A PRECIPITATION-RUNOFF MODELING SYSTEM FOR EVALUATING THE HYDROLOGIC IMPACTS OF ENERGY RESOURCES DEVELOPMENT

By

G. H. Leavesley[1/], R. W. Lichty[1/], B. M. Troutman[1/], and L. G. Saindon[1/]

INTRODUCTION

Increasing development of the Nation's energy resources has led to immediate concern about the hydrologic impacts of surface mining on both local and regional scales. Several Federal programs are funding hydrologic studies of the major coal and oil-shale regions of the western United States; the objectives are to define premining hydrology, and determine the impacts of past and present mining practices on regional and small-basin hydrology. The study of the hydrologic impacts of surface mining can be advanced by using physically-based, distributed-parameter, modeling techniques that account for the temporal and spatial variability of both natural hydrologic characteristics and land-use changes.

A systematic study to develop a precipitation-runoff modeling system to aid in evaluating the impacts of land-use change is underway. The major objectives are: (1) To develop, test, and verify a modeling system for predicting streamflow, sediment yields, and general basin hydrology from normal and extreme precipitation occurring on various land-use conditions; and (2) to develop a theory of errors for the modeling system, to evaluate sources of error in model components, and to quantify the extent to which these errors result in uncertainties in model output.

An overview of the structure and concepts of the system, and a description of the daily-flow and snowmelt components are presented here. In addition, data from a small basin in northwestern Colorado are used to demonstrate results of the optimization and sensitivity-analysis components.

OVERVIEW OF MODELING SYSTEM

A precipitation-runoff modeling system (PRMS) has been developed to provide deterministic physical-process modeling capabilities. Each component of the hydrologic cycle is expressed in the form of known physical laws or empirical relationships that have some physical interpretation and relate to measurable watershed characteristics. The system is designed to function as either a lumped- or distributed- parameter type model and will simulate both mean daily flows and stormflow hydrographs.

PRMS has a modular design. Each component of the hydrologic system is defined by one or more subroutines that are maintained in a computer-system library. All subroutines are compatible for linkage to each other. Given a specific hydrologic problem and its associated constraints, the user can select an established model from the library or can design a model using selected library and user-supplied subroutines. The library also contains subroutines for parameter optimization, sensitivity analysis, and model-output handling and analysis. Initial system subroutines were obtained by modifying an event-type distributed routing rainfall-runoff model (Dawdy and others, 1978) and a daily flow rainfall- and snowmelt-runoff model (Leavesley and Striffler, 1979).

The system structure has three major components: (1) The data-management component handles the manipulation and storage of hydrologic and climatic data into a model-compatible direct access file; (2) the system-library component contains the compatible sugroutines used to generate the hydrologic-simulation model; and (3) the output component provides the model output handling and analysis capabilities (see fig. 1).

PRMS is designed to operate with data retrieved from the WATSTORE data storage and retrieval system of the U.S. Geological Survey. However, for data not stored in the WATSTORE system, programs are available to read and reformat these data to a temporary file in the WATSTORE format. The WATSTORE formatted data are converted and stored in an in-

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[1/] U.S. Geological Survey, Denver, Colorado dexed sequential (ISAM) file which is model compatible (see fig. 1).

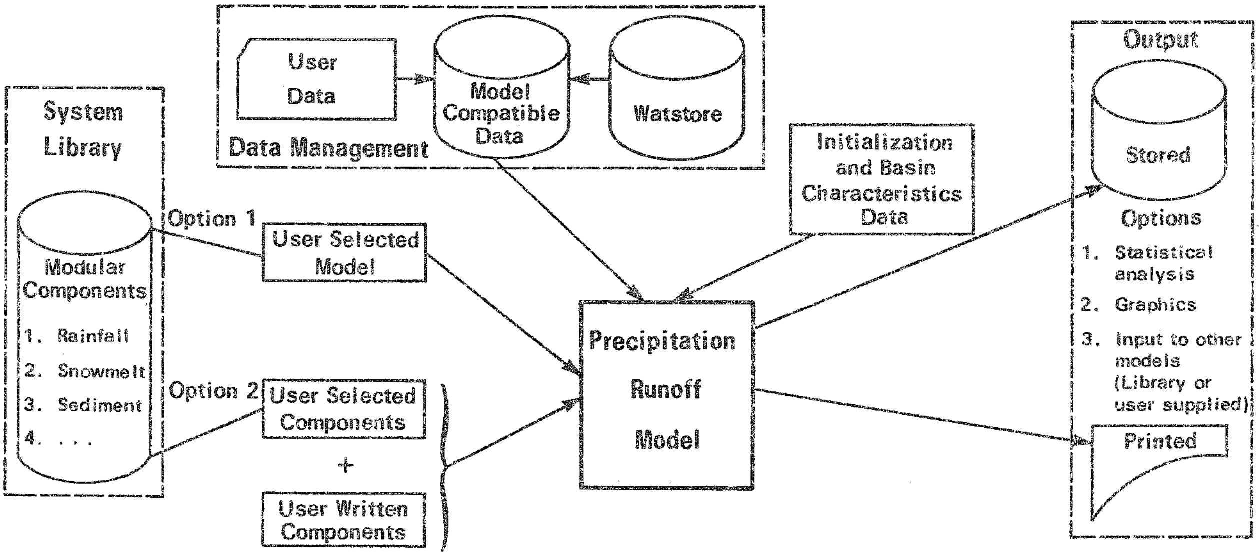

Figure 1. Schematic diagram of the precipitation-runoff modeling system.

