Appendix F
Summary Descriptions of Selected Operational Snowmelt Models

F-1. General Introduction

Many models have been created around the world over the last four decades or so to describe snowmelt runoff. Some 18 different models are listed and summarized in the *Snow Hydrology Guide* (Ontario Ministry of Natural Resources 1989). The World Meteorological Organization (1986) also lists and summarizes 18 different snowmelt runoff models. These many models are listed here in Table F-1.

a. This section will focus on describing six snowmelt models that have been demonstrated as valuable operational models or are thought to have a high potential for future operational use by the U.S. Army Corps of Engineers. These models are as follows:

- The SSARR Model (the Streamflow Regulation and Reservoir Regulation Model).
- The HEC-1 and HEC-1F Models (the Hydrologic Engineering Center - 1, 1F Model).
- The NWSRFS Model (the National Weather Service River Forecast System Model).
- The PRMS Model (the Precipitation Runoff Modeling System Model)
- The SRM (the Snowmelt Runoff Model).
- The GAWSER Model (the Guelph All-Weather Storm-Event Runoff Model).

b. In the following sections, the theoretical basis and application of each of these six models will be briefly described as will their data requirements and significant features. Each model description will include important citations relating to model development and use.

F-2. Brief Descriptions of Snowmelt Models

a. SSARR model. The Streamflow Synthesis and Reservoir Regulation model was originally developed by the North Pacific Division of the U.S. Army Corps of Engineers in 1956 (USACE 1956). This model has been successfully applied to numerous river systems as diverse as the Columbia and Mekong rivers (Rockwood 1978) and is well documented within USACE (1991). Viessman et al. (1977) state that SSARR is one of the earliest continuous streamflow simulation models using lumped parameter representation and has its primary strength in its verified accuracy.

(1) The conceptual logic underlying the watershed model (SSARR also has river system and reservoir system models) is shown schematically in Figure F-1. SSARR watershed model can be visualized as comprising two modules, the snow computation module and the runoff analysis module. The Runoff Analysis Module uses a single soil-moisture reservoir whose level or state determines the percentage of available precipitation or snowmelt that eventually runs off via combined surface, subsurface, and base-flow components. Water that does not run off is apportioned between soil-moisture reservoir gains and evapotranspiration losses. At present the operational SSARR model does not deal directly with moisture of frozen ground or the temperature-dependence of important water properties that affect runoff.

(2) Within the snow computation module, the SSARR program computes snowmelt through the use of two options that allow it to be tailored to specific applications. The first option for computing snowmelt is based on a temperature index approach, while the second option is the generalized snowmelt equation as derived from *Snow Hydrology* (USACE 1956). Within this module, the state of the basin snowpack can also be defined by two different options: the snowcover “depletion curve” option or the “integrated-snowband” option.

(3) The depletion curve model computes snowmelt with an algorithm that is based on the

Table F-1
Listing of Snowmelt Models
(As identified by the Ontario Ministry of Natural Resources (1989) and the World Meteorological Organization (1986))

Model Name	Country of Origin	Reference
Point Energy/Mass Balance Model	USA	Anderson (1976)
HSP-F (Hydrologic Simulation Program-Fortran)	USA	Johanson et al. (1984)
NWSRFS (National Weather Service River Forecast System)	USA	Anderson (1973)
SSARR (Streamflow Simulation and Reservoir Regulation)	USA	USACE (1991)
HEC-1 (Hydrologic Engineering Center-1)	USA	USACE (1990)
USDAHL-74 (Revised Model of Watershed Hydrology)	USA	WMO (1986)
SCS (SCS Snowmelt Model)	USA	WMO (1986)
SWMM (Storm Water Management Model)	USA	WMO (1986)
USGS (U.S. Geological Survey Model)	USA	WMO (1986)
SIMFLO (Continuous Streamflow Simulation Model)	Canada	Bishop and Watt (1975)
GAWSER (Guelph Agricultural Watershed Storm-Event Runoff Model)	Canada	Ghate and Whiteley (1977)
MOEHYDRO2 (Comprehensive Watershed Model)	Canada	Logan (1976)
WRB (Water Resources Branch Model)	Canada	Kite (1978)
UBC (University of British Columbia Watershed Model)	Canada	Quick and Pipes (1977)
QFORECAST (Continuous Simulation and Real-Time Forecast Model)	Canada	WMO (1986)
SRM (Snowmelt Runoff Model)	Switzerland	Martinec (1975)
HBV (Conceptual Runoff Model for Swedish Catchments)	Sweden	Bergström (1975)
SHE (Systems Hydrologique European Snow Model)	France	Morris and Godfrey (1978)
CEQUEAU	Canada	WMO (1986)
ERM (Empirical Regressive Model)	Czechoslovakia	WMO (1986)
NEDBOR-AFSSSTROMNINGSMODEL (Rainfall -Runoff Model v. II)	Denmark	WMO (1986)
TANK (Tank Model with Snow Model)	Japan	WMO (1986)
IHDM (Institute of Hydrology Distributed Model)	UK	Morris (1983)
PRMS (Precipitation-Runoff Modeling System)	USA	Leavesley et al. (1983)
YETI	Czechoslovakia	WMO (1986)
SCHNEE	GDR	WMO (1986)
WSRM (Winter Season Runoff Model)	Poland	WMO (1986)
HRO (Hydro Resources Optimization)	USA	WMO (1986)
GMTs-1 (Model of Snowmelt Formation of Lowland Rivers)	USSR	WMO (1986)
GMTs-2 (Model of Snowmelt Formation in a Mountainous Basin)	USSR	WMO (1986)
GMTs-3 (Model of Snowmelt-Rainfall Runoff Formation)	USSR	WMO (1986)

temperature index or energy budget and a snow cover depletion curve. The depletion curve is based on a theoretical relationship between a snow-covered area as a percentage of watershed area versus accumulated generated runoff as a percentage of seasonal total. The actual snow-covered area and accumulated runoff for a computation period are compared with the theoretical snowcover. This approach can treat a watershed as a single lumped unit or as a split watershed with snow-covered and snow-free areas, as in the case of mountainous watersheds where there is a snowline.

