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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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STRATEGIES FOR USING REMOTELY SENSED DATA IN HYDROLOGIC MODELS

JULY 31, 1981

Final Report

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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 characterictss 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 <u>some</u> 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
Category 1			
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
Category 2			
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; MULTI-SPECTRAL SCANNER SATELLITE: MULTISPECTRAL SCANNER OR LANDSATs RESOLUTION: LANDSAT: 80m AIRCRAFT: 1-10m	CORRECT DISCRIMINATION OF AREAS HAS ACCURACY OF 10-16 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*	8 TO 10 DAYS OR LONGER BETWEEN SATELLITE SCENES, DEPENDING ON CLOUD COVER AIRCRAFT DATA AS REQUIRED SUBJECT TO WEATHER
LAND COVER	AIRCRAFT: PHOTOGRAPHY; MULTI-SPECTRAL SCANNER SATELLITE: PRIMARILY MULTI-SPECTRAL 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	8 TO 10 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 1800 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: 500m	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 absolutelv 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 predicting the amount of infiltration.

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

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL 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
LAND COVER	1. N/A 2. No 3. No	1. N/A 2. Update retention index (RI) 3. Define basin constant (RA) related to interception
AREAL EXTENT SNOW COVER	1. No 2. No 3. No	1. No 2. Objective procedure to determine area subject to snowmelt 3. No
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. Objective technique to adjust RI 3. Define variation in RA during winter
WATER EQUIVALENT SNOW 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

*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. In[illegible]t; 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. Ir[illegible]; 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 the measurements.

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

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	SEE NWSRFS MODEL	
IMPERVIOUS AREA	SEE NWSRFS MODEL	
LAND COVER	SEE NWSRFS MODEL	
AREAL EXTENT SNOW 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
AREAL EXTENT FROZEN GROUND	SEE NWSRFS MODEL	
WATER EQUIVALENT SNOW 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

*1. 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.

*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)