The library component is the core of the modeling system. It contains the compatible subroutines that can be used in system-established or user-selected combinations to simulate hydrologic processes in a watershed. The library contains a Main-program module as a central point for time and computational sequence control and a set of subroutines representing individual components of the hydrologic cycle. Each subroutine is designed to be independent from other component subroutines. The library provides several options for model development and application. Among these are: (1) Using a system cataloged procedure; (2) compiling a new model using the system Main program with a combination of library- and user-supplied subroutines, and (3) compiling a new Main program with library- and user-supplied subroutines.

The output component provides the user with several options for displaying or storing simulation results for further analysis; these include printed summaries, printer plots of observed and predicted discharge, and storage of selected prediction results for use with system and user-written analysis programs. For daily flow simulations, printed output options include annual, monthly, and daily summaries of major climate and water-balance elements for both the total watershed and for the user-defined subunits within the watershed.

Watershed System

The watershed system is conceptualized as a series of reservoirs whose outputs combine to produce the total system response (see fig. 2). The upper soil-zone reservoir (USZ) represents that part of the soil mantle that can lose water through the processes of evaporation and transpiration. Average rooting depth of the predominant vegetation covering the soil surface defines the depth of this zone. Water storage in the USZ is increased by infiltration of rainfall and snowmelt and depleted by evapotranspiration. Maximum retention storage occurs at field capacity; minimum storage (assumed to be zero) occurs at wilting point. The USZ is treated as a two-layered system. The upper layer is termed the recharge zone and is user defined as to depth and water-storage characteristics. Losses from the recharge zone are assumed to occur from evaporation and transpiration; losses from the remainder of the USZ occur only through transpiration.

The computation of infiltration into the USZ is dependent on whether the input source is rain or snowmelt. All snowmelt is assumed to infiltrate the USZ until field capacity is reached. At field capacity, any additional snowmelt is apportioned between infiltration and subsequent seepage to the subsurface reservoir (S_1), and surface runoff (Q_1). The USZ at field capacity is assumed to have a maximum daily snowmelt infiltration capacity SRX. All snowmelt in excess of SRX contributes to Q_1. All water available for infiltration as the result of a rain-on-snow event is assumed to be snowmelt. For rainfall events with no snowcover, the volume infiltrating the USZ is computed as a function of

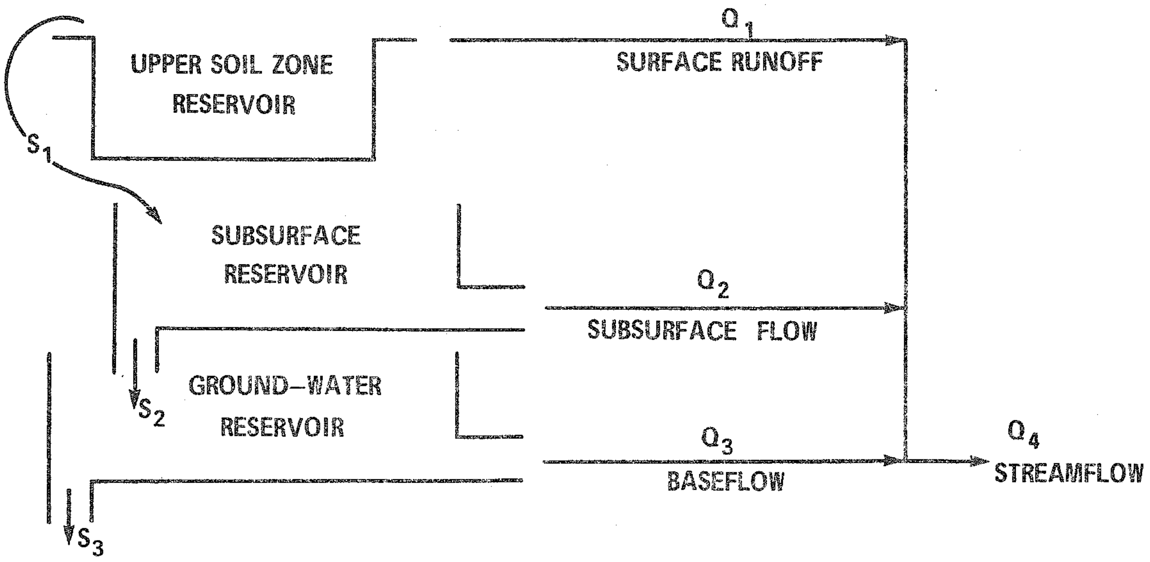

Figure 2.--Schematic diagram of the watershed system; S_1, S_2, and S_3 denote water movement between or out of reservoirs.

soil characteristics, antecedent soil-moisture conditions, and storm size. For daily-flow computations, the volume of rain that becomes Q_1 is computed using a contributing area concept. Daily infiltration is net precipitation less Q_1. For stormflow-hydrograph generation, infiltration is computed using a form of the Green and Ampt equation (Philip, 1954). Q_1 for these events is the net precipitation less computed infiltration.