(4) The integrated-snowband provides the ability to formulate the watershed into bands of equal elevation, on which snow accumulation and ablation, as well as soil moisture, are accounted for independently. Key elements include the following:

- Snow conditioning or accounting for the snowpack heat deficit.

- A vegetation interception algorithm.

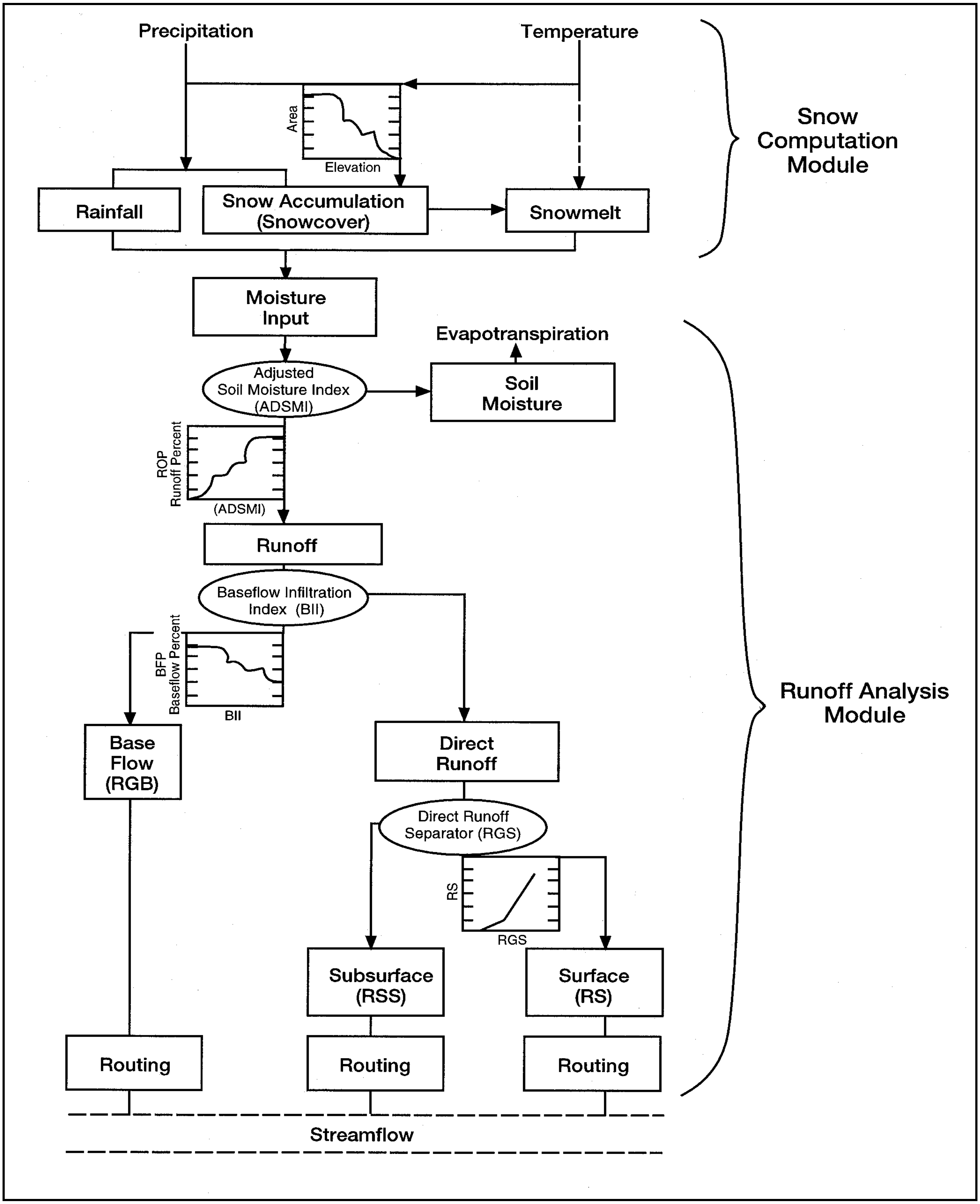

Figure F-1. Flowchart of SSARR Model

- A flexible evaporation simulation.

- Routing to simulate long-term return flow from groundwater.

Snowmelt is calculated using the temperature index method during a nonrain event and by a modified melt equation for snowmelt during a rain event in a heavily forested area. The integrated-snowband model uses Anderson's (1978) heat deficit approach for its snow-pack conditioning routine. Liquid water does not enter the soil system to be available for runoff until the "cold content" and snowpack liquid water deficiency are satisfied. Ground melt resulting from conduction of heat from the ground is assumed to be constant or a function of the month of the year. This logic is summarized in Figure F-2.

(5) The SSARR model program is written in IBM-VS FORTRAN-77. It has also been made available for the VAX-11/780 computer and IBM PC-compatible microcomputers. Data management and analysis programs to support operational day-to-day forecasting and long-term simulations are also available (USACE 1991), and interface with HECDSS is possible. Data are input in fixed-column card formats, free-form card formats, or as responses to prompting messages by an interactive driver. Output has a wide range of formats and varies from plots of key variables and statistics to "card-image" output that may be used for subsequent SSARR runs.

b. HEC-1 and HEC -1F models. The HEC-1 Flood Hydrograph Package is a flood runoff event simulation model first developed in 1967 by the Hydrologic Engineering Center of the USACE. It has been revised and updated a number of times to improve its computational methods and user interface (USACE 1990). It has also been connected to the HEC Data Storage System (DSS) for storage and retrieval of data and improved graphical and tabular output capabilities. HEC-1 is a generalized program that simulates the runoff from snowmelt or rainfall, or both, for virtually any type of watershed or river basin. There is no limit to the size or number of subbasins and routing reaches needed to describe a basin. The HEC-1F program is a special version of HEC-1 for use in real-time forecasting. It includes real-time optimization and blending routines. Some HEC-1 options are not available in HEC-1F, however.

(1) HEC-1 is basically a general calling program that can access any one of a number of options within six subroutines. These subroutines are as follows:

- Optimal determination of unit hydrographs.

- Streamflow routing.

- Snowmelt computations.

- Unit hydrograph computations.

- Hydrograph routing and combining computations.

- Hydrograph balancing computations.

