DATE REQUIREMENTS
AND
REFERENCE DOCUMENTS
FOR THE
SACRAMENTO WATERSHED MODELLING SYSTEM

of the

Interface Hydrology Section
Hydrology Research Division
Water Resources Branch

D.W. Lawson
S.Y. Shiau

Inland Waters Directorate
Environment Canada
Ottawa December 1977

CONTENTS

Page

INTRODUCTION 1

DATA REQUIREMENTS 2

General 2

Coding Instructions for the Daily Data File 5

LITERATURE REVIEW (Reference Documents) 9

Introduction 9

Basic Documentation 9

Refinements and Improvements 10

Parameter Optimization 10

Correlation of Model Parameters with Watershed Characteristics. 11

Seasonally Frozen Ground 11

Studies of Watershed Response 12

Flood Forecasting Applications 13

Developing a Transposable Watershed Model 14

Studies of Land Use Change 16

BIBLIOGRAPHY (Reference Documents) 18

APPENDIX 20

General Description of the SACRAMENTO Watershed Model 20

Modifications to the Original Concepts 31

ILLUSTRATIONS

Page

Table 1. Coding Instructions: data codes, field lengths, and decimal locators for the 14 input data options and the 1 card output option (rain + melt) ... 6

Figure 1. Card layout for Data with Field Length equal 3 7

Figure 2. Card layout for Data with Field Length equal 4 7

Figure 3. Coding form with example data 8

Figure 4. Conceptual Schematization of the SACRAMENTO Model 21

Figure 5a. Basin Response during a Sequence of Hydrometeorological Events - Very Dry Conditions 22

Figure 5b. Basin Response during a Sequence of Hydrometeorological Events - Starting to Rain 23

Figure 5c. Basin Response during a Sequence of Hydrometeorological Events - Rain Continuing 24

Figure 5d. Basin Response during a Sequence of Hydrometeorological Events - Rainfall Rate Increasing 25

Figure 5e. Basin Response during a Sequence of Hydrometeorological Events - Rain Continuing and Rate Increasing 26

Figure 5f. Basin Response during a Sequence of Hydrometeorological Events - Rainfall Rate Decreasing 27

Figure 5g. Basin Response during a Sequence of Hydrometeorological Events - Rain Over 28

Figure 5h. Basin Response during a Sequence of Hydrometeorological Events - No Rain over a Period of Time 29

INTRODUCTION

The SACRAMENTO modelling system of the Interface Hydrology Section contains an early version of the soil-moisture accounting scheme which now constitutes the heart of the United States National Weather Service flood forecasting modelling system. This early version of the accounting scheme has been modified to suit Canadian conditions and the entire modelling system is currently being documented. Until such time as this documentation becomes available, the present report will (i) assist interested users of the system in the preparation of input data, and (ii) serve to inform such users of the available literature concerning the system. In the interests of completeness, a general description of the SACRAMENTO watershed model has been provided as an appendix.

Once a decision is reached to implement the system; the system programs, a month of typical data, and several years of test calibration data can be obtained from the Interface Hydrology Section. Then, after the programs and the typical data have been successfully run on the users computer (the system is currently operating on a CDC 6400), the user can commence to acquire the necessary skills to operate the system and calibrate a watershed. The Section is prepared to instruct interested users; and, depending upon the user's previous experience in watershed modelling, the time required for this instruction is estimated to range from less than a week to, at most, a month. However, as with any other such comprehensive watershed model, it should be realized that one's calibration skills will improve with accumulating experience.

The literature review examines the available documentation of the SACRAMENTO model, recent refinements and improvements, studies of watershed response, flood forecasting applications, a strategy for transposing the model to ungauged areas, and an approach towards using the model to study the hydrological effects of land use change; thus serving to introduce the reader to virtually the full spectrum of conceptual watershed modelling, and the use therein of the SACRAMENTO system. A cursory reading of the data requirements section will be of value before proceeding to the literature review, as the discussion of these requirements begins to establish the authors' perspectives on watershed modelling. The appendix describing the SACRAMENTO model can be read on an if, as, and when required basis.

Both the Interface Hydrology Section and the U.S. National Weather Service are currently committed to the further improvement of this model and its associated forecasting and predicting capabilities.

DATA REQUIREMENTS

General

As now employed and described herein, the model uses predominantly daily data; however, provision has been made to accept monthly averages of certain variables. While the system can accommodate six hourly data and could be modified to accept hourly data, it is recommended that the initial calibration runs consist of continuous daily simulations of several years of data. In order to ensure a valid calibration, the period of record should contain the full range of local climatological conditions (e.g., wet and dry autumns, deep and shallow snowpacks, cloudy and cloud-free springs, wet and dry summers, long and short duration storms, high and low intensity storms, etc.).

Precipitation, stream discharge, and maximum and minimum air temperature are the minimum daily data requirements of the model. However, in this mode of operation the user must also specify his own best estimates of the monthly potential evapotranspiration (in units of inches per day). In this case, snowmelt is calculated by the model using a simple temperature-index method. This option has yet to be employed by the Interface Hydrology Section.

Data on humidity, wind, pan evaporation and sunshine or radiation can be accommodated by the model and should improve the simulations. Daily estimates of potential evapotranspiration can then be directly provided by the model and, where possible, modified by pan readings. In this case, a second snowmelt subroutine is employed which can accept daily sunshine or radiation data. The Interface Hydrology Section generally runs the model using monthly humidity and wind data, and daily sunshine data, in conjunction with the standard daily streamflow, precipitation and temperature data. Pan measurements are employed if and when available.

Monthly estimates of potential evapotranspiration are generally calculated using the Penman equation and monthly input data. These monthly estimates are then linearly interpolated from month to month to yield daily values. However, when daily pan evaporation data are available the monthly Penman totals continue to be accepted, but daily estimates are modified to follow the pan readings. Monthly Penman calculations can also be performed using daily input data.

Groundwater, soil-moisture and snowcover data are not required in order to operate the model. However, such data and/or information can be used to guide and, perhaps, verify the calibrations; and the more effective use of such data is an area of continuing research by the Section.

The daily potential evaporative demand is converted into an estimate of actual evapotranspiration on the basis of the contents of the model's soil-moisture and groundwater storages. These storage contents are continuously calculated on a daily basis (see the Appendix).

The Section is continuing to conduct research into the evapotranspirative process, with the ultimate objective of improving operational models.

It should be noted that the daily "rain plus melt" is calculated by the model, and that this consists of that precipitation which is assumed to be rain (on the basis of a temperature criterion) plus the output from the snowmelt subroutine. The program can supply these calculations as a card deck.

More specifically, the daily input-data options of the model can be summarized, and further elaborated upon, as follows:

1. Streamflow (daily mean discharge; cfs)

These data are generally obtained, with the exception of the province of Quebec, from the Ottawa master files of the Water Resources Branch. The Ottawa files contain the latest corrections and are usually only six to seven months behind the actual field data collection by the Water Survey of Canada.

2. Precipitation (daily; inches of water)

Basin and sub-basin averages can be stored; and/or values for any number of gauges. No distinction is made between rain or snow.

3. Maximum Air Temperature (daily; ^{o}F)

This is used with the minimum temperature (item 4) to calculate the daily mean temperature as a simple arithmetic mean.

4. Minimum Air Temperature (daily; ^{o}F)

See item 3.

5. Relative Humidity (daily mean; %)

These data can be used in potential evapotranspiration calculations and were regularly published in the AES "Monthly Record"until 1972. The daily values are subsequently averaged by the model into a mean value for the month. See item 6.

6. Vapor Pressure (daily mean; millibars)

Such data can be used in potential evapotranspiration calculations to estimate the relative humidity. In 1972, relative humidity figures ceased to be published in the AES "Monthly Record", but were replaced by vapor pressure figures. The daily values are subsequently averaged by the model into a mean value for the month.

7. Wet Bulb Temperature (daily mean; ^{o}F)

Such data could be used in potential evapotranspiration calculations to estimate the relative humidity. However, they need only be used when relative humidity or vapor pressure data (items 5 and 6) are not available.* Dew point temperatures (item 8) are also required in order to make the calculations. This option has never been used by the Interface Hydrology Section.

---

*NOTE: This recommendation is based upon the general availability of input data. It is recognized that the best estimates of relative humidity are probably provided by vapor pressure data, that the second best estimates are probably obtained using wet bulb and dew point temperatures, and that the least reliable estimates are provided by hygrothermographs. The user is free to select any desired option or combination of options.

8. Dew Point Temperature (daily mean; ^{0}F)

Recall item 7 (wet bulb temperature) and note that these two options have never been used by the Interface Hydrology Section.

9. Wind Movement (daily; miles)

Wind movement is incorporated into both the Penman potential evapotranspiration calculations and the radiation/sunshine snowmelt subroutine. If daily values are unavailable then monthly means can be specified.

10. Pan Evaporation (daily; inches)

When available, these data are used to provide daily estimates of potential evapotranspiration which are modified to agree with the monthly Penman total.

11. Bright Sunshine (daily; hours)

These data are generally more readily available than radiation data, and hence are routinely used in the radiation/sunshine snowmelt subroutine in lieu of radiation data, i.e., as an index of incoming solar (short-wave) radiation, i.e., insolation.

In using this data option, no other daily radiation data, as specified below, need be supplied; however, the user must provide his own best estimate of the snow albedo. This permits the model to calculate an estimate of the net short-wave radiation. The model further calculates an estimate of the long-wave radiation using the temperature and sunshine data, and hence ultimately an estimate of the net radiation.

The sunshine data are also employed in the Penman potential evapotranspiration calculations.

12. Insolation (daily; langleys)

Radiometer values can be specified in lieu of sunshine recorder values. This option has never been employed by the Interface Hydrology Section. See item 11.

13. Albedo (daily; %)

Daily values can be specified in lieu of the user's "best guess" estimate (see item 11), but are rarely available. This option has never been employed by the Interface Hydrology Section.

14. Net Radiation (daily; langleys)

Net radiometer values can be specified in lieu of sunshine or insolation values. This option has never been employed by the Interface Hydrology Section. See item 11.

Interested users are invited to discuss their choice of input data options with the Interface Hydrology Section.

Coding Instructions for the Daily Data File*

All daily input data are coded in the following punch card format:

Col. 1 to 4	contain a card number, 0001 to 9999. Cards are numbered consecutively in any one deck.
Col. 5	contains the data field length (see Table 1).
Col. 6	contains one digit which indicates the number of digits following the decimal point (see Table 1).
Col. 7 to 15	contain a basin/station identifier provided by the user.
Col. 16 to 18	contain the data time increment in hours, eg. 024 for daily data.
Col. 19 to 20	contain a two-digit data code indicating the type of data on the card (see Table 1).
Col. 21 to 28	contain the time of the first data entry on the card in the form hour, day, month, year (eg. 08160575 = May 16, 1975 at 8 a.m.).
Col. 29 to 80	contain 52 columns as the data field. As explained below, the number of data entries per card depends on the data field length indicated in Col. 5.

For those data types with a data field length equal to 3, two cards per month are required. The first card always begins at day 1 of each month and contains 15 data entries while the 2nd card always begins at day 16 and may contain 13, 14, 15 or 16 data entries depending upon the number of days in that particular month. For those data types with a data field length equal to 4, three cards per month are required. The first and second cards always begin at day 1 and day 11 of each month respectively and both cards contain 10 data entries each. The third card begins at day 21 and may contain 8, 9, 10 or 11 data entries depending upon the number of days in that particular month. Figures 1 and 2 show the layout of the data field for the two data field lengths mentioned above.

In all cases, missing data are indicated by filling the data fields with nines. Negative quantities are indicated by placing a minus sign in the first column of the data field.

Figure 3 provides an example of some typical data coding.