The subsurface reservoir (SSR) performs the routing of soil-water excess that percolates to shallow saturated zones near stream channels or that moves laterally from point of infiltration to some point of discharge above the water table. Subsurface flow (Q_2) is considered to be water that is available for relatively rapid movement to a channel system and supports the recession of snowmelt and stormflow hydrographs. The SSR can be defined as either linear or non-linear.

Seepage to the ground-water reservoir (S_2) is computed as a function of a daily seepage rate and the volume of water in storage in the SSR. The ground-water reservoir (GWR) is a linear reservoir and is the source of all baseflow (Q_3). Movement of water through the ground-water system to points beyond the area of interest or measurement can be handled by seepage S_3 which is computed as a function of storage in the ground-water reservoir.

Streamflow (Q_4) is the sum of the outputs Q_1, Q_2, and Q_3. For daily flow simulations, no channel routing is done for Q_4.

Watershed Partitioning

The distributed-parameter modeling capability is provided by partitioning a watershed into "homogeneous" units. Watershed units can be delineated on the basis of any combination of characteristics such as slope, aspect, elevation, soils, vegetation, and precipitation distribution. Each watershed unit is considered to be homogeneous with respect to these defined characteristics. Partitioning provides the ability to account for spatial and temporal variations of physical and hydrologic characteristics of the watershed, climate variables, and system response.

Three levels of partitioning are available. The first level divides the watershed on the basis of some or all of the physical characteristics discussed previously; the resulting units are called hydrologic-moisture units (HMUs). A second level of partitioning further divides the HMUs, based on the number and location of precipitation gages available for defining the distribution of precipitation; the resulting units are called hydrologic-response units (HRUs). When only a single precipitation gage is used for model input, a HMU is equivalent to a HRU; when more than one precipitation gage is used, a HMU may consist of one or more HRUs. A maximum of three precipitation gages can currently be used for model input. The third level of partitioning delineates overland flow planes and channel segments for the purpose of routing surface runoff and channel flow from rainfall events.

The conceptual watershed system shown in figure 2 can be defined for each HRU. However, for normal small-watershed applications, one upper soil zone (USZ) is defined for each HRU, while one ground-water reservoir (GWR) is defined for the entire basin. The number of subsurface reservoirs (SSRs) is a function of the variation in soils and geology and the detail to which subsurface flow is to be defined and routed.

SYSTEM-LIBRARY COMPONENTS

The system-library subroutines are grouped into the general categories of daily, storm event, optimization, sensitivity analysis, and data handling components. The assumptions and equations used in the current library are presented by process without reference to specific subroutines.

Daily Components

The daily components are those subroutines that simulate the daily accretion, depletion, storage, and movement of water in a HRU. The rates and volumes of these processes are a function of HRU physical and hydrologic characteristics. A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRUs, weighted on a unit-area basis, produces the simulated watershed response.

Climate

Input variables needed to drive the daily components are daily precipitation, maximum and minimum air temperature, and solar radiation. Where solar-radiation data are not available, they can be estimated by the modeling system using air-temperature and precipitation data. For regions where snow is a negligible part of precipitation input, pan evaporation data can be substituted for air-temperature and solar-radiation data.

Daily climate data are extrapolated to each HRU using a set of user-defined adjustment coefficients developed from regional climate data. Maximum and minimum daily air-temperature data are adjusted using monthly lapse rates (TLX for maximum and TLN for minimum) and the elevation difference between the climate station and each HRU. An additional correction is applied to adjust for variations in HRU aspect. Observed solar radiation is adjusted to account for its variation with slope and aspect.

Precipitation volume on each HRU can be adjusted to account for changes with elevation and deficiencies in gage catch. Separate precipitation coefficients can be applied to summer and winter periods to account for changes in storm characteristics. Precipitation-form (rain, snow, or both) is determined from the maximum and minimum daily air temperatures and their relationship to a base temperature (BST); all precipitation is rain above BST and all precipitation is snow, below it (Willen and others, 1971). The precipitation form estimation procedure can be overridden for days when the form is known; also, snowpack volumes on each HRU can be adjusted using measured snowcourse data.

Land Phase

Daily precipitation is first reduced in amount by interception. Interception storage is computed as a function of vegetation type and density (COVDN), precipitation form and amount, and antecedent interception storage. The remaining net precipitation reaches the snowpack or soil surface. All intercepted rain is assumed to evaporate the same day. Intercepted snow undergoes sublimation for a period of days (defined by the user), and then is unloaded to the snowpack or soil surface. Evaporation and sublimation losses are computed as a function of the potential evapotranspiration demand for the day.

Surface runoff (Q_1) from rainfall on a snowfree HRU is computed by using a contributing-area concept. A percentage of each HRU area is assumed to contribute directly to surface runoff. This contributing-area percentage (CAP) for each HRU is computed by:

$$CAP = SCN + [(SCX-SCN) * (RECHR/REMX)] \tag{1}$$

where SCN is the minimum contribution area;
SCX is the maximum contributing area;
RECHR is the amount of water in the recharge zone of the USZ at the time of the rainfall event; and
REMX is the storage capacity of the recharge zone between field capacity and wilting point.