In addition to the basic hydrological simulation, HEC-1 has several capabilities to assist in hydrological investigations. These capabilities include the following:

- Automated parameter estimation for Infiltration Rates, Unit Hydrographs and Streamflow Routing.

- Snowmelt parameter estimation.

- Dam breach simulation.

- Automatic precipitation depth area adjustments.

- Multiple basin developments and storm size simulation.

- Streamflow diversions and pumping plants.

- Flood damage compilation.

- Flood frequency curve modification.

- Annual flood damage expectation.

- Flood control projects size optimization.

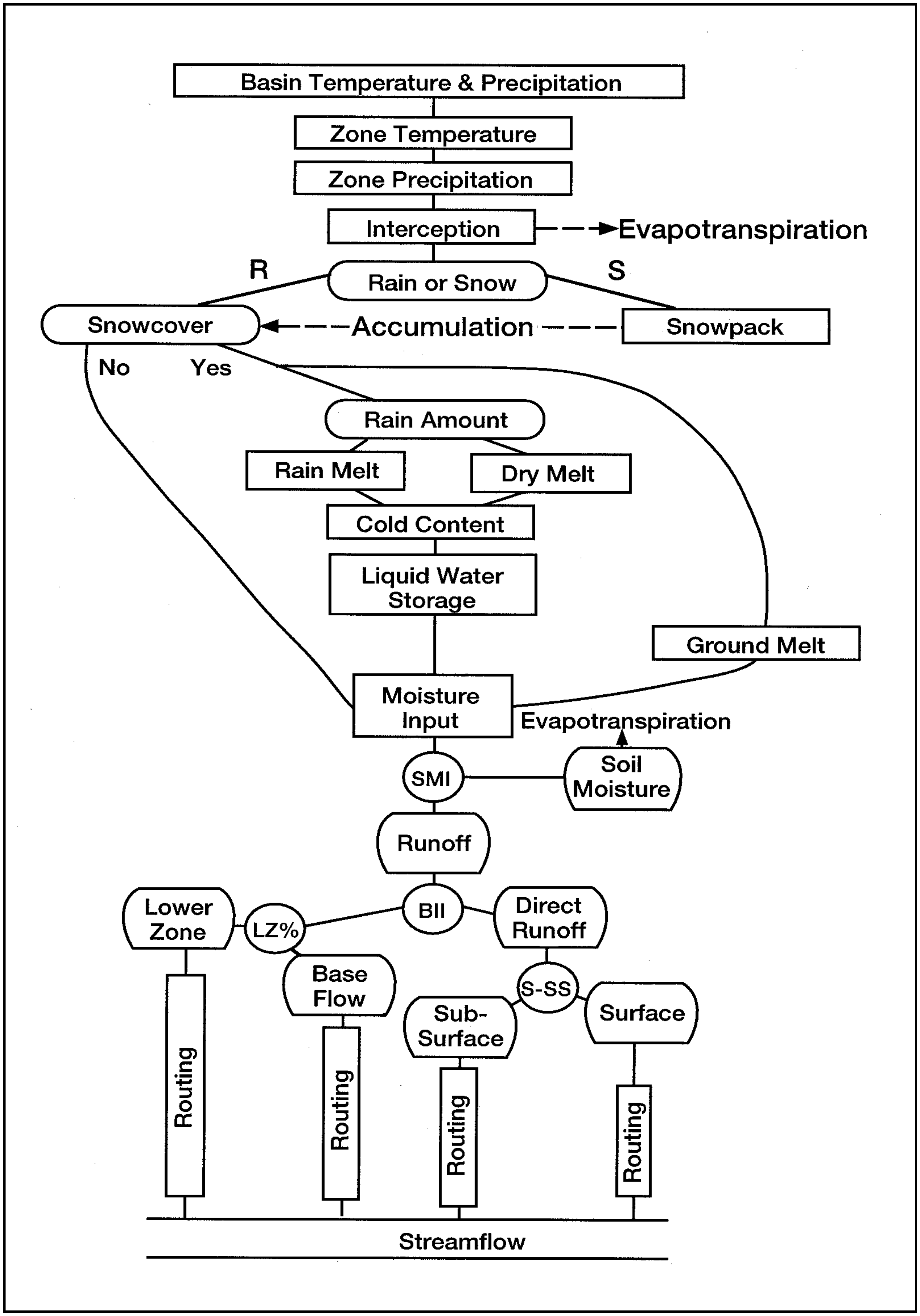

Figure F-2. SSARR Integrated Snowband Model

(2) HEC-1 is an event-type model, applicable for modeling flood runoff only. Runoff is simulated by applying rainfall and snowmelt to a unit hydrograph, then computing the total hydrograph by adding base flow. Several loss-rate functions are available. There is no representation of the effects of frozen ground. There is no direct accounting for water properties that change with temperature.

(3) Snowmelt is calculated using either the degree-day (temperature index) or energy budget methods as described in *Snow Hydrology* (USACE 1956). The energy budget approach is used for rain-on-snow events. There is a provision to account for up to 10 elevation zones within a subbasin, with the temperature being lapsed in degrees per increment of elevation in each zone. Snow accumulation is accounted for and precipitation may fall as rain or snow, depending on zone temperature. Heat deficit or the "ripeness" of the pack are not considered.

(4) HEC-1, including the DSS interface, is written in ANSI standard FORTRAN 77 as is available on the IBM PC, mainframe, and UNIX-based workstation computers (USACE 1990), and on the Macintosh computing platform. Since DSS offers a wide range of input and output options, as well as access to many databases that are necessary for modeling large-scale river systems, the DSS interface with HEC-1 is an important feature for the operational use of this model.

c. NWSRFS model. The National Weather Service River Forecast System (NWSRFS) model is a further development of the Standard Watershed Model (Crawford and Linsley 1966). It was developed in 1972 by the Hydrologic Research Laboratory (HRL) of the NWS, Office of Hydrology. The Snow Accumulation and Ablation Model within the NWSRFS model is described in HYDRO-17 (Anderson 1973).