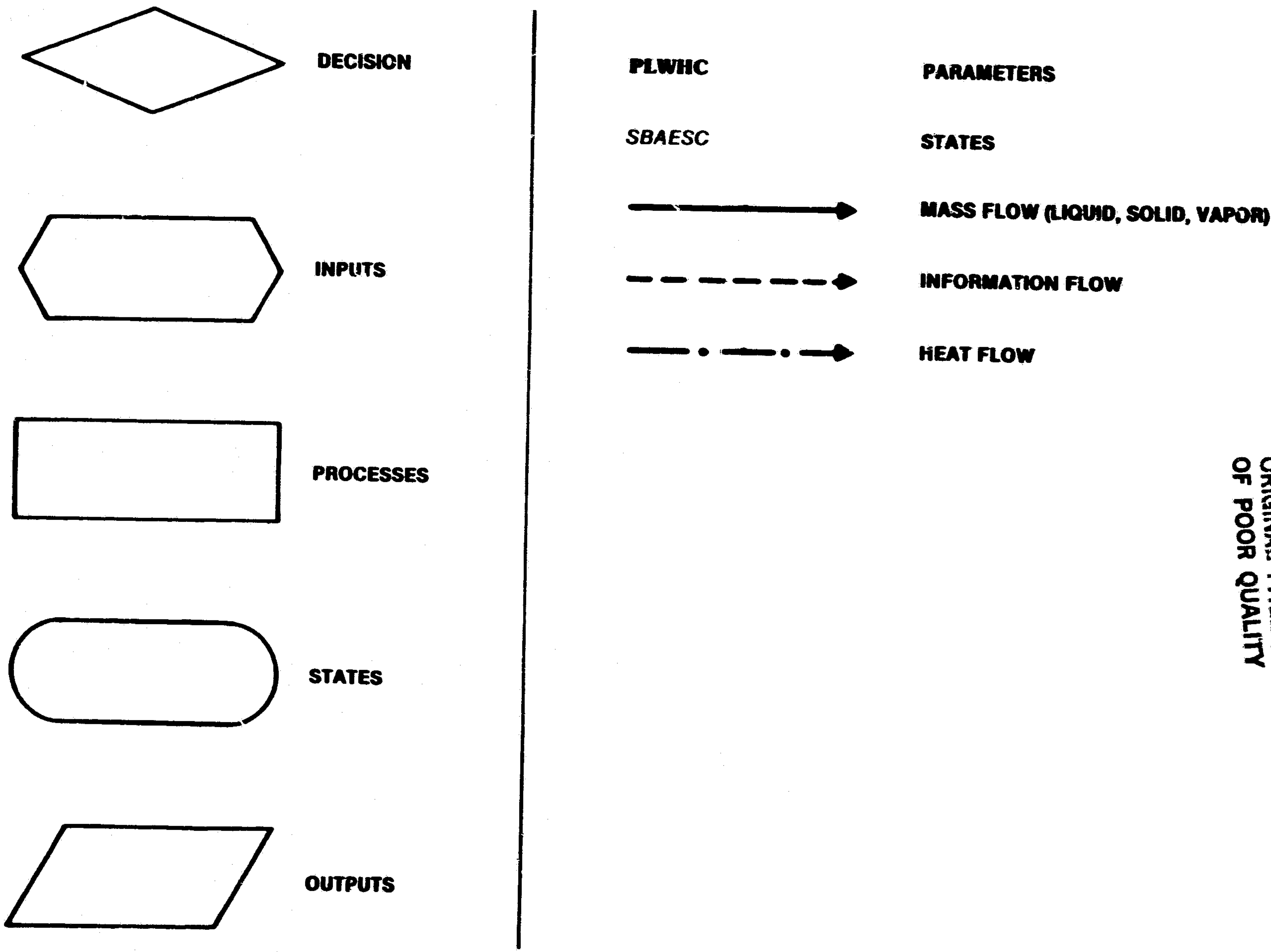

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Figure 1. LEGEND FOR SCHEMATIC DIAGRAMS OF MODEL

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.

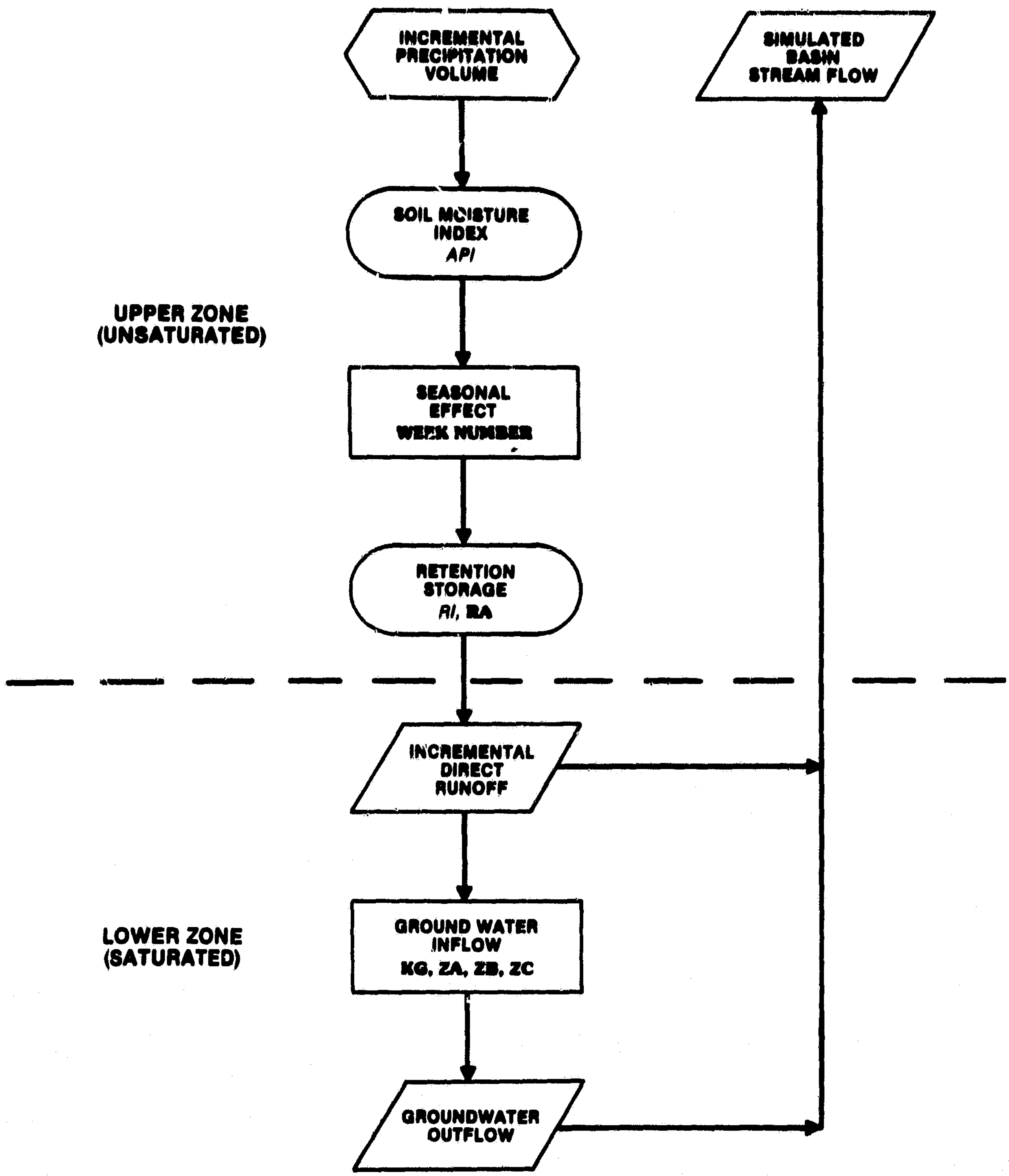


Figure 2. API MODEL SCHEMATIC DIAGRAM

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 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 4. 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.