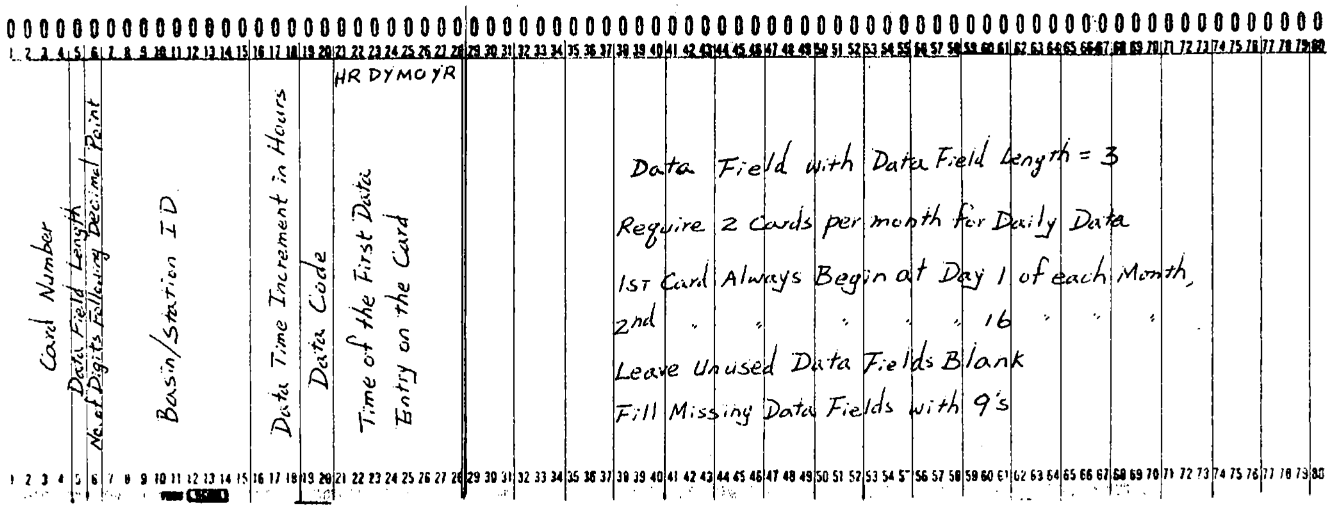
---

*Monthly averages (mean daily values) for Relative Humidity, Wet Bulb Temperature, Dew Point Temperature and Wind Movement (Format (12F6.1)); Vapor Pressure and Potential Evapotranspiration (Format (12F6.2)); and Albedo (Format 12F6.0)) can be stored in a separate punch card file.

	Data Type	Units (per day)	Data Code Col. 19-20	Data Field Length Col. 5	Decimal Point Col. 6	Example	
						Data Entered in Data Field (right justified)	Quantity
1.	Streamflow (mean)	Cfs	1	4	1	1225	122.5
2.	Precipitation	Inches	10	3	2	25	.25
3.	Max. Temperature	^{o}F	32	4	1	725	72.5
4.	Min. Temperature	^{o}F	34	4	1	-125	-12.5
5.	Relative Humidity (mean)	Percent	58	4	1	625	62.5
6.	Vapor Pressure (mean)	Millibars	48	4	2	1525	15.25
7.	Wet Bulb Temp. (mean)	^{o}F	46	4	1	525	52.5
8.	Dew Point Temp. (mean)	^{o}F	56	4	1	425	42.5
9.	Wind Movement	Miles	61	4	1	1525	152.5
10.	Pan Evaporation	Inches	70	3	2	25	.25
11.	Bright Sunshine	Hours	80	4	1	125	12.5
12.	Insolation	Langleys	82	4	1	4225	422.5
13.	Albedo	Percent	81	3	0	25	25.
14.	Net Radiation	Langleys	84	4	1	2225	222.5
	Rain + Melt	Inches	11	3	2	125	1.25

Table 1. Coding Instructions: data codes, field lengths, and decimal locators for the 14 input data options and the 1 card output option (rain + melt).

Fig. 1. Card Layout for Data with Data Field Length Equal 3



Data Field with Data Field Length = 3

Require 2 Cards per month for Daily Data

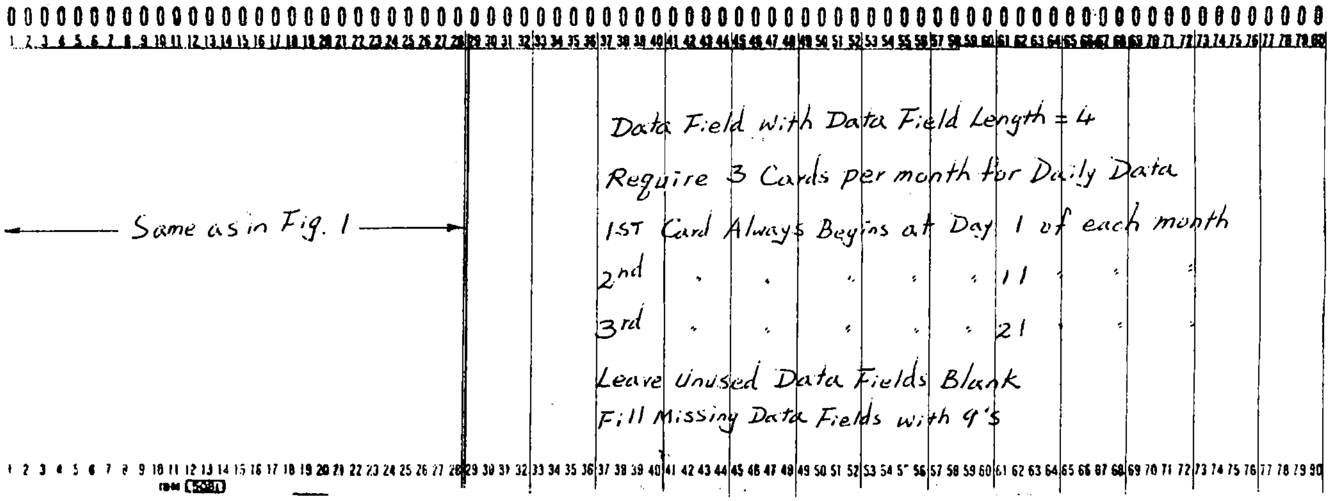
1ST Card Always Begin at Day 1 of each Month,

2nd " " " " " 16 " " "

Leave Unused Data Fields Blank

Fill Missing Data Fields with 9's

Fig. 2. Card Layout for Data with Data Field Length Equal 4



Data Field with Data Field Length = 4

Require 3 Cards per month for Daily Data

1ST Card Always Begins at Day 1 of each month

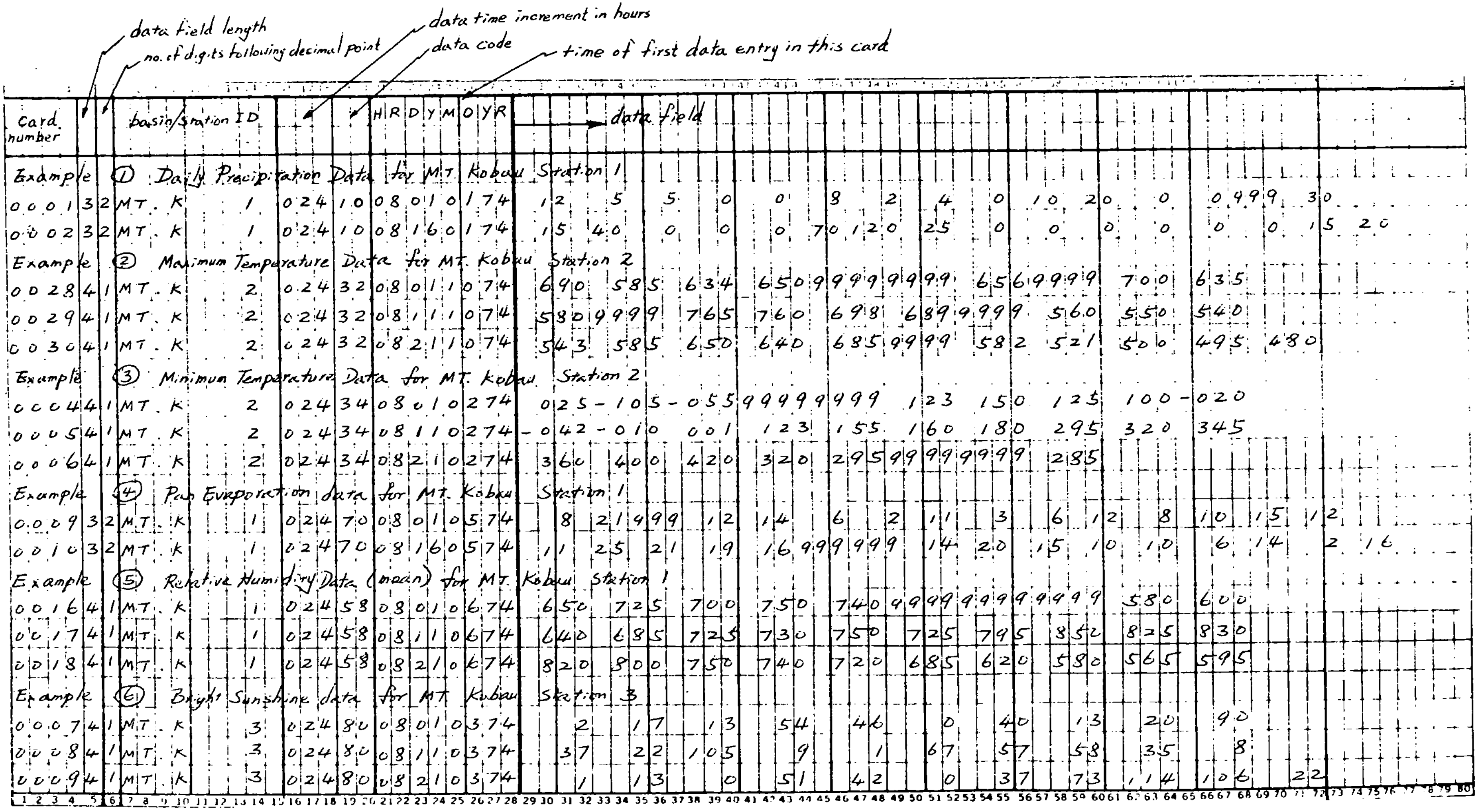
2nd " " " " " 11 " "

3rd " " " " " 21 " "

Leave Unused Data Fields Blank

Fill Missing Data Fields with 9's

Figure 3. Coding form with example data



Card number			basin/station ID			HR	DY	MO	YR	data field
Example ① Daily Precipitation Data for MT Kobau Station 1										
0001	3	2	MT. K 1	024	10	08	01	01	74	12 5 5 0 0 8 2 4 0 10 20 0 0 999 30
0002	3	2	MT. K 1	024	10	08	16	01	74	15 40 0 0 0 70 120 25 0 0 0 0 0 0 15 20
Example ② Maximum Temperature Data for MT. Kobau Station 2										
0028	4	1	MT. K 2	024	32	08	01	10	74	690 585 634 650 9999 9999 656 9999 700 635
0029	4	1	MT. K 2	024	32	08	11	10	74	580 9999 765 760 698 689 9999 560 550 540
0030	4	1	MT. K 2	024	32	08	21	10	74	543 585 650 640 685 9999 582 521 500 495 480
Example ③ Minimum Temperature Data for MT. Kobau Station 2										
0004	4	1	MT. K 2	024	34	08	01	02	74	025 -105 -055 9999 9999 123 150 125 100 -020
0005	4	1	MT. K 2	024	34	08	11	02	74	-042 -010 001 123 155 160 180 295 320 345
0006	4	1	MT. K 2	024	34	08	21	02	74	360 400 420 320 295 9999 9999 285
Example ④ Pan Evaporation data for MT. Kobau Station 1										
0009	3	2	MT. K 1	024	70	08	01	05	74	8 21499 12 14 6 2 11 3 6 12 8 10 15 12
0010	3	2	MT. K 1	024	70	08	16	05	74	11 25 21 19 16 999999 14 20 15 10 10 6 14 2 16
Example ⑤ Relative Humidity Data (mean) for MT. Kobau Station 1										
0016	4	1	MT. K 1	024	58	08	01	06	74	650 725 700 750 740 9999 9999 9999 580 600
0017	4	1	MT. K 1	024	58	08	11	06	74	640 685 725 730 750 725 795 852 825 830
0018	4	1	MT. K 1	024	58	08	21	06	74	820 800 750 740 720 685 620 580 565 595
Example ⑥ Bright Sunshine data for MT Kobau Station 3										
0007	4	1	MT. K 3	024	80	08	01	03	74	2 17 13 54 46 0 40 13 20 90
0008	4	1	MT. K 3	024	80	08	11	03	74	37 22 105 9 1 67 57 58 35 8
0009	4	1	MT. K 3	024	80	08	21	03	74	1 13 0 51 42 0 37 73 114 106 22