SCN and SCX are functions of HRU physical characteristics and are user-defined. Q_1 for snowmelt occurs only when the USZ is at field capacity and the snowmelt exceeds the daily infiltration capacity, SRX.

Infiltration first satisfies any moisture storage deficit in the USZ. Infiltration in excess of field capacity of the USZ is routed to the subsurface reservoir. After soil-water accretions and routing are completed, evapotranspiration losses are computed. Potential evapotranspiration (PET) is computed using a modified Jensen-Haise technique (Jensen and others, 1969). The basic equation is:

$$PET = CTS*(TAV-CTX)*RIN \tag{2}$$

where TAV is mean daily air temperature;
RIN is daily solar radiation expressed as an equivalent depth of evaporation; and
CTS and CTX are air-temperature coefficients.

CTS is a model parameter that can be fitted during calibration. However, both CTS and CTX can be estimated using regional air-temperature, elevation, vapor-pressure, and vegetation data. Transpiration is assumed to begin when the sum of the maximum daily air temperatures for a user-defined month exceed a degree-day sum (TST) estimated for the HRU vegetation. Actual evapotranspiration (AET) is computed by:

$$AET = PET * f(SMAV/SMAX) \tag{3}$$

where f(SMAV/SMAX) is a set of functions based on soil type (sand, loam, clay), (Zahner, 1967);
SMAV is the water currently available in the USZ; and
SMAX is the maximum available water holding capacity of the USZ.

The vertical movement of water from the subsurface reservoir to the ground-water reservoir (S_2) is computed by:

$$S_2 = SEP * (RES/RESMX)^{REXP} \tag{4}$$

where SEP is a daily seepage rate;
RES is the current volume of storage in subsurface reservoir; and
RESMX and REXP are coefficients to define the routing characteristics of this vertical seepage.

The vertical seepage from the ground-water reservoir (S_3) is computed by:

$$S_3 = GSNK * GW \tag{5}$$

where GSNK is the daily seepage rate to a ground-water sink; and
GW is the current volume of storage in the ground-water reservoir.

Flow contributions to streamflow (Q_4) from the subsurface reservoir (Q_2) and the ground-water reservoir (Q_3) are computed as a function of the volume of water in storage. Q_2 is computed by:

$$Q_2 = (RCF*RES) + (RCP*RES^2) \tag{6}$$

where RCF and RCP are routing parameters fitted during model calibration. Initial estimates of RCF and RCP can be made from historic flow records. Q_3 is computed by:

$$Q_3 = RCB*GW \tag{7}$$

where RCB is a routing coefficient computed from historic flow records.

Snow

The snow components simulate the initiation, accumulation, and depletion of a snowpack on each HRU. A snowpack is maintained and modified on both a water-equivalent basis and as a dynamic-heat reservoir. A snowpack water balance is computed daily and an energy balance is computed twice each day for two 12-hour periods (designated day and night).

The energy-balance computations are a combination of equations and functional relationships taken or derived from several sources. The conceptual model for the snowpack system and its energy relationships is one described by Obled and Rosse (1977). The snowpack is assumed to be a two-layered system. The surface layer consists of the upper 3-5 centimeters of the snowpack, and the bottom layer is the remaining snowpack. Heat transfer between the surface layer and the snowpack occurs by conduction when the temperature of the surface layer (T_s) is less than 0°C (Celsius). When T_s equals 0°C, heat transfer occurs as conduction when the net energy balance at the air-snow interface is negative; but heat transfer occurs as mass transfer by surface melting when the net energy balance is positive. Heat transfer from precipitation occurs as a mass-transfer process. Conduction of heat from the soil surface to the snowpack is assumed to be negligible compared to the energy exchange at the air-snow interface.

T_s for the day period is computed as the mean of the maximum and mean daily air temperature for a HRU. For the night period, it is computed as the mean of the minimum and mean daily air temperature for a HRU. T_s equals 0°C, when these means exceed 0°C. When T_s is less than 0°C, the mean air temperature for that 12-hour period is assumed to integrate the effects of the radiation, latent heat, sensible heat, and diffusion processes expressed in the complete equation for T_s; see Anderson (1968) for complete discussion of equation.

The conduction of heat between the snow surface and the snowpack (QCOND) is computed by:

$$QCOND = 2*DEN*CS*\sqrt{\frac{KEFF}{(DEN*CS)} * \frac{\Delta t}{\pi}} *(T_s - PACT) \tag{8}$$

where DEN is snowpack density;
CS is the specific heat of ice;
PACT is the temperature of the snowpack; and
Δt is the time period.

KEFF is the effective thermal conductivity of the snowpack and is assumed equal to $0.0077*DEN^2$ (Anderson, 1968). DEN is computed daily using an algorithm developed by Riley, Israelsen, and Eggleston (1973). PACT is recomputed each 12-hour period to reflect the net gain or loss of heat.

When T_s equals 0°C, an energy balance at the air-snow interface (Q_T) is computed by:

$$Q_T = Q_{SWN} + Q_{LWN} + Q_P \tag{9}$$

where Q_{SWN} is net shortwave radiation absorbed by the surface layer;
Q_{LWN} is net longwave radiation exchange between the surface layer and the environment; and
Q_p is the heat content of precipitation.

