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Technical Report

REMOTE SENSING AND HYDROLOGIC MODELS

Part 1: Review of Hydrologic Models for Evaluating Use of Remote Sensing Capabilities

Part 2: Strategies for Using Remotely Sensed Data in Hydrologic Models

E.L. Peck, R.S. McQuivey, T.N. Keefer, E.R. Johnson, J.L. Erekson

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PREFACE TO THE COMBINED REPORT

Parts 1 and 2 of Remote Sensing and Hydrologic Models were originally published separately. Since the original publication, requests for copies of the reports have exceeded the number printed. Recently, numerous additional requests for copies have been received from the international hydrologic community. In order to satisfy the demand for these documents, they have been reprinted in one volume in their entirety.

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REMOTE SENSING AND HYDROLOGIC MODELS

Part 1: Review of Hydrologic Models for Evaluating Use of Remote Sensing Capabilities (AgRISTARS Document CP-G1-04102, NASA CR 166674)

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16. Abstract

Hydrologic models most commonly used by federal agencies for hydrologic forecasting are reviewed. Six catchment models and one snow accumulation and ablation model are reviewed. Information on the structure, parameters, states, and required inputs is presented in schematic diagrams and in tables. The primary and secondary roles of parameters and state variables with respect to their function in the models are identified. The information will be used to evaluate the usefulness of remote sensing capabilities in the operational use of hydrologic models.

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PREFACE

The review of hydrologic models presented in this report is a part of the Hydrological Modeling Survey Studies being conducted by the Hydex Corporation for the National Aeronautics and Space Administration under Contract No. NAS5-26446. The general objective of the overall project is to determine the suitability of present and planned remote sensing capabilities for commonly used river forecast models.

Several models were selected for study. During the initial review of these models it quickly became evident that available descriptions of the models were not in formats convenient for evaluating the suitability of using remote sensing capabilities operationally.

The purpose of this report is to present information on the structure, parameters, states, and required inputs that should be of value for evaluating the usefulness of remote sensing capabilities. The primary uses of remote sensing to be evaluated in the overall project are (a) for calibration of the models, (b) for improved estimates of inputs and (c) for updating the states for a model.

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CHAPTER 1

INTRODUCTION

This review of hydrologic models is part of the Hydrological Modeling Survey Studies being conducted by Hydex Corporation for the National Aeronautics and Space Administration (NASA). The objective of these studies is to determine the suitability of present and planned remote sensing capabilities for commonly used river forecast models.

To accomplish the above objectives requires a knowledge of remote sensing capabilities and a knowledge of how remote sensing information can be used to improve the usefulness of hydrologic modeling.

A separate review is being conducted on remote sensing capabilities of possible value for use in hydrologic modeling. A catalog will be prepared describing the physical parameters that can be measured by current and planned remote sensing, with information on the accuracy and resolution of the measurements.

The available literature describing hydrologic models was generally not prepared with the view of using remotely sensed data. For some models it is difficult to understand conceptually the function and relation of the states and parameters of the model with hydrologic processes or storages of moisture.

This report has been prepared to assist hydrologists and scientists dealing with remote sensing to visualize more clearly the concepts underlying the hydrologic models and the role of parameters, states,and inputs.

1. SELECTION OF MODELS

The hydrologic models most commonly used by federal agencies for hydrologic forecasting were selected for review. In addition the hydrologic model recently developed by the Science and Education Administration was added because of its use in the field of agriculture. The following six hydrologic models were selected for review:

- Antecedent Precipitation Index (API)
- Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS)
- National Weather Service River Forecast System (NWSRFS)
- Storage, Treatment, Overflow, Runoff Model (STORM)
- Stanford Watershed Model IV (SWM)
- Streamflow Synthesis and Reservoir Regulation (SSARR)

In addition to the basic hydrologic models, one snowmelt model was chosen for review. Most of the hydrologic models employ very simple degree-day snow cover outflow relations of the types, Melt= Index X Mean Temperature. The NWSRFS Snow Accumulation and Ablation Model (1) is the only model commonly in use that uses air temperature as an index to energy exchange across the snow-air interface and accounts for heat deficit and liquid water in the snowpack.*

2. GLOSSARY OF TERMS

A prerequisite to effective communication is an agreed upon vocabulary. The following terms are introduced and described for use in the review of the hydrologic and snowmelt models.

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*All references are presented at the end of this report.

Inputs

The set of driving forces required periodically by the model. Common examples are precipitation, potential evapotranspiration, and temperature. For most hydrologic models the inputs are all meteorologic factors, but some require inputs describing man's activities (cropping practices).

The key phrase in the definition of the inputs of a model is "required periodically." If it is possible to run the model without providing a value for a particular item, that item is not an input. Likewise, if the model can be run with a particular item provided only once or perhaps intermittently, that item is not an input. Some models, however, may have default values for certain inputs (e.g., precipitation is zero if not entered).

Parameters

The set of values that are changed to make a general hydrologic model apply to a particular location. Parameters are constant with time or at most, vary only slightly with time as compared to inputs.

States

The set of internal model values sufficient to start the model. The states of the model completely define the past history of inputs. These are usually values of moisture stored in various model components (e.g. upper zone tension water contents), indices to model status(e.g.,API), or computational carryover values (e.g., the carryover values of a unit hydrograph operation). In each time step of operation, the model uses the initial values of the states along with parameters and inputs for that time step in order to compute the state for the next time step.

Outputs

Variables of interest that can be computed from knowledge of the states and inputs. Usual examples are streamflow and actual evapotranspiration. In many cases an output will be identical to some state of the model, but such does not have to be the case. The model may produce an output that is of vital interest to the model user but is not necessary to the model computations.

3. DESCRIPTION OF MODELS

Depending on the intended use of a model the description of the hydrologic models in the literature may or may not be adequate for the purpose of evaluating the usefulness of remote sensing capabilities in the operational use of the model. The amount of narrative description for each model in this report relates to the evaluation by the authors as to the usefulness of the published information for the purpose of this study. For all models,references on original and subsequent published material are included.

For all models a brief history of the model and its use is presented. Information on the type of concepts underlying the model are discussed as well as factors relating to the application of the model.

4. DIAGRAMS

The most important parts of the models for which remote sensing could be of greatest value are those dealing with snowmelt, soil moisture accounting and channel inflow computation. Since there are numerous methods for routing water within channels, those portions of the models are not considered in this review.

For each model a schematic diagram is presented. These have been designed to show inputs, processes, states, and outflows as shown in the legend for the diagrams in Figure 1-1. All parameters and states are identified. In addition, the solid arrows indicate flow of mass (liquid, solid, or vapor) in the model, dashed lines the flow of information, and in the case of the snowmelt model, a special dashed line to indicate heat flow.

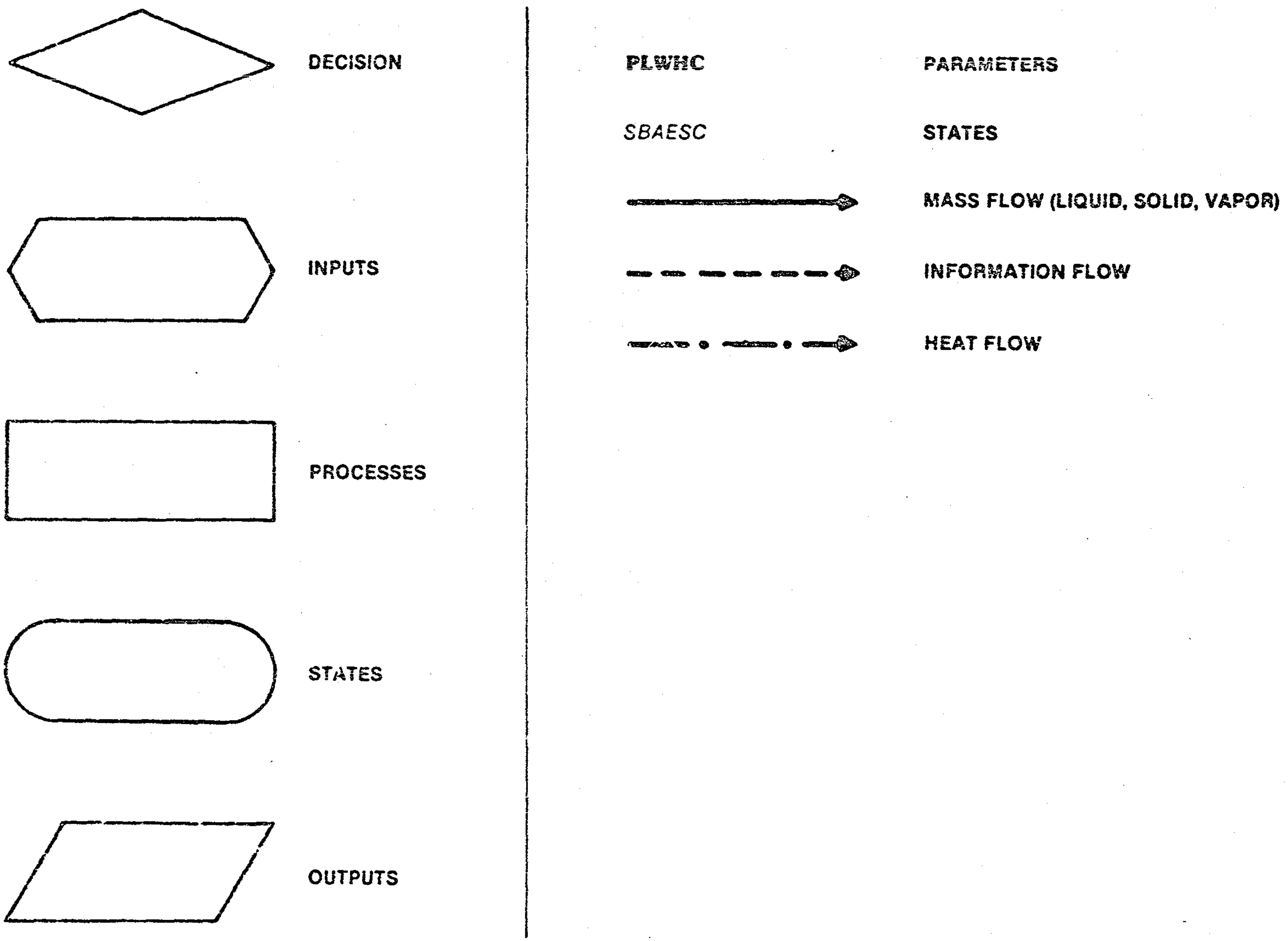

Figure 1-1. LEGEND FOR SCHEMATIC DIAGRAMS OF MODELS

The location of the various components in the diagram indicates the various levels of moisture zones (upper, lower, etc.) and the relative positioning with depth, the location of states, and operating processes.

5. ROLE OF PARAMETERS AND STATES

To assist in understanding the role of each parameter and state variable, three tables are presented. Definitions of parameters and state variables, the role of the parameters and the role of the states variables, respectfully, are tabulated in the tables for each model. In those tables, the role of the parameters and states are divided into several categories as follows:

GROUP 1 Runoff Components

- Immediate
- Surface
- Interflow
- Baseflow

GROUP 2 Soil Moisture Horizons

- Single zone
- Multiple zone
- Upper zone
- Lower zone

GROUP 3 Processes

- Infiltration
- Percolation
- Evaporation
- Interception
- Losses

Each parameter (and state variable) is assigned to the most appropriate category (primary) and to those categories where it plays a somewhat lesser role (secondary). These tables should be useful in identifying which parameters (state variables) are related to specific runoff components, soil moisture horizons, or hydrologic process. The information in the tables also give an immediate indication of the overall complexity of the model and which runoff components, process, and soil moisture horizons are modeled most precisely.

Information on the inputs to the model are covered in the written narrative for the model.

CHAPTER 2

ANTECEDENT PRECIPITATION INDEX (API) MODEL

1. HISTORY

The Antecedent Precipitation Index (API) approach was originally a rainfall/runoff relation for event modeling using coaxial graphical techniques (2). The continuous hydrograph synthesis model was developed by the U. S. Weather Bureau, now the U. S. National Weather Service (NWS), Hydrologic Research Laboratory in the late 1960s (3).

The primary purpose was to have a continous forecasting technique based on the proven API method for evaluating the newer continuous conceptual models then being developed. Such comparisons were reported by the NWS(4). A secondary purpose was to provide NWS field offices with a method for providing continuous forecasting for individual basins during periods when the flow consists of groundwater discharge with relatively small amounts of direct runoff.

The API is often considered to be a black box model, but in essence it can be considered as the forerunner of the present day conceptual models. The flow simulated by the model considers only two components, direct runoff and groundwater flow. Direct runoff is considered to represent channel precipitation, surface runoff, and subsurface (interflow) runoff. The groundwater flow is considered to be derived from the saturated groundwater aquifers.

The direct runoff component of the hydrograph is computed from precipitation by the use of a modified API type rainfall-runoff relation and a unit hydrograph. The groundwater discharge hydrograph is represented as a function of the direct runoff hydrograph.

The above hypothesis does not recognize the condition of depletion of groundwater supply to a point below that corresponding to zero channel inflow and is consequently applicable only to continuous streams. To use this approach with intermittent or ephemeral streams will require some modifications to the basic theory.

2. DESCRIPTION

The model consists of the following four parts:

- Relation for evaluating the groundwater recession coefficient
- Relation for expressing the groundwater as a function of the direct runoff hydrograph
- The rainfall-runoff relation
- Unit hydrograph

2.1 Groundwater Recession Coefficient

The first part of the model to be evaluated is a relation for expressing the groundwater recession coefficient as a function of groundwater discharge and week number. The daily coefficient is defined by

$$Kg=Q_2/Q_1 \qquad (1)$$

where Q_2 and Q_1 are the discharges at some time on two successive days when there is no direct runoff. To derive the relationship several years of historical mean daily hydrograph record are inspected to select periods meeting this criterion.

Equation (1) is solved for a very large number of pairs of discharge values. A curve through the points represents the average relation between Kg and discharge. The seasonal parameter is then introduced by correlating the deviations of the individual events from the curve with week number.

2.2 Groundwater Flow Hydrograph

Analyzing several years of historical mean daily streamflow data and applying Equation (2):

$$G_2 = \frac{(Z)(C_o)(Q_1+Q_2) + (G_1)(C_2-ZC_o)}{(1+ZC_o)} \qquad (2)$$

where

$$C_o = \frac{1}{(8K+1)}$$

$$C_2 = \frac{(8K-1)}{(8K+1)}, \text{ and}$$

$$K = -\frac{1}{Kg}$$

Equation (2) gives the groundwater hydrograph ordinates in terms of the preceding ordinate, G_1, and Points Q_1 and Q_2 on the total flow hydrograph; Z can be an assumed value or can be calculated from

$$Z = ZA + ZB(Q) \qquad (3)$$

where ZA and ZB are basin constants and Q is the total discharge. A third constant, ZC, is a limit that Z may not exceed.

2.3 Rainfall-Runoff Relation

The development of the rainfall-runoff part of the model consists of developing a conventional total storm relation and then converting it to the incremental type by evaluating the parameter RA in Equation (3)

$$FI = AI(RA)^{RI}, \tag{3}$$

where FI is the final index, AI is the antecedent index, and RI is the retention index. In this conversion several trial values of RA are used. With each value, all precipitation events are run through the relation and the total computed increments for each event is compared to the observed total runoff.

The incremental rainfall-runoff reation used in the API model is given in Figure 2-1.

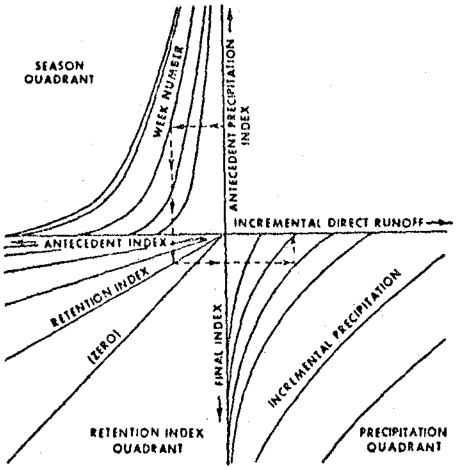

Figure 2-1. INCREMENTAL RAINFALL-RUNOFF RELATION.

In using the API type of relation, the precipitation of each unit time period (six hours normally) is converted to runoff on the basis of its own updated antecedent condition.

In the season quadrant, Figure 2-1, the state variable API is combined with a seasonal parameter, (week number) to produce an antecedent index (AI) which is intended to represent antecedent conditions completely. This seasonal effect is considered a process.

The precipitation quadrant in Figure 2-1 expresses direct runoff (an output) as a function of FI and incremental precipitation.

From the incremental direct runoff (a process), the groundwater inflow is computed based on Equation (2).

The groundwater output is combined with the incremental direct runoff to simulate the total basin streamflow.

In the retention index quadrant in Figure 2-1, the AI is combined with the retention index (RI) and results in a final index (FI).

Figure 2-2 is a schematic diagram of the complete model illustrating the states and outputs.

2.4 Parameters

Of the six parameters in the model, four (Kg, ZA, ZB, and ZC) relate to groundwater. The parameter week number is related primarily with evapotranspiration, and RA with interception losses. A list of parameters with definitions is shown in Table 2-1; primary and secondary roles of the parameters are shown in Table 2-2.

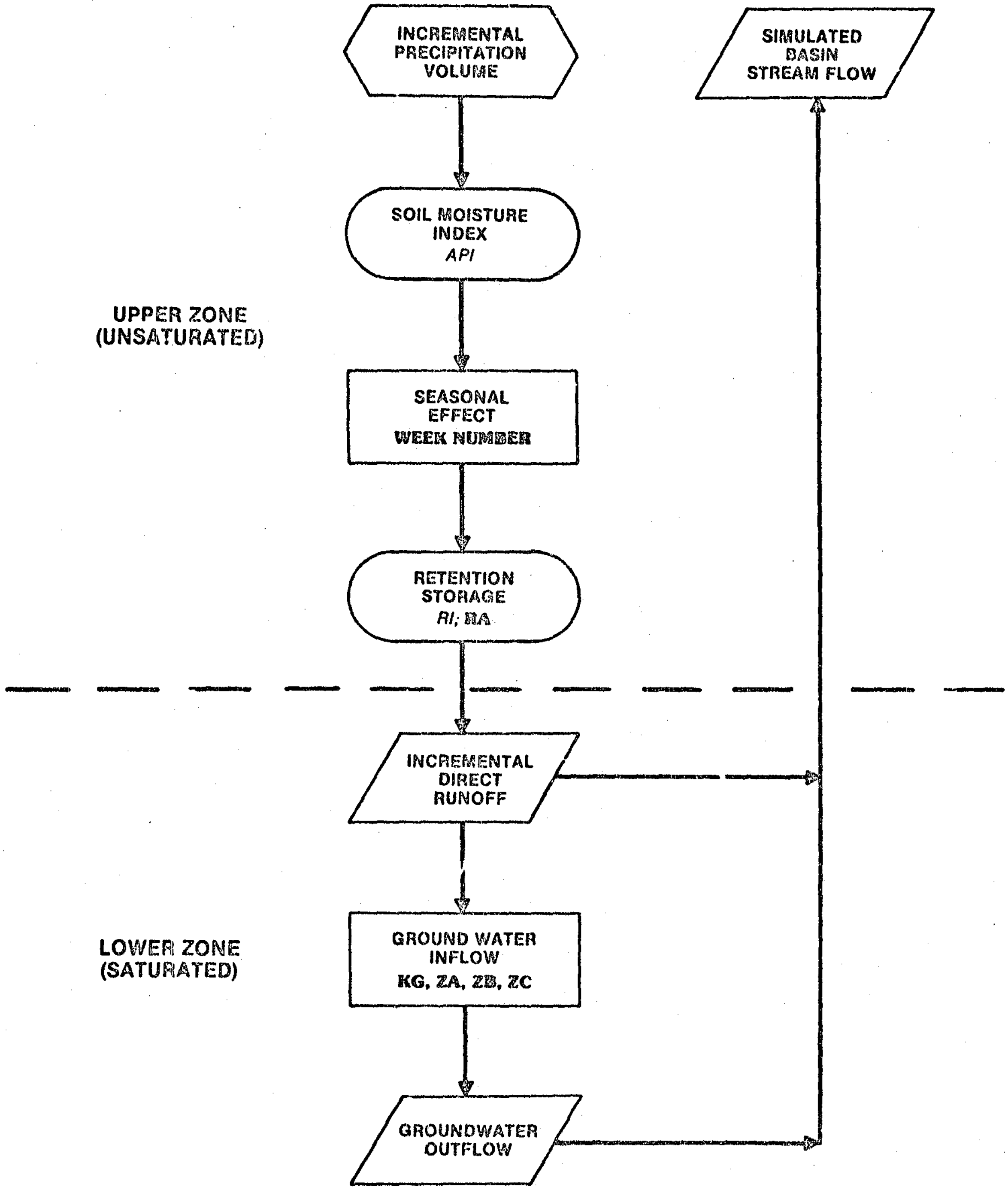

Figure 2-2. API MODEL SCHEMATIC DIAGRAM

Table 2-1. PARAMETERS (DEFINITIONS) API MODEL

Kg	Groundwater Recession Coefficient.
RA	Basin Constant.
WEEK NUMBER	Weeks of the Year Numbered Sequentially.
ZA	Basin Constant.
ZB	Basin Constant.
ZC	Basin Constant.

Table 2-2. ROLE OF PARAMETERS - API MODEL

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff		Week Number, RA
Interflow		
Baseflow	Kg, ZA, ZB, ZC	
SOIL MOISTURE HORIZON		
Single Zone		
PROCESSES		
Infiltration		Week Number
Percolation		
Evaporation	Week Number	
Interception	RA	Week Number
Losses		

2.5 States

The model has two state variables. The Antecedent Precipitation Index (API) is an index of soil moisture as described by Linsley et.al., (3). It is a function of precipitation and reflects the precipitation regime for about 1 month prior to the event.

The Retention Index (RI) is a short-term moisture index reflecting the presence of water in interception and depression storage. The roles of both states in the model are listed in Table 2-3.

2.6 Inputs

As noted, the model provides acceptable output using only one parameter, precipitation.

3. APPLICATION

The model has been applied to basins of various sizes. If significant changes in the physical characteristics of the basin have been made recently or are being anticipated, the manner in which these affect the hydrologic characteristics can be quantitatively estimated.

The model was not developed to include snowmelt. However, where snow exists, it is not ignored but is dealt with in a rudimentary but rational manner. The procedure is to adjust the precipitation record on the basis of temperature. Each period or record is categorized as liquid or solid. If solid, it is deleted from the record and added to snow cover. This snow cover is melted on the basis of temperature, and the melt figures are inserted into the precipitation record, which is then used as the model input.

Table 2-3. ROLE OF STATES - API MODEL

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff		API, RI
Interflow		
Baseflow		
SOIL MOISTURE HORIZON		
Single Zone	API	
PROCESSES		
Infiltration		
Percolation		
Evaporation		API
Interception	RI	
Losses		

CHAPTER 3

CREAMS MODEL

1. HISTORY

The CREAMS model (a field size scale model for Chemicals Runoff, and Erosion from Agricultural Management Systems) was completed in May 1980 by the staff of the Science and Education Administration - Agriculture Research of the U. S. Department of Agriculture (USDA) (5). CREAMS was developed to simulate the hydrology, erosion/sedimentation, and chemistry of field size tracts of land in order to evaluate nonpoint source pollution and to aid in implementing best management practices to limit nonpoint pollution. The model is designed to be applicable to tracts of land having a single land use, relatively homogeneous soils, spatially uniform rainfall, and single management practices (such as conservation tillage, terraces, etc.). Since the purpose of the model is to predict the degree of nonpoint source pollution resulting from agricultural practices, CREAMS major sophistication and emphasis is found in its erosion/sedimentation and chemistry submodels. Its hydrology submodel (which is the sole concern of this report) is a very simplified representation of the hydrologic cycle and incorporates only those components of the cycle that directly affect erosion, sedimentation, and chemical processes in agricultural systems.

2. DESCRIPTION

The CREAMS hydrology submodel is essentially a deterministic, lumped-input, lumped-parameter type model. It has only three components,which are for infiltration/runoff, percolation, and evapotranspiration. Figures 3-1 and 3-2 show the relation of these components for the model's two options. There are no components for interflow, baseflow, or channel routing. Therefore, the model sees precipitation as either running off the land and leaving the system or remaining as infiltration. The infiltration water then either returns to the atmosphere through evapotranspiration or is lost to the system as seepage below the root zone. This is a simple representation, but it is sufficiently complex for the pollution prediction purposes of the model.

2.1 Infiltration/Runoff

The infiltration/runoff component of the CREAMS model has two options, which are based on the type of input data that is available.

Option 1 accepts total daily rainfall as input and uses the Soil Conservation Service Curve Number (SCS-CN) method for calculating daily runoff. The SCS-CN method is based on a family of empirically developed curves that predict daily runoff from daily precipitation for various soil types, land uses, treatment practices, etc. The method can be used by determining the recommended Curve Number (CN) for the soil type, land use, treatment practice etc., which is of interest and then reading from that numbered curve the predicted runoff directly from the daily precipitation. A complete description of this method may be found in the National Engineering Handbook of the USDA (6).

Option 2 takes breakpoint rainfall for its input and uses the Green and Ampt infiltration relation (7) for predicting breakpoint infiltration. This means that Option 1 determines runoff and assumes that the remaining water infiltrates while Option 2 calculates infiltration and assumes that the remainder runs off. Option 2 provides perhaps a more accurate representation of the actual physical processes, but when breakpoint rainfall data are not available, Option 1 can give a reasonable approximation of runoff and infiltration.

Both options have a simple snowmelt component that assumes that precipitation occurring on days with an average temperature less than freezing is snow and hence adds it to any existing snow pack. When the average temperature is above freezing the daily snowmelt (M_i) is determined by

$$M_i=0.18T$$

where

T=average daily temperature in °C

until the snow pack is exhausted. All snowmelt is then added to the top layer's soil moisture, and no provision being made for the snowmelt to run off. This snowmelt representation is quite simplistic, but a better approximation is not possible without detailed temperature and radiation data, which are available for only a few sites in the United States.

