THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM--UPDATE 1976

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ABSTRACT

The National Weather Service River Forecast System (NWSRFS) is described. Functions of the basic conceptual elements comprising the NWSRFS are listed, and an overview of techniques used in each element is presented. Both manual and automatic calibration techniques for hydrologic and dynamic wave components of the NWSRFS are briefly described.

The nature of conceptual modules in the NWSRFS allow improvements to be incorporated by updating only a single basic element. Additional aspects of river system simulation (i.e., temperature, water quality, channel bed form changes) can be included by inserting new components into the NWSRFS.

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INTRODUCTION

The primary purpose of the United States National Weather Service (NWS) hydrology program is to provide accurate and timely hydrologic information to the general public. While flood forecasts and warnings are the most widely known hydrology products, NWS river forecasts are also used for water supply, navigation, irrigation, power, reservoir operation, recreation, and water quality interests. These forecasts are an effective tool in the development and management of total water resources.

The River Forecast Center (RFC) is the focal point of the river forecast network (fig. 1). Staffed by professional hydrologists, the RFC receives hydrometeorologic data, prepares forecasts, and transmits forecasts to other Weather Service Forecast Offices (WSFO's) for dissemination. Reception of accurate and timely forecasts by riverside interests enables decision-making that can minimize loss of life and property due to extreme riverine events.

Twelve RFC's prepare river forecasts and warnings for approximately 2,500 communities. Approximately 97 percent of the United States (including Alaska) is covered by this service. The area of responsibility of each RFC includes one or more major river systems (fig. 2).

Forecasts of seasonal snowmelt or water-year runoff are prepared by five RFC's in Western United States. Two additional RFC's in the Northeast prepare seasonal snowmelt and monthly runoff forecasts. These water supply forecasts for 600 points where snow is the principal source of streamflow are distributed to water users monthly by local WSFO's.

RIVER FORECASTING TECHNIQUES

In the late 1960's a commitment was made by the NWS to move from an index type catchment response function to continuous conceptual hydrologic models for use in river forecasting /1,2/. Conceptual models with a strong physical basis have several distinct advantages over index type relationships, as follows.

1. Accurate mathematical representation of a catchment enhances the probability of adequately predicting future events, especially events of a magnitude unexperienced in the past.

2. Parameters based on conceptual considerations can sometimes be subjectively altered to reflect changes made or to be made to the physical characteristics of the catchment.

3. A conceptual model can be extended to problems other than simulating catchment streamflows. For example, algorithms could be added to simulate the movement of pollutants through the soil matrix.

4. A model that is physically based is an effective tool for future research and modification.

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Studies were undertaken by the NWS Hydrologic Research Laboratory (HRL) to determine which of the hydrologic models available at the time were best suited for river forecasting purposes. Based on these studies, a modified version of the Stanford watershed model /3/ was included in the initial version of the National Weather Service River Forecast System (NWSRFS) /4/. Since 1971, several important modifications to NWSRFS have been made:

1. The Stanford soil moisture accounting routine has been replaced by a model developed by the NWS RFC at Sacramento, California /5/.

2. A snow accumulation and ablation model has been added /6/.

3. A dynamic river routing model has been added /7/.

4. The data management capabilities have been greatly expanded and changed from a magnetic tape oriented data storage system to a direct access disk storage system.

This report summarizes the various elements and experiences of NWSRFS to date.

NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

The NWSRFS is the set of techniques and computer programs used to produce river forecasts. Included are programs to manage the large volumes of data associated with a national forecasting system and programs to perform the hydrologic and hydraulic computations necessary to forecast river system response.