(1) The NWSRFS model uses the Sacramento soil-moisture accounting model (Burnash, Ferrall, and Richard 1973), which divides soil moisture among five reservoirs, using both “free” water and “tension” soil-moisture levels. Available runoff is computed also using the Sacramento soil-moisture accounting model and is translated to runoff using a unit hydrograph approach. An index approach for dealing with frozen ground has been implemented (Anderson and Neuman 1984). No temperature effect on water-holding capacities or rounding constants are accounted for.

(2) The snow accumulation and ablation model described in HYDRO-17 is one of the most successful operational applications of air temperature-index methods. As is stated in HYDRO-17, “The basic philosophy of the model is that each significant physical component be represented separately, rather than to use a single index to explain several processes ....” This is accomplished in NWSRFS with only air temperature and precipitation as the necessary meteorological input parameters. A flowchart showing the basis for the snow accumulation and ablation model in NWSRFS is given in Figure F-3.

(3) The snow accumulation and ablation model in NWSRFS includes consideration of the important components of the energy budget of the snowpack, including snowpack accumulation, heat exchange at the air/snow interface, areal extent of snowcover, heat storage within the snowpack, liquid-water retention and transmission, and heat exchange at the ground/snow interface. Snowmelt is calculated differently for rain and no-rain periods. Melt during nonrain periods is calculated using a degree-day approach, employing a seasonally varying melt-factor. Melt during rain is computed from an energy balance equation that calculates the net radiative, latent, sensible, and rainwater heat transfer to calculate the amount of melt. A key feature of NWSRFS is its snow-conditioning accounting that simulates the cold content and liquid water available in the pack and thereby characterizes the “ripeness” of the snowpack. Areal distribution of the snowpack is dealt with using an areal depletion curve that relates extent of the snow cover to the ratio of mean areal snow water equivalent. This areal depletion curve is considered to be constant from year to year for a particular modeled area. In either rain or nonrain cases, once the heat deficit of the snowpack has been satisfied, the available melt water is lagged and attenuated to simulate the transmission of water through snow. The final excess liquid water is then made available to the runoff portion of NWSRFS.

(4) The snow accumulation and ablation model in NWSRFS is written in FORTRAN IV, has typically been run on IBM mainframe computers (IBM 360/195 at NWS River Forecast Centers), and has been widely

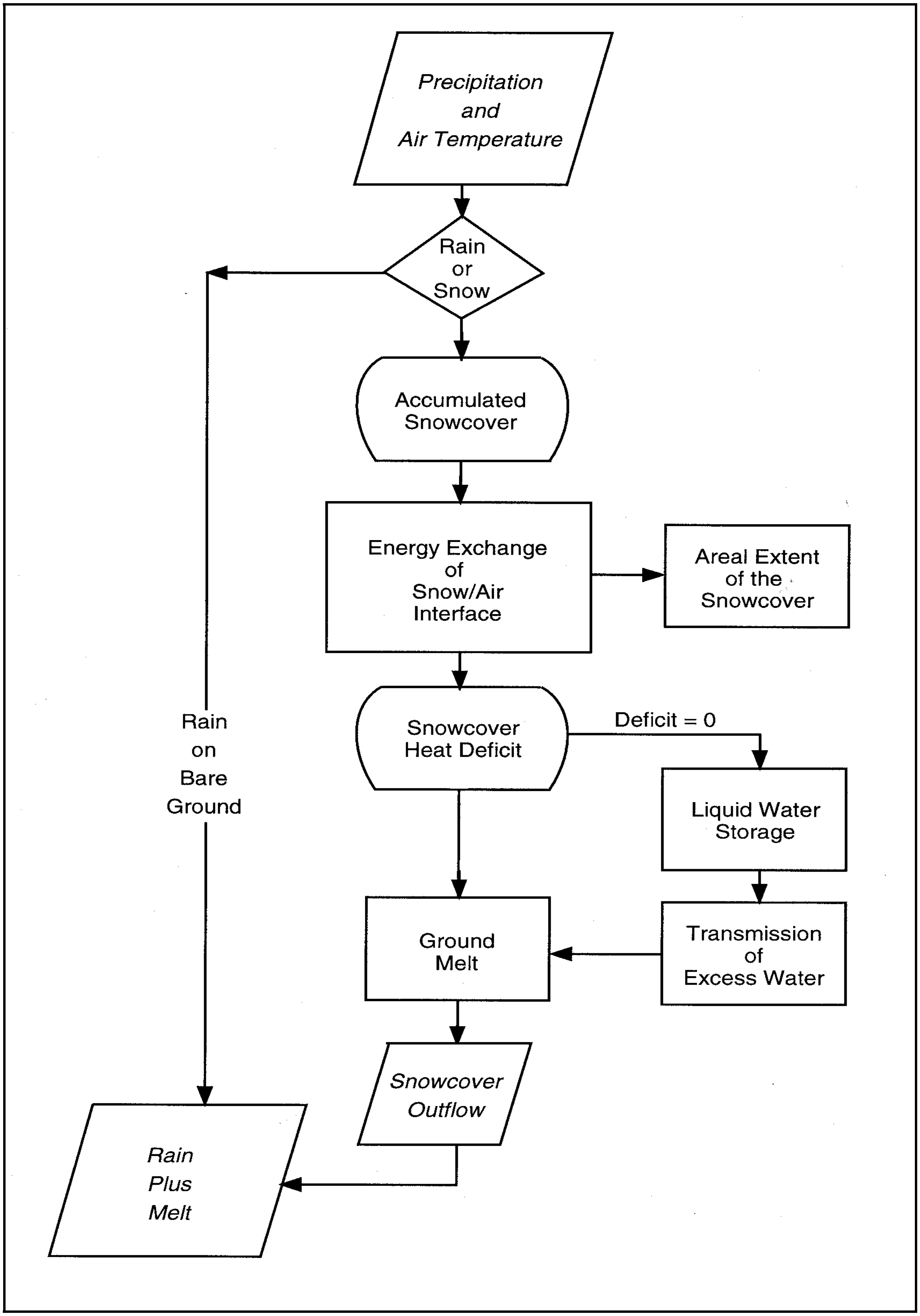

Figure F-3. Flowchart of NWSRFS Snow Accumulation and Ablation Model (after Anderson 1978)

used in research studies. It is fully supported by the Hydrologic Research Laboratory, Office of Hydrology, NWS, and has been used in joint USACE/NWS operational modeling activities (Burnash, Ferrall, and Richard 1973).

d. The PRMS model. The Precipitation-Runoff Modeling System (PRMS) was developed by the U.S. Geological Survey, Water Resources Division, in 1973 (Leavesley 1973). According to Leavesley et al. (1983), PRMS was developed to "evaluate impacts of various combinations of precipitation, climate and land use on surface water runoff...." It is a multipurpose model for stormflow hydrographs and long-term simulations of mean daily runoff from snowmelt. The relationships between available runoff and streamflow are based on a deterministic physical-process model. PRMS is a modular-design modeling system to provide a flexible modeling capability. The PRMS is structured into three major components: the data management component, the PRMS library component, and the output component. These three components are shown schematically in Figure F-4. The model is discussed in detail in Leavesley et al. (1983).