When Q_T is negative, heatflow occurs by conduction only. When Q_t is positive, this heat is assumed to melt snow in the surface layer. This melt then transports heat into the snowpack by mass transfer. When PACT is less than 0° C, the melt water is refrozen and decreases the cold content of the snowpack. When the snowpack becomes isothermal at 0° C, snowmelt is first used to satisfy the freewater holding capacity of the snowpack. Any remaining melt leaves the bottom of the snowpack to become infiltration or surface runoff. Q_{SWN} and Q_{LWN} are computed for each HRU using the equations developed by the U.S. Army (1956). Q_{SWN} is computed as a function of daily shortwave-solar radiation, the transmission coefficient (TRNCF) of the vegetation canopy above the snow surface, and the snow surface albedo. Q_{LWN} is computed as a function of the temperatures and emissivities of the snow-surface, air, and vegetation canopy. Longwave energy radiated from these sources is computed using the Stefan-Boltzmann law.

Evaporation and sublimation from the snow surface are assumed to occur only when there is no transpiration from vegetation above the snowpack. Loss from the snow surface is computed daily as a percentage of the PET value computed in equation 2. The daily percentage is a constant and is user-defined.

Optimization and Sensitivity-Analysis Components

Optimization components control the automatic adjustment of model parameters to obtain better agreement between observed and predicted runoff. A model parameter is broadly defined as a value that is used to represent a physical or hydrologic characteristic of a watershed, and is held constant during a simulation run. This definition produces a large number of parameters for optimization and sensitivity analysis; however, the availability of a large number of parameters is not meant to encourage optimization of all of them. They are available primarily for development work in the theory of errors for the modeling system and to permit the user to evaluate the sensitivity of each parameter, and its interactions with others.

The method used to obtain an optimal set of parameter values is the Rosenbrock optimization technique (Rosenbrock, 1960). Spatially distributed parameters have an initial value assigned to each HRU, subsurface reservoir, or ground-water reservoir. Temporally distributed parameters have an initial value assigned for each time increment. One or any combination of parameters can be selected for optimization. During each iteration of the fitting procedure, a single parameter is adjusted and the objective function is computed and tested for improvement. For each iteration of a distributed parameter, all values of the parameter are moved in the same direction at the same time. The amount that each value is moved can be selected as the same magnitude or as the same percentage of the initial value. A major assumption in this fitting procedure is that the initial estimates of the values of a given distributed parameter are correct with regard to their relative differences in space or time.

Sensitivity-analysis components allow the user to determine the extent to which uncertainty in the parameters results in uncertainty in the predicted runoff. When sensitivity analysis is coupled with optimization, the user also can assess the magnitude of parameter standard errors and parameter intercorrelations. Discussions of sensitivity analysis and its interpretation are given by Mein and Brown (1978) and Beck and Arnold (1977).

The sensitivity-analysis computations begin by letting n denote the number of days or rainfall events under consideration and letting P_i denote the predicted runoff volume for the *i*th day or event, $1 \leq i \leq n$. A matrix with n rows and p columns (where p is the number of parameters), known as the sensitivity matrix, is computed. The element in the ith row and jth column (a_{ij}) of this matrix is

$$a_{ij} = \partial P_i / \partial \beta_j | \hat{\beta} . \qquad (10)$$

This notation indicated that the partial derivative is evaluated at $\hat{\beta}$, where $\hat{\beta}$ is the vector of parameter values used for the model run. The jth component of the vector $\hat{\beta}$ is denoted by $\hat{\beta}_j$. These partial derivatives are approximated by running the model first with parameter value $\hat{\beta}_j$, and then again with parameter $\hat{\beta}_j + \Delta\hat{\beta}_j$, where $\Delta\hat{\beta}_j$ is a small fraction of $\hat{\beta}_j$. The quantity $\partial P_i / \partial \beta_j | \hat{\beta}$ is approximated by the change in P_i divided by $\Delta\hat{\beta}_j$. A (scaled) information matrix is then computed. This matrix is the transpose of the sensitivity matrix times the sensitivity matrix itself.

When the parameter estimates $\hat{\beta}$ are obtained by optimization, the approximate covariance matrix of the parameter estimates is computed as the product of the inverse of the information matrix and the scalar residual variance $\hat{\sigma}^2$. The residual variance is taken to be the objective function (least squares form) divided by n-p. The residual standard error, $\hat{\sigma}$, also is computed. The parameter standard errors, s_j, and correlation matrix are then obtained from the resulting parameter covariance matrix. If s_j, is referred to as a joint standard error, an individual standard error, s'_j, is computed by:

$$s'_j = (z_{jj})^{-\frac{1}{2}} \hat{\sigma} \qquad (11)$$

where z_{jj} is a diagonal element of the information matrix. s'_j is actually the standard error of β_j conditioned on given values of the other parameter estimates.

The influence of individual days or storm events on parameter values fitted in an optimization is analyzed by the use of a HAT matrix. The HAT matrix is computed as the product of three matrices; the sensitivity matrix, the inverse of the information matrix, and the transpose of the sensitivity matrix. The diagonal elements of this matrix represent one day in the optimization period. The diagonal elements all lie between 0 and 1; the closer to 1, the greater the influence of that day on the objective function fit. A complete discussion of the interpretation of the HAT matrix is given by Hoaglin and Welsch (1978).