The basic elements of NWSRFS are:

1. Data management.--Routines that store, retrieve, and manipulate data from the appropriate direct access disk files.

2. Soil moisture accounting.--Routines that simulate the movement of water through the soil profile.

3. Snow accumulation and ablation.--Routines describing the buildup and subsequent melt of a snow cover.

4. Channel routing.--Hydrologic and hydraulic techniques to route flows through natural channels.

5. Mean areal precipitation.--Routines converting point precipitation values to areal means.

6. Mean areal evapotranspiration.--Routines to compute mean areal evapotranspiration.

7. Mean areal temperature.--Routines to convert point temperature values to areal means.

NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM BASIC ELEMENTS

Calibration Data Management

Vast amounts of data are required to implement the NWSRFS throughout the United States. One component of the NWSRFS is designed to manage and prepare data for use in hydrologic calibration models. Except for units conversion, the data management portion of the NWSRFS does not transform the data. It is a system which selects appropriate time series from a magnetic tape or card source and transcribes them into a format more efficiently managed and used by the hydrologist.

The data management system consists of three parts (fig. 3). Each of these parts performs a function necessary in reducing the available data into an efficient format for use by the hydrologic programs. The three parts are:

1. inventory of data on National Climatic Center (NCC) or U.S. Geological Survey (USGS) magnetic tapes,

2. copying of selected data from the tape to direct access data files, and

3. management of data in data files.

The four types of data presently stored on magnetic tape are: (1) hourly precipitation, (2) daily climatological observations, (3) synoptic meteorological observations, and (4) daily streamflow data. For each data type programs are available to inventory a tape, extract and label selected data (time series), and place them into data files on a direct access disk. Once the various data are in data files, a package of subroutines can be used to manage and analyze these data. This package of subroutines is called the data file utility system and can perform such tasks as listing which files are available for data storage or the contents of a particular file, copying all or part of a file from one location to another, editing data within a file, removing unwanted data from a file, and plotting one or more time series as a function of either time or another time series.

A key component of the file utility system is the labeling of each time series to allow rapid data access and retrieval. This label, or time series header, contains unique identifiers, as well as information about the location, length, and type of data in the time series. Identifiers contained in the time series header enable the direct access device to move to the exact location of the requested data residing in a disk file. This shortens computer access time by eliminating sequential searches of entire data files to find the desired time series.

The NWSRFS data management component reduces vast amounts of data stored on magnetic tapes or punched cards to an easily accessible form in data files on direct access disks, which are accessed by hydrologic programs in catchment calibration.

Soil Moisture Accounting

Classification

The version of the Sacramento soil moisture accounting model (fig. 4) included in NWSRFS is a deterministic model with a limited distributed input and distributed parameter capability. Soil moisture accounting is accomplished for a particular soil moisture accounting area. Within a soil moisture accounting area, precipitation inputs are evenly distributed and soil conditions are assumed uniform. Thus, with respect to a soil moisture accounting area, the model is a lumped input and lumped parameter type. However, it is not necessary for the boundaries of a soil moisture accounting area and the natural catchment to coincide. This feature allows the catchment to be described by more than one soil moisture accounting area. If the inputs and parameters differ between soil moisture accounting areas, the model is "distributed" with respect to the inputs and parameters for the catchment.

Structure

On a vertical plane, the model defines two soil moisture accounting zones. An upper zone represents the upper soil layer and interception storage, while a lower zone generally accounts for most of the soil moisture and the groundwater storage.

Moisture storage. Both the upper and lower zones are conceptualized as storing "tension" and "free" water. Tension water storage represents water closely held by soil particles. Free water storage represents water that is available for drainage, either horizontally or vertically. In the upper zone, tension water requirements must be met before water is transferred to upper zone free water storage. The stipulation that tension water requirements be met before substantial drainage begins represents the movement of a wetting front through the soil mantle. In the lower zone a fraction of the incoming water can be directly transmitted to free water storage even if the lower zone tension storage is not full. The capacity to "short circuit" tension water requirements in the lower zone aids the simulation of catchments where significant lower zone drainage is evident, even though area-wide lower zone tension water requirements have not been fulfilled.

Free water can move vertically through percolation, horizontally as interflow, be depleted by evapotranspiration, or replenish tension water requirements. Tension water storages can only be depleted by the evapotranspiration process.