(1) A key feature of PRMS allows it to function as a lumped or distributed parameter type model. PRMS allows the watershed to be disaggregated into subareas called Hydrologic Response Units (HRUs) on the basis of soils, vegetation, and climatic and physiographic characteristics. Each HRU is then modeled with the parameters being lumped within the HRU. With the increased availability of Geographic Information Systems (GIS) to USACE field-operating agencies, the disaggregation of basins into HRUs is becoming more practical.

(2) PRMS must receive input variables that describe the physiography, vegetation, soils, climate, and hydrological characteristics of each HRU. The minimum input parameters for driving this model are daily maximum and minimum temperatures, precipitation, and solar radiation.

(3) Snowmelt is modeled using an energy budget approach, as presented by Obled and Rosse (1977). The snowpack routines account for initiation, accumulation, and depletion of the snowpack for each HRU. The energy budget considers net shortwave and long-wave radiation, as well as the heat content of precipitation. The snowpack routine accounts for water equivalent and heat deficit and thereby considers the ripeness of the snowpack. Condensation, advection, and ground conduction are not accounted for in the energy budget terms. Frozen ground or the temperature dependence of important water properties are also not included.

(4) The runoff is computed from each HRU using a series of linear and nonlinear reservoirs whose output sums to stream outflow. These reservoirs depict surface flow, subsurface flow, and base flow. In practice, each HRU has its own surface flow reservoir; however, there is typically only one subsurface and one base-flow reservoir for an entire basin. More individual subsurface reservoirs are used for each HRU, depending on the variability of soil characteristics in the basin. The hydrological responses of the individual HRUs are summed to compute the total watershed runoff. A schematic diagram of the concepts that underlie PRMS is presented in Figure F-5.

(5) PRMS is written in FORTRAN 77 and can be run on any machine with this compiler. The model is fully supported by the USGS, Water Resources Division, Denver, CO, and is documented in Leavesly et al. (1983).

e. SRM model. The Snowmelt Runoff Model (SRM) was originally developed in 1973 at the Federal Institute for Snow and Avalanche Research in Davos, Switzerland (Martinec 1975). The SRM simulates or forecasts daily average streamflow in mountainous basins where snowmelt is a major contributor to runoff (Martinec, Rango, and Major 1983). The model has been applied to watersheds ranging from 2.65 km^2 (1.66 square miles) to 4,000 km^2 (2,500 square miles) in both humid and semiarid climates with no serious limitations (Martinec, Rango, and Major 1983; Rango 1989). It is necessary, however, to carefully define the model parameters and variables if accurate results are to be obtained.

(1) SRM uses percentage areal snowcover, air temperature, and precipitation as critical input variables. SRM divides the watershed into elevation zones and accounts for degree-days in each elevation zone to drive the amount of snowmelt. Specific basin