MODELING DATA BASE

Through its own programs and a cooperative study with the U.S. Bureau of Land Management, the U.S. Geological Survey has established a number of small-basin studies in coal and oil-shale regions of the western United States (fig. 3). One of the purposes of these studies is to define the hydrology of basins typical of those to be mined within a given region. Modeling will be used as one of the tools for defining the hydrology of these basins and for extrapolating information to ungaged basins within that region.

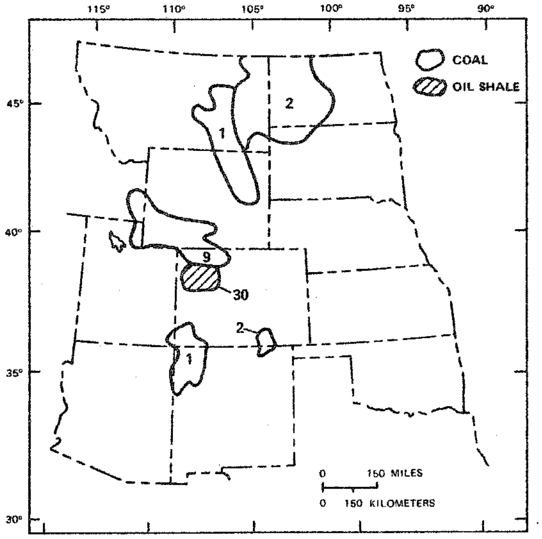

Figure 3.--Location and number of study basins in the coal and oil-shale regions of the western United States.

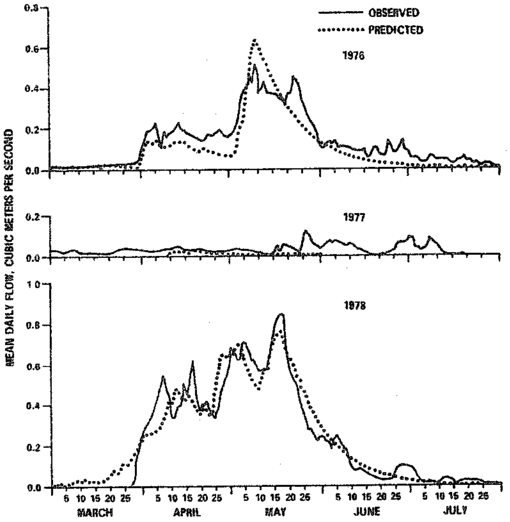

Figure 4.--Observed and predicted mean daily flow hydrographs for March through July, 1976-78 water years. (Model parameters were optimized using data for 1978 water year.)

Data being collected from these study basins include continuous measurements of streamflow, daily measurements of sediment discharge, and periodic measurements of selected water-quality constituents. A meteorological station is established for each basin or group of basins. Air temperature, relative humidity, wind travel, wind direction, and integrated shortwave-solar radiation are recorded hourly. In Montana and North Dakota, soil-temperature and soil-moisture profiles are also recorded hourly. A precipitation network is established in each basin using weighing-bucket type rain gages for daily precipitation depths and digital rainfall recorders for recording rainfall depth at a 5-minute interval. Snow courses are measured monthly when snow is present. The basins in North Dakota are included in the National Weather Service's Airborne Gamma Radiation Snow Survey Program (Carroll and Vadnais, 1980). Periodic measurements of soil moisture are taken either gravimetrically or with a neutron soil-moisture gage from selected HRUs in the basins. Water-level data for the major aquifers in the basins also are collected periodically.

TESTING, EVALUATION, AND VERIFICATION

Testing, evaluation, and verification of the modeling system and its theory of errors are being completed as a multiphase program. The first phase is testing of the conceptual model to insure applicability. The second phase is evaluation of specific model components and parameter estimation procedures. The third phase is verification of the modeling system for predicting the impacts of surface mining and reclamation on watershed hydrology. The phases are not sequential, but overlap. Data collected from the study-basin network before, during, and after mining will provide the background data for all program phases. In each phase, modifications and improvements in components will be developed from evaluation of the accuracy and sensitivity of simulation results. The program is currently completing phase one and continuing into phase two.

An example of test and evaluation results is demonstrated by using data for Middle Creek watershed, located in the semiarid coal region of northwestern Colorado. It is 6.9 square kilometers in size and is covered by sage brush, scrub oak, and scattered stands of aspen; elevation ranges from 2,073 meters to 2,499 meters.

The watershed was divided into 19 HRUs. The parameters defining the climate and HRU characteristics were estimated using current (1981) techniques. Preliminary runs were made to define those parameters most influencing streamflow prediction. The nine parameters described in table 1 were selected for use in optimization and sensitivity-analysis runs using data for the 1978 water year.