Percolation. Movement of water from the upper zone to the lower zone is controlled by a percolation algorithm which relates the contents and capacities of upper and lower zone storages as well as drainage parameters for the respective free water storages. The formula controls the movement of water in all portions of the soil profile, both above and below the percolation interface, and is itself controlled by the current state of the soil moisture storage system.

Evapotranspiration. In most rural catchments, evapotranspiration is a dominant hydrologic process; thus, accurate continuous hydrograph simulation is heavily dependent upon successful description of evapotranspiration. Two types of evapotranspiration information can be input to the Sacramento soil moisture accounting model: (1) a seasonal evapotranspiration demand curve or (2) potential evaporation data with an adjustment curve to account for the effect of the current state of the vegetation cover on the actual evapotranspiration.

Variable impervious area. A fraction of the precipitation falling on a particular catchment is assumed to be deposited on impervious area directly connected to or adjacent to the channel system. This fraction contributes directly to channel flow and does not enter the soil matrix. In the Sacramento soil moisture accounting model a minimum and maximum percentage impervious area is specified on the theory that as respective soil moisture storages become satisfied an increasing amount of pervious area begins to behave as impervious area. An algorithm evaluates the current state of the soil moisture storage system and adjusts the total percentage of impervious area accordingly.

Flow components. The model recognizes and generates five components of channel flow:

1. direct runoff, resulting from moisture input applied to the variable impervious area;

2. surface runoff, resulting from moisture input applied at a rate faster than upper zone intake;

3. interflow, lateral drainage from upper zone free water storage;

4. supplementary base flow, drainage from lower zone supplementary storage; and

5. primary base flow, drainage from lower zone primary storage.

Computational technique. Movement of water through a soil matrix is a continuous process. The rate of movement at a particular point is a function of the current state of the moisture supply and soil moisture storage system. A quasi-linear, open form computation is used to model soil moisture movement. Use of this technique assumes that movement of soil moisture during a time step is defined by conditions existing at the beginning of each time step. To utilize this assumption effectively, a short time step must be selected. The basic computational interval of NWSRFS is 6 hours. However, in the soil moisture accounting model, time steps are set such that no more than 5 mm of water is involved in a single execution of the computational loop. This rather arbitrary limit has been set small enough to logically fulfill its function but not so small as to cause unwarranted execution times. The state of the soil moisture storage system can be output at the end of each 6-hour period.

Snow Accumulation and Ablation Model

The snow accumulation and ablation model is a conceptual model that describes the important physical processes taking place during the accumulation and ablation of a snow cover (fig. 5). Although written for NWSRFS, the model can be used in conjunction with almost any soil moisture accounting and channel routing routine. Output from the snow model serves as input to the soil moisture accounting procedure. The output from the snow model is snow cover outflow (snowmelt water and rain water leaving the snow cover) plus rain that fell on bare ground.

The snow model uses air temperature as the only index to energy exchange across the snow-air interface. Two basic reasons exist for using air temperature as the sole index to energy exchange.

1. Air temperature data are readily available throughout the United States on a real-time operational basis.

2. Comparison tests conducted by the NWS HRL, though limited to two experimental watersheds, have indicated that at least in these two cases the hydrograph simulations produced by using air temperature as the sole index to snow cover energy exchange are comparable to those produced using an energy balance snow cover model.

Obviously, under certain meteorological and physiographic conditions, an energy balance model will provide more accurate estimates of snow cover energy exchange if the necessary data are available. Extensive research on snow cover energy exchange is being conducted by the HRL /8,9/. It is planned to include an areal energy balance snow cover model in the NWSRFS within the next few years for use in areas where the necessary data are available and a meaningful increase in accuracy can be attained.

Model Components

Accumulation of the snow cover (fig. 5). The model first determines the form of precipitation input by using a reference air temperature. Precipitation falling when air temperature is greater than the reference value is assumed to be rain, while snowfall is assumed when air temperature is below the reference value. Generally, the reference temperature is set to about 1°C.