LITERATURE REVIEW (Reference Documents)

Introduction

In 1971, Burnash and Ferral (U.S. National Weather Service, River Forecast Center, Sacramento, California) first reported on a streamflow simulation system which was intended to represent watershed response in a physically consistent manner. To them, this meant filling a gap in the current state-of-the-art between two other emerging models. They recognized that on the one hand, unfortunately, complex conceptual models may incorporate false premises and still be capable of producing apparently effective simulations of streamflow. While, on the other hand, many models utilize mechanics which are more pragmatic than realistic in their formulation of the physical processes which are occurring within a basin. In attempting to fill this gap they adopted, on the basis of their experience, several very sound guiding principles:

1. To organize the conceptual logic into an approximation which was physically realistic.
2. To develop preliminary analysis techniques which would allow reasonable approximations of the parameters (coefficients) from streamflow records and other observable characteristics of the watershed.
3. To use these preliminary analyses to place rational constraints on any parameter optimization sub-routine and hence produce a stable analysis.
4. To concentrate on effective solutions from daily data fields, yet provide for the future use of shorter time increments.

A general description of the resulting SACRAMENTO watershed model is provided as an appendix to this report and further details are available elsewhere (1,2). The following review is intended to acquaint the reader with the various literature which has accumulated concerning the use of the model.

Basic Documentation

Documentation (1) of the SACRAMENTO modelling system first became widely available in 1973; including:

1. A discussion of the general problems involved in determining (a) effective basin precipitation, (b) basin evapotranspiration and (c) basin characteristics.

2. A detailed description of the moisture accounting model, its parameters (coefficients), and the means of obtaining preliminary values for these parameters (i.e., calibration procedures).

3. Further comments on calibration procedures, including man-machine interactions and the use of automatic parameter optimization techniques.

4. A discussion of data preparation.

It was at this time that the Interface Hydrology Section acquired the modelling system from the Sacramento River Forecast Center and began adapting it to studies of Canadian IHD Representative Basins.

During the period 1973-1976 the National Weather Service revised their River Forecast System (NWSRFS), with the SACRAMENTO model replacing the STANFORD IV model of the original 1972 System (10). Documentation (2) released in 1976 presents a second version of the parameter calibration procedures, provides a further example of the use of these procedures, discusses a minor modification to the use of the unit hydrograph, and further elaborates on the National Weather Service approach towards watershed modelling. As used in the NWSRFS the SACRAMENTO model employs 6-hour time periods. It is noteworthy that the National Weather Service has found that 8 to 10 years of continuous data are typically required for adequate calibration.

An internal Inland Waters Directorate report (3) is available which describes the approach taken by a 3rd-year engineering student in successfully calibrating/simulating five watersheds. This required four months of effort, starting with no knowledge whatsoever of the modelling system, and involved the use of a preassembled data base containing a total of forty years of daily record (8 years per basin). Day to day guidance of the student was provided by the Interface Hydrology Section. This report (3) constitutes a valuable extension to the calibration procedures described by Burnash et al (1) and Peck (2).

Refinements and Improvements

Parameter Optimization

The watershed calibration process can be regarded as consisting of three sequentially related steps:

1. Preliminary estimation of the parameter values using (a) the available input data in standardized hydrological techniques, (b) observed characteristics of the basin, and (c) previous experience.
2. Well conceived and standardized trial-and-error simulations to improve the estimates.
3. Automatic parameter optimization to refine the estimates.

The previously mentioned reports by Burnash et al (1) and Peck (2) present a mix of steps one and two but are heavily oriented towards step one, and do not stress the use of automatic optimization. Harvey's report (3) concentrates on step two, whereas a report by Monro (4) describes the automatic optimization subroutine employed by the National Weather Service.

The National Weather Service (2) states that ideally the calibration procedure "should be one involving both manual and automatic fitting where the strong points of each compensate the weak points of the other. Generally, much more is achieved by fitting manually first, then using the automatic optimization after a reasonable fit has been obtained". The Interface Hydrology Section has yet to find it either necessary or desirable to employ an automatic optimization subroutine in any of its SACRAMENTO simulations. Nevertheless, the Section supports the attitude of the National Weather Service towards automatic optimization, and would like to further investigate the use of such techniques.

Correlation of Model Parameters with Watershed Characteristics

Armstrong (5) has further refined the use of the SACRAMENTO model by relating the model parameters (coefficients) to soil properties. This permits the initial parameter values to be estimated from soil survey data; and promises to provide a better starting simulation which should, in turn, reduce the number of trial-and-error simulations. Furthermore, if the initial parameters are realistic, then there is a greater probability that the final "optimum" parameters will be conceptually correct; this being especially important in any attempts to use the model to study the hydrological effects of changing land use. It is noteworthy that this technique also makes possible the estimation of parameter values for ungauged basins (i.e., the development of a transposable watershed model). However, in order for such a transposable model to be employed with any confidence, it is essential that the parameter values be physically consistent between basins. Armstrong's technique is thus a promising contribution to the modelling of land-use change and the development of transposable models, but it has only been applied to a single basin and requires further testing and development on a large number of diverse basins.

The soil properties used by Armstrong are those which are readily available from U.S. Soil Conservation Service soil surveys (thickness, permeability, available water capacity, infiltration, texture and shrink-swell potential), but analogous techniques have yet to be developed for use with routinely available Canadian soil survey data. There are some 16 parameters in the SACRAMENTO model and Peck (2) indicates that four can be readily computed, six are considered more difficult to derive, one can be estimated from maps, two can be substituted from a nearby basin and nominal starting values used for three parameters. Armstrong has developed equations to estimate twelve of these parameters and a thirteenth is provided in one of his Tables.

Seasonally Frozen Ground

In many areas of Canada and the United States a high percentage of the annual runoff occurs in a two-month period during late winter and early spring which is often associated with melting snow and spring rains running off nearly impervious, frozen, or saturated soils. Farnsworth (6) has examined the effects of frost and high soil moisture content on runoff during periods of freezing weather and developed a model for predicting/forecasting significant changes in infiltration capacity. More specifically, the model simulates soil frost formation and penetration, and inferences by the model as to frost type provide warnings of the impervious conditions associated with concrete frost.

Farnsworth's model operates on a sub-portion of a watershed as defined by a single slope, aspect and cover type. A moisture accounting scheme provides an estimate of soil moisture and snow depth, and an attempt is made to account for snow drifting. Litter exerts a controlling influence on frost formation and its effects are also considered. In addition to the normal watershed modelling data, a wide variety of special soil and cover data are required, most of which have yet to be routinely employed in hydrological investigations. The model has been successfully tested on two of the Coshocton, Ohio research watersheds.

Farnsworth's study represents an excellent example of the synthesis of existing knowledge into a near operational hydrological model. With further work his model could be simplified into a useful sub-model for a watershed modelling system such as the SACRAMENTO system. However, complimentary to this simplification, the successful use of such a sub-model would probably require innovative surveys to collect certain soil and cover data.

Studies of Watershed Response

Shiau (7, 8) has presented the results of SACRAMENTO modelling of two Canadian IHD basins, Trapping Creek in the Southern Interior of British Columbia and Perch Lake in north eastern Ontario. Both basins necessitated the development of a snow accumulation and ablation subroutine to simulate snowpack water content plus effective daily rain plus melt. The effective daily rain plus melt being used as input to the model's moisture accounting scheme. The simulations provided daily soil-moisture and groundwater storage contents, plus the usual runoff and evapotranspiration calculations. These were then used to assess monthly and annual water balances, the modelling being largely performed under IHD objectives relating to the provision of an improved water balance.

The Perch Lake runoff records were found to be contaminated by sudden releases from beaver dams which were unrelated to rainfall events, and the simulations were so conducted as to detect these peaks. The SACRAMENTO estimates of the groundwater inflows into Perch Lake were in good agreement with those provided by other techniques.

It is noteworthy that the Perch Lake simultions have revealed the need to introduce the groundwater discharge phenomenon into lumped conceptual models. A model such as the SACRAMENTO should work well on any basin where the natural groundwater recharge is balanced by natural discharge. Furthermore, it should perform satisfactorily on any basin where groundwater recharge out balances groundwater discharge, the excess groundwater being routed out of the basin as a groundwater outflow. However, if properly applied, the model should be observed to consistently under simulate any basin which is receiving significant quantities of groundwater inflow from outside of the basin's topographic boundary. Such consistent under simulations have been obtained for one of the Perch Lake sub-basins which has long been hypothesized by other researchers to be receiving groundwater inflows from some unidentified external source. Lawson (9) has outlined a plan for the further modelling of this sub-basin, including (i) modifications to the SACRAMENTO model which will permit it to directly accept groundwater inflows as inputs to the lower zone storages (i.e., without passing through the upper zone storages representing the soil mantle) and (ii) the development of a related calibration procedure.

Further modelling of selected Perch Lake sub-basins is now being conducted (i) in support of detailed hydrometeorological research by investigators at the U. of Toronto, (ii) as part of the Interface Hydrology Section's research into seasonally frozen ground, and (iii) as part of the Section's continuing research into the development of improved watershed modelling techniques. Studies of the Trapping Creek Basin are now being directed towards detecting the hydrological effects of logging activities. It is noteworthy that the watershed modelling objectives of Canada's International Hydrological Program now relate to the development of transposable models, and that the modelling of

Canada's IHP basins should soon be directed towards this more challenging goal.

Flood Forecasting Applications

In 1972 the U.S. National Weather Service provided a description of their complete river forecasting system (10). Since then the SACRAMENTO model has replaced the STANFORD watershed model and changes have been made to the streamflow routing subroutines. Thus the 1972 publication is considerably out of date, and interested users of the system would have to obtain supplementary guidance from the National Weather Service. The Interface Hydrology Section has yet to consider the further development of their SACRAMENTO watershed modelling system into a real-time flood forecasting system, but would seriously consider the acquisition of the present NWS system rather than (or before) undertaking any such development.

The SACRAMENTO model was involved in a comparison of ten operational forecasting models by the World Meteorological Organization (11, 12). No attempt was made by the WMO to identify a "best" model, but rather to provide a prospective user with the information he would need to decide which model is "best" for his purpose. The conclusions presented in both reports are thus of necessity general in nature and the interested user will have to adapt these conclusions to his own specific set of circumstances. Anyone wishing to thoroughly study these reports in an attempt to select a model, or to reach more specific conclusions, will have to have otherwise acquired a great deal of knowledge concerning the various models, and preferably should already have obtained some practical experience with several of the models and some experience in operational flood forecasting. In general, the SACRAMENTO model compared favourably with the other models; and the relatively minor points in its disfavour are inconclusive, but they could probably be compensated for during any carefully planned yet routine operational use of the model.

In a paper describing the development of a SSARR flood forecasting system for the Ottawa River (13) the senior author reaches three general conclusions concerning further research and development needs with resepct to flood forecasting:

1(a) The most crucial need is to develop improved watershed modelling procedures for ungaged and poorly gauged (streamflow) areas (i.e., to develop accurate transposable models).

In the case of the Ottawa River, 46% of this 56,000 square mile basin was ungauged.