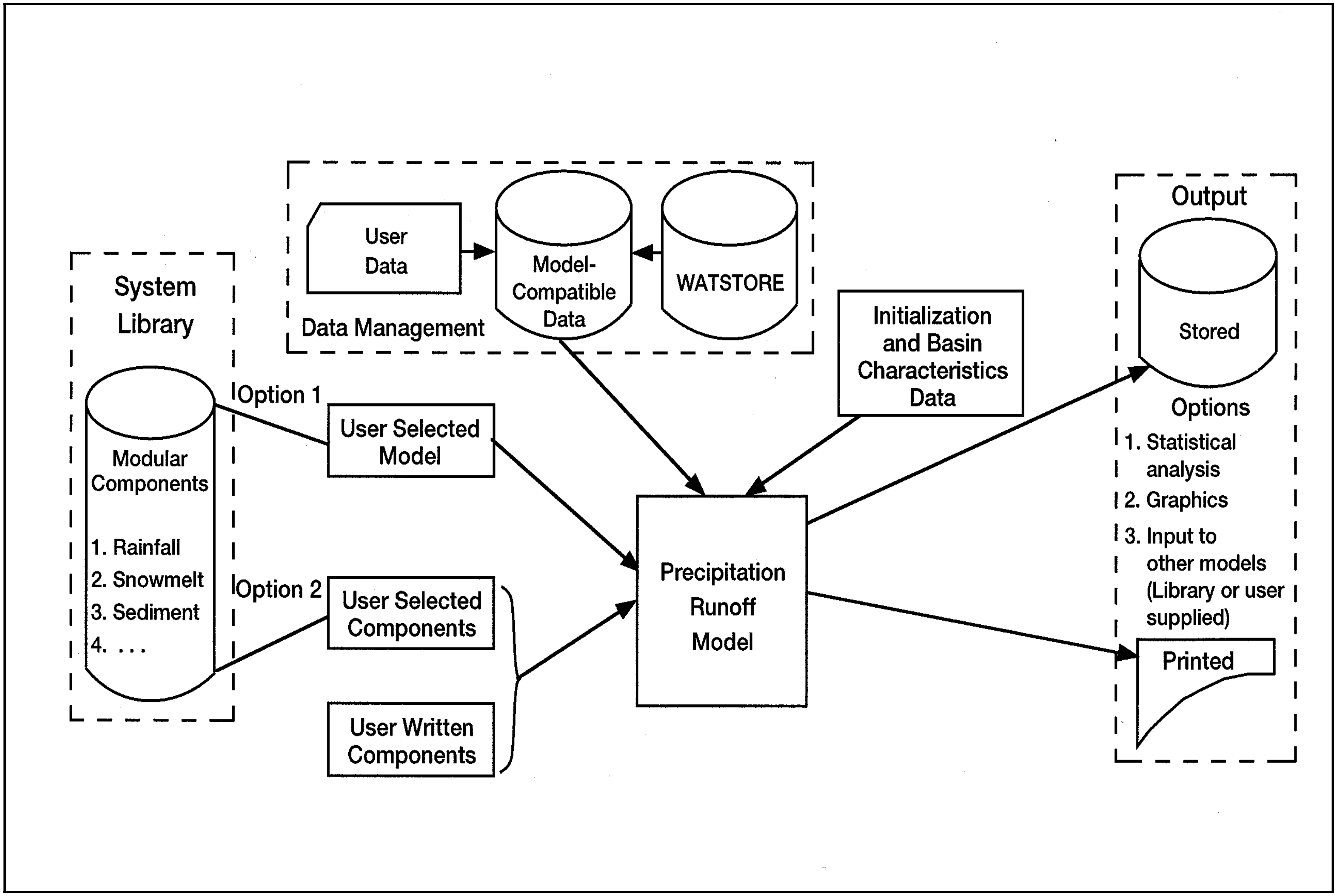

Figure F-4. Flowchart of PRMS (after Leavesley et al. 1983)

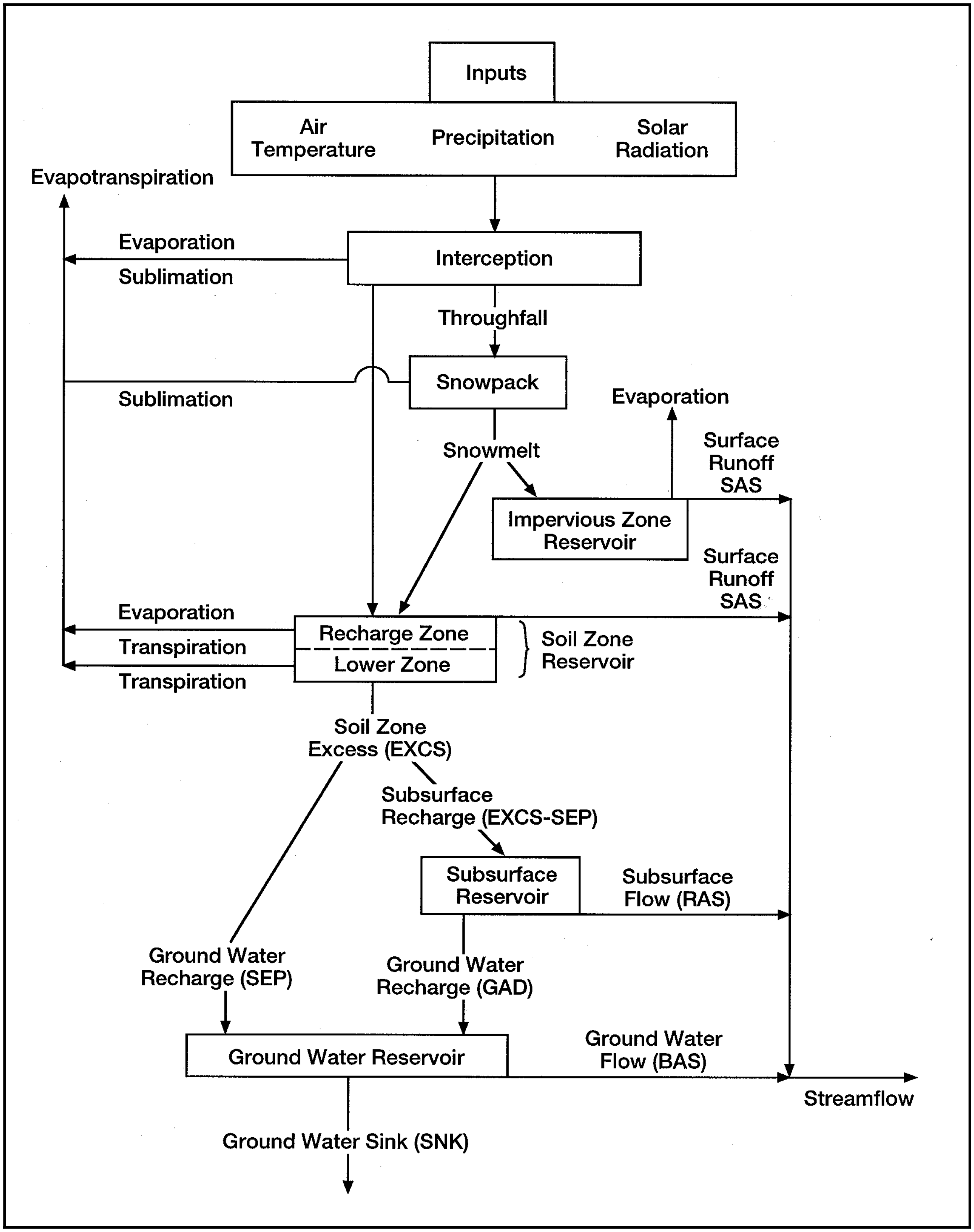

Figure F-5. Schematic of PRMS concepts (after Leavesley et al. 1983)

characteristics include runoff coefficients, degree-day factors, and historical recession coefficients (Shafer, Jones, and Frick 1982). Definition of the basin includes careful determination of basin areas and, once the elevation zones are established, finding the area of each zone. The zonal mean hyposometric elevation is determined for each zone from an area-elevation curve. It is also necessary to know the temperature lapse rate for the basin.

(2) In SRM, "Each day during the snow melt season, the water produced from snow melt and from rainfall is computed, superimposed on the calculated recession flow and transformed into daily discharge from the basin" (Martinec, Rango, and Major 1983). A simple transformation model computes runoff using empirical constants and coefficients for runoff, snowmelt-degree-days, and flow recession. The snowmelt water and precipitation are calculated and superimposed on a calculated recession flow to obtain daily discharge. The strength of SRM is its primary reliance on snow cover areal extent. This allows for limited data input needs, and the snow-covered-area data can be derived from satellite, aircraft, or ground measurements.