* Common to both options
**Option 2 only

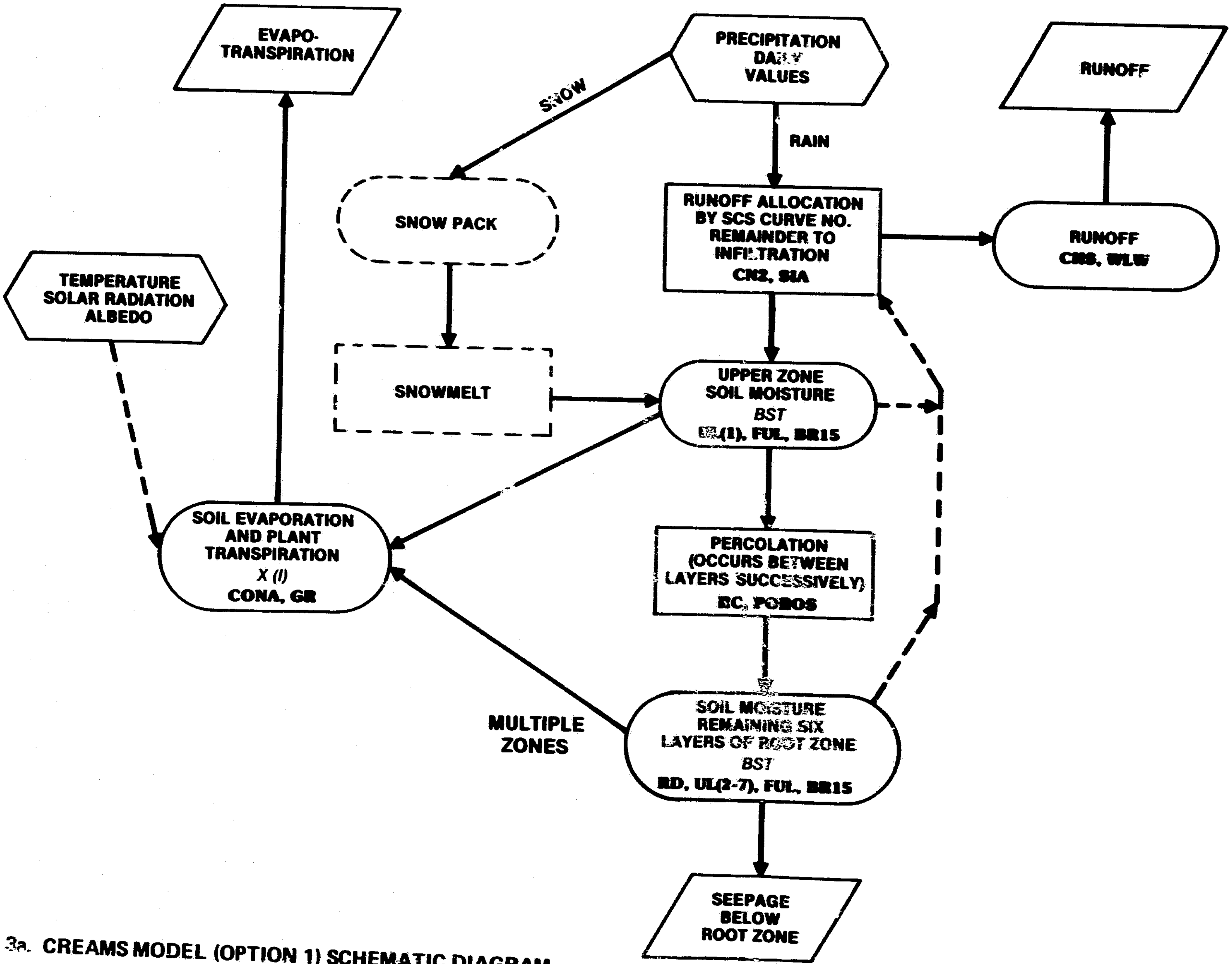


Figure 3a. CREAMS MODEL (OPTION 1) SCHEMATIC DIAGRAM

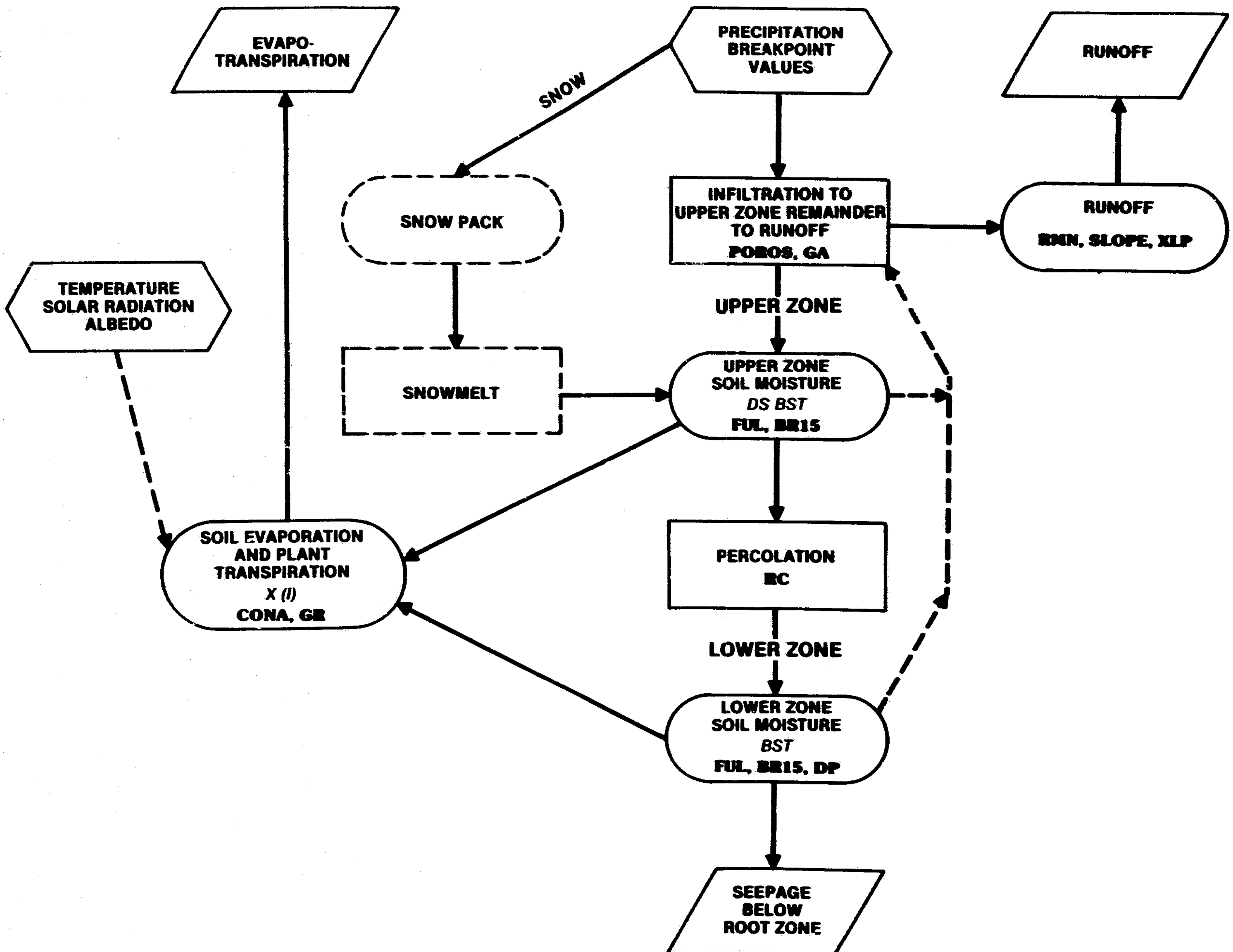


Figure 3b. CREAMS MODEL (OPTION 2) SCHEMATIC DIAGRAM

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 moisture is 100 percent deficient.