There is a further discussion of transposable models in a following section of the present report, and the work of Armstrong (5) has already been discussed.

(b) The SSARR model (14) is <u>not</u> amenable to the development of such transposable modelling techniques because it provides continuous parameter calibration <u>curves</u> rather than the discrete parameter <u>values</u> of the SACRAMENTO model.

Discrete parameter values can be more readily and objectively related to watershed characteristics. Furthermore, trial-and-error parameter calibration curves are not readily amenable to further refinement using optimization procedures.

2. There is need for improved modelling of snow-melt runoff, including the effects thereon of seasonally frozen ground.

   Farnsworth's (6) pioneering efforts have already been described.

3. There is a need for improved long-term runoff forecasting of a probabilistic nature.

   The probabilistic forecasting procedures of the National Weather Service are described below.

The paper by Lawson et al (13) contains further information concerning these three conclusions, and some additional yet related conclusions are also presented.

Twedt et al (15) have described the long-term runoff forecasting model of the National Weather Service. In this model a number of years (10-20) of actual historical data consisting of precipitation and temperature time series are input to a calibrated SACRAMENTO sub-model; separate simulations being run for each yearly set of time series inputs, using in each such simulation the current hydrologic conditions on the catchment as initial conditions. The result is a corresponding number of years of possible streamflow records which are conditioned to the current state of the catchment at the time of issuing the forecast. This set of 10 to 20 years of streamflow values is then subjected to a frequency analysis; and forecasts of streamflow can be provided for any future time in the current year at user-selected levels of probability. The Interface Hydrology Section has yet to examine such long-term forecasting procedures.

Developing A Transposable Watershed Model

Lawson (16) has described a preliminary strategy for developing a transposable SACRAMENTO watershed model for the Manitoba escarpment. A generalized and revised version of this strategy is presented here which, depending upon the availability of data, could be applied in other physiographic/climatic regions or in large river basins such as that of the Ottawa River:

1(a) Calibrate the SACRAMENTO model using 8 years of continuous daily data from a carefully selected and well-instrumented watershed in the region of interest.

This would yield a starting set of model parameter values for the watershed.

(b) Test the above calibration using 4 to 8 years of additional data for the same watershed.

This would yield a preliminary measure of simulation accuracy for the watershed.

(c) Decide, on the basis of step 1(b), on the need to recalibrate the model using the entire 12 to 16 years of record; and recalibrate as necessary.

This would yield a confirmed, or revised set of parameter values for the watershed and a measure of the "attainable" daily simulation accuracy for the watershed.

2(a) Select and simulate 3 other gauged watersheds located in the region of interest, using the SACRAMENTO model and the parameter set of step 1(c). This first group of watersheds would be chosen to be as similar as possible to the initial watershed (i.e., the watershed of step 1).

This would provide a preliminary measure of the direct transposability of the initial parameter set, i.e., a measure of the directly "attainable" simulation accuracy for watersheds which are similar to the initial watershed.

(b) Select and simulate 3 additional gauged watersheds located in the region of interest, using the SACRAMENTO model and the parameter set of step 1(c). This second group of watersheds would be chosen to differ from the initial watershed in terms of physiography, geology, soils, forest cover, etc.

This would provide a second measure of the direct transposability of the initial parameter set, i.e., a measure of the directly "attainable" simulation accuracy for watersheds which differ from the initial watershed.

3(a) Decide, on the basis of step 2, on the need to seek an improvement in simulation accuracy by attempting to relate model parameter values to watershed characteristics (e.g., physiography, soils, etc.).

If attempted, this would involve (i) calibrating the two groups of watersheds in step 2 to provide 7 parameter sets (3 for each group and 1 for the initial watershed) and (ii) efforts to relate (e.g., statistically) these parameter sets to corresponding sets of watershed characteristics. Square-grid regression techniques could be employed.

The resulting parameter/characteristic regression equations could be tested by employing them to generate parameter sets for the 7 basins and comparing the simulations using these parameter sets with (i) the simulations obtained using the parameter sets arising from the calibrations and (ii) the observed record.

(b) A third group of 3 additional gauged watersheds should probably be selected in order to further test this indirect method of transposing model parameters; i.e., parameter sets would have to be generated for these 3 basins using the step 3(a) parameter/characteristic regression equations, and SACRAMENTO simulations would then have to be undertaken.

This would yield a further measure of the indirectly "attainable" simulation accuracy for the region.

4. Decide, on the basis of steps 2 and 3, on the need to repeat step 3(a) using all of the suitable watersheds in the region.

   If attempted, this would yield a final set of parameter/characteristic regression equations and some final measure of the indirectly "attainable" simulation accuracy for the region.

5. Evaluate the above, and if necessary decide on a plan to repeat all, or parts, of the above steps using 6 hourly simulations and/or 1 hourly simulations of selected events (e.g., spring storms).

Note that real-time flood forecasting accuracies should normally be less than the above-mentioned "attainable" accuracies. Real-time flood forecasting studies would be a further extension of the above outline, as would any regional studies of the hydrological effects of land use change.

The Wilson Creek experimental watershed has been selected as the "initial (step 1)" watershed for a study of the Manitoba escarpment, whereas the Perch Lake IHP watershed is centrally located in the Ottawa River basin and could serve as the "initial" watershed for a study of this region. The data used to calibrate the 27 watersheds in the Ottawa River SSARR Forecasting Model are readily available (17).

Studies of Land Use Change

Formal research into the hydrological effects of land use change is usually conducted on experimental watersheds; and these watersheds are often paired, with one of the watersheds remaining in a natural state as a "control" and the other being modified after collecting data on both basins for a suitable period of time. The use of conceptual watershed models within this "paired watershed" approach is beyond the scope of the present report and has yet to be fully examined by the Interface Hydrology Section. However, the paired watershed approach has come under criticism because of the protracted time and expense involved and, to date, the rather inconclusive nature of the results.

In some cases, an alternative or complementary approach would be to use routinely available data, for a wide variety of basin types and sizes, over a large physiographic region which has undergone a significant change in land use, e.g., commercial timber harvesting. As a first step in this direction, Lawson (18) has outlined a SACRAMENTO modelling study for the 50-square mile Trapping Creek basin located in the Southern Interior of British Columbia. Over the 8-year period of available record, 20% of the natural forest cover of this basin was gradually and progressively removed by commercial logging activities. The generalized simulation strategy is as follows:

1. <u>Calibration</u> of the SACRAMENTO model for the 8-year period of record, with <u>no regard for the effects of logging</u>.

   This would provide a starting set of model parameter values and a "standard" set of simulated vs observed hydrographs.

2(a) Rerun the above simulations using the above set of parameter values, only accounting for the assumed effects of the timber harvest on (i) snow-melt timing, (ii) snow-melt volume, and (iii) evapotranspiration.

(b) Present the results of the above to a selected group of experts for suggestions as to further reruns, and repeat step 2(a) as required.

This would provide a revised set of simulated hydrographs for an initial comparison with the "standard" set of simulated hydrographs from step 1 and the observed hydrographs.

3. Rerun the final simulations of step 2 in a calibration mode using two samples (i) the first four years of record, and (ii) the last four years of record.

This would provide two sets of model parameter values which might reflect the changing basin conditions.

4. Attempt to interpret the two parameter sets in step 3, and if feasible:

(i) Rerun the 8-year simulation using the "best guess" parameter set for "natural" basin conditions, i.e., assuming no logging effects.

This would provide a "natural" simulation for the entire period of record.

(ii) Rerun the 8-year simulation using the "best guess" parameter set for each of the 8 years and "modified" basin conditions, i.e., incorporating the hydrological effects of the logging as delineated in step 2.

This would provide a "modified" simulation for the entire period of record.

5. The "natural" simulation could then be compared with both the "modified" simulation and the observed record, and appropriate conclusions drawn.

It would of course be preferable if the available period of record approached 16 years, if more than 30% of the timber had been removed during the last 8 years of record, if some control had been exerted over the logging, and if 16 years of corresponding data were available from a "control" watershed. But such demands, however valid, lead one back to the experimental watershed approach, and the objective here is to make the best use of available data.

BIBLIOGRAPHY (Reference Documents)

Documentation of the SACRAMENTO Model

1. Burnash, R.J.C., R.L. Ferrel and R.A. McGuire, 1973. A generalized streamflow simulation system, conceptual modeling for digital computers. United States Department of Commerce, National Weather Service and State of California, Department of Water Resources; Joint Federal-State River Forecast Center, Sacramento, California, 204 p.

2. Peck, E.L., 1976. Catchment modeling and initial parameter estimation for the National Weather Service River Forecast System. NOAA Technical Memorandum NWS HYDRO-31, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Office of Hydrology, Washington, D.C., 63 p.

3. Harvey, K.D., 1977. The trial and error calibration of the SACRAMENTO watershed model. Inland Waters Directorate, 23 p. (first draft)

Refinements and Improvements

4. Monro, J.C., 1971. Direct search optimization in watershed modeling and a watershed model application. NOAA Technical Memorandum NWS HYDRO-12, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, Maryland, 52 p.

5. Armstrong, B.L., 1977. Selection of initial soil moisture accounting parameters from soil properties for a conceptual runoff model. M.Sc. thesis, Oklahoma State University, 78 p.

6. Farnsworth, R.K., 1976. A mathematical model of soil surface layers for use in predicting significant changes in infiltration capacity during periods of freezing weather. Ph.D. thesis, University of Michigan, 169 p.

Studies of Watershed Response

7. Shiau, S.Y., 1975. Evaluation of watershed hydrological response by application of a generalized hydrologic model. Publication No. 117, IASH symposium of Tokyo, pp. 87-98.

8. Shiau, S.Y., 1975. System simulation of surface and groundwater inflow to Perch Lake from Perch Lake sub-basins 1, 2, 3, 4, 5 and B. Hydrological studies on a small basin on the Canadian Shield, Atomic Energy of Canada Limited, AECL-5041/II, pp. 683-730.

9. "Possibilities for Refined SACRAMENTO Modelling of Perch Lake Sub-basins 4 and 5", Environment Canada letter from D.W. Lawson to P.J. Barry (Atomic Energy of Canada Ltd.), November 24, 1977, 5 p.

Flood Forecasting Applications

10. Staff, Hydrologic Research Laboratory, 1972. National Weather Service River Forecast System forecast procedures. NOAA Technical Memorandum NWS HYDRO-14, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, Maryland, 258 p.

11. World Meteorological Organization, 1977. Intercomparison of conceptual models used in operational hydrological forecasting. Operational Hydrology Report No. 7, WMO-429, Geneva, Switzerland, 172 p.

12. Sittner, W.T., 1976. WMO Project on Intercomparison of Conceptual Models used in Hydrological Forecasting. Hydrological Sciences Bulletin, XXI, 1 3, pp. 203-213.

13. Lawson, D.W., C. Guillaud, J. Cerceau, G. Brown and J.M. Power, 1977. Developing a flood forecasting system for the Ottawa River. Second Conference on Hydrometeorology, October 25-27, 1977, Toronto; American Meteorological Society/Canadian Meteorological Society, pp. 37-48.

14. U.S. Army, 1972. Program description and user manual for SSARR model. Program 724-K5-G0010, 188 p.

15. Twedt, T.M., J.C. Schaake, Jr., and E.L. Peck, 1977. National Weather Service extended streamflow prediction. 45th Annual Meeting, Western Snow Conference, Albuquerque, New Mexico, 10 p.

Developing A Transposable Watershed Model

16. "Sacramento Modelling of the Wilson Creek (Manitoba) Watershed", Environment Canada memo from D.W. Lawson to D.H. Lennox (Chief, Hydrology Research Division), October 7, 1977, 5 p. (including attachment).

17. Rousseau, Sauvé, Warren Inc., 1977. Etude de prévision des crues de l'Outaouais, Addendum no 1, pour la Direction des ressources en eau du gouvernement fédéral, 180 p.