2.2 Soil Moisture Zones

After water from rainfall or snowmelt has entered the soil, the model assumes that it either percolates down to subsequent soil layers or returns to the atmosphere through evaporation or transpiration. Both of the options use essentially the same equations for percolation, evaporation, and plant transpiration. However, the division of the soil strata into layers

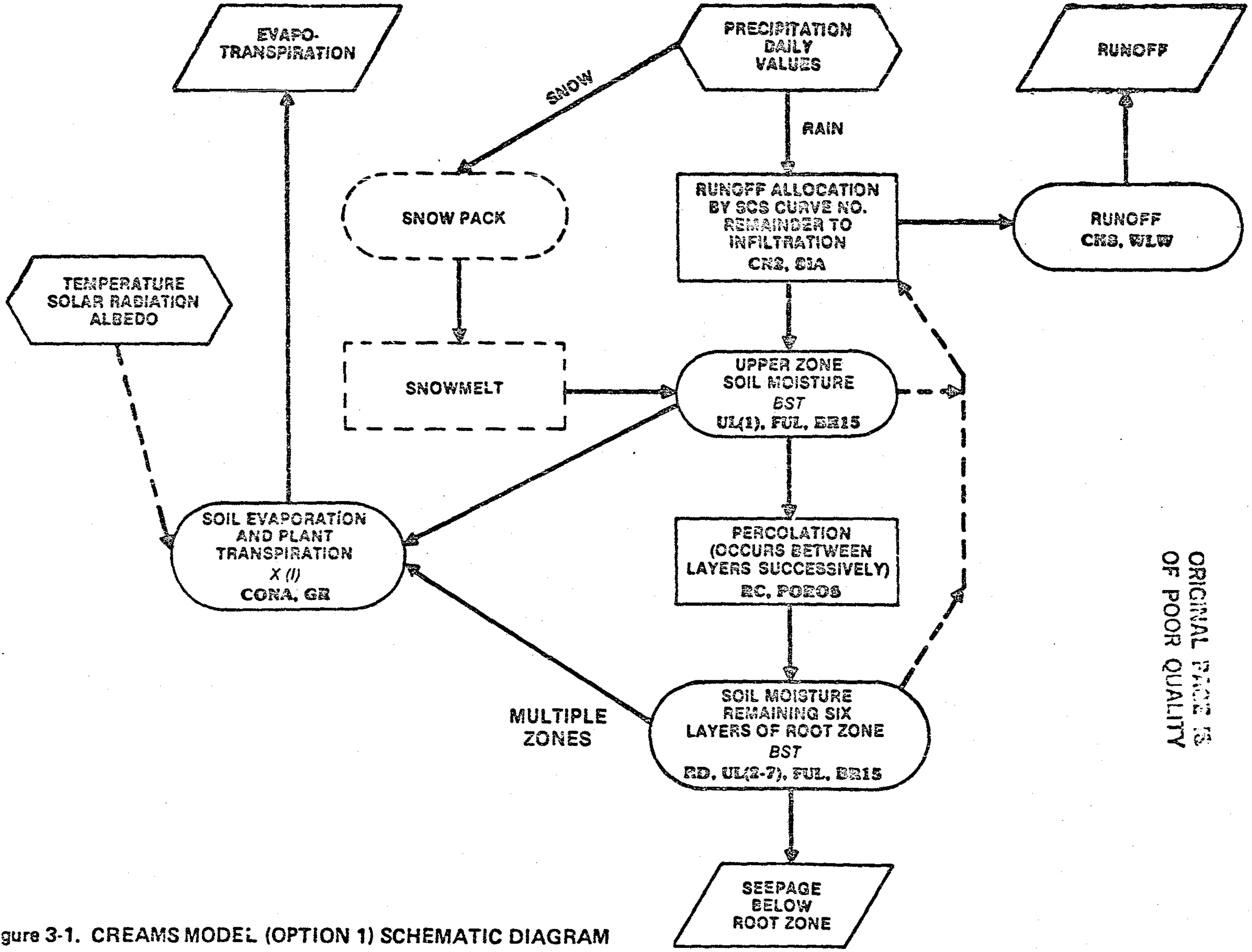

Figure 3-1. CREAMS MODEL (OPTION 1) SCHEMATIC DIAGRAM

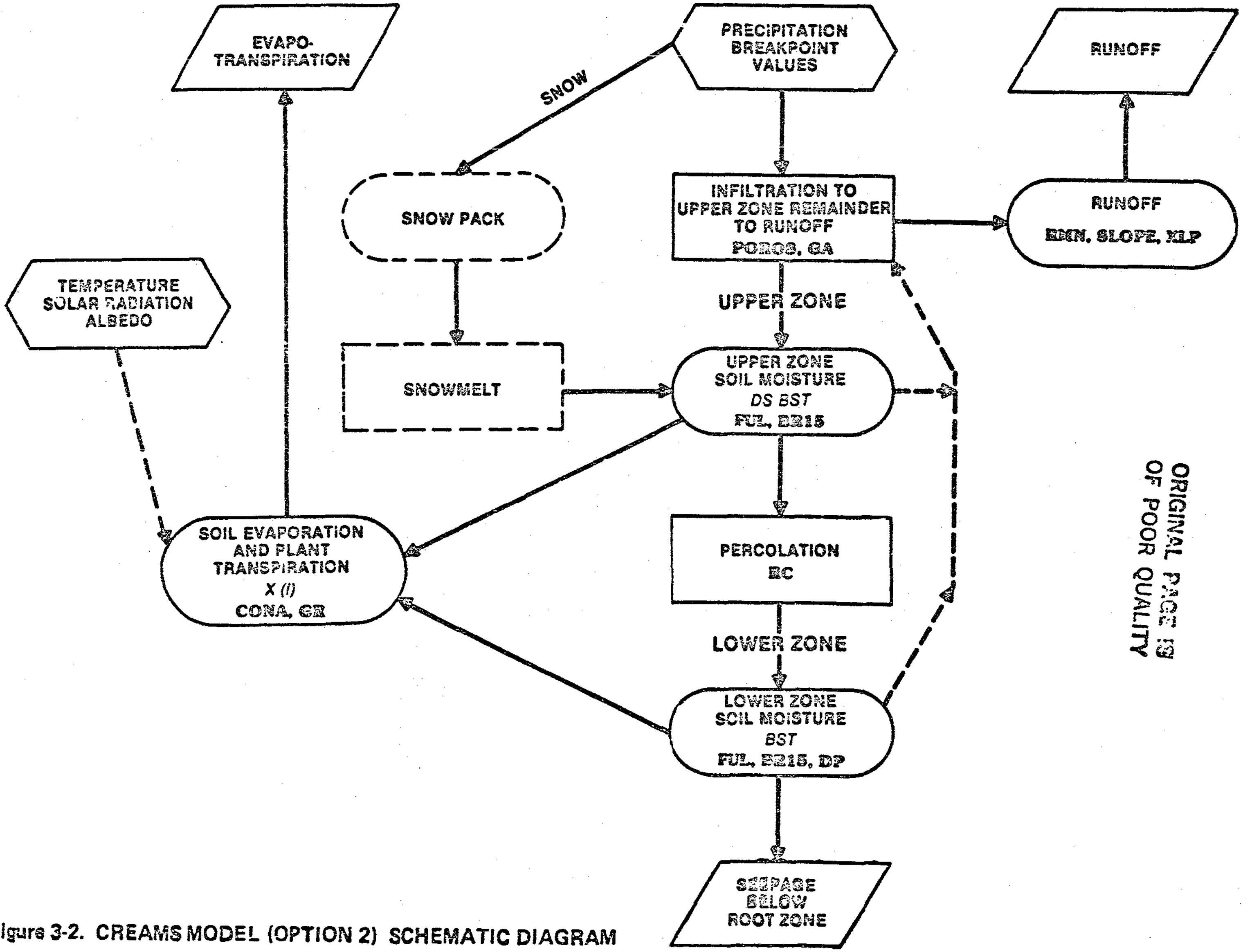

Figure 3-2. CREAMS MODEL (OPTION 2) SCHEMATIC DIAGRAM

for percolation and transpiration purposes is different for the two options. Option 1 divides the root zone into seven separate layers each having its own moisture content. This is a departure from the standard SCS-CN method, which assumes only one soil layer. The multilayer modification is made to allow the surface soil layer to be wetter or drier than the remaining soil layers. This in turn gives perhaps a better prediction of SCS-CN runoff. Option 2 divides the root zone into only two layers: an upper layer that controls infiltration and direct evaporation and a lower layer that controls infiltration below the root zone. The surface layer controls infiltration through a state called "surface depth" (DS), which is calculated for the upper layer according to its relative saturation at the beginning of each storm. The "surface depth" value represents the available porosity of the soil's surface to infiltration. It can be thought of as the infiltration capacity of the upper soil layer expressed in inches of water.

2.3 Percolation and Evapotranspiration

The model allows percolation to occur when soil moisture is greater than the specified field capacity. Direct evaporation is considered to occur only from the surface soil layer. However, transpiration can occur from all soil layers according to the actual root depth. The daily variation of root depth, transpiration activity and shading (all of which directly affect evapotranspiration) is represented by a leaf area index curve, State Variable X(I). This curve indicates the ratio of leaf area to land area on a daily basis,and the magnitude of the above-mentioned effects is assumed to be proportional to the leaf area index. The model can also modify the leaf area index curve to simulate the effects of drought on plant activity if soil moisture conditions drop below the 15-bar tension level (BR15)defined in Table 3-1.

Table 3-1. PARAMETERS (DEFINITIONS) CREAMS MODEL (OPTION 1)

*BR15	"Immobile" soil moisture content at 15 bars tension.
CHS	Channel slope.
CN2	The SCS curve number specified for the land use, treatment practice, soil group, etc., being considered for modeling, assuming an Antecedent Moisture Condition II (AMC II).
*CONA	Soil evaporation parameter that indicates the soil water transmission characteristics of the surface layer of soil.
*FUL	Portion of plant-available water storage filled at field capacity.
*GR	Winter cover factor that reduces soil evaporation as a result of ground cover. Varies from 0.5 for excellent cover to 1.0 for bare soil.
*POROS	Soil porosity; the average porosity of all soil layers found in the maximum rooting depth.
*RC	Fraction of pore space filled at field capacity.
RD	Maximum rooting depth in inches.
SIA	Initial abstraction coefficient for the SCS-CN method. It indicates the amount of interception, infiltration, and surface storage that occurs before runoff begins. Unless there is very strong evidence to the contrary, the value 0.2 should be used.
UL(1-7)	Maximum plant-available water storage in each of the seven soil layers of the maximum rooting depth. It is the difference between the total soil porosity and the BR15 water content.
WLW	Watershed length-to-width ratio.

*(common to both options)

2.4 Parameters

The parameters for CREAMS hydrology options are listed with their definitions in Table 3-1 and 3-2. Those common to both options are indicated in the listings. As can be seen from these tables, most of the CREAMS parameters can be directly measured or at least can be obtained from standard tables for land use, treatment practice, soil group, etc. This allows the CREAMS model to be used directly without lengthy calibration iterations to match known data. Tables 3-3 and 3-4 classify each of the parameters of Options 1 and 2 into primary or secondary categories according to components of the hydrologic cycle. A primary classification indicates the component that a particular parameters most affects. Secondary classifications show other components on which a parameters has lesser effects.

2.5 States

Only two types of states are involved in the CREAMS model; those that represent soil moisture conditions and the leaf area index, which represents the state of plant development and activity. Option 1 keeps tract of soil moisture conditions through a BST state variable for each of the seven soil layers. Option 2 employs a single BST state variable for soil moisture in the upper and lower soil moisture zones and a separate state variable, DS, for moisture in the surface soil moisture layer. Both options use the state variable leaf area index, X(I), to represent actual rooting depth, plant development, and transpiration activity to calculate evapotranspiration. The above states are all defined in Table 3-5. The primary and secondary role of the states in the hydrologic cycle are listed in Tables 3-6 and 3-7 for Options 1 and 2, respectively.

Table 3-2. PARAMETERS (DEFINITIONS) CREAMS MODEL (OPTION 2)

*BR15	"Immobile" soil moisture content at 15 bars tension.
*CONA	Soil evaporation parameters that indicate the soil water transmission characteristics of the surface layer of soil.
DP	Depth of root soil zone.
*FUL	Portion of plant-available water storage filled at field capacity.
GA	Effective capillary tension for the surface layer of soil.
*GR	Winter cover factor that reduces soil evaporation as a result of ground cover. Varies from 0.5 for excellent cover to 1.0 for bare soil.
*POROS	Soil porosity; the average porosity of all soil layers found in the maximum rooting depth.
*RC	Fraction of pore space filled at field capacity.
RMN	Manning roughness number for the field surface.
SLOPE	Average slope of the field.
XLP	Length of flow plane.

*(common to both options)

Table 3-3. ROLE OF PARAMETERS - CREAMS MODEL (OPTION 1)

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	CHS, WLW	CN2, SIA
Interflow		
Baseflow		
SOIL MOISTURE HORIZONS		
Multiple Zones	UL(1-7), FUL BR15	POROS
PROCESSES		
Infiltration	CN2, SIA	UL(1-7)
Percolation	RC, POROS	FUL, CN2, UL(1-7)
Evaporation	CONA, GR	BR15, RD, FUL
Interception		SIA
Losses	RD	

Table 3.4 ROLE OF PARAMETERS - CREAMS MODEL (OPTION 2)

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	RMN, SLOPE, XLP	
Interflow		
Baseflow		
SOIL MOISTURE HORIZONS		
Upper Zone	FUL, BR15	POROS
Lower Zone	FUL, BR15	POROS
PROCESSES		
Infiltration	POROS, GA	
Percolation	RC	FUL, POROS
Evaporation	CONA, GR	DP, FUL
Interception		
Losses	DP	

Table 3-5. STATE (DEFINITIONS) CREAMS MODEL

*BST	Fraction of plant-available water storage filled when simulation begins. It represents the soil's water content above the BR15.
*X(I)	Leaf area index, which indicates the area of plant leaves relative to soil surface area. Up to 366 values may be specified to describe the daily variation of the leaf area index.
**DS	Depth of surface soil layer. This state represents the available infiltration capacity of the soil surface and is made to vary with soil moisture content.

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* Common to both options
**Option 2 only

Table 3-6. ROLE OF STATES - CREAMS MODEL (OPTION 1)

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff		BST
Interflow		
Baseflow		
SOIL MOISTURE HORIZONS		
Multiple Zones	BST	
PROCESSES		
Infiltration		BST
Percolation		BST
Evaporation	X(I)	BST
Interception		
Losses		X(I)

Table 3-7. ROLE OF STATES - CREAMS MODEL (OPTION 2)

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff		DS, BST
Interflow		
Baseflow		
SOIL MOISTURE HORIZONS		
Upper Zone	BST, DS	
Lower Zone	BST	
PROCESSES		
Infiltration		BST, DS
Percolation		BST
Evaporation	X(I)	BST
Interception		
Losses		X(I)

2.6 Inputs

There are three basic inputs to the CREAMS model: precipitation, temperature, and radiation. The model provides two options for the types of precipitation data available. The perhaps more accurate option (Option 2) accepts for its input breakpoint rainfall, which consists of the times at which changes in rainfall rate occur and the corresponding rates which are established. Breakpoint data of this type are difficult to obtain for most of the United States. Therefore, Option 1 is also provided; it predicts surface runoff from total daily rainfall based on the empirical daily precipitation/runoff relations developed by the SCS.

Monthly mean air temperature and mean solar radiation are also required inputs and are used to calculate daily evapotranspiration. Daily values of temperature and radiation are calculated from the mean monthly values fitted to an annual curve by Fourier analysis. Long-term averages or actual monthly data for the specified period of simulation can be used. Temperature data are regularly published by the National Weather Service. However, current solar radiation data are not readily available. Therefore, it is recommended that the monthly average daily radiation data found in publications such as the Climatic Atlas of the United States be used.

3. APPLICATION

The CREAMS model is designed to be applicable to tracts of land having a single land use, relatively homogeneous soils, spatially uniform rainfall,and single management practices (such as conservation tillage, terraces, etc.). In other words it is a field or at most a farm scale model. CREAMS cannot be directly applied to watershed size tracts of land. However, small watersheds may be divided according to land use, etc., and then the model can be run on each of the divisions separately and the resulting outputs added to obtain the watershed's hydrologic response. This method, is too lengthy and complex for medium and large size watersheds.

CREAMS has been tested with relative success on research lysimeters and small watersheds in Texas, Ohio, Georgia, Oklahoma, Nebraska, Arizona, New Mexico, West Virginia, Mississippi, Iowa, and Montana (5). The results relating to surface runoff must be considered good since no attempt was made to calibrate the model by successive iteration runs. (One of CREAMS major development criteria was the employment of observable parameters so that calibration iterations could be minimized or preferrably eliminated.) It must be remembered, however, that the major purpose of CREAMS is not the total simulation of hydrologic processes but the prediction of nonpoint-source pollution, an area to which it has closer correlation.

CHAPTER 4

NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM MODEL

1. HISTORY

The National Weather Service River Forecast System (NWSRFS) is a comprehensive collection of hydrologic techniques needed by the NWS River Forecast centers to perform their operational functions. An initial publication (4) contains information on all of the data processing and hydrologic models in use at that time. In that publication, the basic soil-accounting model was a modification of the Stanford Watershed Model IV.

In 1973, a soil moisture accounting system was developed in the Sacramento, California, River Forecast Center by Burnash, el.al. (8). The basic soil moisture and accounting technique now used in NWSRFS is the Sacramento Model with only slight modification.

The NWS Hydrologic Services Division maintains and publishes a loose-leaf users manual on the NWSRFS. The present procedures are based on an operational table concept that permits a field forecast office to have a wide range of choices in selecting techniques best suited to his forcast area. For example, it is possible to use the Sacramento model for one basin (where data are adequate) and an API model for another. In addition, channel routing could be accomplished by lag and K methods or by use of the SSARR model (Chapter 7). Any hydrologic model or procedure routine can be placed in the operational table and used in conjunction with others.

2. DESCRIPTION

The Sacramento model is a deterministic lumped input, lumped parameter type model. However, a basin is divided into pervious, variable impervious,and impervious areas.

2.1 Soil Moisture Zones

Two soil moisture zones, upper and lower, are identified. (Figure 4-1). Each is thought of as storing moisture in two forms, "tension water" and "free water." The amount of water in each of these storages represents a state of the model.

The model has a rather complex groundwater flow withdrawal function which allows for accurate simulation of the streamflow during low flow periods.

2.2 Percolation

The flow of water from the upper zone to the lower zone is expressed by a formula considered to be the "heart" of the model (Figure 4-2). In this formula, a percolation rate "PBASE" is defined as the maximum lower zone flowthrough rate. This rate is numerically equal to the outflow rate from the lower zone under saturated conditions.

Under conditions of unlimited moisture availability in the upper zone, the actual percolation rate may vary between "PBASE" when the lower zone is full and a maximum value that would occur if the lower zone were empty. This maximum rate is defined by a percolation parameter, "ZPERC", such that the maximum rate is equal to the product of "PBASE" and "1+ZPERC."

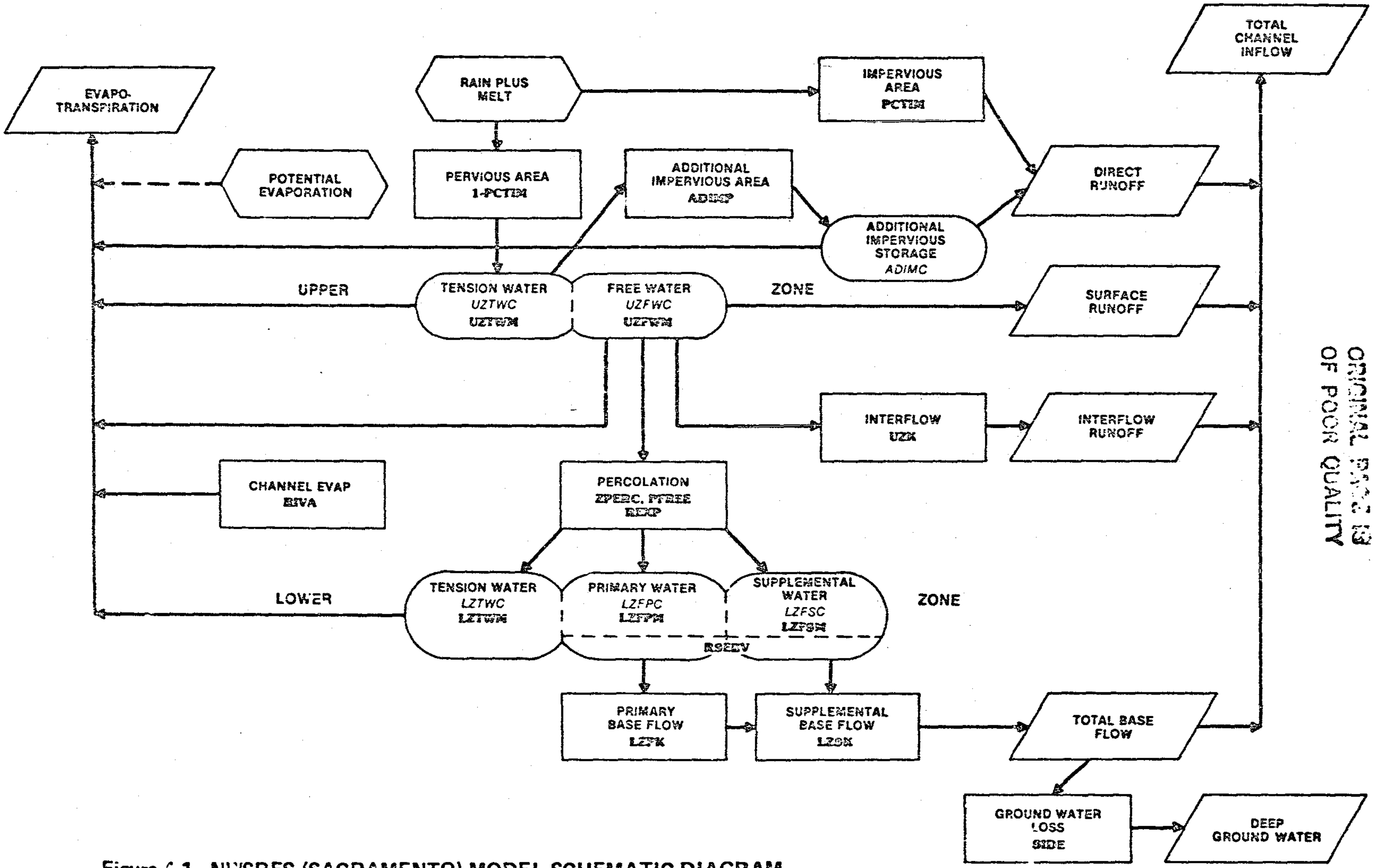

Figure 4-1. NWSRFS (SACRAMENTO) MODEL SCHEMATIC DIAGRAM

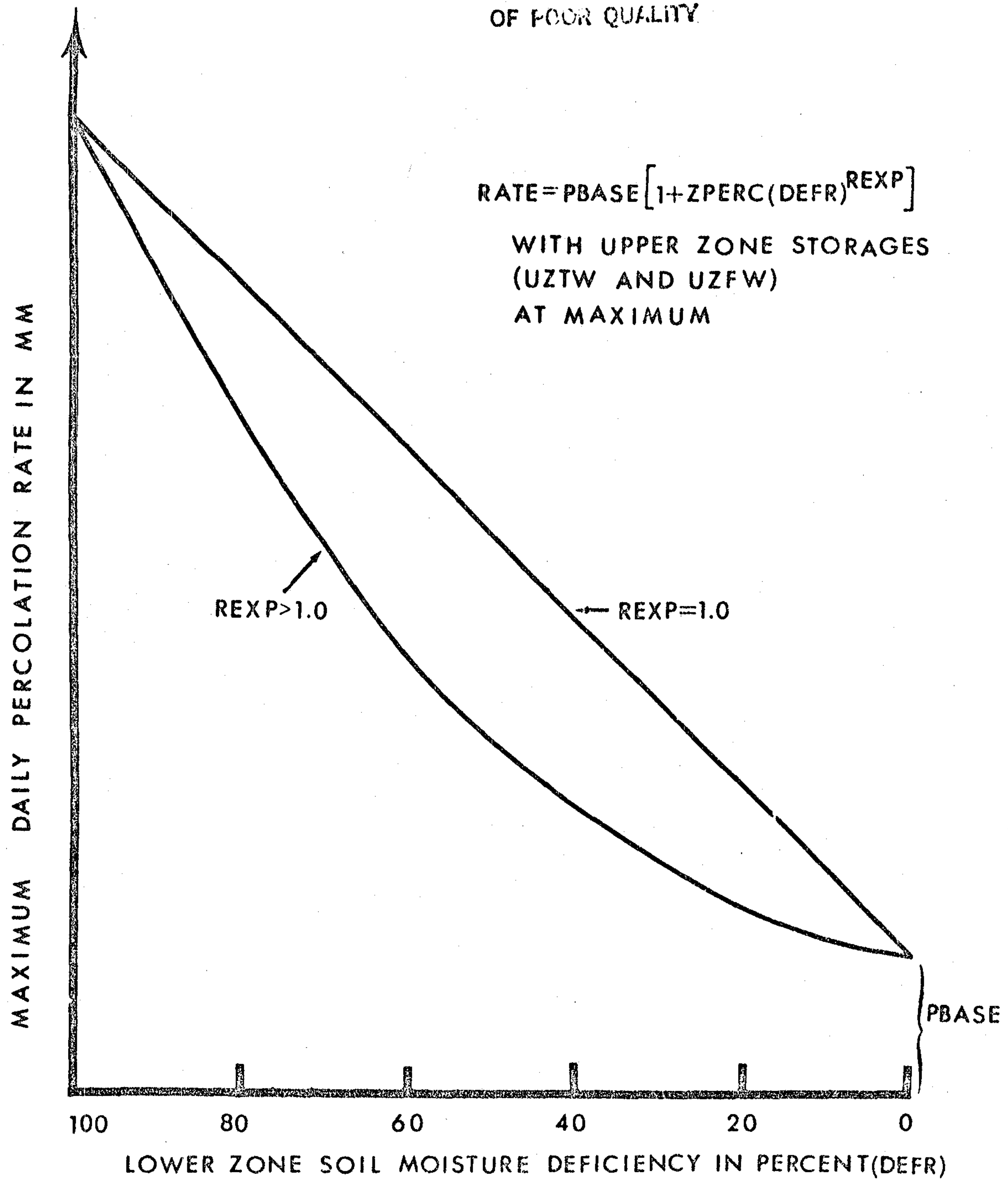

Figure 4-2. PERCOLATION REPRESENTATION NWSRFS MODEL
[After Peck, 1976 (9)]

The variation of percolation rate between the minimum and maximum values thus defined occurs as a function of the lower zone deficiency ratio (DEFR). This ratio is simply the difference between lower zone contents and capacity divided by the capacity. The ration may vary from zero (lower zone full) to unity (lower zone empty). In its computation, both tension and free water are considered. In order to permit the effect of the deficiency ratio to be nonlinear and to vary among catchments, a parameter "REXP," is applied to the ratio as an exponent. Thus, the actual percolation rate under conditions of unlimited moisture availability in the upper zone is given by

$$\text{RATE} = \text{PBASE}\ (1 + \text{ZPERC} * \text{DEFR}^{\text{REXP}}).$$

The true percolation rate is equal to the product of "RATE" and the "upper zone driving force," which is the ratio of upper zone free water contents to upper zone free water capacity. Thus, the percolation will be zero if upper zone free water is empty and equal to "RATE" if the upper zone is full.

The formula involves eight model parameters. Two of them, ZPERC and REXP, appear only in this formula. The remaining six serve their primary purpose in other parts of the model. Four model parameters related to storages in both zones also appear. The formula interacts with other model components in such a way that it controls the movement of water in all parts of the soil profile, both above and below the percolation interface and is, in turn, controlled by the movement in all parts of the profile.

2.3 Parameters

The soil moisture accounting portion of the Sacramento model exclusive of those associated with evapotranspiration demand, involves 16 parameters, which are listed in Table 4-1 with definitions. All parameters are also identified in Figure 4-1. Detailed information on parameters and calibration of the model have been discussed by Peck (9). In Table 4-2 each parameter is assigned to a primary category (to which it best belongs) and a secondary category that it impacts.

2.4 States

The six states of the model are defined in Table 4-3. The primary and secondary role of states in the model with respect to the runoff, soil moisture horizons, and processes are listed in Table 4-4.

2.5 Inputs

The two required inputs are precipitation and some estimate of average values for potential evaporation. A continuous record of 6-hour basin mean precipitation normally is required, but amounts for any ΔT divided evenly into 24 hours can be used. The NWSRFS users manual contains procedures for deriving these means from any combination of recording and daily precipitation gages in and around the basin.

The model uses for its evapotranspiration demand the product of potential evaporation (PE) and a seasonal correction curve that is optimized as part of the model. The PE record can be day-by-day-computed PE (from pan measurements or meteorological data) or a curve representing the long-term averages of these figures.

Table 4-1. PARAMETERS (DEFINITIONS) NWSRFS MODEL

ADIMP	That fraction of the basin that becomes impervious as all tension water requirements are met.
LZFPM	Maximum capacity of lower zone primary free water storage.
LZPK	Lateral drainage rate of lower zone primary free water expressed as a fraction of contents per day.
LZFSM	Maximum capacity of lower zone supplemental free water storage.
LZSK	Lateral drainage rate of lower zone supplemental free water expressed as a fraction of contents per day.
LZTWM	Maximum capacity of lower zone tension water.
PCTIM	Fraction of impervious basin contiguous with stream channels.
PFREE	The percentage of percolation water that directly enters the lower zone free water without a prior claim by lower zone tension water.
RSERV	Fraction of lower zone free water not available for transpiration purposes (incapable of resupplying lower zone tension water).
REXP	An exponent determining the rate of change of the percolation rate as the lower zone deficiency ratio varies from 1 to 0 (1 = completely dry; 0 - lower zone storage completely full)
RIVA	Fraction of basin covered by riparian vegetation.
SIDE	The ratio of unobserved to observed baseflow.
UZFWM	Maximum capacity of upper zone free water.
UZK	Lateral drainage rate of upper zone free water expressed as a fraction of contents per day.
UZTWM	Maximum capacity upper zone tension water.
ZPERC	A fraction used to define the proportional increase in percolation from saturated-to-dry lower zone soil moisture conditions. This parameter, when used with other parameters, indicates the maximum percolation rate possible when upper zone storages are full and the lower zone soil moisture is 100 percent deficient.