(3) Through the use of the zonal mean hyposometric elevations, the actual elevation of the temperature measurement station and the temperature lapse rate, the melting degree-days for each elevation zone are calculated. The precipitation for each zone is determined to be either rain or snow, depending on the average zonal temperature and a critical temperature selected to be slightly above freezing. The snow coverage for each zone is determined by ground observation, aircraft photography, or by satellite and is arrayed as a depletion curve over the snowmelt period.

(4) Runoff coefficient estimation requires knowledge of the basin and its hydrology, and it varies over the year (Martinec, Rango, and Major 1983). The snowmelt-degree-day factor can be varied throughout the snowmelt period to account for the changing density and albedo of the snowpack. The recession coefficient is estimated from historical records of the actual daily average flows.

(5) SRM accumulates the number of degree-days in each elevation zone over the snowmelt period and discriminates the input precipitation into snow or rain by comparing the assigned critical temperature to the average daily temperature. Snowmelt is calculated using a degree-day factor that is applied to the portion of the elevation zone that is snow covered. Within each elevation zone, an average snow cover depletion curve is used to estimate the temporal change in the snow-covered area. The snowmelt is distributed according to the chosen elevation zones and summed to give total average daily runoff from the entire watershed.

(6) SRM is written in FORTRAN and has been documented in Martinec, Rango, and Major (1983). Although originally run on mainframes, the SRM has been modified to a microcomputer version (Rango and Roberts 1987) by the Agricultural Research Service, Beltsville, MD.

f. GAWSER model. The Guelph All-Weather Storm-Event Runoff (GAWSER) model was originally created at the School of Engineering, University of Guelph, in 1977 (Ghate and Whiteley 1977). It is a modification of the HYMO program developed by the U.S. Department of Agriculture in 1972 (Williams and Hahn 1972). Since 1977 it has evolved from a research tool to a fully operated package for synthesis of storm-event hydrographs and large basin reservoir regulation (Grand River Conservation Authority 1989). GAWSER version 5.4 is documented in the GAWSER Training Guide and Reference Manual (GRCA 1989).

(1) GAWSER separates each subwatershed in a basin system into impervious and pervious zones (see Figure F-6). All rainfall and snowmelt incident on impervious zones are routed to overland flow. The pervious areas are desegregated into four soil types (or fewer), with each type being modeled as a two-layered system. Available rain and snowmelt water are routed between overland flow and infiltrated on the basis of the component's characteristics of the soil type for the pervious zones. GAWSER employs two methods for routing the combined overland flow from impervious and pervious areas. They are an area/time versus time method (Viessman et al. 1977) or a single linear reservoir plus lag and route channel routing. GAWSER uses a linear reservoir approach to compute the outflow from subsurface and groundwater storage that the infiltrated water on impervious zones produces. The routed

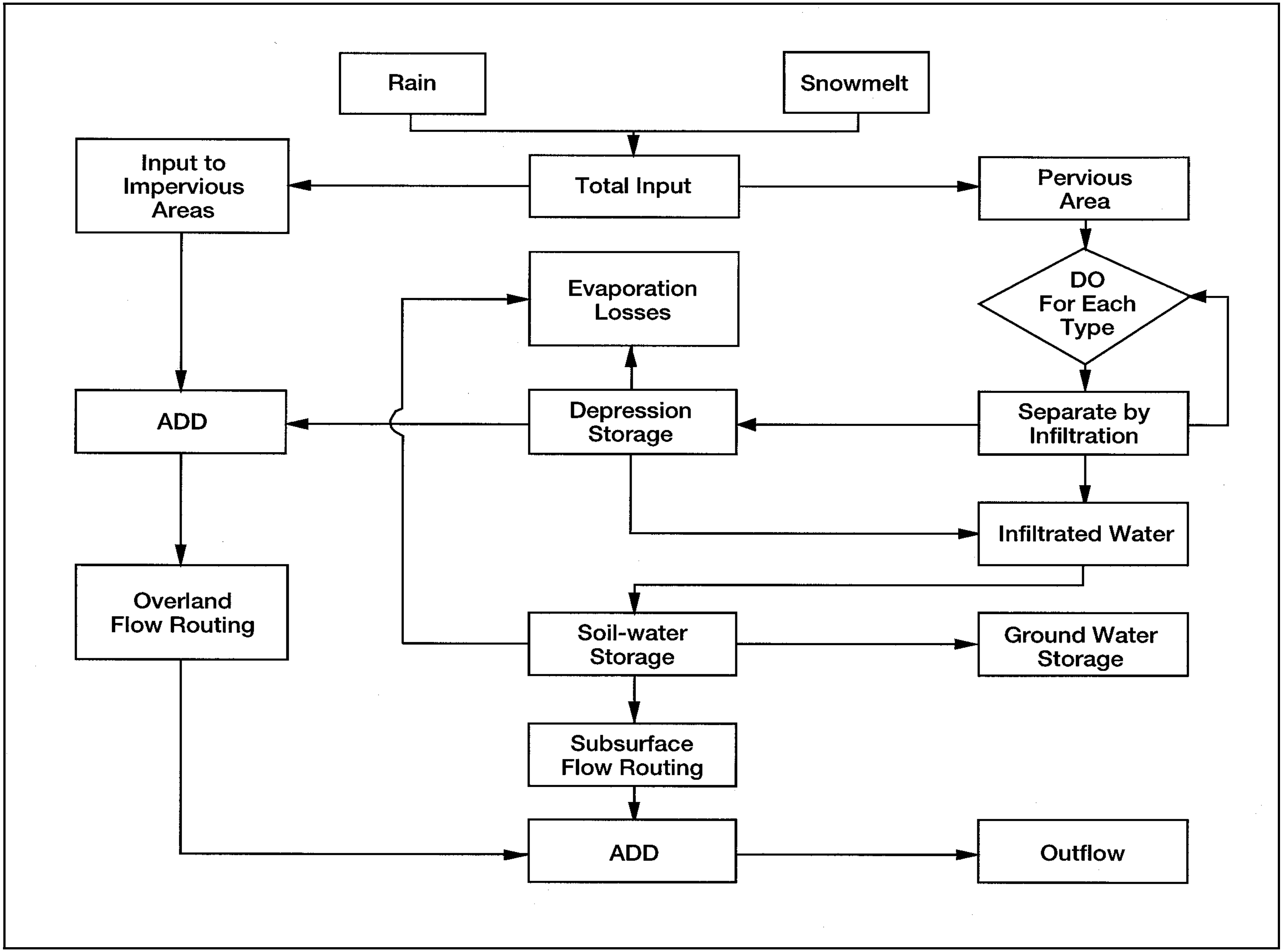

Figure F-6. Flowchart of GAWSER Subwatershed Model (after Schroeter and Whiteley 1987a,b) overland flow, subsurface flow, and groundwater outflow are summed to produce basin discharge.