Studies of Land Use Change

18. "Sacramento Modelling of the Trapping Creek (British Columbia) Watershed", Environment Canada letter from D.W. Lawson to E. Hetherington (Canadian Forestry Service), October 4, 1977, 4 p.

APPENDIX

General Description of the SACRAMENTO Watershed Model*

Figure 4 is a conceptual schematization of the model which illustrates its various sub-surface storages and associated streamflow components. A general description of the functioning of these storages and the generation of their related streamflows is given below. Further details as to the equations and parameters are available elsewhere (1, 2). Figures 5a to 5h illustrate the response of the model to a hypothetical rainfall event and hence serve to quickly provide the reader with an overall understanding of the functioning of the model.

The Sacramento watershed model (1) is of the explicit moisture accounting type in which lumped parameters are used to simplify the areal soil moisture accounting while retaining a generalized description of the vertical distribution of water in the soil profile. The model is based on a system of infiltration, percolation, soil-moisture and groundwater storage, drainage, and evapotranspiration relationships which express the basin as a set of storages of determinable capacities that hold water temporarily and gradually recede as their contents are diminished by vertical percolation, evapotranspiration and lateral drainages. Every parameter included in the model is deemed to be necessary for the analysis of a significant hydrologic process. The definition of model parameters is achieved by establishing a soil moisture and groundwater computation which allows the determination of basin discharge from basin moisture input. Effective moisture storage capacities in the soil profile are estimated not by sampling of the soil profile, but by inference from the precipitation and discharge records. The equations and formulations used allow a preliminary evaluation of many of the model parameters from the hydrometeorological data base and other observable characteristics of the basin.

The model utilizes two subsurface moisture zones (upper and lower) containing two levels of tension water and three levels of free water storage (Fig. 4). Tension water represents that water which is closely bound to soil particles and constantly depleted by evapotranspiration. Free water is not bound to soil particles and moves through the ground in response to gravitational and pressure forces. Upper-zone tension water storage represents that volume of water which would be required under dry conditions to meet all interception requirements and to provide sufficient moisture to the upper soil mantle so that infiltration to deeper parts of the soil profile can begin. Lower-zone tension

---

*This description is restricted to the soil-moisture and groundwater accounting (water balancing) aspects of the model and the related generation of runoff volumes. The snow-melt subroutines (temperature index or temperature/"radiation" index), the transformation of the runoff volumes into outflow hydrographs, and the model's data management system are not described. However, it should be realized that the soil-moisture/groundwater accounting scheme is the crucial element in any conceptual watershed model.

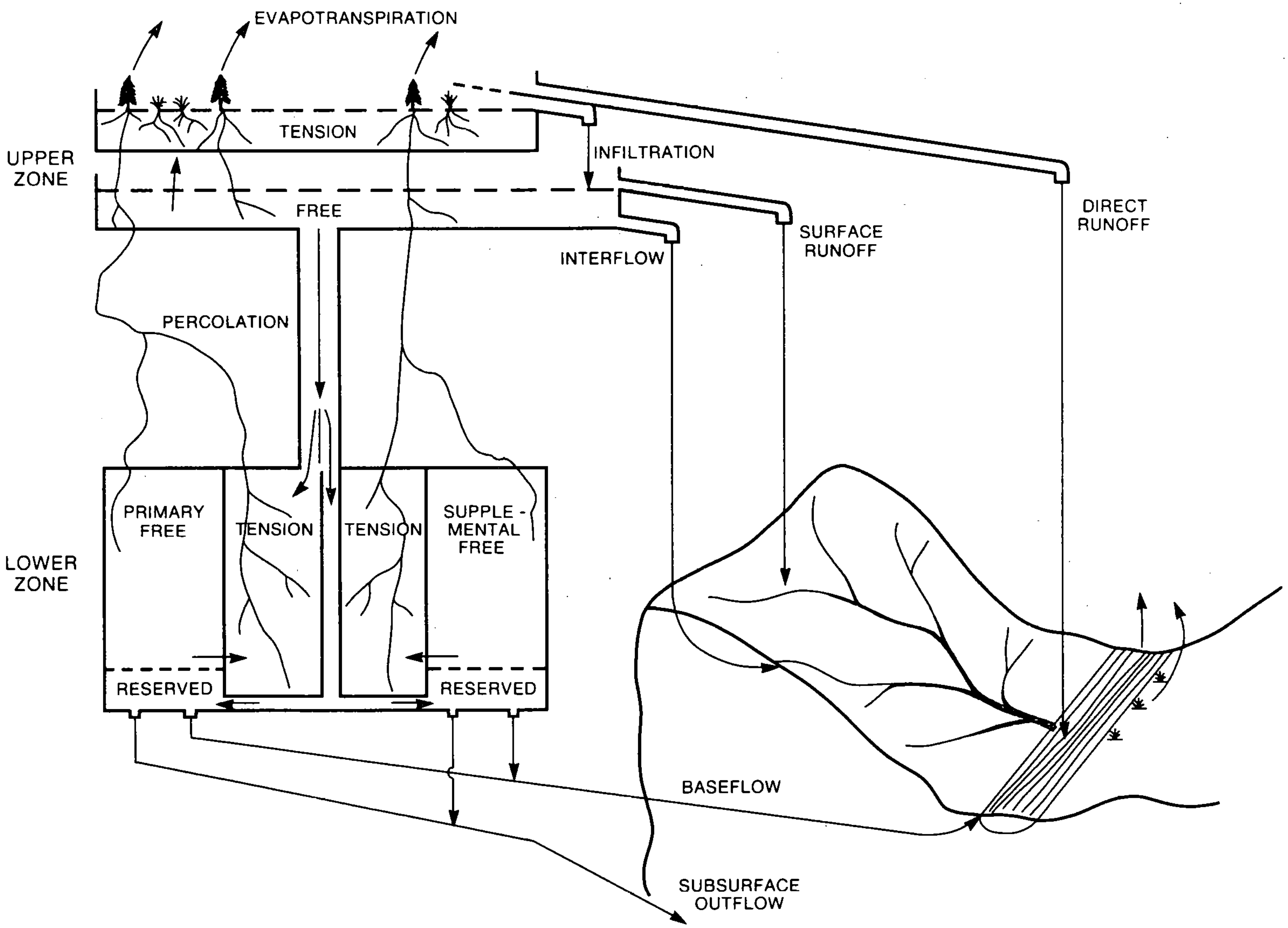
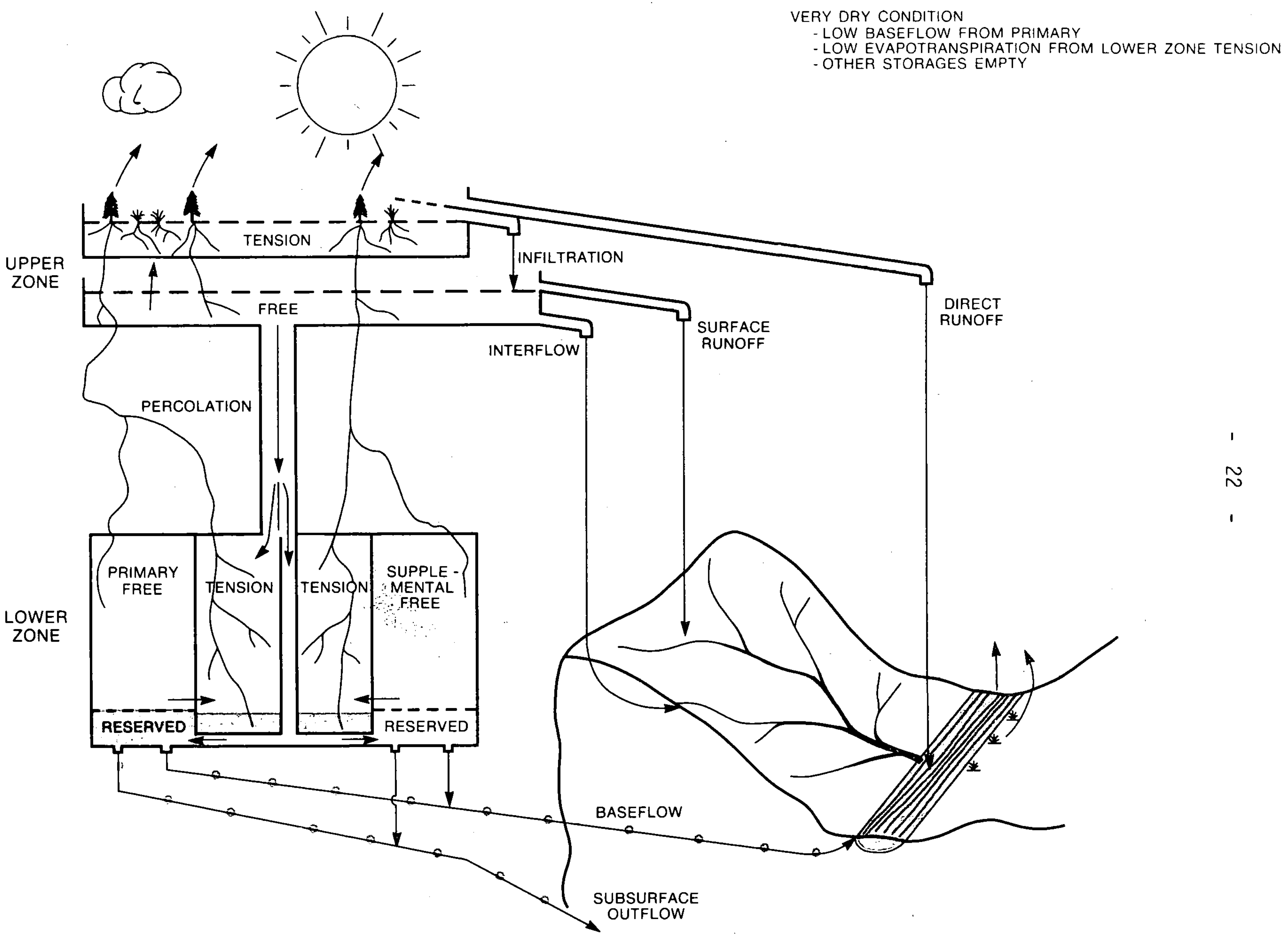
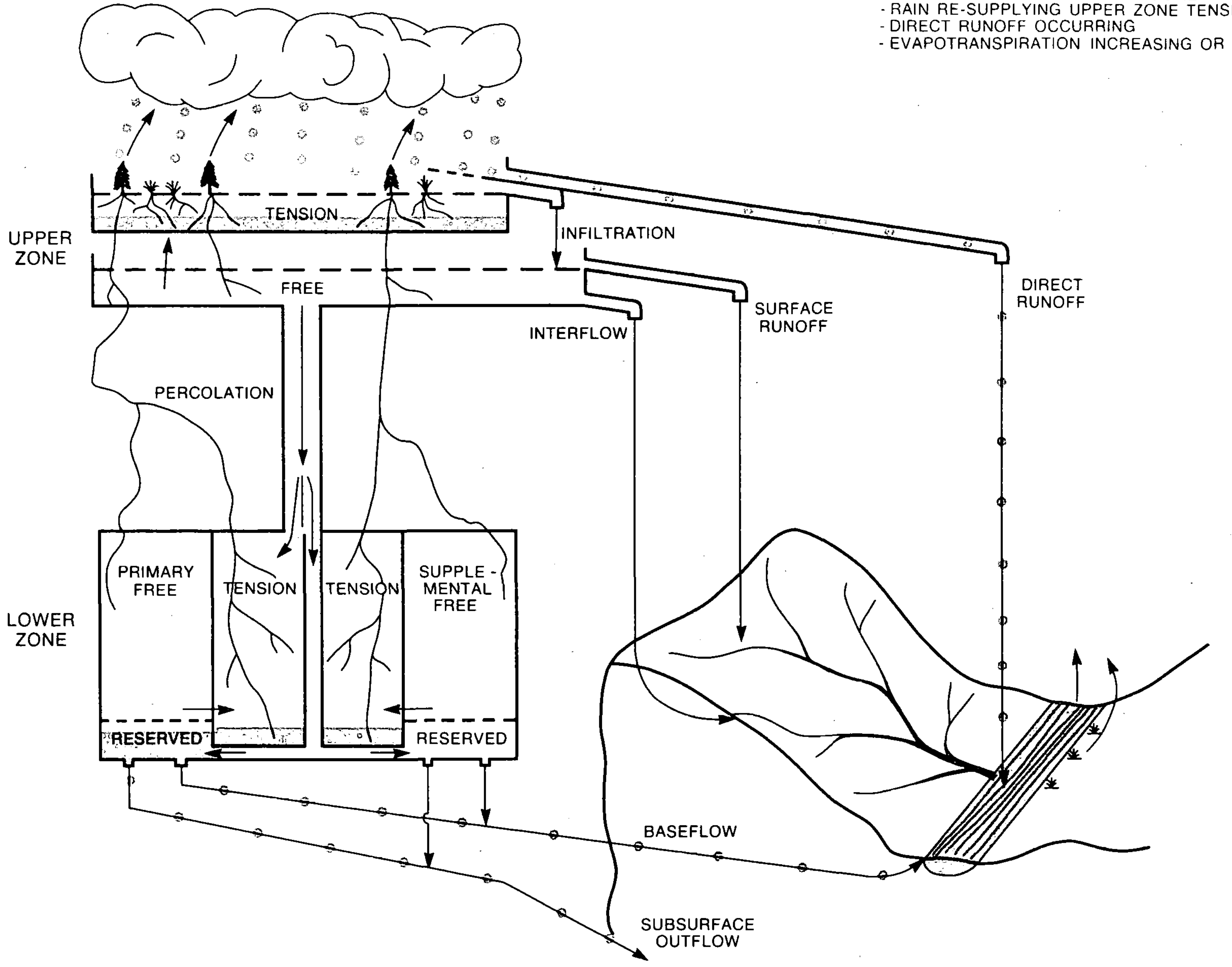