Table 6. STATES (DEFINITIONS) NWSRFS MODEL

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

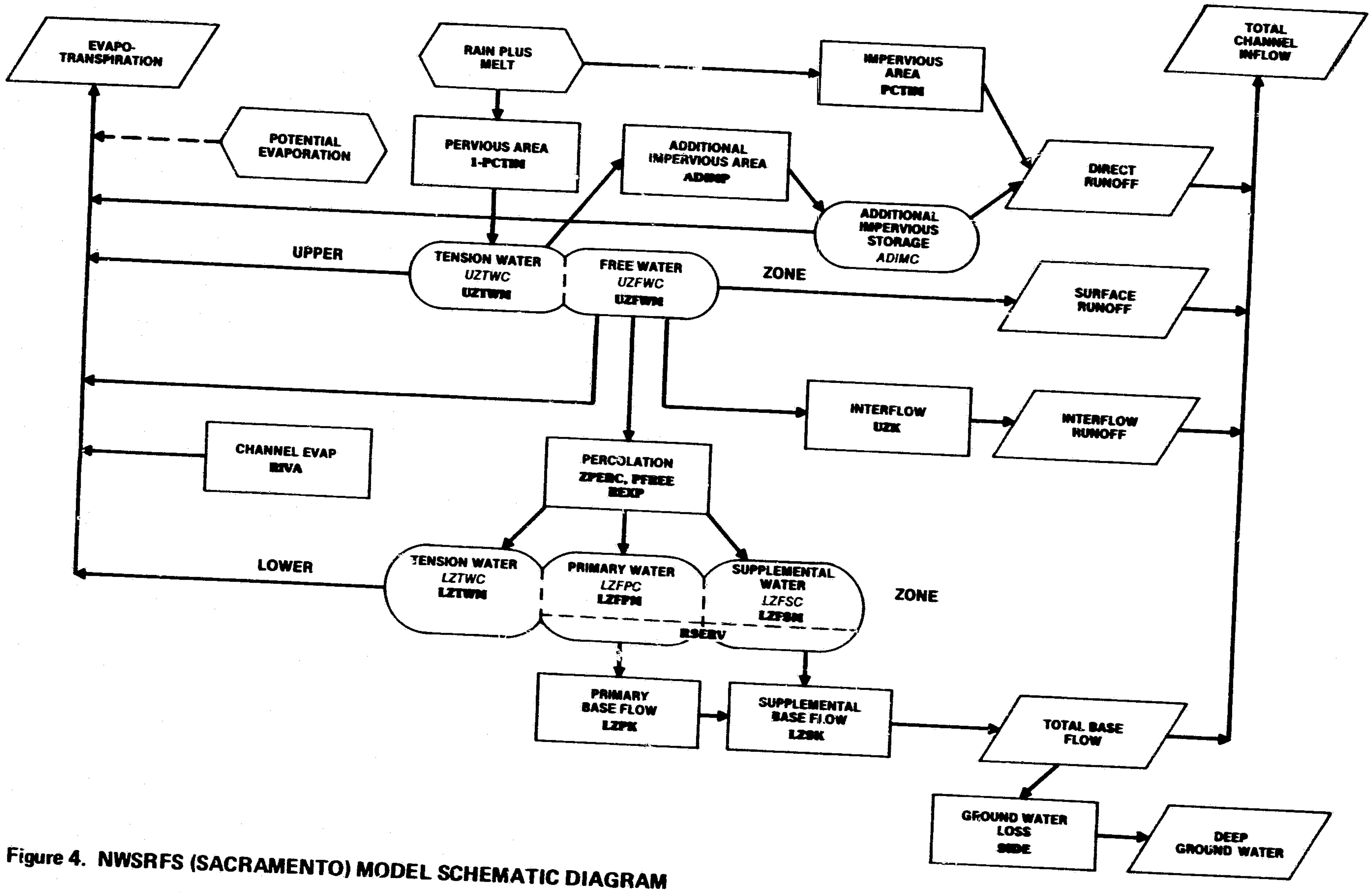


Figure 4. NWSRFS (SACRAMENTO) MODEL SCHEMATIC DIAGRAM

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.

