, channel erosion, and basin sediment yield using daily precipitation, air temperature, and solar radiation as input. A soil moisture balance and snowpack accumulation and melt routine maintain an accounting of water storage within the system. The soil and topographic characteristics of the pasture or basin being modeled are utilized within the SCS Runoff Curve Number procedure (USDA 1972)[2] and the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977) to predict runoff and sediment yield at various points within the system. In the pasture scale model, the simulated hydrologic response is considered only an index to the site. The output from the basin scale model is considered to be a more accurate representation of the hydrologic response.

The basin scale model allows the watershed to be partitioned into a number of stream channel segments and upland contributing areas. Thus, the heterogeneous characteristics of a basin due to different vegetation types, soils characteristics, and topography can be accounted for. The initial conditions and parameters describing these spatial units are input by the user.

At present, there is an indirect feedback mechanism from livestock to watershed response through leaf area index and its effects on evapotranspiration. As livestock utilize forage, the plant biomass is reduced, resulting in a reduced leaf area index. This then affects the amount of soil water withdrawn from the site.

Another more direct feedback mechanism is planned for inclusion in the model. Through the use of biomass versus vegetation cover functions, the cover can be reduced by livestock consumption. The cover factor in the MUSLE can then be influenced by changes in plant cover to produce a more realistic sediment yield response. A modification of the curve number for changes in vegetation cover is also planned, to allow improvements in runoff estimates.

Through the use of a stochastically generated set of climate data, flood-frequency and sediment yield relationships can be developed from the output for various sets of resource characteristics. The effect of increased canopy cover on a site can be modeled by reducing the cover factor in the MUSLE and recalculating the sediment-discharge curve.

The hydrology component can simulate the effects of stock ponds on streamflow volumes and timing. The sediment yield and routing capability of the model may provide the manager with information for estimating the maintenance interval for cleaning proposed stock ponds. Flood-frequency relationships developed from the model output can be used in designing small structures such as stock ponds and culverts.

ECONOMICS

The economics component of the SPUR model helps evaluate the cost effectiveness of the various scenarios that can be simulated. With the previously mentioned modifications

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[2] The author's name followed by the year underlined, refers to Literature Cited, p. 116.

to allow simulation of rest-rotation management, multiple pastures, and different classes of livestock, the model should be able to evaluate the effects of different management strategies on ranch income. This would require a great deal of information concerning ranch operations--from livestock numbers and movements to ranch labor costs and cattle prices.

Nonmarket values, such as wildlife and water quality, are becoming increasingly important when it comes to obligating money for their management. Ideally, the economic analysis of any range improvement should include the possible benefits to these and other nonmarket values.

LIMITATIONS

A model of this scope and complexity should undergo rigorous testing and validation under a wide range of resource and management conditions before it can be relied upon to satisfactorily simulate land management actions. The individual components have each been tested under varying degrees of resource conditions, but the model as a whole has only begun to be tested.

The major limitation to management application of the SPUR model in its present state, is the large amount of input data required. Information for many of the parameter value estimates and initial conditions may not be available for many management situations. The plans to make some components essentially self-parameterizing will alleviate this problem to some extent. An analysis of the model sensitivity to various parameters and initial conditions will also help management and research determine the consequences of insufficient input data.

The storage and operating time required by the SPUR model will indicate the minimum size of computer needed. Individual model components could possibly be run on smaller desktop computer systems for situations where the entire model is not required.

Trained personnel will be required to operate the model and utilize its full capabilities to simulate a vast array of management scenarios. Some understanding of the mechanisms and assumptions inherent in the component representations will also be needed to ensure that the model is not applied to situations for which it was not designed. In essence, field knowledge and experience cannot be replaced by the model, but can be complemented by the ability to objectively evaluate numerous management actions with respect to their effects on the resources.

The SPUR model can potentially become a useful tool for management applications as long as its limitations are realized.

SUMMARY

The SPUR model can become a useful tool for management, both through direct application to land use activities and through an improved understanding of the key variables that control rangeland ecosystems. As personnel and operating costs increase, models such as SPUR will be utilized to a greater extent for assisting resource managers in making decisions regarding alternative actions. With proper application and interpretation, the model could be used to identify variables for a rangeland and monitoring program.

The effective application of the model may be limited by the availability of detailed resource data. Any interpretations of model output must be made in light of the assumptions inherent in the components as well as the user's knowledge of the resources in the field.