Table 4-2. ROLE OF PARAMETERS - NWSRFS MODEL

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff	PCTIM, ADIMP	UZTWM, LZTWM
Surface Runoff		UZFWM
Interflow	UZK	UZFWM, ZPERC, REXP, LZFPM, LZFSM, LZSK, LZPK
Baseflow	LZPK, LZSK	LZFPM, LZFSM
SOIL MOISTURE HORIZONS		
Upper Zone	UZTWM, UZFWM	UZK, PFREE, ZPERC, REXP, LZFPM, LZPK, LZFSM, LZSK
Lower Zone	LZTWM, LZFPM, LZFSM, RSERV	LZPK, LZSK, PFREE, ZPERC, REXP
PROCESSES		
Infiltration		UZTWM, UZFWM
Percolation	PFREE, ZPERC, REXP	LZFPM, LZSK, LZFSM, LZSK, UZTWM, UZFWM
Evaporation	RIVA	ADIMP, UZTWM, UZFWM, LZTWM, RSERV
Interception		UZTWM
Losses	SIDE	

Table 4-3. STATES (DEFINITIONS) NWSRFS MODEL

ADIMC	Additional impervious area.
LZFPC	Lower zone free primary water storage.
LZFSC	Lower zone free supplemental water storage.
LZTWC	Lower zone tension water storage.
UZFWC	Upper zone free water storage.
UZTWC	Upper zone tension water storage.

Table 4-4. ROLE OF STATES - NWSRFS MODEL

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff	ADIMC	
Surface Runoff		UZFWC
Interflow		UZFWC
Baseflow		LZFPC, LZFSC
SOIL MOISTURE HORIZONS		
Upper Zone	UZTWC, UZFWC,	
Lower Zone	LZTWC, LZFPC, LZFSC	
PROCESSES		
Infiltration		UZTWC, UZFWC
Percolation		UZTWC, UZFWC, LZTWC, LZFSC, LZFPC
Evaporation		UZTWC, UZFWC, LZTWC, ADIMC
Interception		UZTWC
Losses		LZFPC, LZFSC

3. APPLICATION

The NWS uses a combination of manual and automatic optimization techniques (10) for calibration of the model. As with any conceptual model, considerable hydrologic skill is required to produce a set of parameters that "best fit" the physical characteristics of the basin. The length of the data base required for adequate calibration depends on a number of factors including the hydroclimatic characteristics of the catchment and the amount of hydrologic activity during the period in question. In general, the data base should be long enough to represent both extremely dry and extremely wet conditions and should reflect current land use conditions.

A basin may be divided into separate areas with a set of parameters fitted for each area. For example, a basin may be divided into forested and nonforested areas. Division of a basin is especially of value when the NWSRFS snow accumulation and ablation model is used in conjunction with the soil moisture and accounting model (Chapter 8). For high elevation basins in the West, a division is generally made between areas of heavy continuous snow cover and the lower valleys were snow cover is intermittent.

The model has been applied successfully to small research basins 7.3 km^2 (2.8 mi^2) and to a basin as large as the Sanaga River in the Republic of Cameroon [131,500 Km^2 (50,772 Mi^2)]. The NWS normally applies it to operational basins ranging from 500 Km^2 (200 mi^2) to 2500 Km^2 (1000 mi^2).

CHAPTER 5

STORAGE, TREATMENT, OVERFLOW, RUNOFF MODEL (STORM)

1. HISTORY

The STORM model was originally developed as a means to economically assess the need for urban stormwater runoff treatment on a continuous basis. The original version of the program was completed in January 1973 by Water Resources Engineers, Inc. (WRE) of Walnut Creek, CA., while under contract with the Hydrologic Engineering Center (HEC) (11). Parts of the program had been previously developed by WRE for the Environmental Protection Agency and the City of San Francisco.

2. DESCRIPTION

2.1 Type

The STORM model is a "grey-box." It does not solve basic differential equations that govern the basic rainfall/runoff processes. The model is based primarily on continuity of mass and various coefficients that govern whether water runs off, infiltrates, or simply disappears (is lost).

STORM provides a method of analysis to estimate the quantity and quality of runoff from small, primarily urban, watersheds. Nonurban areas may also be considered. Land surface erosion for urban and nonurban areas is computed in addition to the basic water quality parameters of suspended and settleable solids, biochemical oxygen demand (BOD), total nitrogen (N), and orthophosphate (PO_4). The purpose of the analysis is to aid in the selection of storage and treatment facilities to control the quantity and quality of urban storm water runoff and land surface erosion. Only the rainfall/runoff portions of the model are considered here.

2.2 Components

The components of STORM are illustrated in Figure 5-1.

2.2.1 Soil Moisture Zones

The STORM model specifically accounts only for moisture retained on the ground surface. A value for depression storage (a model state) is updated on the basis of evaporation and the number of dry days since a previous storm.

2.2.2 Soil Moisture Accounting

No soil moisture accounting is done in the STORM model although surface depression storage is considered.

2.2.3 Percolation-Infiltration

The mechanisms of percolation and infiltration are not specifically modeled in the older reversions of STORM. Runoff coefficients (C_u) are assigned to basin subareas. The coefficients determine what percent of precipitation runs off or infiltrates/percolates. Infiltrated/percolated water is actually a loss since no means are provided for routing the water and returning it to surface flow. New versions allow the user to substitute the SCS curve number method of determining infiltration(11). The reader should refer to the CREAMS model description (Chapter 3, Section 2.1) for information on the curve number method.

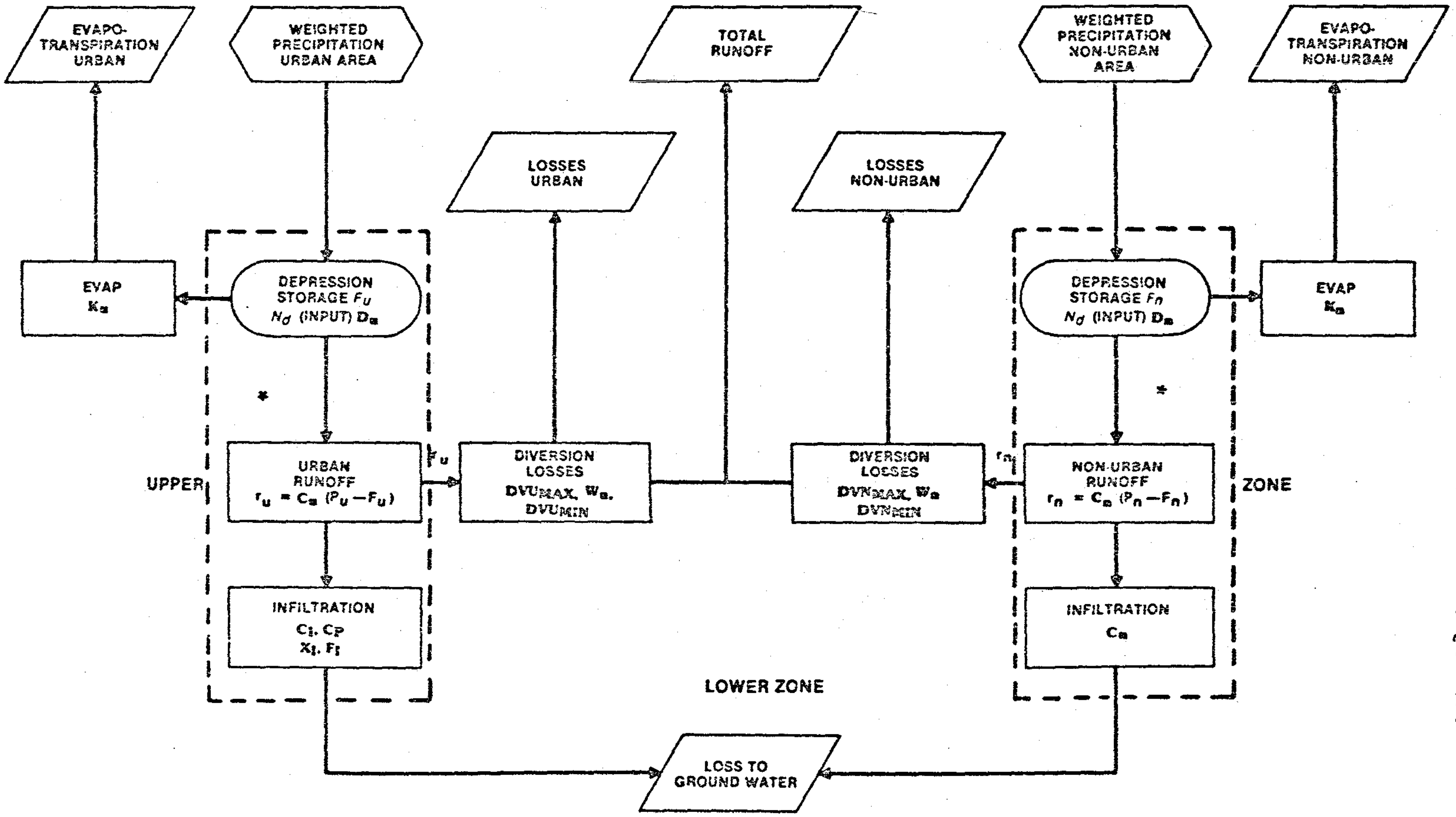

Figure 5-1. STORM MODEL SCHEMATIC DIAGRAM

*Depression storage, and runoff/infiltration portion of model may optionally be done by the SCS curve number method.

2.2.4 Surface Runoff and Diversions

Runoff calculations are carried out by two nearly identical submodels (Figure 5-1). Runoff from urban areas is computed by one submodel, and runoff from nonurban areas is computed by the other. The two results are added to obtain total runoff.

Both the urban and nonurban submodels make no provision for "routing." That is, the outflow hydrographs mirror the rainfall inputs modified only slightly by the water quality storage routine (not considered here). Provisions are made, however for "diversions," which are sinks of water. Water diverted disappears from consideration.

2.3 Parameters

The STORM model has 16 basic parameters, which are listed and defined in Table 5-1. The parameters are also identified in Figure 5-1. In Table 5-2, each parameters is assigned to a primary category (to which it most belongs) and to a secondary category that it impacts.

2.4 States

STORM has only two state variables, F_u and F_n, the current depression storage in the urban and nonurban areas, respectively. Table 5-3 shows that the two variables are primarily related to the surface runoff and in a secondary manner to infiltration.

2.5 Inputs

The primary input to the STORM model is weighted basin precipitation. Provisions are also made to use snowmelt as

Table 5-1. PARAMETERS (DEFINITIONS) STORM MODEL

C_I	Runoff coefficient of I^{th} impervious segment of urban area.
C_n	Composite runoff coefficient, nonurban area.
C_p	Runoff coefficient of I^{th} pervious segment of urban area.
C_u	Composite runoff coefficient, urban.
D_n	Maximum depression storage, nonurban.
D_u	Maximum depression storage, urban.
DVN_{max}	Runoff at which diversion begins, nonurban.
DVN_{min}	Runoff at which diversion peaks, nonurban.
DVU_{max}	Runoff at which diversion begins, urban.
DVU_{min}	Runoff at which diversion peaks urban.
F_I	Fraction of I^{th} land use area that is pervious.
K_n	Recession factor (evaporation from depression storage), nonurban.
K_u	Recession factor (evaporation from depression storage), urban.
X_I	Area of land use or fraction of total urban area.
W_n	Fraction of runoff diverted, nonurban.
W_u	Fraction of runoff diverted, urban.

Table 5-2. ROLE OF PARAMETERS - STORM MODEL

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	C_u, C_n	C_I, C_p, X_I, F_I, K_u, K_n
Interflow		
Baseflow		
SOIL MOISTURE HORIZON		
Single Zone		
PROCESSES		
Infiltration	C_I, C_p, X_I, F_I	
Percolation		
Evaporation	K_u, K_n	
Interception		
Losses	W_u, DVU_{max}, DVU_{min}, W_n, DVN_{max}, DVN_{min}	

Table 5-3. ROLE OF STATES - STORM MODEL

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	F_u, F_n	
Interflow		
Baseflow		
SOIL MOISTURE HORIZON		
Single Zone		
PROCESSES		
Infiltration		F_u, F_n
Percolation		
Evaporation		
Interception		
Losses		

input based on degree-day formulas. Daily temperatures then become a model input.

3. APPLICATION

STORM is designed for application to small (400 to 500 mi^2 or less) basins composed primarily of urban or combined urban-rural land use. It is a continuous simulation model designed for use with many years of continuous hourly precipitation records or precipitation and temperature records.

STORM was not designed to be a highly accurate rainfall/runoff model. It was designed to give reasonable runoff estimates and to provide an economical means of evaluating various land use/storage/treatment methods for controlling urban runoff pollution.

An important aspect of the STORM model is its extensive areal segmentation. The user may divide the area being modeled into many land use and runoff categories. This division of area by use types is important when considering the use of remotely sensed data since land classification by remote sensing is highly developed.

CHAPTER 6

THE STANFORD WATERSHED MODEL IV

1. HISTORY

A series of continuous watershed simulation models was developed at Stanford University in the early 1960s. The most widely known and distributed of these is the Stanford Watershed Model Version IV (SWM). The original SWM (12) was written in ALGOL. It has spun off many modifications since. Major ones of these are the Kentucky Watershed Model (KWM); a self-calibrating version of KWM known as OPSET; the Ohio State University version; the Texas version; the Hydrocomp Simulation Program; and the National Weather Service Hydro-14 version. A good description of these versions of the Stanford model is available in Viessman et.al.(13).

There were several motivations for these modifications to SWM. Most of these modified version change from ALGOL to FORTRAN and include cosmetic changes (Plotting, output, etc.). A more significant change is the addition of self-calibrating features in OPSET and the National Weather Service versions although these features have little impact on the application of remote sensing to the Stanford model. A major motivation for modification has been to change the time step of the original model. The original model used basic 1-hour precipitation inputs with provision for including 24-hour values. Modifications to allow both shorter and longer time steps for the precipitation inputs have been made,and this change of time step is usually reflected in the computational details of the particular version. In particular, the National Weather Service version uses a 6-hour time step and therefore, uses a much simplified computation for surface runoff.

2. DESCRIPTION

2.1 Version Described

This review of the Stanford Model is based on the original Stanford Watershed Model IV. It is hoped that hydrologists using various versions of the original SWM will be able to relate the discussion here to their model and that a larger community of potential users will be served by limiting discussion to the "original" SWMIV rather than some derivative model. The snowmelt computations of the Stanford Model are not included because they are similar to the NWS snowmelt model described elsewhere. Also, the procedures for channel routing are not included in the exposition. The components of the Stanford Model that are included in this exposition are shown on Figure 6-1. Both potential evapotranspiration and computation of rain plus snowmelt are considered exogenous.

2.2 Type

A basic modeling philosophy of SWM is to recognize explicity the spatial variability of infiltration, interflow prediction, surface runoff, and evapotranspiration. This philosophy is illustrated in Figure 6-2,which shows the basic moisture allocation component of SWM. (The values b and c vary with moisture conditions.) A similar concept is used in area-wide allocation of evapotranspiration opportunity.

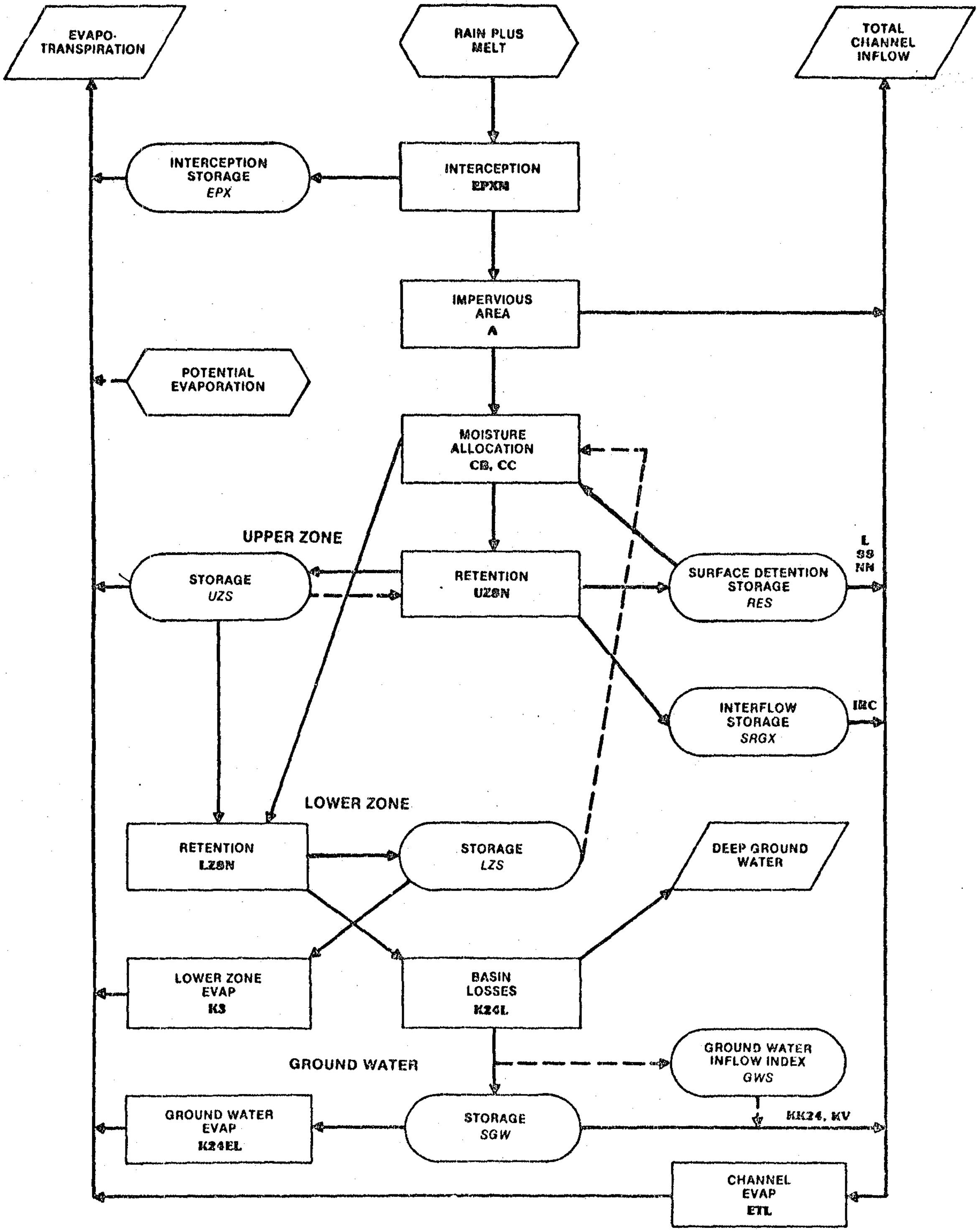

Figure 6-1. STANFORD WATERSHED MODEL IV SCHEMATIC DIAGRAM

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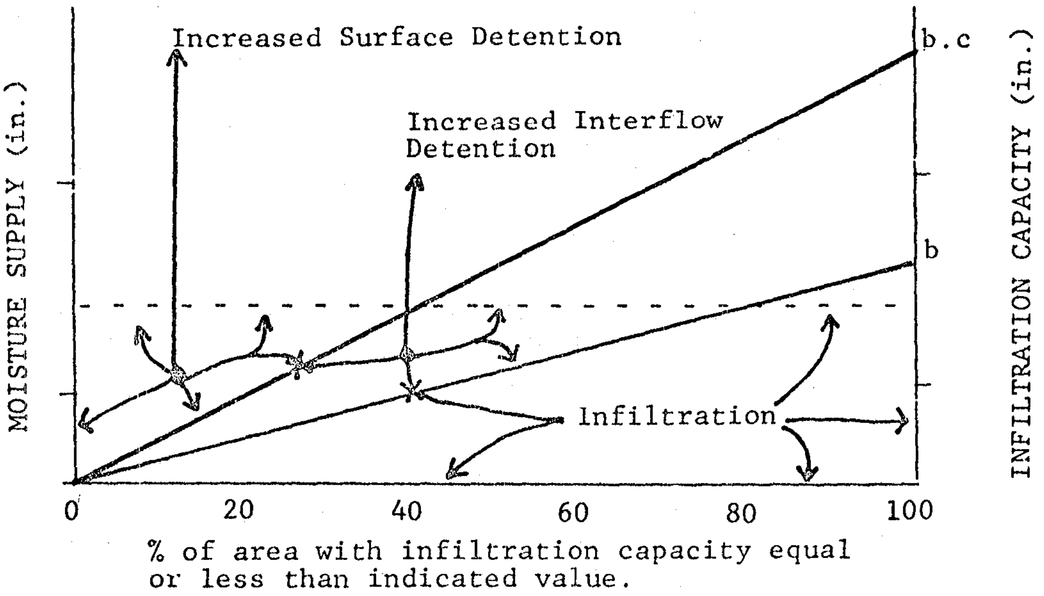


Figure 6-2. MOISTURE ALLOCATION COMPONENT OF STANFORD WATERSHED MODEL IV

In spite of the modeling philosophy that recognizes spatial variabilities, the SWM is a lumped input model. The user can subdivide a watershed into catchments each of which has a separate parameter set, but SWM does not lend itself readily to subdivisions based on elevation or land use or aspect or other characteristics that lead to zones that are not contiguous catchments.

2.3 Components

Descriptions of the Stanford model are widely available in the literature. In addition to the original report (12), descriptions are available in varying detail in several hydrology texts (13,14,15). As a result, the components of the Stanford model are not presented in detail here.

The SWM is shown schematically in Figure 6-1. Interception occurs over the entire basin, and a parameter allows for the impervious area hydraulically connected to the stream. The basin pervious area is divided into three zones (upper, lower, and groundwater). The allocation of moisture between the upper and lower zone components is depicted in Figure 6-2.

The upper zone includes a surface runoff component based on the kinematic wave formulation for overland flow. The upper zone also includes an interflow component modeled as a linear reservoir. Soil moisture storage in the upper zone is also included. There is a provision for percolation from the upper to lower zone although the major moisture allocation to the lower zone is immediate via the mechanism shown in Figure 6-2.

Moisture that passes from the upper zone (whether immediate or by percolation) is divided between lower zone storage and groundwater storage. This division depends on the amount of lower zone storage available.

An interesting feature of the groundwater zone is a variable recession coefficient for groundwater storage. This allows for more rapid depletion of groundwater during times of comparatively rapid accretion and slower depletion during dry periods.

There is a provision in the model for basin losses from groundwater.

Evaporation occurs at the potential rate from interception, upper zone storage, and lake surfaces. Any remaining potential evaporation is distributed over the basin in a manner analogous to that shown in Figure 6-2 and withdrawn from the lower zone storage.

2.4 Parameters

The soil moisture accounting procedure SWM has 16 parameters as defined in Table 6-1. Table 6-2 shows primary and secondary categories for these parameters.

2.5 States

The seven states of the Stanford model are defined in Table 6-3, and Table 6-4 shows primary and secondary categories for these states. An interesting feature of the moisture storages in the Stanford model is the lack of any upper limit on the amount of water stored.

2.6 Inputs

The Stanford model has two basic inputs; daily potential evapotranspiration and hourly rain plus snowmelt. Both of these are averages over the segment or subbasin to which a single set of parameters applies. The original model had provisions to weight individual precipitation stations to obtain segment precipitation.

The original model includes a snow model although it is not described here. The soil moisture accounting procedure of the Stanford model can be linked to any continuous snow model that can provide rain plus melt as required.

3. APPLICATION

The original Stanford model used only manual calibration procedures, but later versions also have automatic calibration methods. The length of record required for calibration depends primarily on the region. For any area the data base should represent both dry and wet seasons.

A basin may be divided into segments and calibrated using a single streamflow record. Each segment has a separate set of parameters. The original Stanford model report included examples of calibration of segments from about 250 acres to 250 mi^2 with segments combined into watershed up to 1342 mi^2. It has since been modified and calibrated throughout the world to segments up to about 2000 mi^2. The Stanford model is not intended as an urban model though it has been used on watersheds that encompass urbanized areas.

Table 6-1. PARAMETERS (DEFINITIONS) STANFORD WATERSHED MODEL IV

A	Percent impervious area.
CB	Infiltration index.
CC	Interflow index, which determines the ratio of interflow to surface runoff.
EPXM	Maximum amount of interception storage.
ETL	Ratio of total stream and lake area to the total watershed area.
IRC	Daily interflow recession coefficient.
KK24	Daily groundwater recession coefficient.
KV	Weighting factor to allow variable groundwater recession rates.
K24EL	Percent of watershed stream surfaces and riparian vegetation.
K24L	Percent of groundwater recharge assigned to deep percolation.
K3	Evaporation loss index for the lower zone.
L	Overland flow length.
NN	Manning's "n" for overland flow.
LZSN	Nominal lower zone storage, an index to the magnitude of lower zone capacity.
UZSN	Nominal upper zone storage, an index to the magnitude of upper zone capacity.
SS	Overland flow slope.

Table 6-2. ROLE OF PARAMETERS - STANFORD WATERSHED MODEL IV

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff	A	
Surface Runoff	L, SS, NN	CB, CC, LZSN, UZSN
Interflow	CC, IRC	LZSN, CB
Baseflow	KK24, KV	K24L, LZSN
SOIL MOISTURE HORIZONS		
Upper Zone	UZSN	CB, CC, LZSN
Lower Zone	LZSN	CB, CC, KK24
PROCESSES		
Infiltration	CB	LZSN
Percolation		CB, CC, LZSN, UZSN
Evaporation	K3, ETL, K24EL	EPXM, UZSN
Interception	EPXM	
Losses	K24L	

Table 6-3. STATES (DEFINITIONS) STANFORD WATERSHED MODEL IV

RES	Surface detention depth.
SRGX	Interflow storage.
SGW	Active groundwater storage.
GWS	Groundwater inflow index.
UZS	Upper zone storage.
LZS	Lower zone storage.
EPX	Interception storage.

Table 6-4. ROLE OF STATES - STANFORD WATERSHED MODEL IV

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	RES	LZS, UZS
Interflow	SRGX	LZS
Baseflow	SGW, GWS	LZS
SOIL MOISTURE HORIZONS		
Upper Zone	UZS	SRGX, RES, EPX
Lower Zone	LZS	SGW
PROCESSES		
Infiltration		LZS, UZS
Percolation		LZS, UZS
Evaporation		LZS, UZS, EPX
Interception	EPX	
Losses		SGW

CHAPTER 7

STREAMFLOW SYNTHESIS AND RESERVOIR REGULATION (SSARR) MODEL

1. HISTORY

The SSARR model was developed initially to meet the needs of the North Pacific Division of the U. S. Army Corps of Engineers to provide mathematical hydrologic simulations for systems analyses as required for the planning, design, and operation of water control works. The program has been in the process of development and application since 1956 (16). The SSARR model has been further developed for operational river forecasting and river management activities in connection with the Cooperative Columbia River Forecasting Unit, sponsored by the NWS, the Corps of Engineers, and the Bonneville Power Administration. In recent years, numerous river systems in the United States and abroad have been modeled with the SSARR by various agencies, organizations, and universities (17). A "conversational' version of SSARR (COSSARR) is also available. The COSSARR model may be run interactively, while the SSARR model requires card input (18).

2. DESCRIPTION

2.1 Type

The SSARR model is based on what the authors refer to as "a practical engineering approach to program design in order to achieve a balance between hydrologic theory and practical considerations related to daily operational use."

The model may be thought of as a "grey box". It does not solve the differential equations of the fundamental hydrologic processes. Instead, it provides tables of an output value versus one or more input values. Such tables may be adjusted by the user to simulate empirically such processes as infiltration, deep percolation, and soil moisture replenishment. The empirical nature of the SSARR model makes it difficult if not impossible to apply without the existence of considerable historical rainfall/runoff data.