Table 1. Parameters selected for optimization and sensitivity analysis

Parameter	Units	Application
BST	°Celsius	Base temperature, influences form of precipitation.
TRNCF	---	Transmission coefficient, influences computation of shortwave radiation reaching snowpack surface.
TLX	°Celsius/100 meters	Average monthly lapse rate for daily maximum air temperature.
SEP	Centimeters/day	Seepage rate used in computing flow from subsurface to ground-water reservoir.
COVDN	---	Cover density of vegetation expressed as a decimal fraction.
CTS	---	Coefficient used in computing potential evapotranspiration.
SMAX	Centimeters	Maximum available water-holding capacity of the upper soil zone.
TST	Degree-days Celsius	Degree day sum used to initiate start of transpiration period.
RCB	---	Routing coefficient for ground-water reservoir.

The application of the fitted parameters to simulating the runoff from March through July for the period of record is shown in figure 4. The size and timing of predicted daily mean flows compares reasonably well with observed flows. The observed mean and standard error of the estimated mean for daily flows, for the March-July periods, are given in table 2. Expressed as a percentage of the observed mean, the smallest standard error occurred for the optimized water year, 1978, and was 31 percent. The largest standard error was 124 percent and occurred for the 1977 water year. The 1977 water year was one of the lowest snowfall years on record. Also given in table 2 are the water-year totals for precipitation, and observed and predicted discharge for the period of record. Observed annual discharge ranged from 2 to 10 percent of annual precipitation; percentage values which are less than or equal to errors associated with precipitation measurement. The errors in predicted annual flow volumes ranged from 2 percent for 1978 to 89 percent for 1977. The larger standard error of estimate and volume error occurring for 1977 may be the result of precipitation measurement and distribution errors associated with a very low snowfall year, or errors associated with the use of parameters in low snowfall years that were fitted in high snowfall years. More research is needed to better define and minimize the causes of this problem.

Discrepancies between observed and simulated streamflow in all the simulated years can be attributed partly to the lack of observed solar-radiation data. Daily shortwave-solar radiation was estimated from temperature and precipitation data. In addition, several of the streamflow increases in June and July occurred with no measured precipitation. The cause may have been localized thunderstorms or water diverted into the basin for irrigation. No attempt was made to simulate summer-streamflow increases.

Table 2. Summary of annual precipitation and discharge for water years 1976-78, and mean discharge and standard error of estimate of daily mean discharge for periods March through July.
[cm = centimeters; m^3/s = cubic meter per second]

Water year	Annual precipitation (cm)	Observed annual discharge (cm)	Predicted annual discharge (cm)	Observed mean discharge, March-July (m^3/s)	Standard error of estimate, daily mean discharge, March-July (m^3/s)
1976	47.85	3.10	2.08	0.130	0.068
1977	32.66	0.71	0.08	0.029	0.036
1978	52.68	5.05	4.95	0.227	0.070

Results of the parameter optimization and sensitivity analysis are shown in table 3. A measure of the goodness of the initial parameter estimates can be taken from the change in the standard error of estimate of the daily mean discharge. The decrease from 0.284 to 0.070 cubic meter per second indicates a substantial improvement in use of the fitted parameters over the initial estimated parameters. The goodness of individual parameter estimates can be taken from the magnitude of the changes in parameter values resulting from the fitting process. However, this needs to be coupled with the measure of parameter sensitivity reflected in the percentage increase in standard errors. One of the significant parameter changes occurred in SMAX, which increased 55 percent. This indicates a need to improve the estimation procedures for soil-moisture storage or to re-evaluate the soil-moisture accounting components. The most sensitive parameter is BST, which influences the determination of precipitation form. Part of the sensitivity results from the small range of physically realistic values for BST. The next most sensitive are TRNCF and TLX, which influence the energy-balance relationships for computing snowmelt.

Table 3. Estimated and optimized parameter values, the standard error of estimate of daily mean flows using these parameters, and the percentage increase in standard error of estimate resulting from selected deviations in parameters from their optimal value.
[S. E. = standard error of estimate of daily mean flows, cubic meters per second]

Parameter	Estimated value	Optimized value	Percent increase in standard error of estimated daily mean discharge for 5-, 10-, and 20- percent deviations of parameters from their optimal value		
			5	10	20
BST	0.0	1.09	30.3	94.7	248.7
TRNCF	0.38	0.35	10.9	38.4	161.2
TLX	0.77	0.88	3.7	14.0	48.4
SEP	2.54	2.39	2.3	8.9	32.4
COVDN	0.37	0.38	1.7	6.7	24.8
CTS	0.014	0.0145	1.7	6.6	24.5
SMAX	28.4	43.7	1.5	6.0	22.3
TST	250.	471.	1.1	4.3	16.2
RCB	0.118	0.073	0.4	1.6	6.4
S.E.	0.284	0.070			

One additional tool developed in the sensitivity analysis is the parameter correlation matrix which is shown in table 4. A large positive correlation between parameters indicates that an increase (decrease) in one has the same effect on predicted runoff as an increase (decrease) in the other. A large negative correlation indicates that an increase in one and a decrease in the other has a similar influence on predicted runoff. The results show that CTS has the greatest frequency of high correlation with other parameters. It has a high negative correlation with TRANS, SMAX, and SEP. An increase in CTS will increase potential evapotranspiration and thus decrease predicted runoff volume and peak flows. A decrease in TRANS will decrease the rate of snowmelt and make snowmelt available longer for losses through evapotranspiration; thus, predicted runoff volumes and peak flows also are decreased. Decreases in SMAX and SEP also will affect runoff in a similar way. The Rosenbrock optimization algorithm may have difficulty in locating optimal values of parameters that are highly correlated. One approach to minimizing this difficulty may be a step-wise fitting procedure where groups of uncorrelated parameters are fitted in separate runs.