Accurate precipitation data are important if snow cover accumulation is to be simulated satisfactorily. Considerable variation can exist between actual and measured snowfall during a particular event resulting from inaccurate catch caused by the aerodynamic inadequacies of the precipitation gage /10/. Therefore, a constant multiplier, called the snow correction factor, can be used to adjust recorded precipitation amounts to more adequately describe the actual snowfall.

Heat exchange at the snow-air interface. Heat exchange at the snow-air interface is the most critical factor in controlling the ablation of the snow cover. When air temperature is used as the only index to heat exchange, two basic situations arise for which heat exchange must be estimated: (1) when the ambient air is warm enough to cause melting at the snow surface and (2) when the ambient air is too cold for melt to occur.

The model assumes that melt can occur at the snow surface when air temperature is above a base temperature (usually 0°C). To calculate the melting rate, the model distinguishes between rain and non-rain periods.

Development of the energy balance equation to compute the snowmelt rate during rain is based on several assumptions: (1) solar radiation is zero, (2) incoming long-wave radiation equals the blackbody radiation at the ambient air temperature, (3) snow surface temperature is 0°C, (4) the relative humidity is 90 percent, and (5) temperature of the rainwater is equal to the ambient air temperature. The energy balance of a melting snow cover is then expressed as the sum of the net radiative heat transfer, latent heat transfer, sensible heat transfer, and the heat transfer by rainwater.

During non-rain periods, melt at the snow surface is assumed to be proportional to the difference between air temperature and the base temperature. A constant of proportionality referred to as the melt factor is used to linearly relate the temperature difference with snowmelt. To account for seasonal variation in various meteorological factors that affect melt, the melt factor is allowed to vary from a minimum on December 21 and a maximum on June 21. A sine curve is used to interpolate melt factors for other dates. The use of a sine curve to describe the seasonal variation in the melt factor has proved to be adequate throughout the conterminous United States. However, a different curve, which produces a more delayed increase in the melt factor, is provided for use in Alaska.

If the ambient air temperature is below 0°C, the model assumes that snowmelt does not occur. In this situation, the snow cover is either gaining or losing heat. The direction of heat flow is dependent upon the relative temperatures of the snow surface (assumed equal to air temperature) and the temperature at some depth below the snow surface. Heat conduction to or from a snow cover is not only a function of the temperature gradient but also of the snow density. The model indirectly accounts for the effect of snow density on the rate of melt by seasonally varying the potential rate of heat transfer into or out of the snow cover.

Areal extent of snow cover. To estimate the total amount of melt generated over a given area, the portion of the total area covered by snow must be known. If rain is falling, the areal extent of snow cover must also be known to determine how much rain is falling on bare ground and how much rain is falling on the snow.

Since the snow accumulation pattern for a given area is reasonably similar from year to year, a fairly unique curve can be defined that relates the extent of snow cover to the current state of the snow cover in terms of water equivalent. Thus, once the water equivalent of the snow has been computed, the areal extent of the snow cover can be determined from the areal depletion curve.

Snow cover heat storage. The snow model keeps a continuous accounting of heat storage in the snow cover. Maximum heat storage occurs when the snow cover is isothermal at 0°C. When air temperatures are lower than the snow cover temperature, heat is transferred from the snow to the air, creating a heat deficit or negative heat storage in the snow cover. The model accounts for negative heat storage; and as air temperatures rise, sufficient heat must be transferred to the snow cover to eliminate existing heat deficits before melt can occur.

Liquid-water retention and transmission. Snow crystals form a porous medium that retains and transmits water similar to soil particles. The amount of liquid water that can be retained by the snow cover is assumed to be a constant percentage of the ice content of the snow.

Equations for the transmission of excess liquid water through the snow cover are used to lag and attenuate the flow of liquid water to account for the time delay and storage characteristics of the snow cover.

Ground melt. Heat exchange at the soil-snow interface is usually negligible when compared to the heat exchange at the air-snow interface. However, in some catchments, sufficient melt takes place continuously at the bottom of the snow cover to maintain a significant base flow. Therefore, the model allows a constant amount of melt to take place at the soil-snow interface.