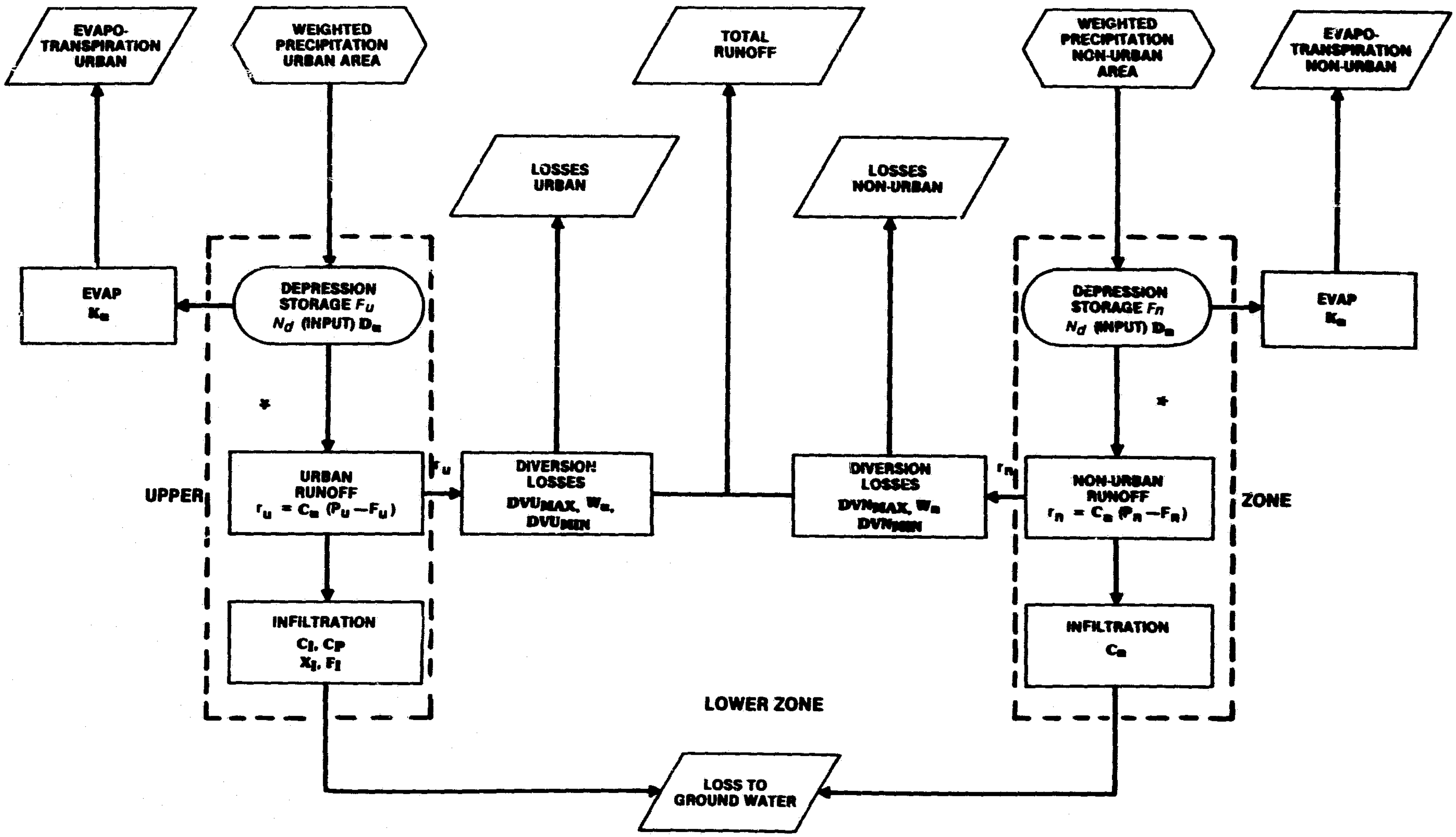


Figure 5. STORM MODEL SCHEMATIC DIAGRAM

*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.