Fig. 4. Conceptual Schematization of the Sacramento Model (After Burnash et al. 1973)



VERY DRY CONDITION
- LOW BASEFLOW FROM PRIMARY
- LOW EVAPOTRANSPIRATION FROM LOWER ZONE TENSION
- OTHER STORAGES EMPTY

Fig. 5a. Basin Response during a Sequence of Hydrometeorological Events - Very Dry Condition



STARTING TO RAIN
- BASEFLOW CONTINUES TO DECLINE
- RAIN RE-SUPPLYING UPPER ZONE TENSION
- DIRECT RUNOFF OCCURRING
- EVAPOTRANSPIRATION INCREASING OR STABILIZING

Fig. 5b. Basin Response during a Sequence of Hydrometeorological Events - Starting to Rain

RAIN CONTINUING
- UPPER ZONE TENSION FILLED
- DIRECT RUNOFF AREA INCREASING
- PERCOLATION RATE EXCEEDS INFILTRATION SUPPLY)
  RATE - NO INTERFLOW
- LOWER ZONE CONTENTS INCREASING
- BASEFLOW INCREASING
- EVAPOTRANSPIRATION STABILIZING OR DECREASING

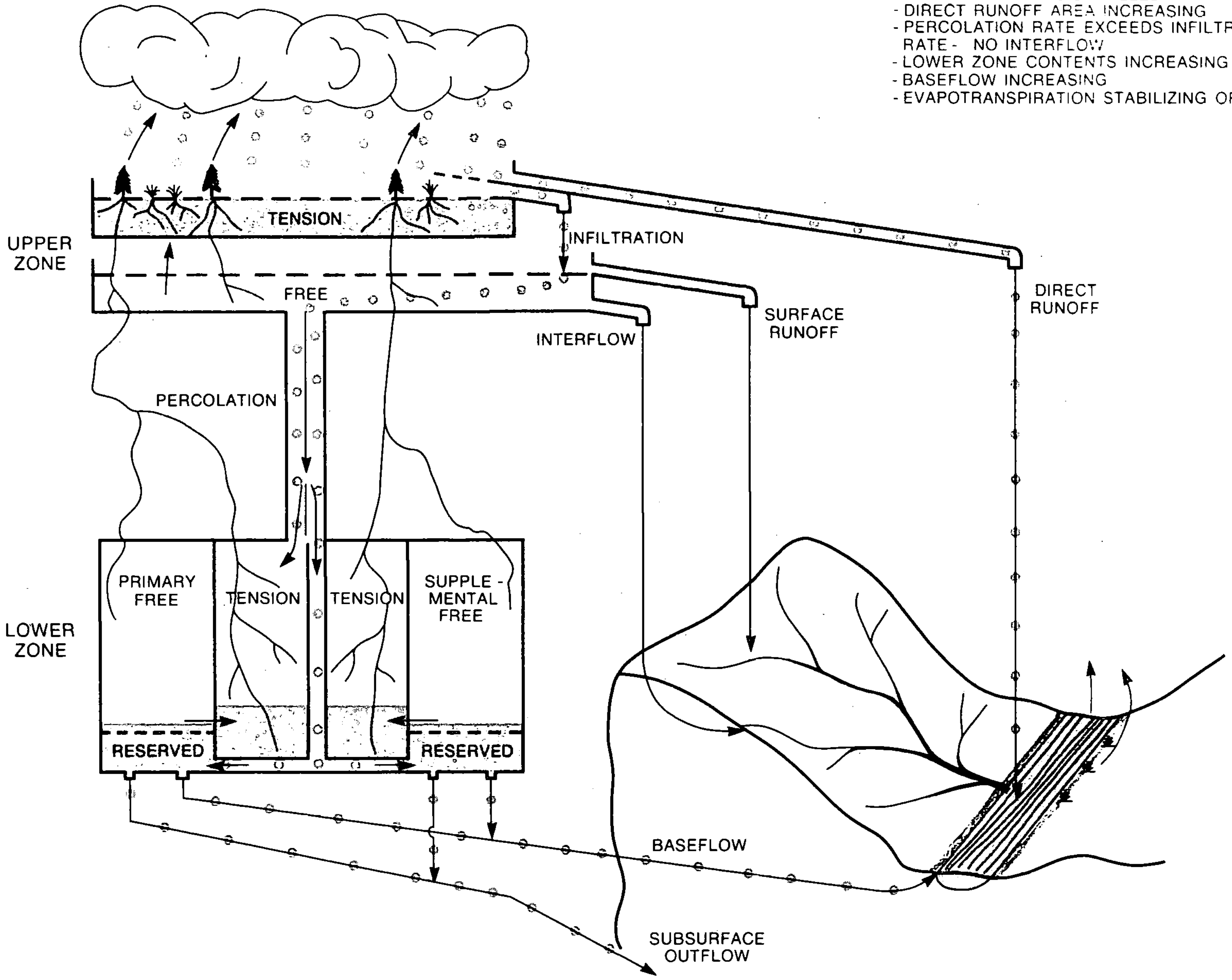
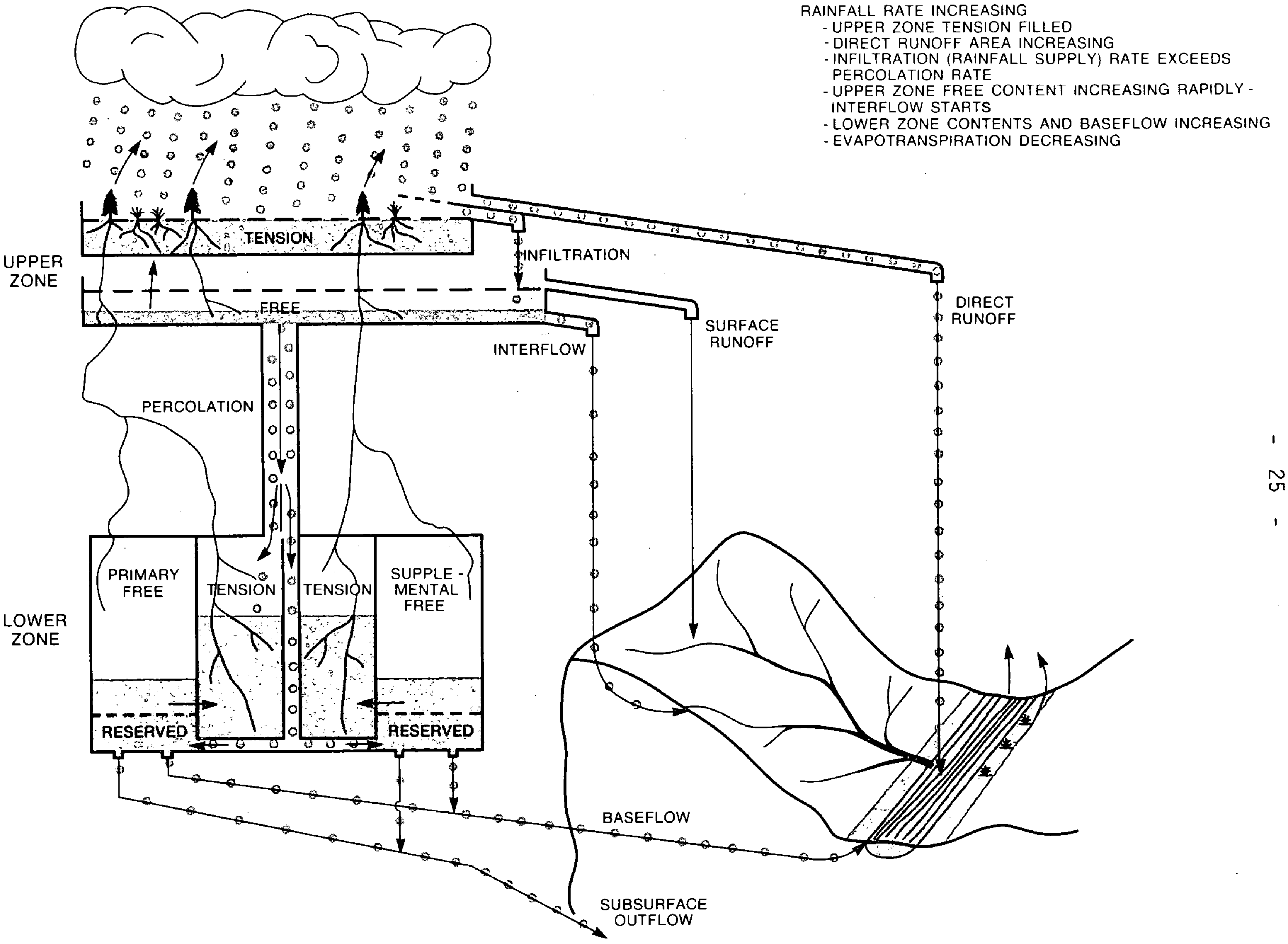
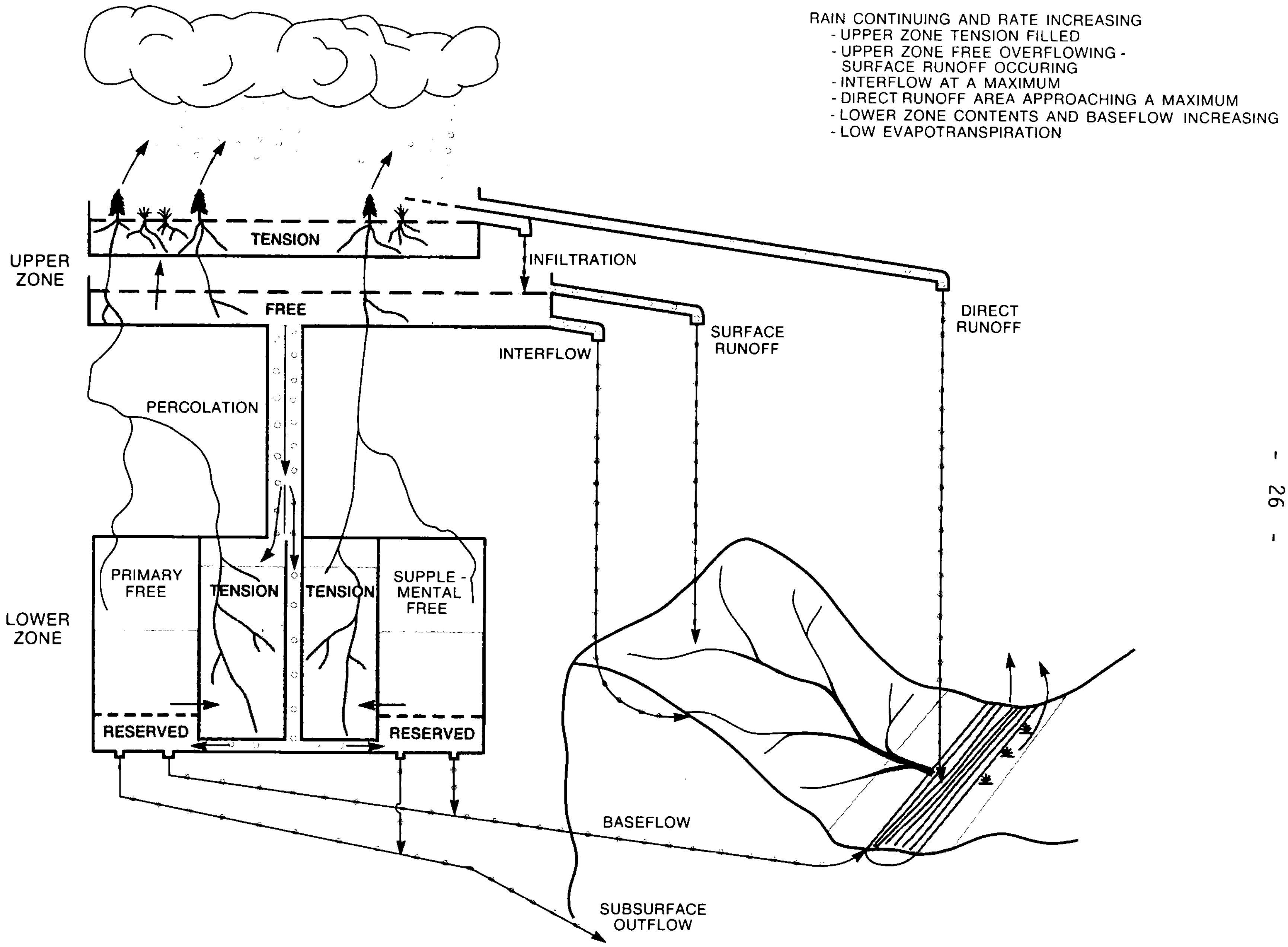