Channel Routing

The soil moisture accounting model generates a volume of runoff available for channel inflow per 6-hour period. Initially, this volume of available water is assumed to be distributed uniformly over a soil moisture accounting area. To account for the temporal distribution of runoff volume reaching the catchment outfall, a time delay histogram and linear reservoir are used.

When runoff reaches the channel, the water is transmitted downstream in the form of a flood wave. As the flood wave moves downstream, storage characteristics of the channel and fluid flow dynamics cause the shape of the flood wave to change. Normally, the flow exhibits a time lag between points in the channel due to finite wave speeds. Also, the flood wave is attenuated due to the storage characteristics of the channel and, to a lesser extent, the inertial properties of the wave.

In rivers where the flow dynamics (i.e., backwater and/or flood wave inertial effects) are not important in describing the movement of a flood wave, a simple hydrologic (storage) routing procedure can be used. If the flow dynamics are important, a more complex hydraulic routing technique may be required.

Currently, the NWSRFS uses a simple storage routing technique known as lag and K /11/ in situations where flow dynamics are relatively unimportant. Experience has shown that the lag and K technique (both variable and constant with respect to flow) is very useful in describing flood flows in uncontrolled rivers where the effects of backwater and in-bank storage are negligible.

In rivers, reservoirs, and tidal reaches, where backwater conditions occur or where hydrologic techniques cannot achieve the desired degree of accuracy, a dynamic wave model /7/ based on the one dimensional equations of unsteady flow (fig. 6) can be used to predict stages and discharges. The first equation in figure 6 conserves the volumes of water in the system and the second conserves the momentum.

Application of these equations to a river system requires some idealization of channel geometry. Channel cross sections are specified at points along the river where significant changes occur. Typically, for large rivers with slowly varying transients, 15 to 25 km between cross sections will be sufficient. Observed stages and discharges can be used to determine channel roughness coefficients. With this information and the upstream discharge or stage hydrograph(s), flow can be routed through the river system.

The unsteady flow equations are solved by the "four-point implicit method," a finite difference technique. This solution technique allows unequal distance intervals between cross sections. Also, the numerical stability properties of the implicit method do not restrict the size of the computational time step /12/. The desired accuracy can be the sole criterion in choosing the time step; and for non-tidal situations, time steps on the order of several hours can be used.

Mean Areal Precipitation

A component of the NWSRFS, called the mean areal precipitation (MAP) program /4/, objectively transforms hourly and daily point precipitation measurements into an areal mean. In addition, MAP estimates missing data based on nearby precipitation records and time distributes daily data based on hourly patterns.

Three weighting techniques are available for distributing precipitation gage information throughout an area. The relative importance of each precipitation gage in an area can be determined as the sum of the $1/d^2$, where d is the distance from each point in the area to the gage. Normalizing the sums of all precipitation gages yields the proportion (or weight) of the MAP contributed by each gage. In certain locations (especially in mountainous regions), the distribution of precipitation gages throughout an area may not accurately reflect the actual pattern of precipitation. Under these circumstances, MAP can accept predetermined weighting factors to distribute the point measurements. Use of predetermined weights allows the modeller to analyze any circumstances peculiar to an area and adjust the precipitation gage weights accordingly. A third technique of determining the distribution of precipitation is by Thiessen weighting factors. In this method, the area is divided such that each precipitation gage is centered in a region containing all points closer to it than to any other gage. The proportion of the total area contained in each region specifies the weight assigned to the associated precipitation records.

The point precipitation weighting techniques described above all rely on complete precipitation gage records to successfully compute MAP. To utilize information available in partial records, a technique for estimating missing data has been developed. The crux of this method relies upon determining the importance of nearby precipitation gage measurements to the estimation of data for the incomplete station record. The importance of nearby stations is computed as $1/D^2$, where D is the distance from the station being completed. With this information, available precipitation measurements can be distributed to complete partial records.

The precipitation patterns exhibited at hourly recording stations are used to time distribute the depths at daily stations. Again, a $1/D^2$ weighting factor is used to determine the relative effects of nearby hourly stations on the daily record.