(2) The snowmelt submodel of GAWSER (see Figure F-7) is based on a simple temperature index model developed by Schroeter and Whiteley (1987a,b) and Schroeter (1988). This submodel, called the Areal Snow Accumulation-Ablation Model (ASAAM), accounts for the processes of refreeze, compaction, new snow deposition, rain deposition, snowmelt, and release of liquid water. ASAAM has also been used to simulate erosion and redistribution of shallow ephemeral snowpacks (Schroeter 1988), which has applicability in midwestern United States winter environments. Refreeze and snowmelt are calculated using a temperature index approach that employs a seasonally variable melt factor. The snowpack water content is accounted for, and all liquid water in excess of the capillary holding capacity is made available for runoff. New snow deposition and snowpack compaction are modeled by accounting for the density of new-fallen snow and the compaction effect of a settling snowpack.

(3) The snow accumulation and melt are distributed by desegregating the watershed into subwatersheds, as described previously, as well as further subdivision by Zones of Uniform Meteorology (ZUM). Therefore, each subwatershed is analyzed, and discharge is computed for each ZUM before summing to the subwatershed scale. In the case of analysis of snowmelt runoff in shallow ephemeral snowpacks, the ZUMs are further separated into blocks or elements of characteristic physical parameter types that control snowpack distribution. Examples of these block types are plowed fields, road ditches, and coniferous forests.

(4) The GAWSER program is written in FORTRAN and can be run on an IBM PC or equivalent running under MS DOS. GAWSER has been recently integrated into a system for real-time reservoir control referred to as GRIFFS (GRCA 1989).

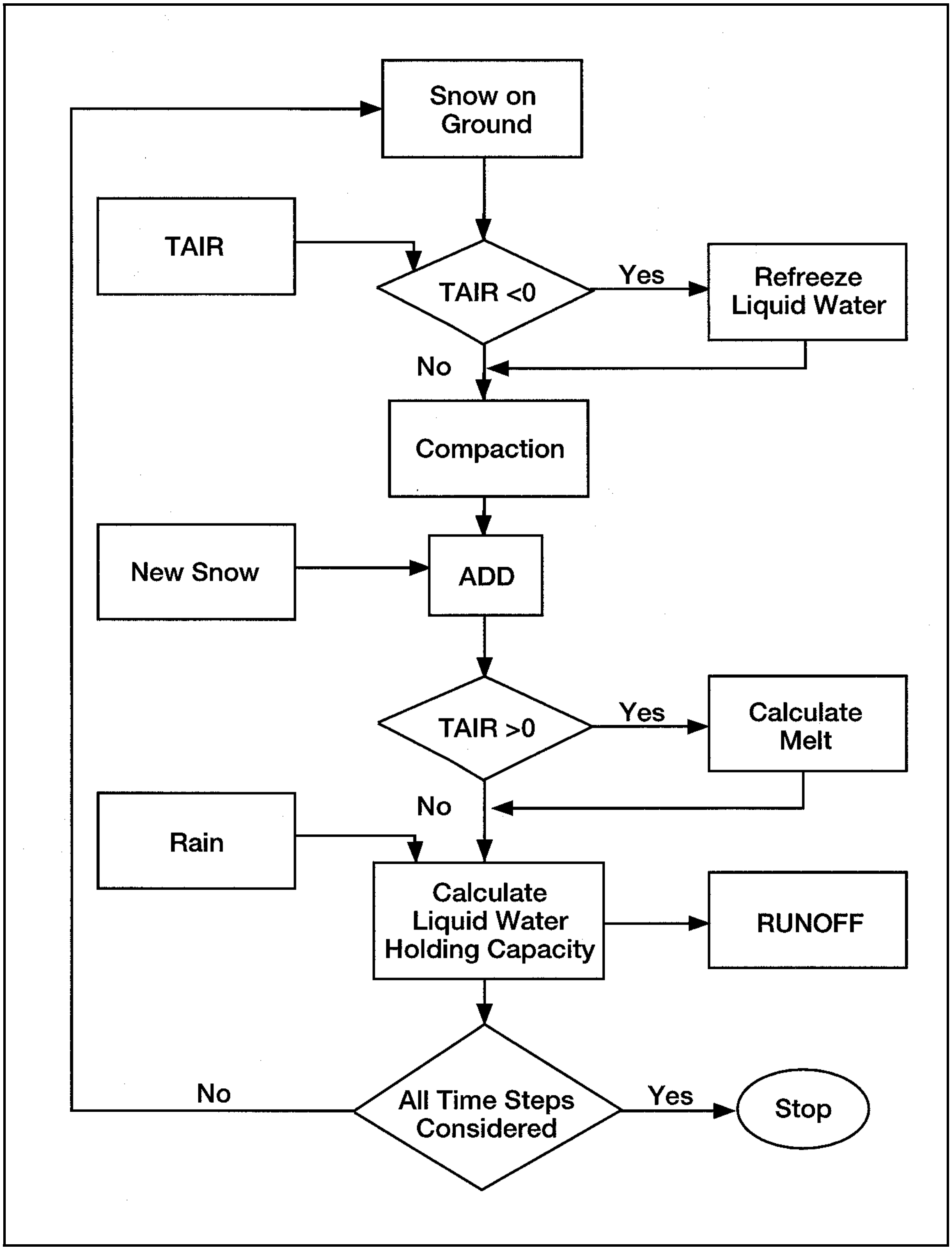

Figure F-7. Flowchart of GAWSER Snowmelt Model (after Schroeter and Whiteley 1987a,b)