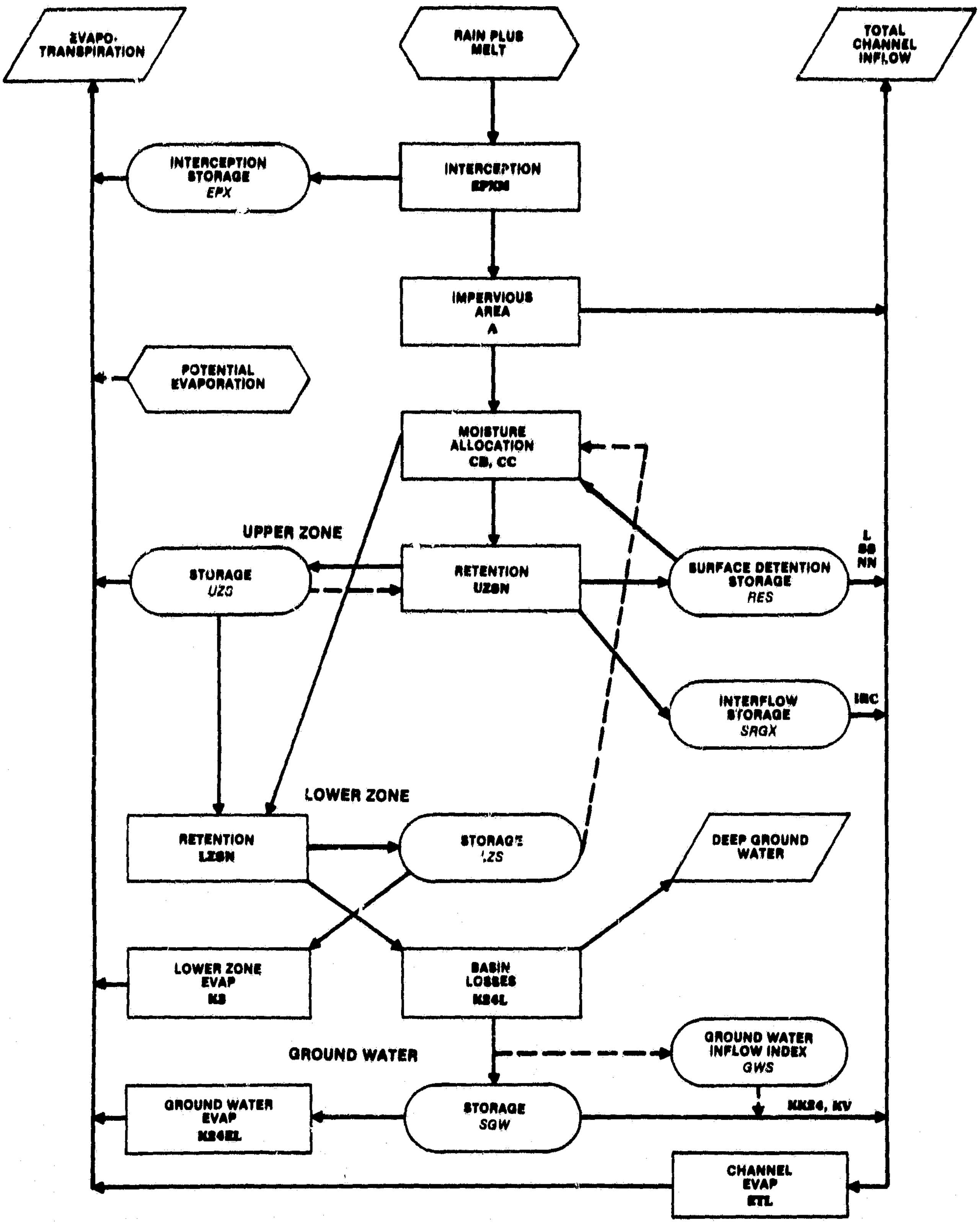


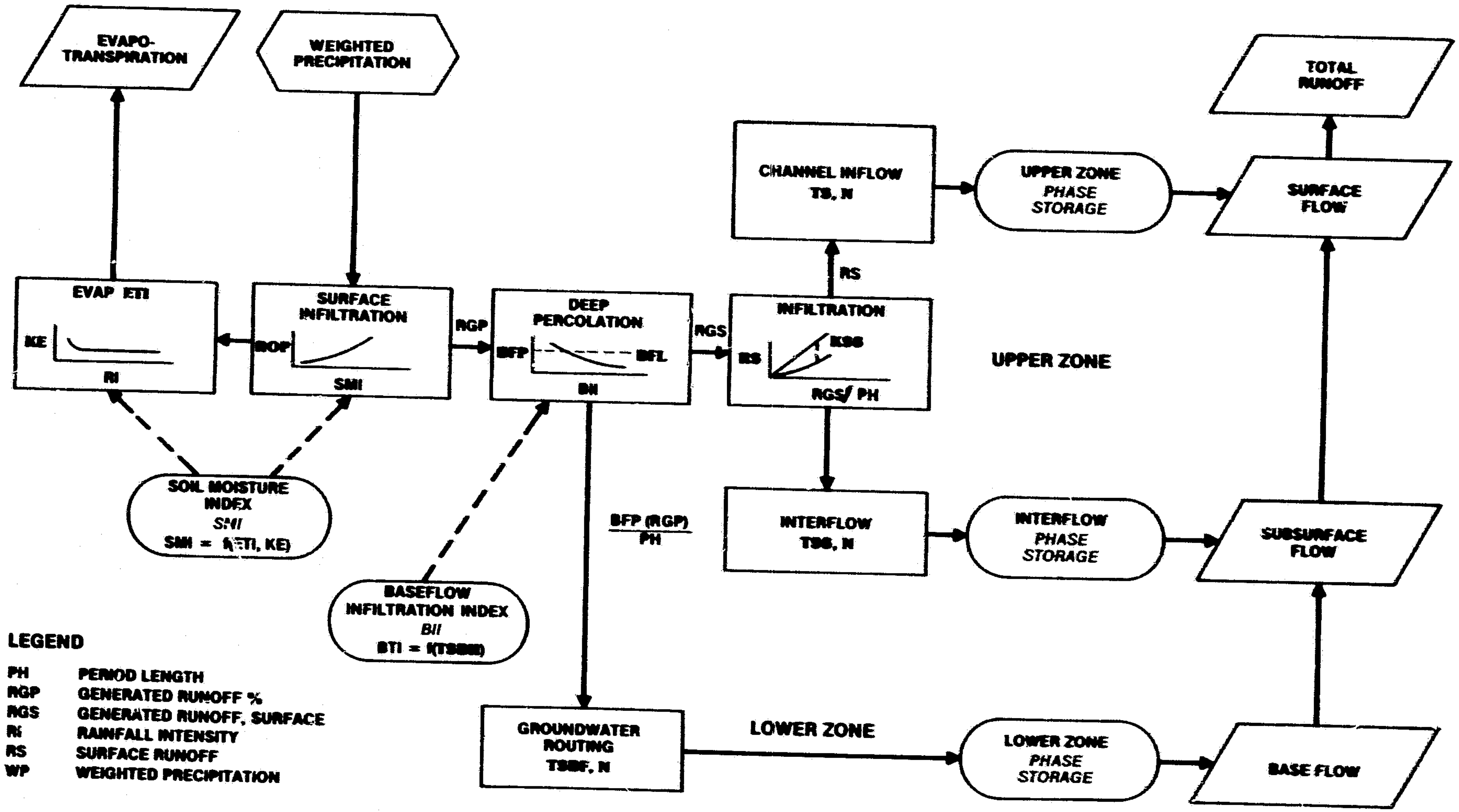
Figure 6. STANFORD WATERSHED MODEL IV SCHEMATIC DIAGRAM