However, this technique will not result in estimations greater than the largest known value or less than the smallest. In mountainous regions, it may be desired to alter the estimated value at a station because of known orographic effects. The MAP program accounts for such modifications when completing a precipitation gage record by applying "characteristic station adjustments." A ratio of the characteristics of the estimating and estimated stations relate the known depths of precipitation to the depth at the incomplete station. For example, setting the characteristic of the station being estimated equal to two doubles the depth of precipitation recorded at an estimating station that will be used by the MAP program to estimate the unknown value. If no specification is made, the characteristics of all stations are assumed equal.

The MAP program produces an estimate of the depth of water falling on an area, which is used as input to the snow accumulation and ablation model and the soil moisture accounting program.

Mean Areal Temperature

The snow accumulation and ablation model uses air temperature as an index to heat exchange processes. The air temperature used in the model is the mean temperature over the area being simulated. Since air temperatures are measured at discrete points, it is desirable to transform point temperature data to mean areal values before the data are used by the snow model. Also, the mean areal temperatures (MAT) must conform to the computational interval used by NWSRFS. The NWSRFS MAT /6/ transforms observed minimum and maximum daily temperatures into 6-hour mean areal temperatures.

The computation of MAT involves inferences regarding the temperature at all points within the area. Available observed temperature records at points within and surrounding the area are used to compute the MAT. When portions of the observed records are missing (due to equipment malfunction, missed observation by observer, etc.), the MAT program estimates missing data using records available at surrounding points. This avoids discarding observed records that are not continuous and losing the information contained in the partial record.

Two separate estimation algorithms are used. One procedure is used in non-mountainous areas, where temperature can be assumed to vary linearly with distance. The estimated temperature is a weighted average (1/D) of surrounding temperatures. The second procedure is used in mountainous areas, where temperature variation between points generally does not vary linearly with distance, but where temperature variation is primarily influenced by elevation differences. A quasi-objective technique is used that employs a weighting procedure of distance and elevation to estimate the unknown temperatures.

Once all maximum and minimum daily temperature time series have been completed, 6-hour MAT can be computed. The first step is to convert the point minimum and maximum temperatures to point 6-hour temperatures. Four equations, one for each 6-hour period of the day, are used to convert the minimum and maximum temperatures to 6-hour temperatures. Six-hour MAT is then calculated as the weighted average of the point 6-hour temperatures.

Evapotranspiration

The determination of the volume of water being removed from a basin through evaporation and transpiration is important in accurately predicting the amount of water available for runoff. The mean areal potential evapotranspiration (MAPE) program will compute areal values of potential evapotranspiration. As with the MAT program, a number of point measurements are to be weight averaged over an area. The technique for distributing point potential evaporation values throughout an area is analogous to that for distributing point temperature values in non-mountainous areas. This technique gives a MAPE value for the total area.

However, evapotranspiration does not occur at the potential (maximum) level at all times. An adjustment must be made to reduce the potential evaporation value to potential basin evapotranspiration. This reduction accounts for such factors as watershed albedo and vegetative cover. The MAPE program uses a set of 12 values corresponding to the area-wide potential evapotranspiration demand for the 16th of each month. A linear interpolation between these 12 values yields an adjustment for each day of the year.

MODEL CALIBRATION

To use the soil moisture accounting, snow accumulation and ablation, and channel routing models for river forecasting, model parameters for each river basin must be estimated. Both trial and error methods and automatic methods are in use. Trial and error methods involve subjective adjustments to parameters, based on specific characteristics of previous model output. Automatic techniques involve the use of direct-search optimization algorithms for the catchment model and an iterative gradient adjustment procedure for the dynamic routing model.

Catchment Calibration

To efficiently achieve a satisfactory set of model parameters by trial and error calibration, two elements are required from the hydrologist: (1) an understanding of the physical processes taking place in the catchment and (2) an understanding of how the model mathematically represents the catchment. The hydrologist compares simulated and observed hydrographs and manually adjusts model parameters based on knowledge of the model mathematics and the physical processes of the natural catchment. However, even an experienced modeller may find the trial and error method time consuming. To shorten calibration time, an automatic calibration technique is available.