Fig. 5c. Basin Response during a Sequence of Hydrometeorological Events - Rain Continuing



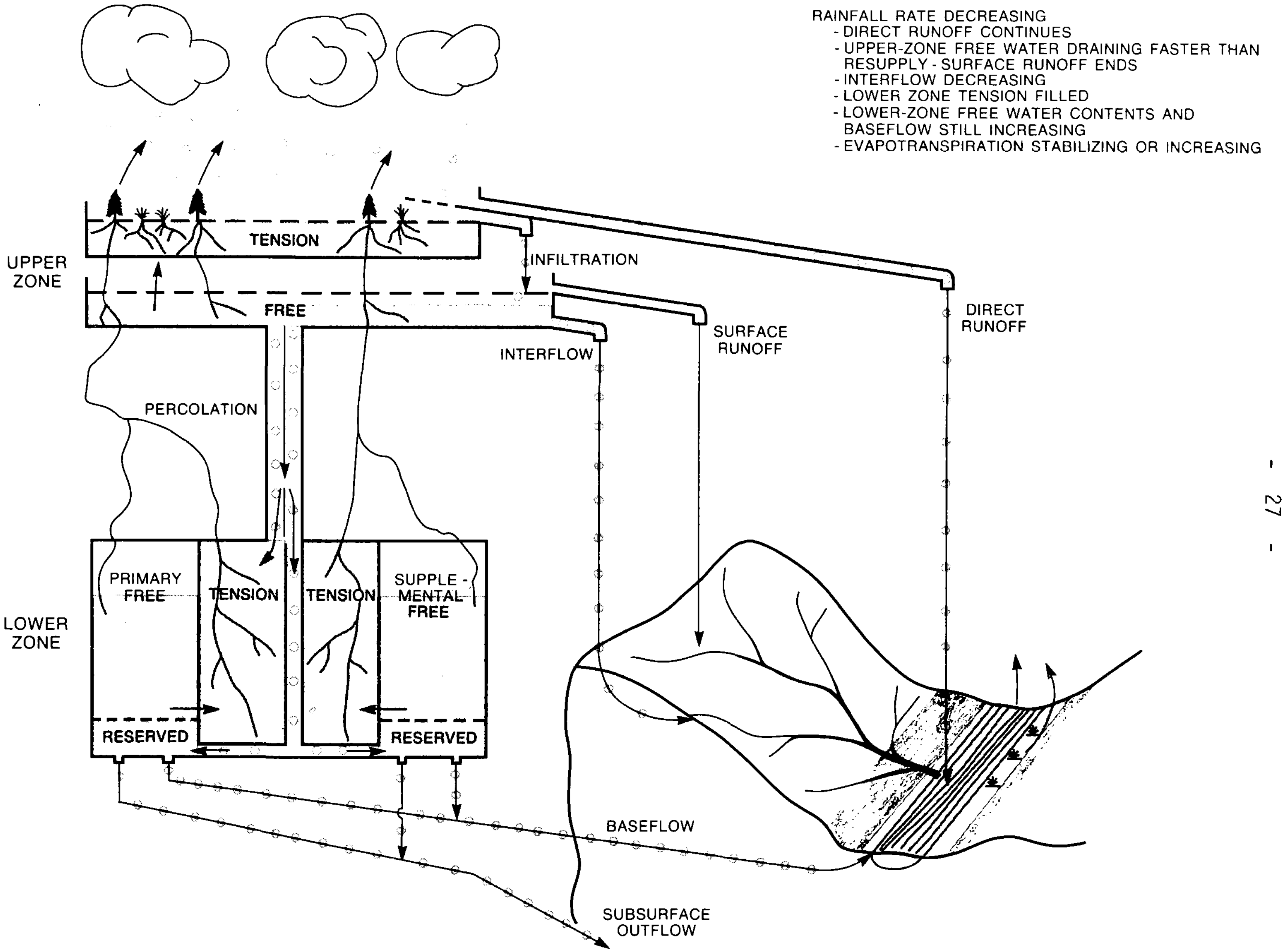
RAINFALL RATE INCREASING
- UPPER ZONE TENSION FILLED
- DIRECT RUNOFF AREA INCREASING
- INFILTRATION (RAINFALL SUPPLY) RATE EXCEEDS PERCOLATION RATE
- UPPER ZONE FREE CONTENT INCREASING RAPIDLY - INTERFLOW STARTS
- LOWER ZONE CONTENTS AND BASEFLOW INCREASING
- EVAPOTRANSPIRATION DECREASING

Fig. 5d. Basin Response during a Sequence of Hydrometeorological Events - Rainfall Rate Increasing



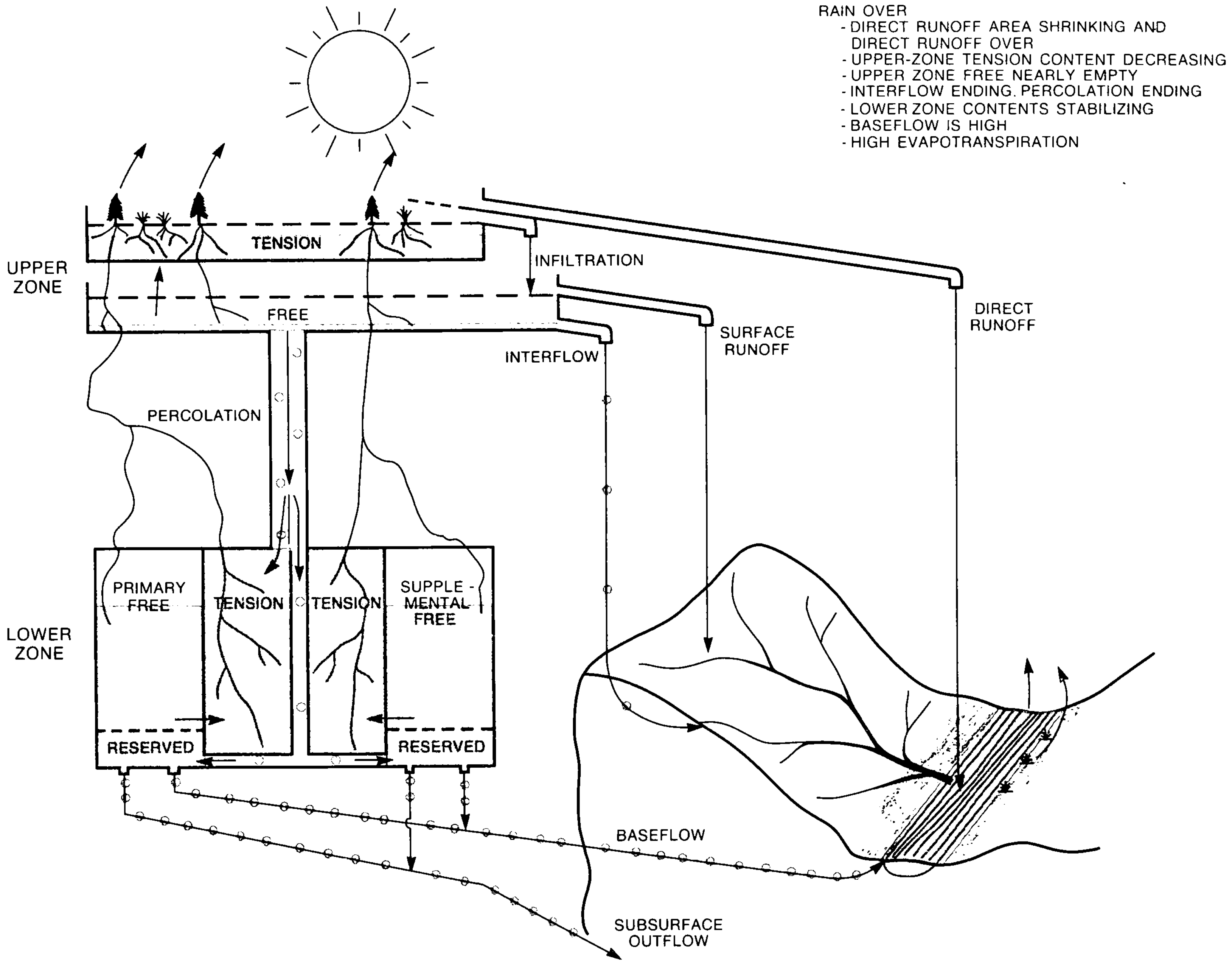
RAIN CONTINUING AND RATE INCREASING
- UPPER ZONE TENSION FILLED
- UPPER ZONE FREE OVERFLOWING - SURFACE RUNOFF OCCURING
- INTERFLOW AT A MAXIMUM
- DIRECT RUNOFF AREA APPROACHING A MAXIMUM
- LOWER ZONE CONTENTS AND BASEFLOW INCREASING
- LOW EVAPOTRANSPIRATION

Fig. 5e. Basin Response during a Sequence of Hydrometeorological Events - Rain Continuing and Rate Increasing