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SPUR APPLICATIONS AND LIMITATIONS - RESEARCH

By G. E. Carlson, R. H. Hart, P. L. Sims, and J. C. Ritchie[1]

SPUR is a model that simulates and integrates the key physical and biological processes that influence the production, utilization, and management of rangelands. It can also be used for identifying imbalances in our understanding of complex agricultural systems and for evaluating research priorities at project and national program levels. Identifying unknown or poorly understood interactive processes, developing strategies for tackling specific scientific problems, and making day-to-day decisions at the research unit level require substantially different information needs than does the process of establishing research priorities for solving major rangeland ecosystem problems. However, both provide essential inputs to the planning and operation of ARS rangeland research programs. To expect models such as SPUR to serve the scientific and technological needs of research scientists, the operational needs of rangeland managers, and in addition provide broad guidance for planning and implementing a national research program may be viewed as ambitious. How well such models might serve these diverse needs remains to be seen, but we believe the potential is there. The first priority is to develop SPUR and use it to assess the sufficiency of our present understanding of rangeland management principles. Details of the SPUR model have been presented in previous papers.

Modeling may be perceived as a systematic way of arranging the elements or components of a system in a hierarchial and interrelated fashion. Models can be "physical" and "abstract." A gene is a physical model which produces proteins by assembling, in a specific order, the amino acids that constitute the components of proteins. The model SPUR does not exhibit the one-to-one correspondence to "reality" that a gene bears to a protein. In this respect, SPUR is not a precise representation but an abstraction of reality, but SPUR is judged to reproduce real-world responses to change sufficiently well so as to provide a reliable estimate of the consequences of a decision. Thus SPUR has the potential to provide significant help to the researcher in making decisions about future studies on a specific plant process, and to the research manager in making decisions about the type of research needed for ecosystem analysis and interpretation.

The modeling process is similar to the conventional decision making process in that both require the operator to: 1) define the objectives; 2) identify and organize existing information; 3) evaluate past experiences; 4) describe the system and its processes; 5) test hypotheses in the real world (validation); 6) apply the process to other analogous situations; and 7) identify key issues and decide priorities. Thus, this process provides a framework for addressing a variety of questions on many different levels.

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What kind of questions, then, can SPUR help the ARS scientist and research manager answer? Suppose we are faced with the question: "Is it in the best interests of society to produce a better cow, a better range plant, or a better range management scheme?" First, of course, the best interests of society must be defined, usually as a compromise between the economic, biological, social, and political optima. Then the broad spectrum of options available to us in selecting plants, cows, and management schemes can be inserted into the model to find which combination of inputs has the greatest potential impact on the desired output. Use of the SPUR will substantially reduce the risk of drawing false inferences from incomplete or oversimplified representations of complex, integrated ecosystems. The following example of a potentially false inference illustrates the point: "Plants exist which are 50 percent more reproductive than the average for all current range plants; the corresponding figure for cows is only 20 percent. Thus, we should concentrate our research on the development and use of better plants." However, such reasoning ignores the possibility that inefficiencies in feed to meat conversion may reduce the impact of a 50-percent improvement in plants to only a 10-percent increase in output, while a 20-percent improvement in the metabolism of feed to animal weight might well produce a 15-percent increase in output. Thus, the research emphasis may have to be placed on component interactions and not on the individual components of the system.

Models can predict the ultimate effect of altering any input or combination of inputs. If the answer to our original question is still "improve the plant," then we can ask, "what plant is most suitable, in what way should it be improved, how should it be done, and what are the best research projects to accomplish the objective?" Here models other than SPUR may be used to predict the time and resources required to achieve a given level of improvement. An example is the model used to predict phenotypic advance at given levels of variability, heritability, and selection pressure. The correct solution to each question asked requires different information. The conceptual frameworks and operational procedures may differ markedly as we shift from choosing broad goals to designing specific experiments, but a well-structured model provides a path, a sequence of mental stepping stones, which leads us from one to the other.

How will SPUR be used by scientists? A model, or the systems approach, forces scientists to be precise in formulating the objectives of their research. Range research is complex; it is composed of many challenging component problems, and it is difficult to single out the most appropriate component or the key interaction among components. Models force us to be explicit about what is known and help us to test our judgment of reality. This judgment is influenced by our past experiences, professional training and interests, and the orderly arrangement of facts and opinions. Presently, SPUR incorporates seven plant species or species groups on up to nine sites. Thus, any combination of up to seven species or species groups can be simulated simultaneously. Production from rangelands is, of course, the product of many species. SPUR can help define the optimum species for differing production sites and the kind of data needed by the plant component of the model. Similarly, SPUR can sharpen the scientific questions that need to be asked about watersheds, livestock, insects, and the environment.

Scientists are constantly faced with decisions as to which of the many components of a problem should be studied first. The process of identifying key components and their interactions is an essential first step for bringing order to a seemingly chaotic situation. As the number of components increases, the number of possible combinations of interactions also increases. Furthermore, one cannot know a priori for each component and for each interaction among components which data to collect. Yet some data must be collected. A model can provide information which will help the researcher determine what data would be most appropriate and valuable. For example, the growth of plants is the product of several processes including photosynthesis, metabolism, and the partitioning of assimilates.