The SSARR model is composed of the following three basic components:

- A generalized watershed model for synthesizing runoff from snowmelt, rainfall, or a combination of the two. Watersheds are separated into relatively homogeneous hydrologic units for independent analysis before they are added into the system.

- A river system model for routing streamflows from upstream to downstream points through channel and lake storage. River flows are routed as a function of multivariable relationships involving backwater effects from tides or reservoirs.

- A reservoir regulation model whereby reservoir outflow and contents are analyzed in accordance with predetermined or synthesized inflow and free flow or any of several modes of operation.

Only the watershed model is considered in this report. The model is discussed as though it were being applied to a single, homogeneous hydrologic unit. The snowmelt model included in the SSARR is not discussed here. The snow model is based on a temperature (degree-day concept) and elevation weighting method. Elevation bands may be considered as separate watersheds.

2.2 Components

2.2.1 Soil Moisture Zones

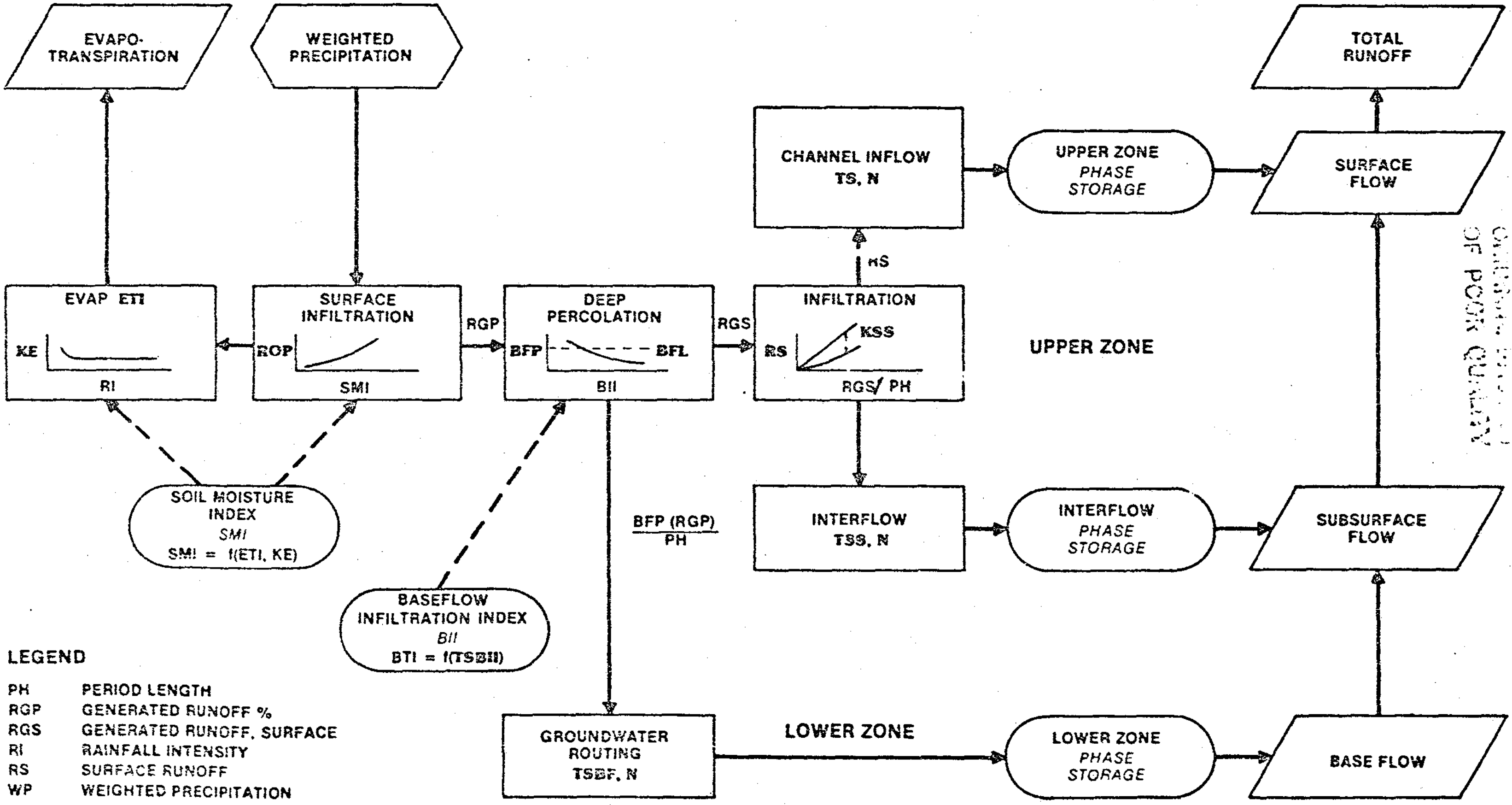
The SSARR model accounts for moisture in two zones, upper and lower zones (Figure 7-1). The quantity of moisture present in the upper zone is measured by the Soil Moisture Index (SMI), a model state. The movement of water into the lower zone is controlled by the Base Flow Infiltration Index (BII) a second model state. Mechanisms are provded for routing water through both the upper zone (interflow) and lower zone (base flow or groundwater flow).

2.2.2 Soil Moisture Accounting

Water infiltrated into the upper soil zone is subtracted from total precipitation based on a table of percent runoff (ROP) versus SMI (Figure 7-1). The model has the option of adjusting the SMI either by a seasonal curve of evapotranspiration or by using daily observed pan evaporation. The SSARR model has provisions for reducing the evapotranspiration rate as a function of rainfall intensity (KE parameter).

2.2.3 Percolation

The percolation mechanism in the SSARR model whereby moisture is transferred from the upper zone to the lower zone is represented by a table. Percolated water is subtracted from precipitation after soil moisture requirements are satisfied (Figure 7-1). The user specifies a table of values that relates the percent of surface runoff that becomes Base Flow (BFP) to BII. A base flow limit (BFL) is also specified, and it fixes the maximum transfer of upper zone water to the lower zone. The BII value is a model



LEGEND

PH	PERIOD LENGTH
RGP	GENERATED RUNOFF %
RGS	GENERATED RUNOFF, SURFACE
RI	RAINFALL INTENSITY
RS	SURFACE RUNOFF
WP	WEIGHTED PRECIPITATION

Figure 7-1. SSARR MODEL SCHEMATIC DIAGRAM

state that is updated as a function of time. The rate of change of BII with time is governed by a "time-of-storage" parameter, TSBII which is a time delay or time of storage decay constant. Separate values of TSBII may be specified for rising and falling hydrograph limbs.

2.2.4 Infiltration/Surface Runoff

The portion of water that infiltrates to become interflow is subtracted from surface runoff based on a table (Figure 7-1). The table specifies the percentage of generated surface runoff, RGS (equal to the amount of precipitation remaining after soil moisture and percolation requirements are satisfied), that infiltrates or runs off as a function of the precipitation input rate. A maximum infiltration rate, KSS, is also specified.

2.2.5 Surface, Interflow, and Baseflow Routing

One feature of the SSARR model that deserves special mention is the routing method used to delay and smooth quantities of flow (surface runoff, interflow, and groundwater flow). Linear storage routing based on the continuity equation is used for up to N "phases" for each of the three flow types. By varying the number of phases and the storage coefficients for each of the flow types, considerable freedom exists in shaping a flow hydrograph predicted by the model.

2.3 Parameters

The SSARR model has 13 basic parameters, which are listed in Table 7-1 along with their definitions. The parameters are also identified in Figure 7-1. In Table 7-2 each parameter is assigned to a primary category (to which it most belongs) and a secondary category. Detailed information on use of the model parameters in calibration is provided in the Corps of Engineers manuals.

Table 7-1. PARAMETERS (DEFINITIONS) SSARR MODEL

BFL	Base flow infiltration limit.
BFP	Base flow, percent.
ETI	Evapotranspiration index.
KE	Percent effectiveness of ETI (function of rainfall intensity, RI).
KSS	Limiting subsurface infiltration rate.
N	Number of routing phases (surface flow)
N	Number of routing phases (subsurface flow)
N	Number of routing phases (baseflow).
ROP	Runoff percent.
RS	Surface runoff percent, function of RS/RGS table.
TS	Time of storage; surface flow.
TSS	Time of storage; subsurface flow (interflow).
TSBF	Time of storage; baseflow.

Table 7-2. ROLE OF PARAMETERS - SSARR MODEL

CATEGORIES	PARAMETER ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	RS/RGS table, TS, N*	ROP/SMI table, KE
Interflow	RS/RGS table, TSS, N* KSS	
Baseflow	BFP/BII table, TSBF, N*	BFL
SOIL MOISTURE HORIZONS		
Upper Zone	ROP/SMI table	KE
Lower Zone	TSBII, BFL	
PROCESSES		
Infiltration	KSS	RS/RGS table, ROP/SMI table
Percolation	BFP/BII table BFL	TSBII
Evaporation	KE	ETI, optional
Interception		
Losses		

*N is listed as a single variable name; there are, however, distinct N's for surface flow, interflow, and base flow.

2.4 States

The five states of the model are defined in Table 7-3. The primary and secondary role of states in the model with respect to the runoff, soil moisture horizons, and processes are listed in Table 7-4.

2.5 Inputs

The primary input to the SSARR model is weighted basin precipitation. For the purpose of the current study the precipitation would be rainfall only since snowmelt is not considered. The basic time unit of precipitation is daily values. Provisions exist in the model for dividing the precipitation into smaller hourly units or for accepting precipitation measurements at intervals of less than one day.

Optionally, the SSARR model will accept daily pan evaporation measurements in place of a seasonal evapotranspiration curve.

3. APPLICATION

Because of the "grey box" nature of the SSARR model, it is unlikely that good results could be obtained without considerable calibration. Extensive historical data over a wide range of conditions is required to set up all the model tables correctly. Good results can be obtained when such data are available.

A great deal of segmentation flexibility exists in the model. The user may define many interconnected basins, channel

Table 7-3. STATES (DEFINITIONS) SSARR MODEL

SMI	Soil Moisture Index.
BII	Base Flow Infiltration Index.
PHASE STORAGE	Phase storage (discharge or stage) for surface flow.
PHASE STORAGE	Phase storage (discharge) for subsurface flow.
PHASE STORAGE	Phase storage (discharge) for baseflow.

Table 7-4. ROLE OF STATES - SSARR MODEL

CATEGORIES	STATE ASSIGNMENT	
	PRIMARY	SECONDARY
RUNOFF COMPONENTS		
Immediate Runoff		
Surface Runoff	Initial Phase Storage (discharge or stage)	
Interflow	Initial Phase Storage (discharge)	
Baseflow	Initial Phase Storage (discharge)	
SOIL MOISTURE HORIZONS		
Upper Zone	SMI	
Lower Zone		BII
PROCESSES		
Infiltration		
Percolation	BII	
Evaporation	ETI*	
Interception		
Losses		

*Optional as input.

units, and reservoirs. The program automatically sums up flows and maintains continuity. Figure 7-2 illustrates a typical SSARR segmentation.

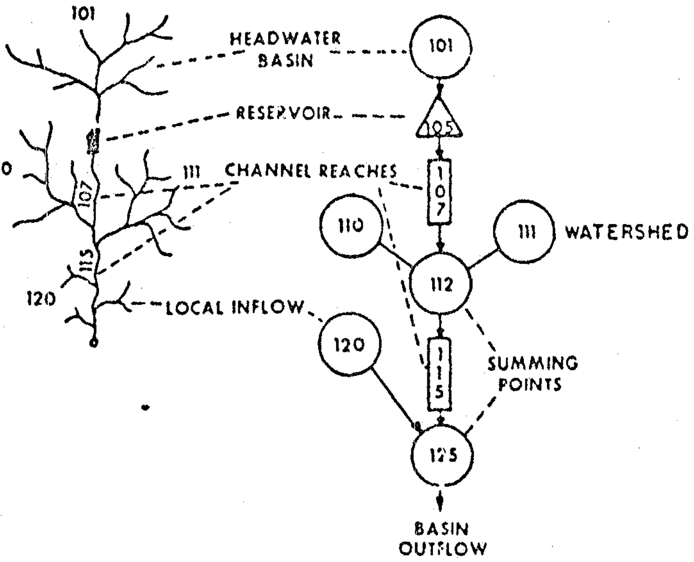


FIGURE 7-2. SCHEMATIC CONFIGURATION FOR THE SSARR MODEL [after Corps of Engineers (17)]

The SSARR model has been successfully applied to basins varying in size from under 500 mi^2 to more than 25,000 mi^2. In general, the smaller the subbasins and the more data available, the better the results. Experience under operational conditions with continuing adjustments in parameters also improves results.

CHAPTER 8

NWSRFS SNOW ACCUMULATION AND ABLATION MODEL

1. HISTORY

The NWSRFS snow accumulation and ablation model was developed within the Hydrologic Research Laboratory of the Office of Hydrology (1). It is a conceptual model, and each of the significant physical processes affecting snow accumulation and snowmelt is mathematically represented in the model(Figure 8-1). The model evolved from two earlier models (19,20). The present model is essentially that described by Anderson (1).

Air temperature has been the most commonly used index for computing snowmelt. It has also been shown to be probably the best single index to areal snow cover energy exchange. Other variables such as incoming solar radiation, vapor pressure of the air and wind speed have been used with net radiation or air temperature but none has proven to be a good index to snowmelt when used by itself.

Anderson (21) has also developed a point energy and mass balance model of a snow cover. The minimal required data inputs (solar radiation, air temperature, vapor pressure, and wind-speed) are not available for most river basins in the United States. In addition, estimating mean representative areal values for all of these inputs from point measurements is much more difficult than for air temperature alone.

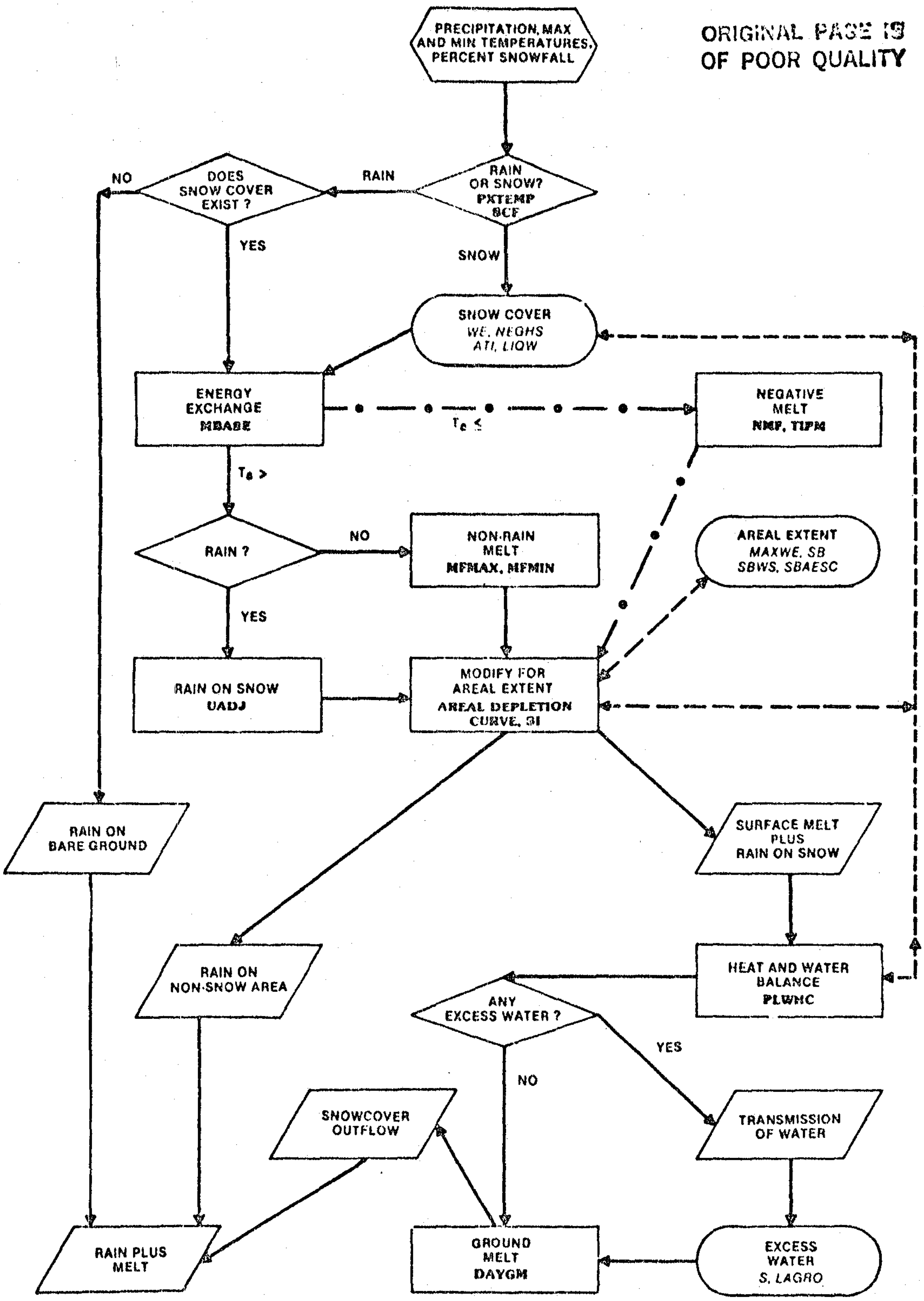


Figure 8-1. NWSRFS (ANDERSON) SNOWMELT MODEL SCHEMATIC DIAGRAM

2. DESCRIPTION

The use of air temperature as an index to energy exchange across the snow-air-interface is considerably different from the old degree-day method that uses air temperature as an index to snow cover outflow. The degree-day method does not explicity account for those processes (the freezing of melt water because of a heat deficit and the retention and transmission of liquid-water) that cause snow cover outflow to differ from snowmelt.

The computation of snowmelt is the most important part of the model. However, the accumulation of the snow cover (the water equivalent of the snow cover) and the computation of the areal extent of the snow cover are also important. The other components (dealing with retention and transmission of liquid water, ground melt, etc.) have less effect but are important at certain times on many watersheds.

2.1 Parameters

Twelve parameters are used for various purposes in the model. Good initial estimates of most parameters can be obtained from physiographic and climatological information. PXTEMP is used to delineate rain and snowfall unless the percentage of precipitation that is snowfall is an input. The parameter SCF is applied to the amount of snowfall as a correction for gage catch deficiency. Rain on bare ground is computed directly and added to the rain and melt leaving the snowcover.

MBASE is the temperature above which melt occurs and below which negative heat exchange occurs. UADJ is the wind function parameter used in the computation of snowmelt for periods with rain. For period of nonrain melt MFMAX and MFMIN are the primary controlling parameters and provide seasonal variation in the snowmelt rate for the same temperature condiditions.

When the mean air temperature is equal to or below MBASE negative heat exchange is computed based on the parameters NMF and TIPM.

All snowmelt computations are modified for areal extent of the snowcover using the areal depletion curve and SI. From these computations the amount of rain on nonsnow areas is one output and becomes part of the total output from the snowcover (rain plus melt).

Computations on the amount of liquid water that is stored in the snowpack is controlled by the parameter PLWHC or the maximum amount (percent) of liquid water that can be held against gravity drainage in the snow cover. The parameter DAYGM is the constant amount of melt at snow-soil interface when snow is present.

Excess liquid water is transmitted through the snowcover using a procedure somewhat analogous to lag and K channel routing resulting in snow cover outflow. The snow cover outflow together with the rain on base ground and rain on nonsnow areas constitute the rain plus melt that is used as input to the soil moisture accounting models.

All of the parameters of the model with definitions are listed in Talbe 8-1.

2.2 States

Four state variables (WE, water equivalent, NEGHS, heat deficit; LIQW, liquid water content; and ATI, index to temperature of the snowpack) depict the state of the snowcover. Three of these (WE, NEGHS, and LIQW) are defined in terms of their areal mean values. The fourth represents the temperature within the

Table 8-1. PARAMETERS (DEFINITIONS) NWSRFS SNOWMELT MODEL

AREAL DEPLETION CURVE	Curve that 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.
DAYGM	Constant amount of melt that occurs at the snow-soil interface whenever snow is present.
MBASE	Base temperature for snowmelt computations during nonrain periods.
MFMAX	Maximum melt factor during nonrain periods; assumed to occur on June 21.
MFMIN	Minimum melt factor during nonrain periods; assumed to occur on December 21.
NMF	The maximum negative melt factor.
PLWHC	Percent (decimal) liquid water holding capacity; indicates the maximum amount of liquid water that can be held against gravity drainage in the snow cover.
PXTEMP	The temperature that delineates rain from snow.
SCF	A multiplying factor that adjusts precipitation data for gage catch deficiencies during periods of snowfall and implicitly accounts for net vapor transfer and interception losses. At a point, it also implicitly accounts for gains or losses from drifting.
SI	The mean areal water-equivalent above which there is always 100 percent areal snow cover.
TIPM	Antecedent temperature index parameter (range is $0.1 \leq \text{TIPM} \leq 1.0$).
UADJ	The average wind function during rain-on-snow periods.

snow cover. These states are the basic factors in the mass balance of the snowcover,and information on them is required for all processes dealing with snowmelt (and negative melt) and liquid water retention or transmission in the snowpack.

There are four basic states (SB, SBWS, MAXWE and SBAESC) relating the estimation of the areal extent of the snowcover. The two final states (S, LAGRO) deal with the amount of excess liquid water (that above the PLWHC value) that is in the process of being transmitted through the snowpack.

A listing of the states (with definitions) is given in Table 8-2.

2.3 Inputs

The precipitation data, used as input to the snow model, are based on point measurements of precipitation from one or more precipitation gages. The present operational model permits the input of the percentage of precipitation that is snowfall, overriding the calculation of rain versus snow by the parameter PXTEMP.

The model uses air temperature as the sole index to energy exchange across the snow-air interface. Normally for calibration 6-hourly mean areal air temperature estimated from daily maximum and minimum temperature values are used.

3. APPLICATION

The model can be used to represent the snow accumulation and ablation process at a point (a single snow course) or over an area. In calibrating the model,a basin can be subdivided into two or more subareas on the basis of elevation or such

Table 8-2. STATES (DEFINITIONS) NWSRFS SNOWMELT MODEL

ATI	Antecedent Temperature Index; represents the temperature within the snow cover.
LAGRO	LAGRO and S together define the amount of excess liquid water in transit in the snowpack.
LIQW	The amount of liquid-water held against gravity drainage.
MAXWE	The maximum water-equivalent that has occurred over the area since snow began to accumulate.
NEGHS	Heat Deficit; the amount of heat that must be added to return the snow cover to an isothermal state at 0°C with the same liquidwater content as when the heat deficit was previously zero.
S	S and LAGRO together define the amount of excess liquid water in transit in the snowpack.
*SB	The areal water equivalent just prior to the new snowfall.
*SBAESC	The areal extent of snow cover from the areal depletion curve just prior to the new snowfall.
*SBWS	The amount of water equivalent above which 100 percent areal snow cover temporarily exists.
WE	Water equivalent of the solid portion of the snowpack.

*These states are only used when there is a new snowfall on a basin with a partial snowcover.

physiographic factors as aspect or vegetation cover. The use of two subareas has proven to be adequate in basins in the western United States with elevation ranges up to 2500 m (8200 ft).

For most meteorological conditions, the NWSRFS model provides as reliable estimates of snow cover outflow as would the use of a complete energy and mass balance model. Under the following conditions, however, the estimates may be biased:

- After the snow has ripened under clear skies with abnormally cold temperatures, the index does not indicate enough melt.
- Under very warm temperatures with little or no wind, the index overpredicts. In this case, the turbulent exchange is much less than normal.
- With high dew points and high winds, the model will underpredict. This condition results in much more latent heat (condensation) transfer and also sensible heat transfer than normal.

The snow model has been applied to many areas of the United States. These include areas with a variety of climatic and physiographic conditions such as New England, the Upper Midwest, the Rocky Mountains, the Sierra Nevada, and Alaska. The results have typically been good in all these areas, as long as the watershed is properly subdivided, the form of precipitation is generally correct, the input data are reasonably unbiased estimates of the true input, and the model is properly calibrated (1).

CHAPTER 9

SUMMARY

This investigation is the first step in evaluating potential uses of remotely sensed data in hydrologic models commonly used by government agencies. The following models were examined in this study:

- Antecedent Precipitation Index (API)
- Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS)
- National Weather Service River Forecast System (NWSRFS)
- Storage, Treatment, Overflow, Runoff Model (STORM)
- Stanford Watershed Model IV
- Streamflow Synthesis and Reservoir Regulation Model (SSARR)
- NWSRFS Snowmelt Model

The purpose of the investigation was to examine the models and develop a framework within which they could be accurately compared with one another and with available and proposed remote sensed data. The framework is designed so that the reader can quickly determine the model variables that serve as

- inputs--the model's driving function(s);
- parameters--the model's calibration constants; and
- states--the model's initial conditions and starting boundary conditions.

For each of the basic soil moisture accounting models, tables are presented identifying the primary and secondary role of each parameter and state. Three categories (runoff components, soil moisture horizons, and processes) are used. For each model these tables provide information on those variables (parameters and states) that are related to a specific category (e.g., upper zone soil moisture) and thus aid in identifying how specific remotely sensed data relate to the model.

Schematic diagrams in the report illustrate the inputs, states, processes, and outputs for all seven models. In addition, all states and parameters are identified on the diagrams, thus providing a visual view of the basic relations of the model.

The results of this initial study are to be used in the overall study to identify and evaluate the potential use of remotely sensed data in the models. For most of the models, no clear, simple relationship exists between the remotely sensed data and a single variable of the model. For example, a given model may have one, two, or three parameters relating to upper zone soil moisture and a single state that reflects detention and interception storages as well as the contents of the upper zone soil moisture. It is essential that the relationships among current and planned remotely sensing techniques and the variables in existing models be understood before recommendations on model additions or modifications can be made.

The material in this report has not been published previously in the present format; it is presented in this format for the use of those who may wish to study the potential use of remotely sensed data.

The diagrams and tables in this report have been prepared to assist those who have a need to understand the functions of the models but do not wish to explore the complete detailed documentation of each model.

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D2

REMOTE SENSING AND HYDROLOGIC MODELS

Part 2: Strategies for Using Remotely Sensed
Data in Hydrologic Models (AgRISTARS
Document CP-GI-04151, NASA CR 166729)

C-2

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16. Abstract

The results of a contract study on the suitability of present and planned remote sensing capabilities are reported. The usefulness of six remote sensing capabilities (soil moisture, land cover, impervious area, areal extent of snow cover, areal extent of frozen ground, and water equivalent of the snow cover) with seven hydrologic models (API, CREAMS, NWSRFS, STORM, STANFORD, SSARR, and NWSRFS Snowmelt) were reviewed. The results indicate remote sensing information has only limited value for use with the hydrologic models in their present form. With minor modifications to the models the usefulness would be enhanced.

Specific recommendations are made for incorporating snow covered area measurements in the NWSRFS Snowmelt model. Recommendations are also made for incorporating soil moisture measurements in NWSRFS. Suggestions are made for incorporating snow covered area, soil moisture, and others in STORM and SSARR. General characteristics of a hydrologic model needed to make maximum use of remotely sensed data are discussed. Suggested goals for improvements in remote sensing for use in models are also established.

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PREFACE

The National Aeronautics and Space Administration (NASA), is one of five federal agencies cooperating in the AgRISTARS (Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing) program. The AgRISTARS program is directed toward developing the technology and testing the capability to use remotely sensed data in more economical ways in seven agriculturally related groups, one of which is conservation and pollution.

In this group, three tasks have been defined:

TASK 1. Conservation Inventory
TASK 2. Water Resources Management
TASK 3. Snowpack Assessment

As part of its program for Task 2, Water Resources Management, NASA contracted (No. NAS5-26446) with the Hydex Corporation for "Hydrological Modeling Survey Studies." The objective was to determine the suitability of present and planned remote sensing capabilities for commonly used hydrologic models.