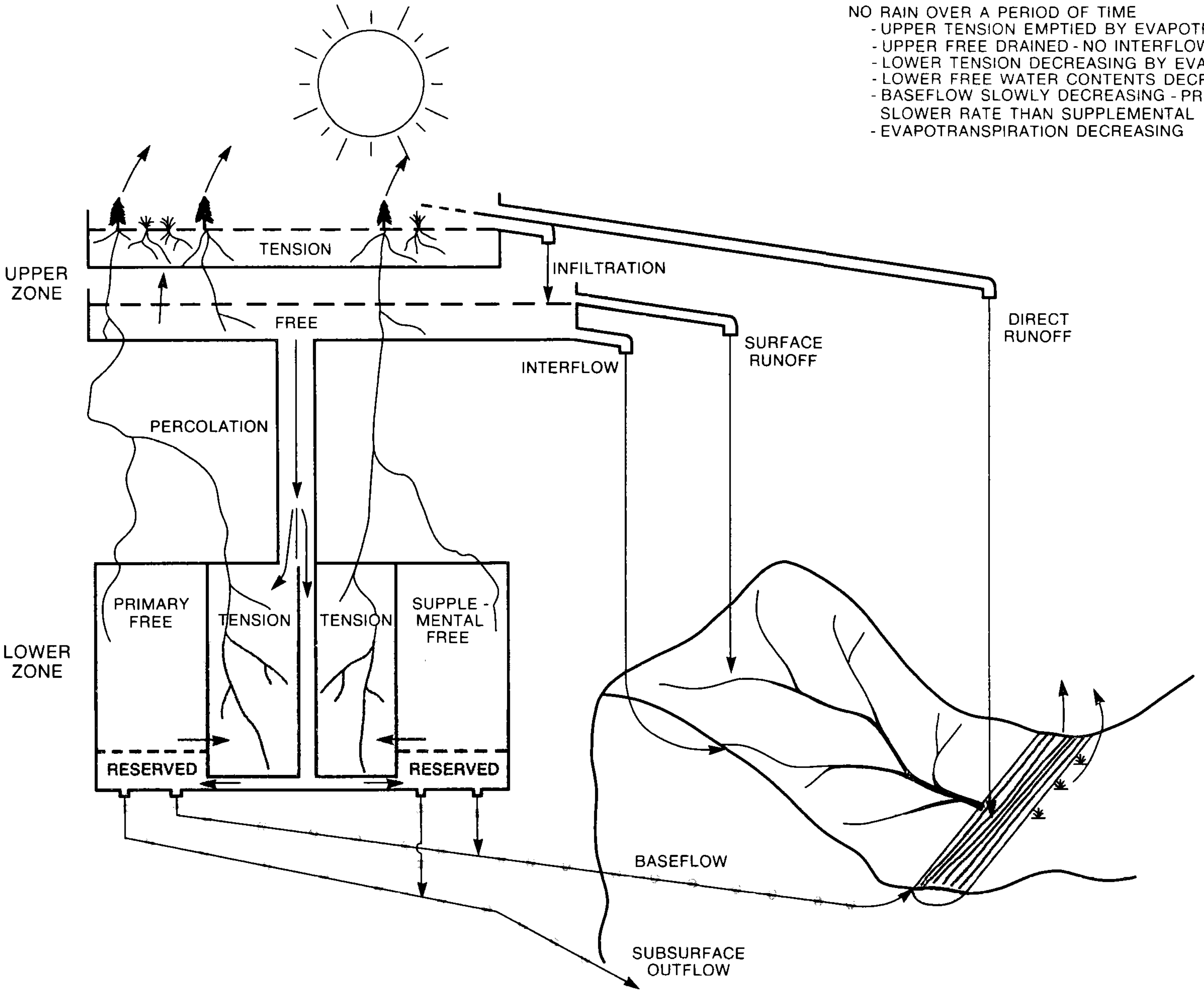
RAINFALL RATE DECREASING
- DIRECT RUNOFF CONTINUES
- UPPER-ZONE FREE WATER DRAINING FASTER THAN RESUPPLY - SURFACE RUNOFF ENDS
- INTERFLOW DECREASING
- LOWER ZONE TENSION FILLED
- LOWER-ZONE FREE WATER CONTENTS AND BASEFLOW STILL INCREASING
- EVAPOTRANSPIRATION STABILIZING OR INCREASING

Fig. 5f. Basin Response during a Sequence of Hydrometeorological Events - Rainfall Rate Decreasing



RAIN OVER
- DIRECT RUNOFF AREA SHRINKING AND DIRECT RUNOFF OVER
- UPPER-ZONE TENSION CONTENT DECREASING
- UPPER ZONE FREE NEARLY EMPTY
- INTERFLOW ENDING. PERCOLATION ENDING
- LOWER ZONE CONTENTS STABILIZING
- BASEFLOW IS HIGH
- HIGH EVAPOTRANSPIRATION

Fig. 5g. Basin Response during a Sequence of Hydrometeorological Events - Rain Over



NO RAIN OVER A PERIOD OF TIME
- UPPER TENSION EMPTIED BY EVAPOTRANSPIRATION
- UPPER FREE DRAINED - NO INTERFLOW NOR PERCOLATION
- LOWER TENSION DECREASING BY EVAPOTRANSPIRATION
- LOWER FREE WATER CONTENTS DECREASING
- BASEFLOW SLOWLY DECREASING - PRIMARY AT SLOWER RATE THAN SUPPLEMENTAL
- EVAPOTRANSPIRATION DECREASING

Fig. 5h. Basin Response during a Sequence of Hydrometeorological Events - No Rain over a period of Time.

water storage is that volume of moisture which will be claimed by dry soil particles when moisture from a wetting front reaches that depth. The rate of percolation to the lower zone is controlled both by the content of the upper-zone free water storage and the deficiency of the lower zone storages.

Interflow occurs only when the rate of infiltration exceeds the percolation rate. Surface runoff is produced by infiltration rates which exceed the capacity of the upper-zone free water storage to store and transmit water. Direct runoff is produced by any rain or effective melt on the impervious portion of the basin directly connected or adjacent to the channel system.

The impervious portion of the basin does not have to remain some constant area. It has been observed in many basins that coincidental with the filling of soil-moisture storages an increasing fraction of the basin may assume impervious characteristics such as are manifested by the enlargement of marshes, swamps, and other transient seepage outflow areas. In the model, this variable fraction of the basin is added to the permanent impervious area, and is defined as an additional impervious area which reaches its maximum when the tension water storages are saturated.

The two lower-zone free water storages, primary and supplemental, represent those volumes of water available for drainage as baseflow and/or subsurface outflow. These storages fill simultaneously from percolated water but drain independently at different rates, representing the long-term and transient groundwater flows and providing a variable groundwater recession. Generally, the percolated water tends to satisfy the tension water deficiency first. However, variations in soil conditions, topography, rainfall and snowmelt rates, etc., cause variations in infiltration and percolation rates over a drainage basin. Thus, the effect of these spatial variations and their associated groundwater recharge and discharge patterns is approximated by diverting a fraction of the percolated water into free water storages before tension water deficiency is fully satisfied. The water made available to the free water storages is distributed between the primary and supplemental storages in response to their relative deficiencies.

The soil moisture accounting within the model applies the evapotranspiration loss to the various storages and/or to the water-covered areas. The amount of evapotranspiration from each storage in the model is determined by a hierarchy of priorities and is limited by the availability of the moisture as well as by the computed demand. Evaporation from the area covered by surface water and/or phreatophytic vegetation is computed at the demand rate. As described below, over other portions of the soil mantle, evapotranspiration is made to vary not only with the demand but also with the contents of both the tension and free water storages. As the soil mantle dries from evapotranspiration, moisture is first withdrawn from the upper zone at the potential rate, multiplied by the proportional loading of the upper-zone tension water storage. If evapotranspiration should occur at such a rate that the ratio of contents to capacities for available free water exceeds those of tension water, then water is transferred from free to tension water and the relative loadings balanced in order to maintain a moisture profile that is logically consistent. In the lower zone, evapotranspiration is calculated by the unmet demand times the proportional loading of the lower-zone tension water storage. Again, as in the upper zone, if the ratio of contents to capacities for available free water exceeds those of tension water, then water is transferred from free to tension water and the relative loadings are brought into balance. Depending upon soil and plant conditions, some fraction of the lower-zone free water is considered to be below the root zone and therefore is unavailable for such transfers. However, this reserved fraction can be drained by baseflow and subsurface outflow.

In summary, there are five streamflow components which are recognized and generated by the model:

1. Direct runoff: Produced by any rain or effective melt being applied to the variable impervious area.

2. Surface runoff: A highly rate dependent component, it occurs only when the rate of moisture input exceeds the capacity of the upper zone to store and transmit water.

3. Interflow: Lateral drainage from upper-zone free water storage; it occurs when the infiltration rate exceeds the percolation rate.

4. Supplemental baseflow: Lateral drainage from lower-zone supplemental free-water storage. The drainage rate of this flow component is less than that of the interflow but greater than that of the primary baseflow. While the duration of this flow component is longer than that of the interflow, it is shorter than that of the primary baseflow.

5. Primary baseflow: Lateral drainage from lower-zone primary free-water storage.

Figures 5a to 5h have been provided to demonstrate the hydrological response of the various moisture storages and the generation of the above-mentioned flow components during a sequence of hypothetical hydrometeorological events. As such, they can serve to facilitate an improved understanding of the basic conceptual logic of the model and to assist in visualizing the hydrological significance of the various model components. It should be obvious from a consideration of these figures that the model could be used for hourly simulations.

Modifications to the Original Concepts

If the basin acted as a closed system, then the above soil moisture and groundwater divisions would be adequate to describe the disposition of moisture applied at the soil surface. However, subsurface drainage may bypass the outlet gauging site in many basins. To approximate this effect, it is assumed that those soils which do not drain to the stream channel have the same basic drainage characteristics as those that do. The capacities of the two lower-zone free-water storages which are assumed to be providing these subsurface outflows can then be simply expressed as fractions of the previously defined lower-zone free-water storage capacities. These previously defined storage capacities are derived from the steam channel outflow hydrographs. In the original model, the fractions were assumed to be the same for both the supplemental and the primary free water; consequently, only one parameter was needed. However, in areas where subsurface groundwater outflow plays an important role in the water balance, two separate fractions (parameters) have been found to be more effective in achieving a satisfactory simulation (7, 8). This probably is due to the fact that the ratio of "non-channel" outflow (underflow and/or some other form of subsurface outflow) storage to "channel" baseflow storage of the supplemental free-water storage should normally differ from that of the primary free-water storage. From the groundwater point of view, one would normally expect a higher ratio for the primary storage, as this storage is assumed to be supporting more regional groundwater flow systems.

Another modification is the introduction of a noncontributing or "sink area" concept into the original model. This modification allows one to take into account any variations in the effective drainage area which occur over time. This phenomenon is particularly significant for basins located in the prairie region. Normally, the fraction of the noncontributing area of a drainage basin increases as the season progresses and the soil mantle becomes drier; and this phenomenon is manifested by the disappearance of flowing water in intermittent streams. The noncontributing area is continuously monitored in the modified model as a function of the tension water storages and is constrained by two parameters representing its minimum and maximum values. Both of these parameters are expressed as decimal fractions of the total basin area and are discernible from topographic maps. Any surface runoff and interflow generated from the noncontributing area are recycled as moisture input to the model in the subsequent computational time step.

Many methods can and have been used to estimate the evapotranspiration demand (1, 2). The present version of the modified model uses the modified Penman method* to estimate monthly potential evapotranspiration at one or more meteorological sites in or near the basin. As an option, the topographic characteristics of elevation, exposure, slope and aspect over the basin can then be compared to these same characteristics at the sites where the potential evapotranspiration was calculated, and the average basin evapotranspiration demand estimated on the basis of this comparison. Daily estimates are obtained using linear interpolation. As an additional option, these daily estimates can be replaced by pan or evaporimeter measurements which are constrained by the monthly calculations of potential evapotranspiration.

---

*Shiau, S.Y. and Davar, K.S., Modified Penman method for potential evapotranspiration from forest regions, J. Hydrol., 18, pp. 349-365, 1973.