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)
$\bar{N}$	Number of routing phases (subsurface flow)
$\bar{\bar{N}}$	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

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 $0.1 \leq TIPM \leq 1.0$).
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 $0^{\circ}C$ 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.

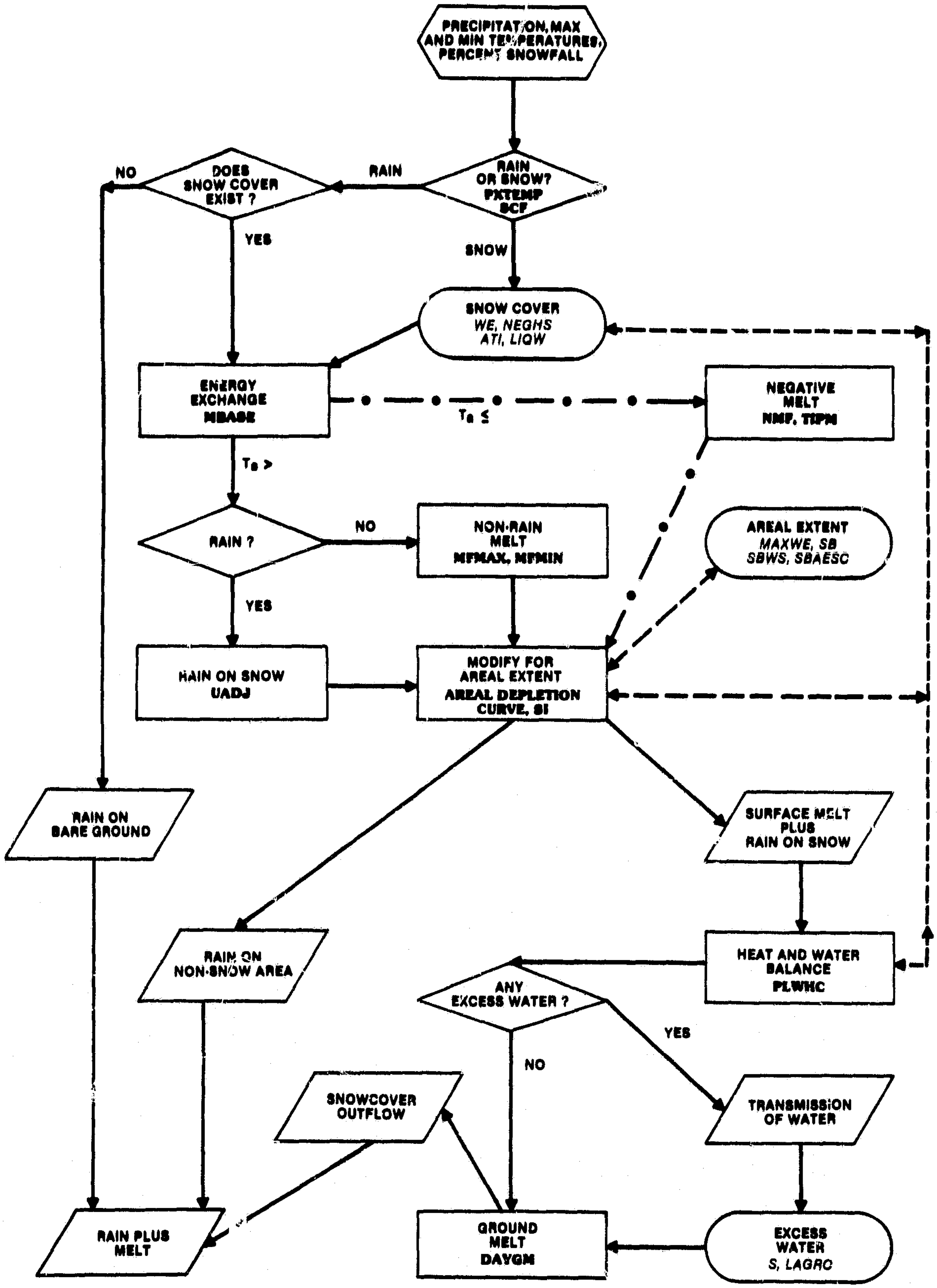


Figure 8. NWSRFS (ANDERSON) SNOWMELT MODEL SCHEMATIC DIAGRAM