Table 4. Parameter correlation matrix.

	BST	TRNCF	TLX	SEP	COVDN	CTS	SMAX	TST	RCB
BST	1.00	-0.123	-0.204	-0.242	-0.177	0.467	-0.746	0.126	0.123
TRNCF	-.123	1.00	.401	.805	-.698	-.830	.515	-.375	-.278
TLX	-.204	.401	1.00	.433	.073	-.299	.055	-.938	-.275
SEP	-.242	.805	.433	1.00	-.213	-.932	.604	-.379	-.048
COVDN	-.177	-.698	.073	-.213	1.00	.298	-.082	-.096	.222
CTS	.467	-.830	-.299	-.932	.298	1.00	-.827	.256	.113
SMAX	-.746	.515	.055	.604	-.082	-.827	1.00	-.058	-.071
TST	.126	-.375	-.938	-.379	-.096	.256	-.058	1.00	.277
RCB	.123	-.278	-.275	-.048	-.222	.113	.071	-.277	1.00

Component testing and analysis is an iterative process. Alternative simulation and parameter-estimation techniques can be evaluated for use under various imposed data constraints. Concurrent work is being done on the influence of data errors on parameter estimation and model prediction errors. The goal is to develop model components and parameter estimation procedures that produce minimum prediction errors without the use of parameter optimization techniques.

SUMMARY

A precipitation-runoff modeling system is being developed to evaluate the impacts of land-use change on watershed hydrology. Initial development, testing, and verification of the daily-flow and snowmelt components of the system are being conducted in the major coal and oil-shale regions of the Western United States. A network of small study basins has been established in these regions to provide the data for this modeling effort. Modeling system components are currently being tested to evaluate and improve relationships between component parameters and measurable watershed and climate characteristics. An ultimate objective is to develop simulation and data collection techniques that minimize or eliminate the need for parameter optimization. While current testing and development are being conducted in the energy-resource regions of the west, similar testing, component development, and verification will be conducted in all physiographic and climatic regions of the United States to develop a diverse and widely applicable modeling system.

REFERENCES

Anderson, E. A., 1968, Development and testing of snow pack energy balance equations: Water Resources Research, v. 4, no. 1., p. 19-38.

Beck, J. V., and Arnold, K. J., 1977, Parameter estimation in engineering and science: New York, John Wiley and Sons, Inc., 501 p.

Carroll, T. R., and Vadnais, K. G., 1980, Operational airborne measurement of snow water equivalent using terrestrial gamma radiation: Laramie, Wyo., Western Snow Conference Proceedings, v. 48, p. 97-106.

Dawdy, D. R., Schaake, J. C., Jr., and Alley, W. M., 1978, Users guide for distributed routing rainfall-runoff model: U.S. Geological Survey Water Resources Investigations 78-90, 146 p.

Hoaglin, D. C., and Welsch, R. E., 1978, The hat matrix in regression and ANOVA: The American Statistician, v. 32, no. 1, p. 17-22.

Jensen, M. E., Robb, D. C. N., and Franzoy, C. E., 1969, Scheduling irrigations using climate-crop-soil data: A paper presented at National Conference on Water Resources Engineering of the Am. Soc. Engineers, New Orleans, La., Feb. 3-5, 20 p.

Leavesley, G. H., and Striffler, W. D., 1979, A mountain watershed simulation model, in Colbeck, S. C., and Roy, M., eds., Proceedings Modeling of Snow Cover Runoff: Hanover, New Hampshire, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, p. 379-386.

Mein, R. G., and Brown, B. M., 1978, Sensitivity of optimized parameters in watershed models: Water Resources Research, v. 14, no. 2, p. 299-303.

Obled, Ch., and Rosse, B., 1977, Mathematical models of a melting snowpack at an index plot: Journal of Hydrology, no. 32, p. 139-163.

Philip, J. R., 1954, An infiltration equation with physical significance: Soil Sci. Soc. Am. Proc., v. 77, p. 153-157.

Riley, J. P., Israelson, E. K., and Eggleston, K. O., 1973, Some approaches to snowmelt prediction, in The role of snow and ice in hydrology: IAHS-AISH publication no. 107, p. 956-971.

Rosenbrock, H. H., 1960, An automatic method of finding the greatest or least value of a function: Computer Journal, v. 3, p. 175-184.

U.S. Army, 1956, Snow hydrology: Portland, Oregon, North Pacific Division, U.S. Army Corps of Engineers, 437 p.

Willen, D. W., Shumway, D. A. and Reid, J. E., 1971, Similation of daily snow water equivalent and melt: Billings, Mont., Western Snow Conference Proceedings, v. 39, p. 1-8.

Zahner, R., 1967, Refinement in empirical functions for realistic soil-moisture regimes under forest cover, in Sooper, W. E., and Lull, H. W., eds., International Symposium on Forest Hydrology: Pergamon Press, New York, p. 261-274.