In interim report, "Review of Hydrologic Models for Evaluating Use of Remote Sensing Capabilities" (NASA Contractor Report CR 166674 dated 31 March 1981), Hydex presented information on the structure, parameters, states, and required inputs for seven hydrologic models.

This report is a summary of the additional finding of the study relating to the use of remote sensing capabilities for hydrologic modeling.

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CHAPTER 1

INTRODUCTION

1. BACKGROUND

The potential value of using remote sensing for water resource management has been recognized for many years. Remote sensing techniques have been used to inventory the surface water resources of the United States at a minimal cost in time and money. Other successful approaches have included measurement of land cover factors and assessment of wetland areas.

Many remote sensing techniques provide direct measurement of land characteristics, vegetative cover, and the states of water in the hydrologic cycle. Such measurements should provide valuable information for improving the ability to model the hydrologic cycle. To date, however, this use of remote sensing techniques has been of limited value. In fact, federal agencies responsible for forecasting the flow of rivers and predicting water supplies are not using remote sensing techniques to provide a primary data base in their operational hydrologic forecasting programs.

For many reasons, remotely sensed information has not been of much value for improving the ability to model the land phase of the hydrologic cycle. One major reason is that current hydrologic models do not necessarily represent the real world. Most such models are physically based, but the concepts are not indicative of the actual physical processes. A second major reason is the dissimilarity in the time and space averages as envisioned by the hydrologic model, as exist in the real world, and as measured by remote sensing systems.

2. IMPORTANCE

A recent panel on Water Resources of the Space Applications Board, Assembly of Engineering, National Research Council (1), stressed the importance of remote sensing techniques for prediction of water resources. The panel recommended that the National Aeronautics and Space Administration (NASA) and the U.S. Army Corps of Engineers (COE) begin a set of studies to determine what remote sensing information -- including frequency, degree of accuracy of measurement, and resolution -- is needed to develop and improve hydrologic prediction models. The panel also stated that to be useful for prediction, remotely sensed data must be compatible with mathematical modeling of hydrologic systems.

The importance of remote sensing for improving the usefulness of hydrologic modeling for water resources prediction has been well stated and supported by the National Research Council Panel on Water Resources. Some other related factors, however, have not been stressed by the panel. Hydrologic modeling currently depends on the data base of ground measurements collected by national networks such as those maintained by the National Weather Service (NWS) of the National Oceanic Atmospheric Administration (NOAA) and the U. S. Geological Survey (USGS) of the U.S. Department of the Interior. The quantity and quality of these networks have been steadily declining as a result of decreased resources for supporting the existing hydrometeorological networks. Remote sensing capabilities provide a viable method to offset this loss of information.

Another factor not adequately covered by the panel is the problem of applying conceptual hydrologic models in the drier areas of the United States. In these areas, precipitation is primarily convective (thunderstorms) and ground-based data-collection network are not adequate to provide accurate information on the average precipitation. The NWS forecasters, therefore, have found it more practical to use simpler (black box) hydrologic models that are easier to adjust. However, with these black box models, it is not possible to predict, for example, low flows during drought periods and associated probabilities of occurrence. If remote sensing techniques could provide enough additional data to warrant the use of improved models, the predictive ability could be increased considerably.

3. STUDY OBJECTIVE

The objective of this study is to evaluate the current strategies for using existing and planned remotely sensed information in commonly used hydrologic models and to develop recommendations for improved use of such information.

To improve the state of knowledge about (a) the characteristics (resolution, error, and precision in space and time) of remote sensing systems for use in hydrologic modeling and (b) the suitability of using the remotely sensed information in existing hydrologic models, the study group first reviewed the structure, parameters, states, and required inputs for hydrologic models and then determined those remote sensing capabilities of most potential value.

An interim report, "Review of Hydrologic Models for Evaluating Use of Remote Sensing Capabilities," (2) presents a detailed review of seven hydrologic models. A summary of the finding is presented in Chapter 2.

The review of remote sensing capabilities was not as straightforward as that of the hydrologic models. The reported capabilities for remotely sensing particular hydrologic or land cover variables often were contradictory. The review was limited to remote sensing of 13 variables that had been considered in the literature as most promising for use with hydrologic modeling. Real-time data with sufficient accuracy, resolution, and timeliness can be provided for seven of the variables by current observing techniques or by techniques that will be available in the foreseeable future. These seven variables are soil moisture, impervious area, land cover, areal extent of snow cover, areal extent of frozen ground, water equivalent of snow cover, and precipitation. All 13 variables are listed in Table 3-1. The ability to measure precipitation characteristics remotely has received more attention than the ability to measure any of the other six variables remotely. Remote sensing of precipitation charactericts would have direct use in hydrologic modeling since precipitation is normally the primary input to hydrologic models. No model modifications would be required to benefit from such measurements. Because of the value of reliable and accurate precipitation measurements for use in hydrologic models, only the other six remote sensed variables listed above were selected for final review. A summary of the review of remote sensing capabilities is contained in Chapter 3.

The review of the hydrologic models and of the remote sensing capabilities provided a sound basis for evaluating the usefulness of remote sensing for operational modeling. For each of the seven selected hydrologic models, the potential use of the six remote sensed variables for input, update, and/or calibration was evaluated for the current model configurations and for the configurations with minor modifications. Information on the evaluations is given in Chapter 3 and Chapter 4.

To maximize the value of remote sensing for hydrologic modeling, existing models will have to be modified or new ones developed. Chapter 5 presents the characteristics that a hydrologic model should have to maximize the overall value of remote sensing. Recommendations for modifying four commonly used models are also presented.

CHAPTER 2

REVIEW OF HYDROLOGIC MODELS

1. SELECTED MODELS

The following five hydrologic models commonly used by federal agencies were selected for review:

- Antecedent Precipitation Index (API) (3),
- National Weather Service River Forecast System (NWSRFS) (4,5),
- Storage, Treatment, Overflow, Runoff Model (STORM) (6),
- Stanford Watershed Model IV (SWM) (7), and
- Streamflow Synthesis and Reservoir Regulation (SSARR) (8).

Two other hydrologic models were reviewed. The Chemicals, Runoff and Erosion from Agricultual Management System, (CREAMS) (9) model was included because of its extensive use in the field of agriculture and the NWSRFS Snow Accumulation and Ablation model (10) was selected since it is commonly used with several of the basic hydrologic models. In addition, the latter model is the only snowmelt model in common use that uses air temperature as an index to energy exchange across the snow-air interface and accounts for heat deficit and liquid water in the snowpack.

2. GLOSSARY OF TERMS

The following terms and definitions are used in the review of the hydrologic and snowmelt models.

Inputs

The set of driving forces required periodically by the model. Common examples are precipitation, potential evapotranspiration, and temperature. For most hydrologic models, the inputs are all meteorologic factors, but some require inputs describing human activities (cropping practices).

A key phrase in the definition of the inputs to a model is "required periodically." If it is possible to run the model without providing a value for a particular item, that item is not an input. Likewise, if the model can be run with a particular item provided only once or perhaps intermittently, that item is not an input. Some models, however, may have default values for certain inputs (e.g., precipitation is zero if not entered).

Parameters

The set of values that are changed to make a general hydrologic model apply to a particular location. Parameters are constant with time or, at most, vary only slightly with time as compared to inputs.

States

The set of internal model values sufficient to start the model. The states of the model completely define the past history of inputs. These are usually values of moisture stored in various model components (e.g., upper zone tension water contents), indices to model status (e.g., API), or computational carryover values (e.g., the carryover values of a unit hydrograph operation). In each time step of operation, the model uses the initial values of the states along with parameters and inputs for that time step in order to compute the state for the next time step.

Outputs

Variables of interest that can be computed from knowledge of the states and inputs. Usual examples are streamflow and actual evapotranspiration. In many cases, an output will be identical to some state of the model, but such does not have to be the case. The model may produce an output that is of vital interest to the model user but is not necessary to the model computation.

3. DETAILED REVIEW OF MODELS

At the time most of the hydrologic models now in use were developed, little consideration was given to the use of remotely sensed data. For that reason and others, the descriptive information in the literature is generally not adequate for evaluating its usefulness with hydrologic models. Since such use is a primary objective of this study, the structure, parameters, states and required inputs of the selected models were reviewed and a report was prepared and published as a NASA Contractor Report (2).

In the review the models were examined and a framework was developed within which the models could be accurately compared and evaluated for use with available and proposed remotely sensed data. The framework was designed so that it was readily possible to determine the model variables that serve as

- inputs--the model's driving function(s),
- parameters--the model's calibration constants, and
- states--the model's initial conditions and starting boundary conditions.

Tabular information on each of the hydrologic models was included in the NASA Contractor Report (2). One set of tables, which lists the parameters and states with definitions, is reproduced in Appendix A of this report.

For each of the basic soil moisture accounting models, a second set of tables identified the primary and secondary roles of each parameters. In those tables, the roles of the parameters and states are divided into three groups as follows:

GROUP 1. Runoff Components

- Immediate
- Surface
- Interflow
- Baseflow

GROUP 2. Soil Moisture Horizons

- Single zone
- Multiple zone
- Upper zone
- Lower zone

GROUP 3. Processes

- Infiltration
- Percolation
- Evaporation
- Interception
- Losses

Each parameter (and state variable) is assigned to the most appropriate group (primary) and to those groups in which it plays a somewhat lesser role (secondary). The tables can then be used to identify which parameters (state variables) are related to specific runoff components, soil moisture horizons, or hydrologic processes. The information in the tables also gives an immediate indication of the overall complexity of the model and which runoff components, soil moisture horizons, and processes are modeled most precisely.

Schematic diagrams for each model were also published and are included in Appendix A of this report. These diagrams illustrate all inputs, states, parameters and outputs of the models. A legend for the diagrams is shown in Figure A-1 in Appendix A.

The diagrams provide a good pictoral view of the structure of each model. The locations of the various components on the diagrams indicate the different levels of moisture (upper zone, lower zone, etc.), and the positioning with depth the relative location of states and operating processes.

The tables listing the states and parameters together with the schematic diagrams provide a good overview for each model. However, the NASA Contractor Report (2) provides more complete information on the interrelationships among the parameters and states and with the runoff components, the soil moisture horizons, and the physical processes.

CHAPTER 3

REMOTE SENSING CAPABILITIES

1. REMOTE SENSING

In a broad sense, remote sensing may be thought of as obtaining information from a location not coincident with that of the user. In this report, the user is a knowledgeable modeler of the behavior of hydrologic system; he seeks to collect information on current inputs to his model and the current states of the model. Typically the key input to all hydrologic models is precipitation, and typical states include snow-covered ground area, volume of moisture in various soil zones, and a number of others.

The term remote indicates that information is to be obtained from some distance. Hydrologic modelers work with basins from one acre to several hundred square miles, with a basin located almost anywhere in relation to the modeler. Thus, the term remote as used in this report implies any distance.

The term sensing is used in a narrow definition. While measuring the level of a stream by means of a float (sensor) and telemetering the value to some central location is remote sensing, such telemetry is not considered in this report. Sensing is taken to mean estimating the average value of a variable over some areal extent by examining the characteristics of the radiation from that area. Passive measurement techniques determine the amount of reflected sunlight or the amount of natural emissions at various wave length. Active measurement techniques direct radiation at an area and measure the reflective characteristics.

Consideration must be given to the location of the remote sensing device. The major emphasis of this report is on satellite-borne sensors.

2. SELECTING REMOTELY SENSED VARIABLES RELATED TO MODELING

Researchers have attempted to use remote sensing techniques for a wide variety of purposes. In this investigation, 13 variables that can be remotely sensed with some degree of success were identified. Each variable was felt to have some relationship to hydrologic processes. The variables are listed in Table 3-1.

The variables in Table 3-1 have been divided into two categories. Category 2 variables are those that have been studied by remote sensing but (a) are less useful in modeling or (b) are measured by techniques that are still in a very early stage of research. Areal extent of ice cover, for example, is not a consideration in any current hydrologic model. Data on the liquid water content of snow cover, on the other hand, could be quite useful but the technology for measuring it is not well developed even though the pressure of liquid water in a snow pack can be easily detected. The water equivalent of snow cover (a Category 1 variable) is more directly useful.

Emphasis in this study has been placed on Category 1 variables with the exception of precipitation. All Category 1 variables have at least an intuitive connection to portions of existing hydrologic models. Precipitation has been excluded from consideration because it is the only remotely sensed variable that normally appears as a model input. Thus, no modifications to the model would be required for its use and its value for modeling is beyond question. Remotely sensed precipitation data can be used immediately when the technology is sufficiently developed and the cost becomes reasonable.

Data on Category 1 variables were considered for possible use in the calibration, updating, and input phases of hydrologic model operation. Calibration is the process of setting model parameters so that the model matches a specific physical situation. Updating is the process of correcting the state variables of a model. For example, a snowmelt model may have a state variable representing the depth of snow. As time passes, this state may or may not match the observed snow depth. Updating matches the model depth to the observed depth. The input phase of modeling is the operational phase. The inputs are entered into the model to initiate a new or continuing prediction.

Data on all Category 1 variables can be used in all three phases of modeling, except that data on impervious area and land cover cannot be used in the input phase. Table 3-1 does not imply that any existing or planned model actually uses the variables for all three phases; it merely indicates that it is possible to develop a model that uses data from the variables in the indicated phases.

3. ABILITY TO SENSE CATEGORY 1 VARIABLES

To develop strategies for using data from Category 1 variables in models, it was necessary to compare the capability to measure each variable with the specific measurement requirements of individual models. The remainder of this chapter presents a brief summary of the "measurability" (i.e., the technique, resolution, time scale, and difficulty) of each Category 1 variable (excluding precipitation).

Complete review of remote sensing technqies are presented in a number of papers and the information is referenced in this report. The primary source is Itten (11), which provides an

Table 3-1. REMOTELY SENSED VARIABLES APPLICABLE TO HYDROLOGIC MODELING

Variables	Possible Phases of Use in Hydrologic Models for Water Resources Management		
	Calibration	Updating	Inputs
<u>Category 1</u>			
Areal Extent Snow cover	x	x	x
Frozen Ground			
Non Snow Areas	x	x	x
Under Snow Areas	x	x	x
Impervious Area	x	x	-
Land Cover	x	x	-
Precipitation (amount, intensity, areal extent)			
Rainfall	x	x	x
Snowfall	x	x	x
Soil Moisture	x	x	x
Water Equivalent of Snow Cover	x	x	x
<u>Category 2</u>			
Areal Extent Ice Cover	-	-	x
Areal Extent Water	x	-	x
Density and Species of Vegetation	x	x	-
Land Use(Rural, Urban, Industrial)	x	x	-
Liquid Water Content of Snow Cover	x	x	x
Surface Temperature	x	x	x

excellent summary of both aircraft-and satellite-based sensors. Schmugge (12) provides a good summary of active and passive microwave research for snow cover and other applications, and Striffler and Fitz (13) also provide a good broad-based summary of sensing capabilities.

Table 3-2 is a summary of the remote sensing capabilities available for each of the six selected Category 1 variables. The measuring technique, problems, future prospects, effort involved, and time frame are given for each variable.

In the measuring techniques column, methods by which the variable may be obtained (satellite, aircraft) are presented with some estimate of the resolution. In the problems column, a brief statement is made on the difficulty of discriminating the desired variable from others and on any difficulties in making the measurement. The future prospects column notes anticipated changes in method or pending improvements. The effort involved column provides a brief description of the work required to transform the sensing system output to a usable number for modeling. The time frame column indicates how often the measurements are available.

Of the six Category 1 variables, only areal extent of snow cover, land cover, and impervious area can be considered to have operational measurement techniques in any sense. All three may be obtained through analysis of LANDSAT images. LANDSAT technology is highly developed and is reasonably accurate (10 to 15 percent classification accuracy). Resolution is approximately one acre, with improvement to a quarter acre resolution planned for mid-1980 satellites. The major drawbacks of the data are that its usefulness depends on special analysis programs or access to an image processing

Table 3-2. REMOTE SENSING CAPABILITIES FOR CATEGORY 1 VARIABLES

CATEGORY 1 VARIABLE	MEASURING TECHNIQUE	PROBLEMS	FUTURE PROSPECTS	EFFORT INVOLVED	TIME FRAME
SOIL MOISTURE	AIRCRAFT: ACTIVE AND PASSIVE MICROWAVE SYSTEMS; THERMAL INFRARED SATELLITE: MICROWAVE SENSING ON NIMBUS 6 AND 7 RESOLUTION: SATELLITE: 2000 10,000m AIRCRAFT: 100m	VEGETATION ATTENUATES SIGNALS ONLY SURFACE LAYER (2-5cm OR SO) CAN BE STUDIED IS SURFACE ROUGHNESS SENSITIVE NO RELIABLE POINT MEASUREMENT FOR COMPARISON	RESEARCH SHOULD PRODUCE COMBINED SENSING METHOD – ACTIVE AND PASSIVE MICROWAVE AND INFRARED – WITH BETTER DISCRIMINATION CAPABILITIES (SOIL MOISTURE VERSUS VEGETATION AND SOIL ROUGHNESS)	CONSIDERABLE AT THIS TIME; AIRCRAFT AND SENSING SYSTEMS ARE NOT WIDELY AVAILABLE AND CONSIDERABLE PROCESSING IS REQUIRED FOR DISCRIMINATION OF SOIL MOISTURE VERSUS OTHER VARIABLES	AIRCRAFT DATA MAY BE OBTAINED AS NEEDED SUBJECT TO WEATHER LIMITATIONS SATELLITE COVERAGE IS AVAILABLE DAILY, BUT 4 TO 8 WEEK DELAY MAY BE ENCOUNTERED OBTAINING DATA TAPES**
IMPERVIOUS AREA	AIRCRAFT: PHOTOGRAPHY; MULTISPECTRAL SCANNER SATELLITE: MULTISPECTRAL SCANNER OR LANDSATs RESOLUTION: LANDSAT: 80m AIRCRAFT: 1-10m	CORRECT DISCRIMINATION OF AREAS HAS ACCURACY OF 10-15 PERCENT MUST HAVE SOME GROUND TRUTH	HIGHER RESOLUTION IS PLANNED FOR SATELLITES IN THE LATE 1980s (40m)	CONSIDERABLE EFFORT MAY BE INVOLVED IN DEVELOPING MEANS TO PROVIDE GROUND TRUTH COMMERCIAL FIRMS CHARGE $5500 TO $8000 TO ANALYZE ONE SATELLITE SCENE (300 BY 300km) AND PRODUCE A SET OF MAPS*	9 TO 18 DAYS OR LONGER BETWEEN SATELLITE SCENES, DEPENDING ON CLOUD COVER AIRCRAFT DATA AS REQUIRED SUBJECT TO WEATHER
LAND COVER	AIRCRAFT: PHOTOGRAPHY; MULTISPECTRAL SCANNER SATELLITE: PRIMARILY MULTISPECTRAL SCANNER OR LANDSAT RESOLUTION: LANDSAT: 80m AIRCRAFT: PHOTO, 6m RANGE SCANNER, 1m OR LESS	GROUND TRUTH IS ESSENTIAL PROBLEMS OF CORRECT DETERMINATION	HIGHER RESOLUTION IS PLANNED FOR SATELLITES IN THE LATE 1980s (40m)	CONSIDERABLE EFFORT MAY BE INVOLVED IN DEVELOPING MEANS TO PROVIDE GROUND TRUTH COMMERCIAL FIRMS CHARGE $5500 TO $8000 TO ANALYZE ONE SATELLITE SCENE (300km BY 300km) AND PRODUCE A SET OF MAPS	9 TO 18 DAYS OR LONGER BETWEEN SATELLITE SCENES, DEPENDING ON CLOUD COVER AIRCRAFT DATA AS REQUIRED SUBJECT TO WEATHER

*THIS IS 10¢/km^2 FOR THE ENTIRE AREA BUT CAN BE A FACTOR WHEN ONLY 800 TO 1000 km^2 BASINS ARE REQUIRED.

**TRUE FOR CURRENT RESEARCH SATELLITES; PHOTO BASED DATA ARE AVAILABLE SOONER; OPERATIONAL SATELLITES SHOULD REDUCE TIME REQUIRED.

Table 3-2. REMOTE SENSING CAPABILITIES FOR CATEGORY 1 VARIABLES (Continued)

CATEGORY 1 VARIABLE	MEASURING TECHNIQUE	PROBLEMS	FUTURE PROSPECTS	EFFORT INVOLVED	TIME FRAME
AREAL EXTENT SNOW COVER	AIRCRAFT: VISUAL SATELLITE: TIROS N LANDSAT HEAT CAPACITY MAPPING MISSION RESOLUTION TIROS N. 1100m LANDSAT: 80m HCM: 600m	VISIBLE–RED WAVE LENGTHS ARE BEST MEASURE OF AREAL EXTENT NEAR INFRARED IS BEST MEASURE OF SURFACE CONDITION CLOUD COVER IS MAJOR PROBLEM, MAKING IT DIFFICULT TO DISCRIMINATE VEGETATION COVER INFREQUENT COVERAGE COMBINED WITH CLOUD COVER MAKE TIME RESOLUTION POOR	RESEARCH ON ACTIVE/PASSIVE MICROWAVE METHODS SHOULD HELP CLOUD PROBLEMS; SATELLITES WITH MICROWAVE MAY BECOME AVAILABLE IN THE 1980s FASTER DATA ANALYSIS AND BETTER AVAILABILITY WILL COME WITH GREATER DEMAND	SPECIAL SOFTWARE IS REQUIRED TO MAKE THE ANALYSIS; THIS IS A ONE-TIME COST COMMERCIAL FIRMS CHARGE SEVERAL HUNDRED DOLLARS AN HOUR FOR USE OF IMAGE ANALYSIS SOFTWARE IF THE USER DOES NOT HAVE HIS OWN KNOWLEDGEABLE PERSONNEL ARE REQUIRED TO MAKE ANALYSIS	LANDSAT COVERAGE IS EVERY 9 TO 18 DAYS AND IS SUBJECT TO CLOUD COVER CONSIDERABLE DELAYS OF 4 TO 6 WEEKS MAY BE ENCOUNTERED IN OBTAINING THE DATA TAPES
AREAL EXTENT FROZEN GROUND	AIRCRAFT: ACTIVE AND PASSIVE MICROWAVE SYSTEMS; THERMAL INFRARED SATELLITE. MICROWAVE SENSING ON NIMBUS 6 AND 7 RESOLUTION: SATELLITE: 2000 10,000m AIRCRAFT: 100m	HOMOGENEOUS AREA REQUIRED SHALLOW SNOW COVER MAY BE PRESENT NO VEGETATION COVER SURFACE ROUGHNESS HARD TO DISTINGUISH AMONG FROZEN GROUND, ROUGH GROUND, VEGETATION, OTHER VARIABLES	ACTIVE MICROWAVE METHODS WILL ALLOW BETTER SNOW PENETRATION COMBINATION OF ACTIVE/PASSIVE MICROWAVE METHODS PLUS INFRARED MAY ALLOW BETTER DISCRIMINATION	TECHNIQUE IS HIGHLY EXPERIMENTAL AT THIS TIME CONSIDERABLE PROCESSING IS REQUIRED TO OBTAIN DATA IN USEFUL FORM	CURRENT RESEARCH EMPHASIZES AIRCRAFT FLIGHTS AND GROUND-BASED SYSTEM THAT CAN BE SCHEDULED AS NEEDED SUBJECT TO WEATHER LIMITATIONS
WATER EQUIVALENT OF SNOW COVER	AIRCRAFT: PASSIVE MICROWAVE ACTIVE MICROWAVE SATELLITE: NIMBUS 6 AND 7 RESOLUTION: AIRCRAFT: 10m	MEASUREMENT IS FUNCTION OF SNOW DEPTH, UNDERLYING SOIL CONDITIONS, AND SNOW CRYSTAL STRUCTURE	RESEARCH ON COMBINED ACTIVE/PASSIVE MICROWAVE METHODS NEEDED	TECHNIQUE IS HIGHLY EXPERIMENTAL AT THIS TIME SPECIAL EXPERTISE AND CONSIDERABLE PROCESSING ARE REQUIRED TO OBTAIN DATA IN USEFUL FORM	CURRENT RESEARCH EMPHASIS IS ON AIRCRAFT FLIGHTS AND GROUND-BASED SYSTEMS THAT CAN BE SCHEDULED SUBJECT TO WEATHER LIMITATIONS

system and the coverage is infrequent. Because of the cloud cover limitations, the 9 to 18 day coverage often becomes 18 to 36 or 45 days. In most cases there is only a 10-day delay for photo display. Considerable delay--up to 4 to 6 weeks--may be encountered in obtaining data tapes. Such delays decrease the usefulness of the data in a real-time forecast environment.

Measurement techniques for the remaining three Category 1 variables, soil moisture, areal extent of frozen ground, and water equivalent of snow cover, are in various states of experimental development. None of the three, with the possible exception of frozen ground, can currently be measured effectively from satellites. All three are awaiting further research on combined active/passive microwave measuring techniques.

Remote soil moisture measurement is the closest to realization. Airborne gamma radiation methods and microwave methods are advanced to the point of justifying a large-scale test to compare results and evaluate the worth of the data.

CHAPTER 4

USEFULNESS OF REMOTE SENSING IN HYDROLOGIC MODELS

1. INTRODUCTION

In spite of the recognized potential value of remotely sensed data for water resource management, the federal agencies responsible for river forecasting and water supply prediction are not using such data as a primary operational data base. To examine the reasons for this and to suggest improvements in remote sensing application, it was necessary to complete two major supportive tasks. The first of these was an in-depth review of the structure of existing hydrologic models. This review is presented in detail in a previously published NASA Contractor Report (2), which is summarized in Chapter 2 and in Appendix A of this report. The second supportive task was a review of remote sensing capabilities, which is presented in Chapter 3. Seven remotely sensed variables were selected on the basis that real-time data with sufficient accuracy and resolution could be obtained in the foreseeable future: soil moisture, impervious area, land cover, areal extent of snow cover, areal extent of frozen ground, water equivalent of snow cover, and precipitation.

There are several strategies for using remotely sensed data, or, indeed, any type of data, in hydrologic models. The first is to estimate the inputs to the models. All hydrologic models require precipitation as an input. Therefore, techniques to improve precipitation estimates using remote sensed data would have universal application in hydrologic modeling. Precipitation is not reviewed on a model-by-model basis because of this universal applicability and the tables and discussion below concentrate on the six remaining selected remote sensed variables.

A second strategy for using remotely sensed data in hydrologic models is to update the state of the model to be consistent with the data. For example, the antecedent precipitation index, which is one of the states of the API model, can be modified so that the model produces the observed total runoff. The distinction between using remote sensed data as an input and using the same data to update the model is important. The inputs to a model are the set of driving forces required periodically by the model. Data used to update the model is not absolutely required for each time step the model is run, and these data may have less stringent accuracy requirements since there are actually two sources of information about the hydrologic state - the modeled state and the observed data. An updating procedure must combine these two sources of information and account for their relative accuracy to arrive at an updated estimate of the state variable(s) of the model. Remote sensed information can be of significant value for keeping a model on track even if it is not a direct measurement of the variable represented by the state of the model.

To clarify the distinction between updating and input, consider using remote sensed observations of soil moisture. If the soil moisture observation is an input to the model, the model cannot be executed without soil moisture data. Presumably, the model has no other information about the status of the soil moisture than the input data. This implies a very simple model with no soil moisture state variables, no soil moisture dynamics, and no evaporation mechanics. There is no need to model what can be observed. However, the input approach does imply accurate observations since there is no other source of information about the soil moisture status than the observation itself. By contrast, an update approach seeks to combine observed soil moisture with modeled soil moisture states. The model states contain information about soil moisture based on the model dynamics and on past observations. A soil moisture observation can be used to modify the modeled soil moisture states. In this approach the soil moisture observation need not be available at every time step since the model can continue to run based on the modeled soil moisture states. Furthermore, the observation need not be as accurate to provide a valuable check to update modeled soil moisture status as it would need to be to directly replace the soil moisture model.