Each of these growth inducing processes is comprised of many subprocesses. These subprocesses may involve physical, chemical, and biological reactions. A validated model of the detailed growth processes of one plant species will help identify gaps in our knowledge of the growth processes of other species, thereby providing the guidelines for future research.

A model can be used to identify the minimum amount of data needed to accept or reject hypotheses and to make predictions on the response of complex systems that have a high probability of success. This is particularly important to range management research, specifically when projecting and predicting beyond the confines of the base data. For example, the effects of a range management practice are commonly evaluated for several years. At best, the data obtained represents rangeland response to the environment of those sample years. A properly constructed model of soil-plant- animal-environment responses would allow extrapolation and interpolation beyond and between those years to other environments and seasons and preclude or reduce the need for more extensive and expensive field testing. A model, by defining the shape of a response curve, can suggest the number of levels of a variable to be tested; two points define a straight line, but more are required to define a sigmoid growth curve. If the scientist has some knowledge of the shape of the response curve, the most effective research strategy would be based on experiments designed to provide the optimum number of data points.

Finally, scientists working individually or as members of a team are faced with establishing priorities. When resources are limited, project efficiency and effectiveness demand that the critical problems be identified and that the scarce resources be focused on these problems. If resources are relatively abundant, then the objective may be to achieve a proper balance among the alternative research approaches while optimizing the overall return on resource investment. A well designed, computationally efficient, model can be used to determine the impact of changing one or more components on the output of a system. Thus, optimal data needs can be established, and the scientist makes efficient and effective use of both time and resources by planning research studies that best provide the needed data.

How can a manager of research use SPUR? The modeling process works for the manager of science as it does for the scientist. Managers tend to be more concerned with larger ecosystems and the interactions among ecosystems. For example, the goal and objectives of the ARS national range program can be used to guide research. We have defined that goal as finding ways for increasing red meat production from rangelands that are cost effective, environmentally sound, and compatible with other rangeland uses. This provides a focus for our research. Further, we believe the four basic strategies necessary to achieve this goal are to develop knowledge and technology for: 1) better management of soil, air, and water resources; 2) improved management of range vegetation; 3) increased efficiency of range livestock production; and 4) an improved understanding of the interrelationships of the major components of rangeland ecosystems. Thus, we have a framework for making decisions about which direction ARS programs should take and which program elements need greater or less emphasis.

We believe that SPUR, as used by both scientists and managers, will provide a systematic look at the management responses of different range ecosystems and will assess the potential interaction between components of these ecosystems. The model will also provide the research manager with knowledge of major gaps in information and assist in planning for the necessary research to fill these gaps consistent with the program's broad goals and objectives. SPUR will also allow for an assessment of range conditions on a regional and national scale, thereby providing research managers with the information needed to target research into ecosystems that are most critical for reaching goals and achieving program objectives.

The management of the ARS range research program is not totally dependent on SPUR, nor should it be. Factors, such as the probability of success, which depend on judgment and experience must also be considered. For the optional research strategies available to the manager, he or she must weigh the advances in knowledge, as estimated by the model, against the possibilities of success, as estimated from his or her knowledge of the human and physical resources to be used. However, SPUR will be an important source of information and a guide to systematizing the decision making process.

Well coordinated research programs are dependent on effective communication among scientists, both State and Federal, at specific locations and among locations. SPUR can be a guide for determining which experiments should be conducted and what data should be collected. SPUR can predict which production system would benefit most from key experiments. An important benefit we see being derived from SPUR is that data from experiments will be compatible, that is, the right data will be taken in the right way and at the right place. Thus, we should be in a better position to optimize the information in both kind and amount to be obtained from each study and to validate more rapidly the model and to improve its value.

Managers of science are involved in setting priorities and evaluating research against the resources available. This translates into increased funds for new and expanded programs, redirections of old, and reductions in some. In arriving at these decisions, the better the data, both quantitatively and qualitatively, and the better the feedback or interaction among the important components, the greater our confidence that the decision made will meet the real need. SPUR, along with other sources of data, can help to give us a clearer picture of these needs. We can assess the contribution of each major component of SPUR for predicting the output for a production site. Thus, we can recommend allocation of resources based on more complete information than is now available. This increased objectivity helps in explaining and defending our programs.

A model, such as SPUR, when used wisely within the limits of the parameters, will give a cautious glimpse of that which exists beyond them. On the other hand, it would be unwise to force SPUR into inappropriate roles. Models are no panacea; they are not magic; they are not a substitute for thinking; but they exist; and they can help us. We must learn to use SPUR--to validate it, to modify it, and to grow with it.

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