Suggestions for use of remote sensed data to update the states of the reviewed hydrologic models are made on the basis of an understanding of the structure of these models and a belief that the indicated state variables are likely to be closely related to remote sensed observations. The precise form these relationships might take and the details of an "update form" of the reviewed models are neither known nor suggested. The effort required to develop such models should not be underestimated.

The state variables of a lumped parameter conceptual hydrologic model represent indices to basin-wide average conditions of one or more components of the hydrologic system. Remote sensed observations represent spatial averages at a difference scale of one or more components of the hydrologic system. In many cases, it appears that several state variables may be related to a single remote sensed observation or that a remote sensed observation measures only part of some state variable.

A third strategy for using remotely sensed data is to calibrate the parameters of the model. In traditional applications, the parameters are estimated once based on current topographic and land cover data and hydrometeorological data for some calibration interval. It is certainly possible to recalibrate a model based on new data. Remote sensed observations can be used for more frequent recalibration of models, thus, blurring the distinction between updating and calibrating the model.

Each of the seven hydrologic models reviewed is discussed below in terms of the usefulness of each of the selected remote sensed variables for application to that model. The results are presented in the form of tables, one for each model. The "present configuration" column presents the potential usefulness of each remote sensed variable to the model as it is currently formulated and without research to determine the relationship between model inputs, parameters, or states and the remote sensed variable. The "minor modification or adaptation" column presents the potential usefulness of the remote sensed variable to the model allowing for minor structural changes to the model and significant effort at adapting the remote sensed observations to objectively incorporate them in the model. The term "minor structural changes" indicates changes that should not require complete recalibration of the model; this is an important distinction since considerable effort has been expended in calibrating these models. Within each box of the table, the three strategies for data use are listed as (1) input, (2) update, and (3) calibrate. A distinction is made between "N/A" and "No"; N/A being used when the remote sensed variable does not apply to the model in question (for example, input of land cover to a model with no land cover variables) and "No" being used in situations in which the remote sensed variable cannot be used in the indicated way.

2. API MODEL

The original API, event forecasting, rainfall-runoff relation uses precipitation as input and has only two parameters week number and basin constant (RA) , and two states antecedent precipitation index (API) and Retention Index (RI) . For this basic model, many processes are reflected by the two parameters and neither is directly related to any of the six remote sensing capabilities in Category 1. Likewise, the two states reflect more than a single moisture storage and therefore do not relate directly to the remote sensed data.

In the continuous API model reviewed for this study (Figure 2 in Appendix A), the additional four parameters relate only to calibration of the base flow component of the runoff and are not related to the remote sensed capabilities.

As may be noted in Table 4-1, none of the remote sensed variables is considered of direct value. Since the API has no snowmelt component, a snowmelt model must be used. The NWSRFS Snowmelt model is used for this purpose by the NWS.

Objective methods can be developed to use the remote sensed information for updating and calibrating the API model as may be seen in Table 4-1. However, the value would be rather limited.

The major advantage of the API model is its simplicity. Many modifications to allow the use of remote sensed data would complicate the model and bring it closer to the more complex models. The value of being able to make one simple adjustment (e.g., a change in the state, API) to bring the predicted streamflow in alignment with observed streamflow is appreciated by operational forecasters and should not be overlooked.

3. CREAMS MODEL

The CREAMS model has two options, which are described in the interim report (2) and illustrated in diagrams in Appendix A (Figure 3a and 3b). Option 1 accepts total daily rainfall as input and uses the Soil Conservation Service (SCS) Curve Number method for calibrating daily runoff. Option 2 uses breakpoint rainfall as input and uses the Green and Ampt infiltration formula for

Table 4-1. USE OF REMOTE SENSED DATA IN API HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
OIL MOISTURE	1. No 2. No 3. No	1. No 2. Technique to update Antecedent Precipitation Index, API 3. No
IMPERVIOUS AREA	1. N/A 2. No 3. No	1. N/A 2. No 3. Aid in developing rainfall-runoff relationships
AND COVER	1. N/A 2. No 3. No	1. N/A 2. Update retention index (RI) 3. Define basin constant (RA) related to interception
REAL EXTENT SNOW COVER	1. No 2. No 3. No	1. No 2. Objective procedure to determine area subject to snowmelt 3. No
REAL EXTENT ROZEN GROUND	1. No 2. No 3. No	1. No 2. Objective technique to adjust RI 3. Define variation in RA during winter
WATER QUIVALENT NOW COVER	Normally a temperature index or NWSRFS Snowmelt model is used	

*1. Input; 2. Update; 3. Calibrate

The CREAMS model was designed to use remote sensing capabilities as much as practicable. The information in Table 4-2 indicates only partial success using the present configuration of the model. For calibration, knowledge of the impervious area has value for determining the parameter Curve Number, CN2, and land cover information has only minimum value for defining the Winter Cover Factor, GR. For both of these, objective procedures would enhance the value of using the remote sensed information.

The land cover information can be used directly for updating the Leaf Area Index, X(I). However, since this index is related to evapotranspiration losses, there is no objective way to evaluate the usefulness of the updating.

With minor modifications, as indicated in Table 4-2, the states representing the upper layer of the soil moisture could be updated. Since the state BST and, in addition, for Option 2, the state DS, reflect more than the upper soil moisture level, measurement of soil moisture would not relate directly to a state of the model. A major modification of the model could be made to have an upper soil moisture state that would be directly related to the remote sensed values.

None of the remotely sensed variables can be used directly for calibration. With minor modification and development of objective procedures, they would be of value for calibration.

4. NWSRFS MODEL

The NWSRFS (Sacramento) model is a true conceptual model in that the model characteristics (storages of moisture, percolation, evapotranspiration, etc.) are intended to represent actual hydrologic processes in a rational manner. Even if the model perfectly represented what occurs in nature, the moisture

Table 4-2. USE OF REMOTE SENSED DATA IN CREAMS HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. To update for available plant water BST and/or depth of surface soil layer, DS (Option 2) 3. To define soil transmission COEFF, CONA, (Option 2)
IMPERVIOUS AREA	1. N/A 2. No 3. Determining weighted SCS Curve Number, CN2 (option 1)	1. N/A 2. No 3. Objective method to determine SCS Curve Number, CN2, in conjunction with other parameters
LAND COVER	1. N/A 2. For leaf area index, X(I) 3. Define winter cover factor, GR	1. N/A 2. Objective method for updating leaf area index X(I) 3. Define winter cover factor, GR
AREAL EXTENT SNOW COVER	1. N/A 2. N/A 3. N/A	1. N/A 2. N/A 3. N/A
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. Use to modify soil water content, BST, during winter 3. Define winter cover factor, GR, and initial abstraction coefficient, SIA, in winter
WATER EQUIVALENT SNOW COVER	1. No 2. No 3. No	1. No 2. Update water equivalent of snow cover procedure 3. No

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* 1. Input; 2. Update; 3. Calibrate

stages would not necessarily correspond directly with remote sensed measurements. For example, the upper soil moisture zone in the model generally represent a much deeper soil layer than the 5 to 10 cm depth measured remotely.

Table 4-3 indicates that none of the selected remotely sensed variables relates sufficiently to the model components to be used for updating for the present configuration of the model. Calibration of the model can be improved by remote measurement of impervious area for the parameters, PCTIM, and land cover measurements are of value in basin segmentation for determining areas for separate calibration.

Remotely sensed information on soil moisture and on the areal extent of frozen ground would be of value for use in objective procedures to define during calibration maximum water storages and the seasonal variation of the potential evapotranspiration demand curve. The same information using objective procedure fitted to the model could be used for updating the states of moisture in the upper soil moisture zone and for adjusting the rate of loss of the upper soil moisture, UZFWC. These are the significant improvements that could be made with minor modification to the model. Improvements requiring significant modification to the model are discussed in Chapter 5.

5. STORM MODEL

The STORM model was designed as an economical means of evaluating various storm-water runoff storage and treatment methods. It is designed primarily for urban or combined urban-rural drainages.

Table 4-3. USE OF REMOTE SENSED DATA IN NWSRFS HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. Update upper zone free water, UZFWC, and tension water, UZTWC 3. Define upper zone free water maximum (UZFWM), some information on (PE demand) curves
IMPERVIOUS AREA	1. N/A 2. No 3. For impervious area, PCTIM	1. N/A 2. No 3. Objective procedure to determine impervious area, PCTIM
LAND COVER	1. N/A 2. No 3. In model segmentation (forested versus non-forested) and for raparian vegetation, RIVA	1. N/A 2. No 3. Objective techniques for model segmentation and riparian vegetation. Also to define seasonal PE demand curves
AREAL EXTENT SNOW COVER	SEE NWSRFS SNOWMELT MODEL	
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. To adjust the rate of loss of upper zone soil moisture, UZFWC 3. To define winter values for UZFWM and UZK
WATER EQUIVALENT SNOW COVER	SEE NWSRFS SNOWMELT MODEL	

*1. Input; 2. Update; 3. Calibrate

The STORM model is not a highly sophisticated rainfall-runoff model. It is a combination of two similar methods for determining runoff from urban and nonurban areas. The model has only two state variables, F_u and F_n, which represent the amount of water stored in depressions in urban and nonurban areas, respectively. The original version of the model has no sophisticated infiltration/percolation method. Water from precipitation, the primary input, either runs off or infiltrates based on runoff coefficients, C_u and C_n, for the urban and nonurban areas, respectively. An option added to the model allows determination of runoff by means of the SCS Curve Number method if desired.

The primary model parameters are those that control segmentation X_I, the area associated with the I^{th} land use, and F_I, the percent of the I^{th} land use that is impervious. The model is calibrated by adjusting C_u and C_n after X_I and F_I are determined.

Table 4-4 compares STORM model requirements with the six Category 1 remotely sensed variables. STORM is one of the few models wherein remotely sensed data may be used without model modification. Remotely sensed data may be used to determine both the land use categories (X_I) and the percentage of impervious areas during model calibration. Jackson, Ragan, and Fitch (14) have demonstrated the utility of LANDSAT data for this purpose and compared the accuracy and cost to similar determinations via aerial photography.

The SCS Curve Number Model Option of STORM may also benefit from remote sensing. Ragan and Jackson (15) have demonstrated the utility of LANDSAT imagery for determining land cover distributions in the SCS model.

Table 4-4. USE OF REMOTE SENSED DATA IN STORM HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. Could be used in versions allowing SCS Curve Number Option 1 3. No
IMPERVIOUS AREA	1. N/A 2. No 3. To determine impervious and urban areas for F_I and X_I	1. N/A 2. No 3. Objective methods for calibration (F_I and X_I)
LAND COVER	1. N/A 2. No 3. Aid in determining urban area, X_I	1. N/A 2. No 3. Objective method for calibration (X_I)
AREAL EXTENT SNOW COVER	1. N/A 2. N/A 3. N/A	
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. A modification could vary the F_I parameter based on frozen ground observations 3. No
WATER EQUIVALENT SNOW COVER	1. N/A 2. N/A 3. N/A	

*1. Input; 2. Update; 3. Calibrate

There are no other obvious applications of current remotely sensed variables with the current version of STORM. With minor modifications it may be possible to establish error bands on the X_I and F_I coefficient to allow more reasonable adjustments for calibration. It should also be possible to develop a method for adjusting the runoff coefficients, C_n, based on the areal extent of frozen ground. Such a modification might make winter runoff prediction more accurate.

STORM was conceived as an economical, simple method for analyzing years of record under various treatment plans. It is unlikely that the model could be further improved for use with remote sensing without losing sight of its original simplicity and purpose.

6. STANFORD WATERSHED MODEL

The Stanford Watershed Model (SWM) is a lumped input conceptual model. A basic modeling philosphy is to recognize explicitly the spatial variability of infiltration, interflow production, surface runoff, and evapotranspiration. Therefore, model parameters and states are indices to average basin conditions. It is not clear that the basin average conditions implied by the Stanford model are the same as the spatial averaging of remote sensed variables. The user may subdivide a watershed into catchments, each of which has a separate parameters set, but SWM does not lend itself readily to subdivisions based on elevation or land use or aspect or other characteristics that lead to noncontiguous zones. It may be possible to use remote sensed land cover data to guide the division of watershed into comparatively homogeneous catchments. As shown in Table 4-5, the present configuration of SWM does not lend itself to use of the selected remote sensed

Table 4-5. USE OF REMOTE SENSED DATA IN STANFORD WATERSHED HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. Update storages, UZS, RES, SRGX, and LZS, in some combination 3. Aid in defining nominal upper zone storage, UZSN, and possible guidance on CB and CC
IMPERVIOUS AREA	1. N/A 2. No 3. For percent impervious, A	1. N/A 2. No 3. Objective procedure to define impervious area, A
LAND COVER	1. N/A 2. No 3. To define water area, ETL, and percent riparian vegetation, K24EL, subjective guidance in basin segmentation	1. N/A 2. No 3. Objective procedures to define maximum amount of interception storage, EPXM, and evaporation loss index lower zone, K3
AREAL EXTENT SNOW COVER	SEE NWSRFS SNOWMELT MODEL	
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. Technique to adjust the infiltration index, CB 3. No
WATER EQUIVALENT SNOW COVER	SEE NWSRFS SNOWMELT MODEL	

*1. Input; 2. Update; 3. Calibrate

variables beyond calibration of three parameters; percent impervious, water area, and percent riparian vegetation.

It may be possible to relate maximum interception storage and the evaporation loss index to remote sensed land cover. It may also be possible to gain some insight into values of nominal upper zone storage and the CB and CC parameters by intertemporal comparisons of remotely sensed soil moisture.

The state variables for surface detention (RES) and interception storage (EPX) are only active during and shortly after rainfall events. Somewhat more long-lived after the end of an event is the interflow storage (SRGX). As a result, an measurement of near-surface soil moisture soon after rainfall may include not only the upper zone storage (UZS), but also SRGX, and perhaps RES and EPX. Also the division of the soil into soil horizons is not a sharp delineation in SWM so that the lower zone storage (LZS) may also be related to remote sensed soil moisture. In short, it may be possible to update several states of SWM using remote sensed soil moisture, but it will require significant effort to determine the relationships of the observations to the states.

Finally, it may be possible to modify the parameters of SWM, particularly the infiltration index (CB) to represent frozen ground conditions. Minor structural changes to SWM would probably be required.

7. SSARR MODEL

The SSARR model is widely used by the U.S. Army Corps of Engineers for runoff forecasting and for design in cases of extreme hydrologic events. The nature of the model does not, however, lend itself to use of many remotely sensed variables.

SSARR has five state variables representing soil moisture, base flow infiltration, and the quantities of water in storage in surface, subsurface, and base flow. Of these, only the soil moisture index has an intuitive relationship to soil moisture as remotely sensed.

The SSARR model is calibrated by setting 13 parameters. Some of the parameters are set directly (such as the N's that determine the number of routing phases), and others are set in relation to one another or to states through three tables (such as runoff percent, ROP, versus the soil moisture index, SMI). The tables take the place of equations describing physical processes such as infiltration or evapotranspiration.

Table 4-6 compares SSARR model requirements with the six Category 1 remotely sensed variables. As currently configured, there is no known connection between any SSARR parameter and any of the six Category 1 remotely sensed variables in the rainfall-runoff portion of the model. SSARR does have a snowmelt model with two options. Both options require some knowledge of snow covered area. Snow covered area can be used in model updating and possibly could help in determining the seasonal depletion curves during calibration.

A promising modification to SSARR to use remotely sensed data would be through the soil moisture index. It appears that when reasonably frequent soil moisture measurements become available (say once a week), an empirical relationship can be developed between the SMI and soil moisture as remotely sensed. Historical record of soil moisture, when available, will help in determining the portion of runoff to soil moisture and, hence, the definition of the ROP/SMI table.

Other possible SSARR modifications might make use of impervious area in determining the shape of the runoff versus

Table 4-6. USE OF REMOTE SENSED DATA IN SSARR HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. Update soil moisture index (SMI) 3. Define ROP/SMI table
IMPERVIOUS AREA	1. N/A 2. No 3. No	1. N/A 2. Could be used to modify or select alternate tables 3. Could infer shape of ROP/SMI, BFP/BII, RS/(RGS/PH) tables
LAND COVER	1. N/A 2. No 3. No	1. N/A 2. To modify or substitute the infiltration table, RS/(RGS/PH) and evapotranspiration table, KE/RI 3. No
AREAL EXTENT SNOW COVER	1. N/A 2. Can be used to update snow covered area 3. Might be used to check model depletion curve calibration if available frequently enough	1. Could be used as input if available frequently enough 2. Update snow covered area 3. Model calibration of depletion curve.
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. Update soil moisture index, SMI. Adjust phase storage for subsurface flow, to modify or substitute the ROP/SMI, BFP/BII, and RS/(RGS/PH) tables 3. No
WATER EQUIVALENT SNOW COVER	1. No 2. No 3. No	1. No 2. No 3. No

*1. Input; 2. Update; 3. Calibrate

soil moisture and the base flow (BFP) versus base flow infiltration index (BII) table. Some information might also be useful for the surface runoff table (RS). Land cover might also be useful for inferring the shape of these tables.

Areal extent of snow cover could conceivably be used as a model input, completely replacing a state variable, if it were available on a daily basis.

Frozen ground definitely affects the infiltration and evapotranspiration processes. Thus, areal extent of frozen ground estimates might be used to modify or substitute several of the tables to more accurately portray frozen conditions.

There is no obvious use for measurements of water equivalent of snow in SSARR without a major revision of the snowmelt portion of the model.

8. NWSRFS SNOWMELT MODEL

The NWSRFS Snowmelt model stands somewhat alone from the other models reviewed. In the development of this model, the possible availability of remote sensed data was considered. When the model has been calibrated and applied, by an expert modeler, it can be subjectively updated using the areal extent of the snow cover (at least for areal averages of more than 30 percent) and to a lesser degree using the water equivalent of the snow cover.

As noted in Table 4-7, modification of the model to objectively use remote sensed observations of the areal extent of the snow cover and the water equivalent of the snow cover would improve the model for general use. The model could be modified without changing the heat budget and liquid water components. The value of such procedures would be enhanced with a longer data base of

Table 4-7. USE OF REMOTE SENSED DATA IN NWSRFS SNOWMELT HYDROLOGIC MODEL

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
IL MOISTURE	SEE NWSRFS MODEL	
MPERVIOUS AREA	SEE NWSRFS MODEL	
ND COVER	SEE NWSRFS MODEL	
EAL EXTENT NOW COVER	1. No 2. Subjective update of areal extent of snow cover 3. No	1. No 2. Redesign to use R S observations of AESC and WE directly - leaving heat budget and liquid water components as is 3. Aid in developing areal depletion curve and SI
EAL EXTENT OZEN GROUND	SEE NWSRFS MODEL	
WATER UIVALENT OW COVER	1. No 2. Subjective update of water equivalent 3. To develop areal depletion curve	1. No 2. Objective procedure to update water equivalent, WE, and areal extent of snow cover 3. Objective techniques to develop areal depletion curve, and for checking water balance

Input; 2. Update; 3. Calibrate

Several years of record of the areal extent of the snow cover and of the water equivalent of the snow cover would also be of considerable value in calibration with minor modification of the model as shown in Table 4-7.

The development of objective procedures for using remotely sensed data for calibration and updating would greatly increase the value and usefulness of the NWSRFS Snowmelt model. This statement is based partially on the fact that the model is designed to accept such information. A second important factor is that remote sensed measurements will probably provide much more accurate information on the characteristics of the snow cover than is now possible using ground measurements to estimate areal average values. The accuracy of remotely sensed measurement of the areal extent of the snow cover is equivalent to or greater than that of other estimates. Remotely sensed measurements of the water equivalent of the snow cover using the aerial gamma radiation method are considered by some to be more representative of the areal average than can be estimated using point measurements (16).

The usefulness of remote sensed measurements of the snow cover for aid in modeling snow accumulation and ablation and predicting snowmelt runoff is undoubtedly the most promising contribution to the field of hydrology.

Because the ability to measure water equivalent is related to snow depth, the first primary contribution will probably be for the North Central Plains area of the United States where snow depth are not large. The area is subject to serious snowmelt flooding as well as drought, and remote sensing could provide substantial information for monitoring both of these conditions. As remotely sensed measurements improve in quality their value will also improve for the different snow cover conditions experienced in the northeast and in the mountainous west.

9. SUMMARY

A review of Tables 4-1 through 4-7 shows that with two exceptions the present configuration of hydrologic models hold little promise for use of remote sensed data. The first exception is the use of remote sensed data to define impervious area and other special land cover categories (water surface, riparian vegetation) in models with parameters closely related to these land cover categories. The second exception is the use of areal extent of snow cover and water equivalent of snow cover to update and calibrate the NWSRFS Snowmelt model.

Minor structural changes and adaptations of existing hydrologic models can greatly increase the usefulness of remote sensed data in hydrologic models.

CHAPTER 5

POTENTIAL USEFULNESS IN HYDROLOGIC MODELS

1. REQUIREMENTS FOR HYDROLOGIC MODELS

Hydrologic models that are currently in widespread use were developed before remote sensed data were available in any significant amounts. These models are better suited to the type of measurements available when they were developed than they are to state-of-the-art measurement techniques. The previous chapter examined the usefulness of remote sensing in hydrologic models as they currently exist or as they might exist with minor structural modifications and adaptations. This chapter, then, examines the potential usefulness of remote sensing to four of the selected models if major structural changes are allowed.

Before specific models are examined, the general features of a hydrologic model that would maximize the usefulness of all available data (both remote sensed and ground) are discussed. When these model features are contradictory, the model builder must find an appropriate compromise.

A major feature of any hydrologic model is the scale of the model. Involved are the horizontal scale, (basin size), the vertical scale (soil and snow horizons), and the time scale (time step). It is desirable to match the scale of the model to the scale of the observations since this will make the observations more directly useable.

The natural horizontal scale for lumped parameter models is the basin. Each model has some range of appropriate basin size. The usual approach is to derive areal average values of precipitation and other input items (e.g., temperature, potential evapotranspirations) over each catchment. This will continue to be the major approach to dealing with mismatched horizontal scales of model and observations, but the data-processing techniques to estimate the appropritate areal average values need to be much more sophisticated in order to combine observations that have various spatial sampling scales.

An alternative approach is to match the horizontal scale of the model to the observations. When the observations have comparatively high resolution (e.g., approximately 1 acre for LANDSAT), this approach leads to distributed models. The great difficulty with distributed models is the enormous increase in the number of parameters. To be practical, all of the parameters of a distributed model need to be directly measurable, a difficult requirement to meet.

The vertical scale of the model should match the observation. If a remote sensed soil moisture measurement represents the top 10 cm of soil, the model should ideally have a single state variable that represents the moisture content of the top 10 cm of soil. There is no guarantee that the most appropriate vertical scale for hydrologic purposes will match the vertical scale of observations.

The time step of the model must be short enough to identify significant variations in observed quantities. If observed quantities undergo significant diurnal variation, it must be possible to identify the modeled hydrologic state at the time of day of the observation.

An inherent tradeoff exists between the accuracy and timeliness of observations and the complexity of a model. For example, many parameters and states will be required to predict the freezing and thawing of the ground. If the frozen ground condition can be observed accurately enough and frequently enough, there is no need to model it. It is important to remember both the accuracy and measurement frequency requirements; intermittent observations may require a model to account for hydrologic conditions between observations. If observations are not very accurate, a model may stabilize the observation error.

Certain structural features of a model can make it more difficult to update the model states. It is helpful to avoid nonfunctional (table driven) components and highly nonlinear components. These features make it difficult to identify the relationship between observations and model states.

2. REMOTE SENSING NEEDS TO HELP MODELING

2.1 The Problems of Remotely Sensed Data

The research presented here shows why so little use is made of remotely sensed data in hydrologic modeling. With very few exceptions no one-to-one correspondence exists between a remotely sensed variable and either a model input or a model state.

The most useful remotely sensed variables that are currently used deal with area. These variables are land cover, impervious areas, and snow covered area. All are currently determined primarily from LANDSAT data and to a lesser degree from aircraft.

The resolution of the three variables from LANDSAT is approximately one acre, which is adequate for most basin modeling activities. NOAA AVHRR data are available several times a day at 1 km resolution, and for many basins may be more useful than LANDSAT data. The time frame of the data is 9 to 18 days with time out for days on which cloud cover dominates. Because of the cloud effects, data are reliable only for initial model calibration (land cover, impervious area) and updating (snow cover).

2.2 Current Requirements

Most of the practical applications in present models using LANDSAT data have been identified. Efforts should now concentrate on data reliability and ready availability in a form usable to modelers. Remote sensed measurement may be of significant value to a specific model but of much less value to a different model. The 5 to 6 week delay in getting the data tapes all but renders the data useless for operational forecast activity.

All computer modelers want more data. Most hydrologic modelers want more precipitation and streamflow data now not six weeks from now. Thus, the primary remote sensing priority should be real-time, already-distributed, precipitation measurements. Reliable precipitation measurements at a reasonable cost will be wholeheartedly adopted by modelers both for real-time forecasts and for use in calibration.

Remote sensing as defined here can do little for streamflow data, which is primarily a telemetry problem. Real-time streamflow data are available through the Geostationary Operational Environmental Satellite (GOES).

The problem of now versus 6 weeks from now must be addressed on two fronts. First, microwave systems that are not significantly affected by cloud cover must be placed in orbit. Data on a number of variables of hydrologic interest appear to be collectable by microwave techniques (frozen ground, soil moisture, snow covered area, water equivalent and liquid water content of snow). Microwave systems would ensure the availability of at least some data every 3 days when used in low earth orbit. (The time interval is better than LANDSAT because of a wider field of view.) Additionally, high resolution sensors capable of 80 m or less from synchronous orbit should be a goal. Remotely sensed data will never be widely used in operational forecasting until more frequent readings are available.

In addition, technology must be developed to permit modelers to obtain data on such variables as soil moisture in their own offices on their own computer at reasonable cost. In other words, soil moisture data must be just as common and reliable as a telemetered stream stage measurement.

There is a need for those engaged in the design and operation of remote sensing systems to obtain feedback from hydrologic modelers. For example, the accuracy of measuring the water equivalent of the snow cover may be much less than the requirement set by hydrologists. However, measurements of less accuracy indicating incremental changes (e.g., by 1 or 2 cm intevals) may be of value for those responsible for forecasting snowmelt floods.

Continued research is needed on discrimination problems. Very few variables can be reliably identified from space without extensive ground truth. Techniques that can only determine snow depth accurately in open areas and flat terrain will not be widely used as techniques which would be used in forested areas and in rough terrain. Multisensor systems that use several spectral bands combined with point observations on the ground may be needed for accurate determination of variables.

3. NWSRFS MODEL

Improving the ability to calibrate a model is important. However, having available greatly improved input data or enhancing the ability to keep the model operationally on track by updating it is more important. Improvements in the measurement of precipitation by remote sensing holds the greatest promise for increasing the usefulness of any hydrologic model. At the present time there is promise for using remote sensing other than precipitation as input to the NWSRFS model.

Remote sensing data can improve modeling by relating the states to the remote sensed measurements. For the NWSRFS model, three remotely sensed variables, soil moisture, land cover and areal extent of frozen ground, are prime candidates for this use. When considering major model modification to improve the usefulness of remote sensing, these variables must be considered. For the purpose of this analysis, each will be discussed separately even though a model incorporating the ability to observe a state of the model by all three remote sensing capabilities would be more valuable.

3.1 Soil Moisture

One approach in the use of remote soil moisture measurement to observe a state* would be to create a state representing the soil moisture in the upper few inches of the soil. This state could be created by dividing the upper zone into a surface layer and a subsurface layer. The surface layer would control the infiltration and relations with direct and surface runoff. The state or states representing the moisture in the subsurface layer of the upper zone would operate to control percolation and interflow as is handled at present in the model. Such a modification could have a minimal impact on the model as it is now constituted but would require considerable modification to several components of the model.

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*Recall that state variables are those whose value must be known to start a model. The states completely define the past history of inputs. Typically states are moisture contents in various model components.

3.2 Land Cover

Land cover is related primarily to evapotranspiration and interception losses. A state variable for the vegetal cover could be introduced to adjust the amount of evapotranspiration loss from depths in the root zone. Likewise, the index could be used to modify the amount of infiltration. These changes would have minimal impact on the remainder of the model. The major changes would be those to ensure a correct water balance.

3.3 Areal Extent of Frozen Ground

The occurrence of frozen ground can result in major changes in the way in which water moves in nature. A hydrologic model that could model frozen ground would require many parameters and states to account for the many heat and moisture fluxes and for freezing and thawing of the various layers of soil. Assuming that ability, the model would have to have data on frozen ground with and without snow cover. A model that could accept the measurement of frozen ground as an input rather than for updating would be most desirable. In this model, the processes would be modified for the frozen area. The introduction of a frozen ground input would affect many processes in the model and would require considerable research to devise the necessary alterrations in processes under frozen conditions. Many questions remain, such as the depth of frozen ground that is reflected by the remote measurements and whether remote sensing could provide any information on the depth or other characteristics of the frozen ground.

4. NWSRFS SNOWMELT MODEL

The NWSRFS Snowmelt model with the modifications recommended in Section 8 of Chapter 4 would have the capability to use both the measurements of the areal extent and the water equivalent of the snow cover. No additional modification for the purpose of using the remote sensing capabilities selected for Category 1 is deemed necessary. However, in the case of this model, two of the items in Category 2--measurements of the liquid content of the snow cover and the surface temperature (of the snow cover) could be of value in the future.

During the past few years, the NWS has used airborne gamma radiation surveys to obtain areal average water equivalent values of the snow cover for selected flight lines (11). These are average values for about 2.0 mi^2 (1,000 ft wide strip over approximately a 10 mile line). The change in the radiation flux from the ground relates to the total change in mass on the surface of the ground and in the surface layer of the soil (about 10 to 20 centimeters). Thus, the survey measures the change in the soil moisture in the surface layer of the soil as well as the mass of the snow cover. These readings must be corrected for the soil moisture under the snow cover (or more exactly for the change in soil moisture between the no-snow calibration survey and the snow survey). The uncertainty in the soil moisture at the time of the snow cover survey, introduces an error (the average areal value under the snow can not be measured). For surveys without snow, measurements of the soil moisture are obtained.

The measurement of the total change in mass (water equivalent of the snow cover and of the soil moisture in the surface layer) contains more information than the water equivalent estimates currently determined. These remote measurements would be better used by coupling the NWSRFS hydrologic model with the NWS snow accumulation and ablation model to provide for updating or direct input of these measurements. The major requirements in developing a combined model would be the formulation of the state relating to both models and in development of methods to regulate the water balance between and within the two models.

5. STORM MODEL

It is not clear that revising the STORM model to use remote sensing information over and above land cover and impervious area would have any great value. The STORM model is not commonly used in runoff forecasting, rather it is used in comparative design studies. Such studies do not require 100 percent calibration accuracy or complete modeling of the physical processes involved.

As with all the models considered here, there is no question that improved measurement of precipitation via remote sensing would be helpful. None of the other Category 1 variables appears to be useful as an input to the STORM model.

In the update phase of modeling, soil moisture and perhaps frozen ground measurements might be incorporated in the model. Frozen ground records could be used to periodically adjust the C_I runoff coefficients or the F_I impervious area coefficients. An empirical method for accomplishing this would have to be developed. Alternatively, a "seasonal" adjustment curve for the F_I and or C_I might be developed if sufficient frozen ground data became available.

Although soil moisture would have no utility in the normal STORM model, it could, however, be used in the SCS Curve Number version. A procedure could be incorporated to use a soil moisture state for selecting the correct curve.

In the calibration phase of modeling only land cover and impervious area appears useful. These variables have already been used in STORM modeling activities. Minor modification could probably be included to establish bounds on the accuracy of the F_I and X_I coefficients. These bounds could be used in sensitivity analysis and in setting limits in adjustments to F_I and X_I during calibration. Objective procedures for relating the runoff coefficients, C_I, for various land uses could also be developed. Programs could be developed to automatically segment and classify a basin from a LANDSAT scene and ground truth. The need for such automation appears small because of the once-only nature of calibration.

6. SSARR MODEL

The SSARR model is widely used for forecasting and for simulation of extreme events. Delay in receipt of data does not seem to be a problem for the use of the STORM model. Modifications to incorporate or more fully use remote sensing thus appear justified. The number of such modifications is somewhat limited by the nature of the model. Much of its internal workings depend on tables of parameters versus state variables. There are no equations describing physical process and hence no direct connection between variables that can be remotely sensed and model behavior. "Modification" of the model may in some cases not be modification at all. Instead, procedures will be developed to allow the modeler to change or set up the existing model in better ways dependent on remote sensing.

For the input phase of modeling the most promising input concerns snow-covered areas. If snow-covered area could be obtained from a synchronous satellite without cloud cover effects, a model could be developed with snow cover used as an input. As currently configured, the SSARR Snowmelt model could use the snow-covered area data to update the area state variable.

In the update phase of modeling, soil moisture, impervious area, land cover, and areal extent of frozen ground appear useful. Data on soil moisture has the most attractive potential for use with model modification. In fact no modification may be necessary; it may be necessary merely to develop an empirical relationship. If soil moisture can be sensed at reasonably frequent intervals, a relationship should be demonstrable between the measurement and the SMI (soil moisture index) in a calibrated model. A simple equation or equations should allow the modeler to update the SMI based on remotely sensed data.

To incorporate impervious area, land cover, and areal extent of frozen ground into SSARR, some means must be added to modify or exchange the model tables. All three variables have an effect on the infiltration process, evapotranspiration, and surface detention and runoff. It would be necessary to carefully calibrate SSARR on a basin and to determine empirically the effect of changes in land cover, frozen ground, and others on the shape of the tables. Possible seasonal variations in tables or alternate tables could be selected based on the appropriate remotely sensed variable.

In the calibration phase of modeling, several possiblities exist for SSARR. Using remotely sensed data in calibration, however, implies that an appropriately modified model exists. Soil moisture records could be corrected with runoff records to help infer the shape of the runoff percent versus soil moisture index (ROP/SMI) table. Continuous records of impervious area, land cover changes, and extent of frozen ground could be used in defining seasonal adjustment curves for the tables in an appropriately modified model.

CHAPTER 6

SUMMARY AND CONCLUSIONS

To date, remote sensing has not been used significantly for operational hydrologic forecasting in the United States. Although its potential value is well documented, two areas in which remote sensing could play a very important role have not been given adequate consideration.

First, remote sensed information could be used to offset the loss in quality and quantity of measurements resulting from the decrease in support for the national hydrometeorological networks. Second, areal averages of hydrometeorological variables over the drier areas of the United States estimated from current and even greatly enhanced ground-based data-collection networks are not sufficiently accurate to meet the input data needs of improved conceptual hydrologic models; remote sensing systems envisioned in the foreseeable future could provide more accurate information.

This study assesses the capabilities of current and planned remote sensing systems for improving the value of commonly used river forecasting models.

Two important reviews were conducted in this study. First, a detailed anlaysis was made of the structure, parameters, states, and required inputs for seven hydrologic models and reported in an interim report (2). Next remote sensing capabilities with possible value for hydrologic modeling were reviewed and are documented in this report. The two reviews provided the basis for evaluating the usefulness of remote sensing measurements for each of the hydrologic models in their present configuration and with minor modifications. Consideration was also given to making major modifications to four of the hydrologic models so that remotely sensed information could be used to improve their usefulness and/or accuracy for hydrologic forecasting.

A significant technology transfer lag continues to exist in the hydrologic community, which makes little use of LANDSAT-based land cover identification procedures. A major barrier is that existing hydrologic models can make only peripheral use of land cover information.

The most obvious conclusion of the study is that most hydrologic models in their present configuration do not have a significant potential for using remotely sensed observations. Two exceptions are (a) the identification of impervious area, water area, and riparian vegetation for those models that explicitely recognize these special land cover categories and (b) the use of observations in the NWSRFS Snowmelt model.

However, with minor structural modifications, some of the models can take advantage of the significant potential for applying remotely sensed data to hydrologic modeling. These modifications can be made without necessarily recalibrating the models for basins to which they are currently applied. Exploiting this potential will require a continuous data base of remotely sensed and ground observations for calibrated basin models in order to investigate the relationship of remotely sensed observations to modeled states.

Of the models reviewed in this study, modification of the NWSRFS Snowmelt model to provide for objective updating using remotely sensed measurements of the areal extent and of the water equivalent of the snow cover offers the most promise for improvement in operational use.

Most of the readily apparent applications of LANDSAT and other satellite data in hydrologic modeling have been identified . More promising applications of remotely sensed data to hydrologic models will be possible with the coming of high-resolution, passive, microwave sensors in satellites. Microwave sensors will make possible operational measurements of soil moisture and possibly water equivalent of snow.

Hydrologic modeling can be improved through the development of a new generation of models or subroutines for existing models which recognize the characteristics of the new remote sensing capabilities.

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APPENDIX A

This Appendix presents

- tables of parameters with definitions,
- tables of states with definitions, and
- schematic diagrams

from the interim report (2) for the following seven models:

1. Antecedent Precipitation Index (API)
2. Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS)
3. National Weather Service River Forecast System (NWSRFS)
4. Storage, Treatment, Overflow, Runoff Model (STORM)
5. Stanford Watershed Model IV (SWM)
6. Streamflow Synthesis and Reservoir Regulation (SSARR)
7. NWSRFS Snow Accumulation and Ablation Model

A legend for the diagrams is shown in Figure 1 (page A-2)

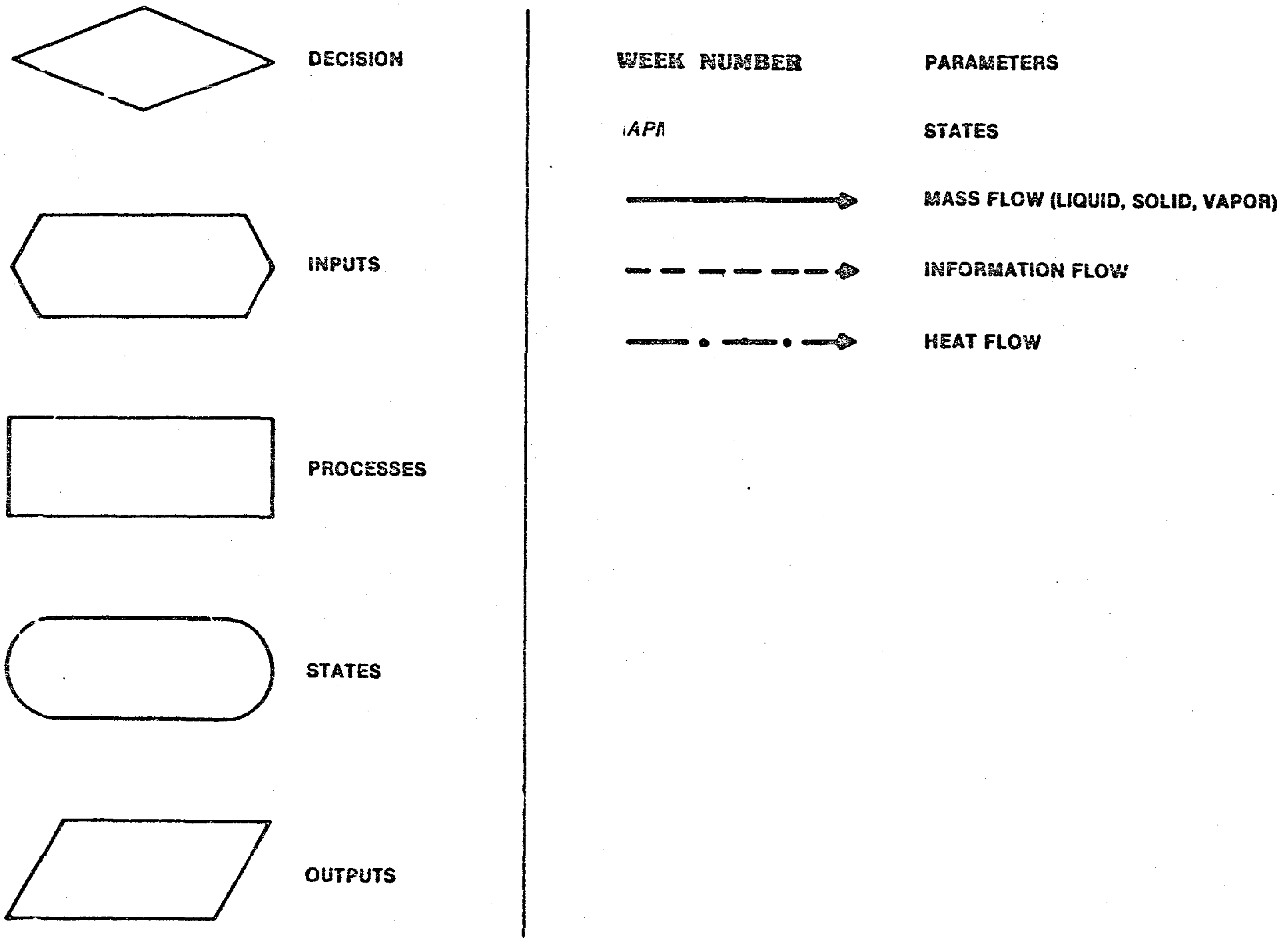


Figure 1. LEGEND FOR SCHEMATIC DIAGRAMS OF MODEL

Table 1. PARAMETERS (DEFINITIONS) API MODEL

Kg	Groundwater Recession Coefficient.
RA	Basin Constant.
WEEK NUMBER	Weeks of the Year Numbered Sequentially.
ZA	Basin Constant.
ZB	Basin Constant.
ZC	Basin Constant.

Table 2. STATES (DEFINITIONS) API MODEL

API	Antecedent Precipitation Index.
RI	Retention Index.

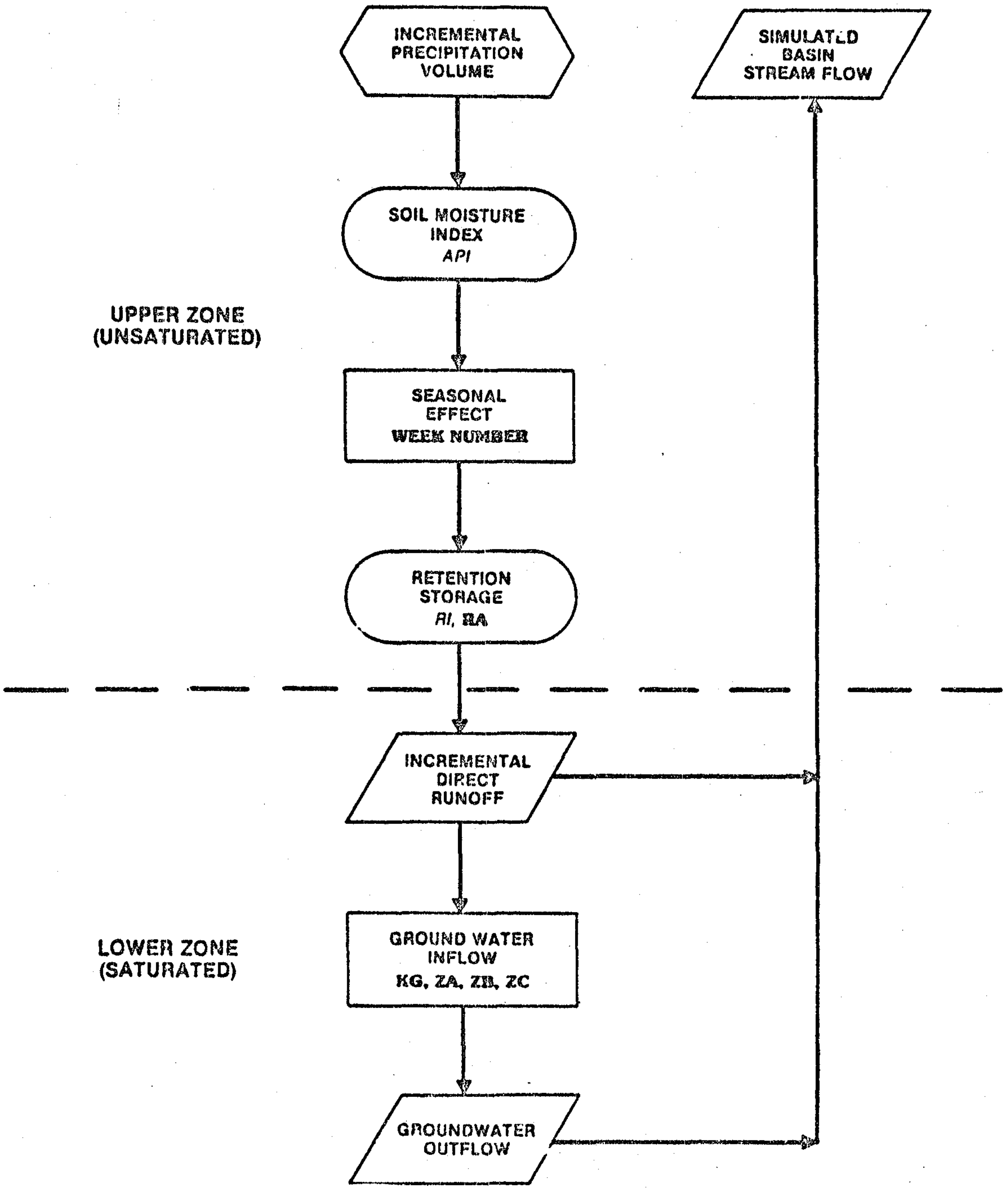


Figure 2. API MODEL SCHEMATIC DIAGRAM

Table 3a. PARAMETERS (DEFINITIONS) CREAMS MODEL (OPTION 1)

*BR15	"Immobile" soil moisture content at 15 bars tension.
CHS	Channel slope.
CN2	The SCS curve number specified for the land use, treatment practice, soil group, etc., being considered for modeling, assuming an Antecedent Moisture Condition II (AMC II).
*CONA	Soil evaporation parameter that indicates the soil water transmission characteristics of the surface layer of soil.
*FUL	Portion of plant-available water storage filled at field capacity.
*GR	Winter cover factor that reduces soil evaporation as a result of ground cover. Varies from 0.5 for excellent cover to 1.0 for bare soil.
*POROS	Soil porosity; the average porosity of all soil layers found in the maximum rooting depth.
*RC	Fraction of pore space filled at field capacity.
RD	Maximum rooting depth in inches.
SIA	Initial abstraction coefficient for the SCS-CN method. It indicates the amount of interception, infiltration, and surface storage that occurs before runoff begins. Unless there is very strong evidence to the contrary, the value 0.2 should be used.
UL(1-7)	Maximum plant-available water storage in each of the seven soil layers of the maximum rooting depth. It is the difference between the total soil porosity and the BR15 water content.
WLW	Watershed length-to-width ratio.

*(common to both options)

Table 3b. PARAMETERS (DEFINITIONS) CREAMS MODEL (OPTION 2)

*BR15	"Immobile" soil moisture content at 15 bars tensior.
*CONA	Soil evaporation parameters that indicate the soil water transmission characteristics of the surface layer of soil.
DP	Depth of root soil zone.
*FUL	Portion of plant-available water storage filled at field capacity.
GA	Effective capillary tension for the surface layer of soil.
*GR	Winter cover factor that reduces soil evaporation as a result of ground cover. Varies from 0.5 for excellent cover to 1.0 for bare soil.
*POROS	Soil porosity; the average porosity of all soil layers found in the maximum rooting depth.
*RC	Fraction of pore space filled at field capacity.
RMN	Manning roughness number for the field surface.
SLOPE	Average slope of the field.
XLP	Length of flow plane.

*(common to both options)

Table 4. STATE (DEFINITIONS) CREAMS MODEL

*BST	Fraction c . plant-available water storage filled when simulation begins. It represents the soil's water content above the BR15.
*X(I)	Leaf area index, which indicates the area of plant leaves relative to soil surface area. Up to 366 values may be specified to describe the daily variation of the leaf area index.
**DS	Depth of surface soil layer. This state represents the available infiltration capacity of the soil surface and is made to vary with soil moisture content.

* Common to both options
**Option 2 only

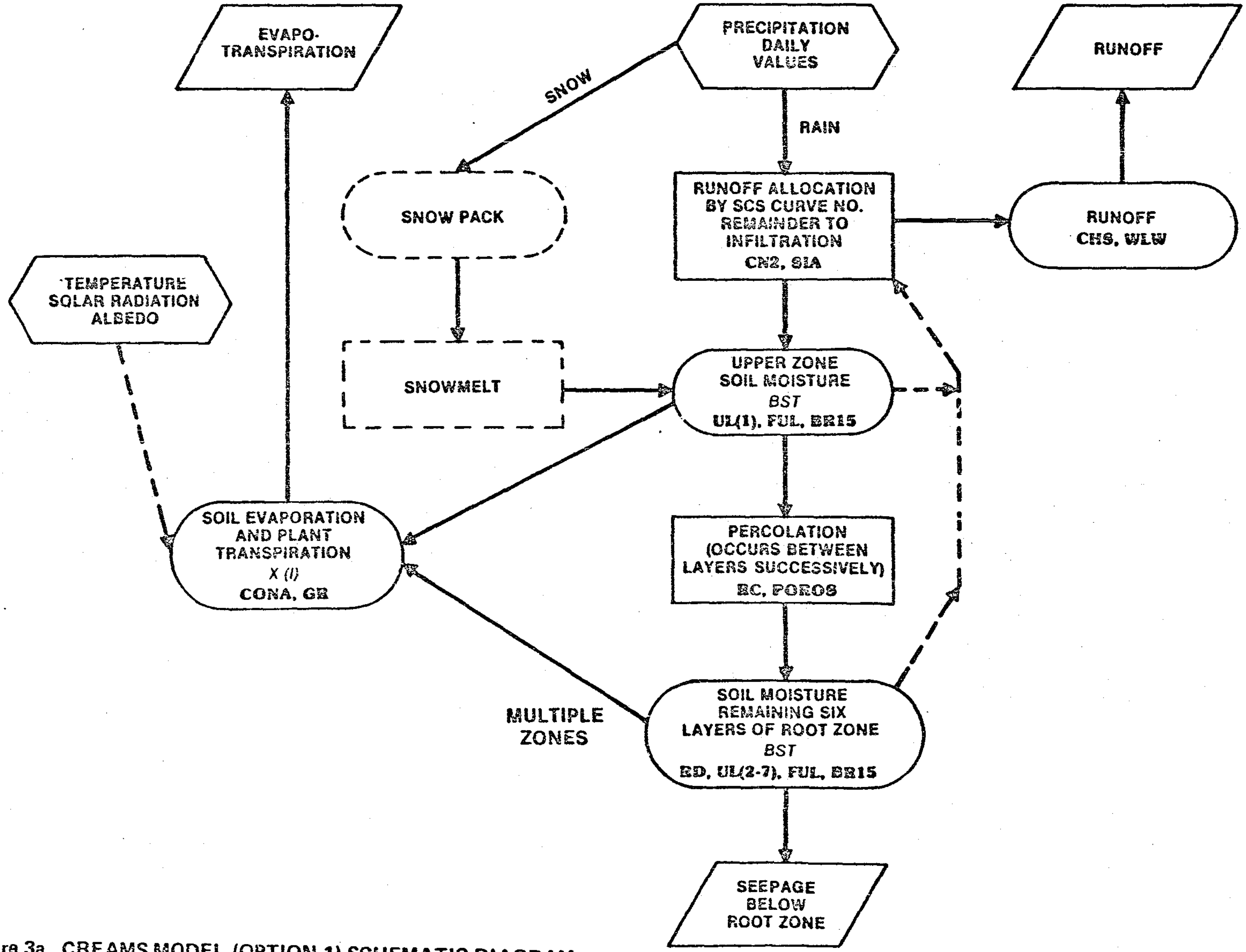


Figure 3a. CREAMS MODEL (OPTION 1) SCHEMATIC DIAGRAM

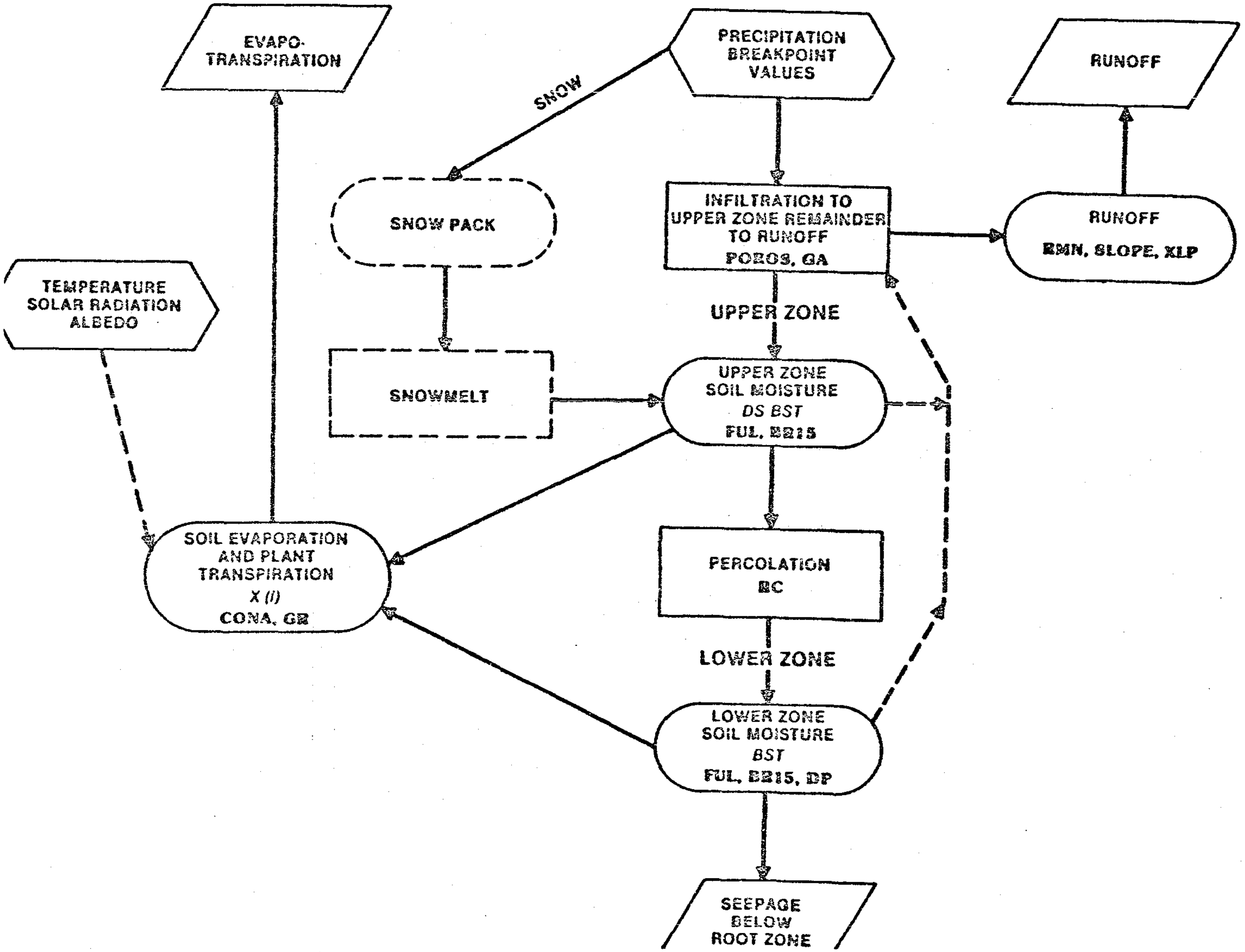

EVAPO-
TRANSPIRATION
PRECIPITATION
BREAKPOINT
VALUES
RUNOFF
SNOW
SNOW PACK
INFILTRATION TO
UPPER ZONE REMAINDER
TO RUNOFF
POROS, GA
RUNOFF
RMN, SLOPE, XLP
TEMPERATURE
SOLAR RADIATION
ALBEDO
UPPER ZONE
SNOWMELT
UPPER ZONE
SOIL MOISTURE
DS BST
FUL, BR15
SOIL EVAPORATION
AND PLANT
TRANSPIRATION
X (I)
CONA, GR
PERCOLATION
BC
LOWER ZONE
LOWER ZONE
SOIL MOISTURE
BST
FUL, BR15, DP
SEEPAGE
BELOW
ROOT ZONE

Table 5. PARAMETERS (DEFINITIONS) NWSRFS MODEL

ADIMP	That fraction of the basin that becomes impervious as all tension water requirements are met.
LZFPM	Maximum capacity of lower zone primary free water storage.
LZPK	Lateral drainage rate of lower zone primary free water expressed as a fraction of contents per day.
LZFSM	Maximum capacity of lower zone supplemental free water storage.
LZSK	Lateral drainage rate of lower zone supplemental free water expressed as a fraction of contents per day.
LZTWM	Maximum capacity of lower zone tension water.
PCTIM	Fraction of impervious basin contiguous with stream channels.
PFREE	The percentage of percolation water that directly enters the lower zone free water without a prior claim by lower zone tension water.
RSERV	Fraction of lower zone free water not available for transpiration purposes (incapable of resupplying lower zone tension water).
REXP	An exponent determining the rate of change of the percolation rate as the lower zone deficiency ratio varies from 1 to 0 (1 = completely dry; 0 - lower zone storage completely full)
RIVA	Fraction of basin covered by riparian vegetation.
SIDE	The ratio of unobserved to observed baseflow.
UZFWM	Maximum capacity of upper zone free water.
UZK	Lateral drainage rate of upper zone free water expressed as a fraction of contents per day.
UZTWM	Maximum capacity upper zone tension water.
ZPERC	A fraction used to define the proportional increase in percolation from saturated-to-dry lower zone soil moisture conditions. This parameter, when used with other parameters, indicates the maximum percolation rate possible when upper zone storages are full and the lower zone soil

Table 6. STATES (DEFINITIONS) NWSRFS MODEL

ADIMC	Additional impervious area.
LZFPC	Lower zone free primary water storage.
LZFSC	Lower zone free supplemental water storage.
LZTWC	Lower zone tension water storage.
UZFWC	Upper zone free water storage.
UZTWC	Upper zone tension water storage.

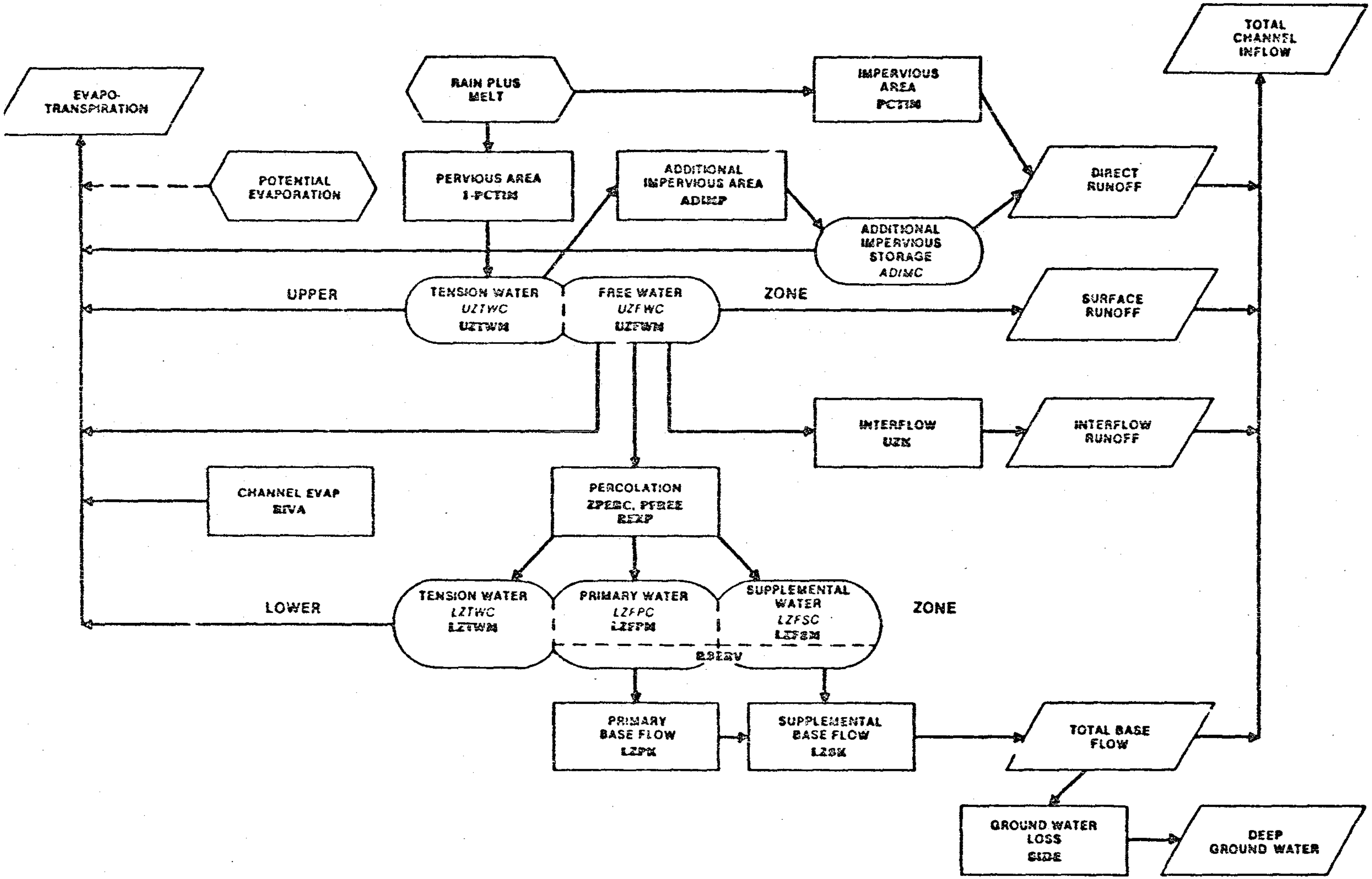


Figure 4. NWSRFS (SACRAMENTO) MODEL SCHEMATIC DIAGRAM

Table 7. PARAMETERS (DEFINITIONS) STORM MODEL

C_I	Runoff coefficient of I^{th} impervious segment of urban area.
C_n	Composite runoff coefficient, nonurban area.
C_p	Runoff coefficient of I^{th} pervious segment of urban area.
C_u	Composite runoff coefficient, urban.
D_n	Maximum depression storage, nonurban.
D_u	Maximum depression storage, urban.
DVN_{max}	Runoff at which diversion begins, nonurban.
DVN_{min}	Runoff at which diversion peaks, nonurban.
DVU_{max}	Runoff at which diversion begins, urban.
DVU_{min}	Runoff at which diversion peaks urban.
F_I	Fraction of I^{th} land use area that is pervious.
K_n	Recession factor (evaporation from depression storage), nonurban.
K_u	Recession factor (evaporation from depression storage), urban.
X_I	Area of land use or fraction of total urban area.
W_n	Fraction of runoff diverted, nonurban.
W_u	Fraction of runoff diverted, urban.

Table 8. STATES (DEFINITIONS) STORM MODEL

F_u	Depression storage, urban areas.
F_n	Depression storage, nonurban areas.

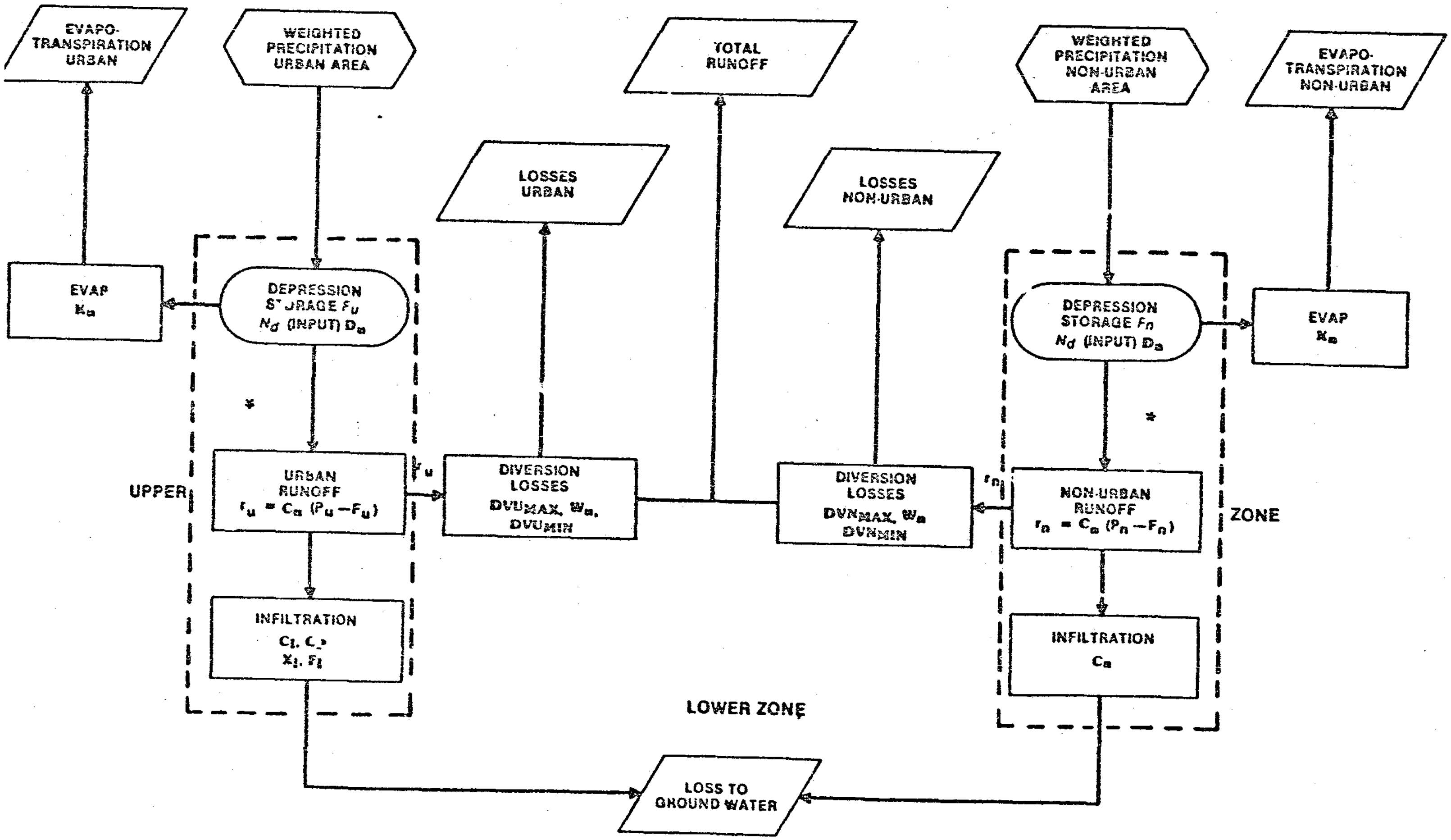


Figure 5. STORM MODEL SCHEMATIC DIAGRAM

*Depression storage, and runoff/infiltration portion of model may optionally be done by the SCS curve number method.

Table 9. PARAMETERS (DEFINITIONS) STANFORD WATERSHED MODEL IV

A	Percent impervious area.
CB	Infiltration index.
CC	Interflow index, which determines the ratio of interflow to surface runoff.
EPXM	Maximum amount of interception storage.
ETL	Ratio of total stream and lake area to the total watershed area.
IRC	Daily interflow recession coefficient.
KK24	Daily groundwater recession coefficient.
KV	Weighting factor to allow variable groundwater recession rates.
K24EL	Percent of watershed stream surfaces and riparian vegetation.
K24L	Percent of groundwater recharge assigned to deep percolation.
K3	Evaporation loss index for the lower zone.
L	Overland flow length.
NN	Manning's "n" for overland flow.
LZSN	Nominal lower zone storage, an index to the magnitude of lower zone capacity.
UZSN	Nominal upper zone storage, an index to the magnitude of upper zone capacity.
SS	Overland flow slope.

Table 10. STATES (DEFINITIONS) STANFORD WATERSHED MODEL IV

RES	Surface detention depth.
SRGX	Interflow storage.
SGW	Active groundwater storage.
GWS	Groundwater inflow index.
UZS	Upper zone storage.
LZS	Lower zone storage.
EPX	Interception storage.

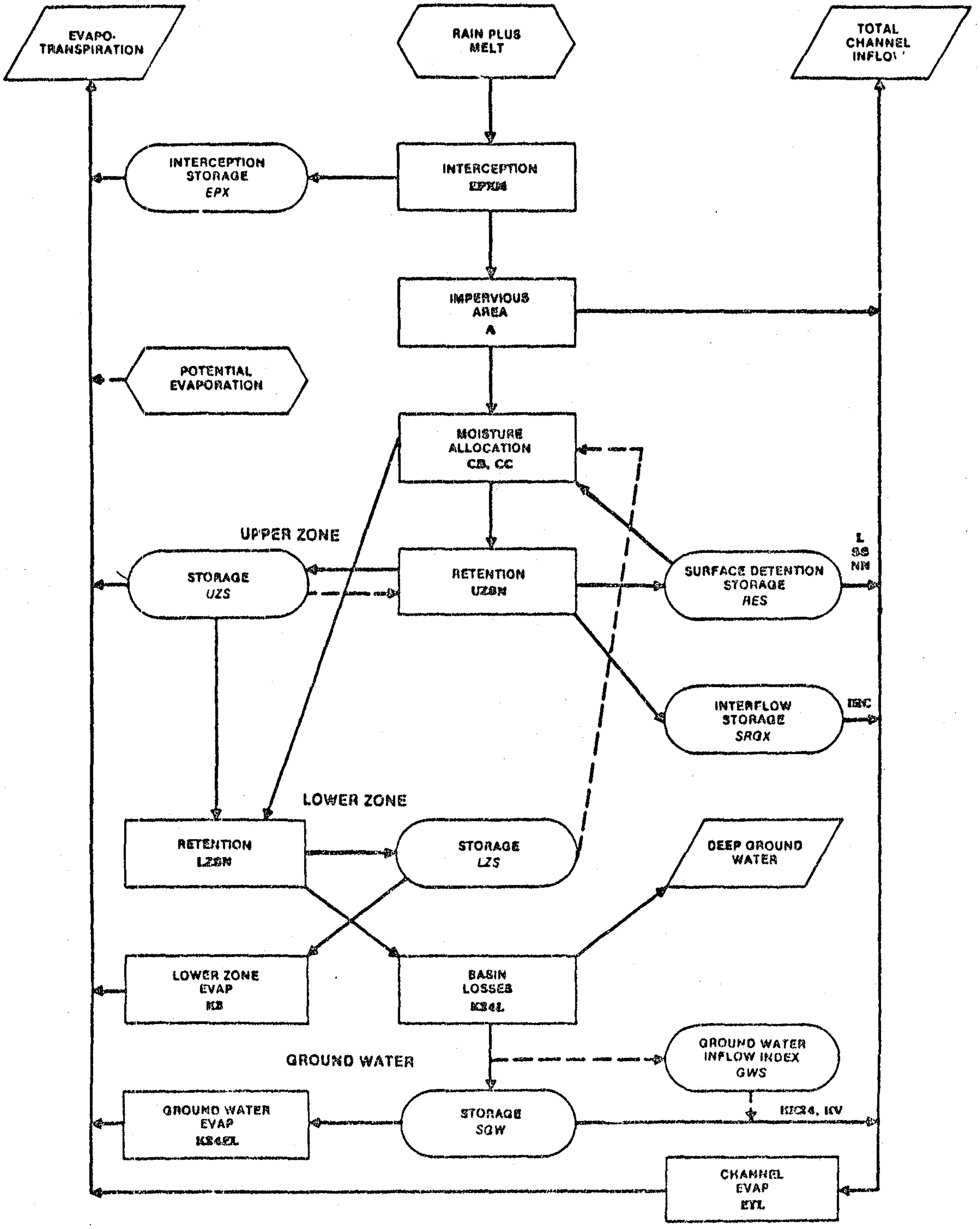


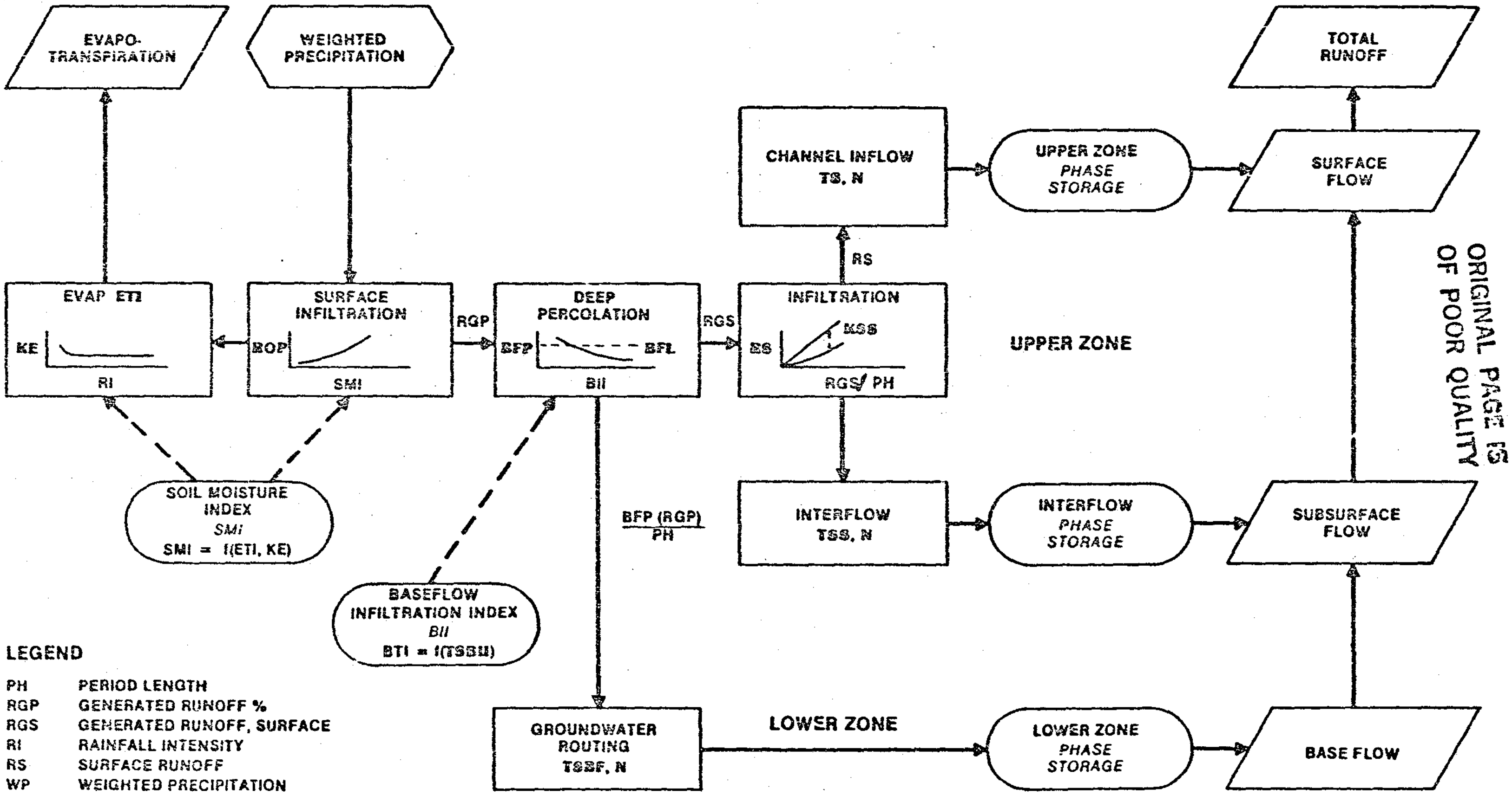
Figure 6. STANFORD WATERSHED MODEL IV SCHEMATIC DIAGRAM

Table 11. PARAMETERS (DEFINITIONS) SSARR MODEL

BFL	Base flow infiltration limit.
BFP	Base flow, percent.
ETI	Evapotranspiration index.
KE	Percent effectiveness of ETI (function of rainfall intensity, RI).
KSS	Limiting subsurface infiltration rate.
N	Number of routing phases (surface flow)
N	Number of routing phases (subsurface flow)
N	Number of routing phases (baseflow).
ROP	Runoff percent.
RS	Surface runoff percent, function of RS/RGS table.
TS	Time of storage; surface flow.
TSS	Time of storage; subsurface flow (interflow).
TSBF	Time of storage; baseflow.

Table 12. STATES (DEFINITIONS) SSARR MODEL

SMI	Soil Moisture Index.
BII	Base Flow Infiltration Index.
PHASE STORAGE	Phase storage (discharge or stage) for surface flow.
PHASE STORAGE	Phase storage (discharge) for subsurface flow.
PHASE STORAGE	Phase storage (discharge) for baseflow.



LEGEND

PH	PERIOD LENGTH
RGP	GENERATED RUNOFF %
RGS	GENERATED RUNOFF, SURFACE
RI	RAINFALL INTENSITY
RS	SURFACE RUNOFF
WP	WEIGHTED PRECIPITATION

Figure 7. SSARR MODEL SCHEMATIC DIAGRAM

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OF POOR QUALITY

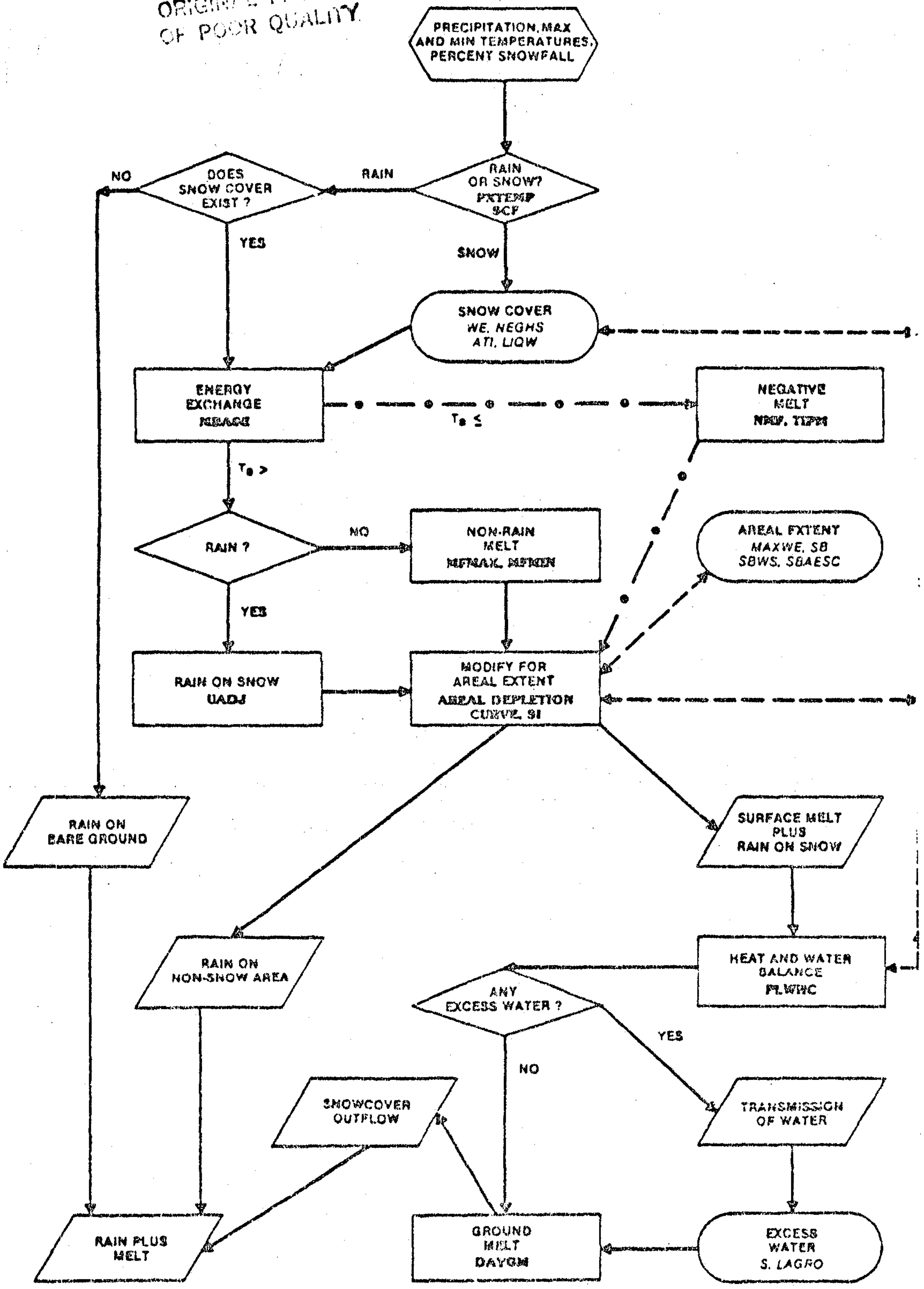
Table 13. PARAMETERS (DEFINITIONS) NWSRFS SNOWMELT MODEL

AREAL DEPLETION CURVE	Curve that 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.
DAYGM	Constant amount of melt that occurs at the snow-soil interface whenever snow is present.
MBASE	Base temperature for snowmelt computations during nonrain periods.
MFMAX	Maximum melt factor during nonrain periods; assumed to occur on June 21.
MFMIN	Minimum melt factor during nonrain periods; assumed to occur on December 21.
NMF	The maximum negative melt factor.
PLWHC	Percent (decimal) liquid water holding capacity; indicates the maximum amount of liquid water that can be held against gravity drainage in the snow cover.
PXTEMP	The temperature that delineates rain from snow.
SCF	A multiplying factor that adjusts precipitation data for gage catch deficiencies during periods of snowfall and implicitly accounts for net vapor transfer and interception losses. At a point, it also implicitly accounts for gains or losses from drifting.
SI	The mean areal water-equivalent above which there is always 100 percent areal snow cover.
TIPM	Antecedent temperature index parameter (range is $0.1 \leq \text{TIPM} \leq 1.0$).
UADJ	The average wind function during rain-on-snow periods.

Table 14. STATES (DEFINITIONS) NWSRFS SNOWMELT MODEL

ATI	Antecedent Temperature Index; represents the temperature within the snow cover.
LAGRO	LAGRO and S together define the amount of excess liquid water in transit in the snowpack.
LIQW	The amount of liquid-water held against gravity drainage.
MAXWE	The maximum water-equivalent that has occurred over the area since snow began to accumulate.
NEGHS	Heat Deficit; the amount of heat that must be added to return the snow cover to an isothermal state at 0°C with the same liquidwater content as when the heat deficit was previously zero.
S	S and LAGRO together define the amount of excess liquid water in transit in the snowpack.
*SB	The areal water equivalent just prior to the new snowfall.
*SBAESC	The areal extent of snow cover from the areal depletion curve just prior to the new snowfall.
*SBWS	The amount of water equivalent above which 100 percent areal snow cover temporarily exists.
WE	Water equivalent of the solid portion of the snowpack.

*These states are only used when there is a new snowfall on a basin with a partial snowcover.


PRECIPITATION, MAX
AND MIN TEMPERATURES,
PERCENT SNOWFALL
RAIN OR SNOW?
PXTEMP
SCF
RAIN
SNOW
DOES SNOW COVER EXIST ?
NO
YES
SNOW COVER
WE, NEGHS
ATI, LIQW
ENERGY EXCHANGE
MBASE
$T_a \leq$
NEGATIVE MELT
NMF, TIPM
$T_a >$
RAIN ?
NO
YES
NON-RAIN MELT
MFMAX, MFMIN
AREAL EXTENT
MAXWE, SB
SBWS, SBAESC
RAIN ON SNOW
UADJ
MODIFY FOR
AREAL EXTENT
AREAL DEPLETION
CURVE, SI
RAIN ON
BARE GROUND
SURFACE MELT
PLUS
RAIN ON SNOW
RAIN ON
NON-SNOW AREA
HEAT AND WATER
BALANCE
PLWHC
ANY
EXCESS WATER ?
YES
NO
SNOWCOVER
OUTFLOW
TRANSMISSION
OF WATER
RAIN PLUS
MELT
GROUND
MELT
DAYGM
EXCESS
WATER
S, LAGRO

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