Experience has shown that calibration efficiency is enhanced considerably by accurate initial estimates of model parameters. Much effort has been directed toward identifying ways to determine initial parameter estimates from an observed hydrologic and geologic data base /5,13/. Physically realistic parameter values will improve the model's capacity to represent catchment response.

The automatic catchment model calibration technique is a direct-search optimization technique known as "pattern search" /14/. The concept of this strategy is to increase the size of parameter adjustment at each stage of optimization if a persistent direction (pattern) of adjustments has been established. The success of improving model performance by parameter adjustment is measured by the sum of the squared errors between the simulated and observed daily flow.

The recommended calibration procedure includes three stages. The initial stage incorporates the experience of the hydrologist with trial and error calibration to test initial parameter estimates and to reveal any gross errors present in the data. After reasonable parameter estimates have been obtained, intermediate calibration can proceed using pattern search optimization to further refine parameter values. In the final stage of calibration, the hydrologist reviews observed and simulated hydrographs for the entire period of record. If bias is absent at low, medium, and high flows, the calibration is considered complete. If, however, bias is present, additional parameter adjustment is necessary.

Dynamic Routing Calibration

The calibration of the dynamic routing model is accomplished primarily through adjustment of the channel roughness coefficients. Channel roughness is assumed constant throughout specified river reaches; however, it is allowed to vary with discharge.

Manual Calibration

The manual calibration technique uses observed stages and discharges throughout the river system as a measure of the model's accuracy. Boundary conditions (upstream and downstream discharge and stage hydrographs) are input to the model and computed stages and discharges at internal (test) points are compared with observed values. Roughness coefficients are adjusted and the simulation is repeated.

Altering a roughness coefficient affects stages and discharges throughout the river system, but the greatest effect is immediately upstream of the altered reach /7/. The manual calibration technique begins with the upstream reach and adjusts the roughness to match computed and observed stages at the upstream test station. The calibration proceeds downstream, matching computed and observed values at each test station in a sequential manner. In general, the reaches with constant roughness are established so that one test point falls within each reach. The manual calibration method requires numerous submissions of the routing system, with only a few adjustments being made each time.

Automatic Calibration

The automatic calibration procedure computes a set of roughness coefficients by calibrating the river system one reach at a time. With this technique, roughness reaches are established so that test stations are at both ends of the reach. Discharge is input at the upstream boundary, while stage is specified downstream. Observed stages at the upstream boundary are tested against computed stages at that point. Statistics are computed for several ranges of discharge so that the roughness coefficients can be calibrated as a function of discharge. For each range of discharge, the adjustment procedure uses the root mean square (RMS) error to determine whether the required change should be positive or negative. Adjustments are automatically made to the roughness coefficients for the reach and the one reach system is rerun. The cycle is repeated until a minimum RMS error for the reach is found. The discharges computed at the downstream boundary using the coefficients associated with the minimum RMS error are input as upstream boundary conditions for the next reach. A compatible set of roughness coefficients which minimizes RMS errors throughout the river system is determined by rationally proceeding through the river system one reach at a time. The automatic calibration procedure makes efficient use of both man and machine time.

OPERATIONAL FORECAST PROGRAMS

Catchment Model

Once a catchment is calibrated, the conceptual models mathematically represent the important hydrologic processes of the catchment. The hydrologic parameters derived in the calibration phase are transferred to the operational forecast programs. In terms of hydrologic computation, there is no difference between calibration and operational programs. The only differences lie in the timeframe of catchment simulation and in the number of catchments simulated per computer run. In calibration, interest is in the reproduction of a long series (5-15 years) of historical data; however, operationally, the timespan is reduced to forecasting catchment response a few days or weeks into the future. During calibration, no more than three adjacent catchments are simulated during one computer run. However, the operational programs are designed to interact with an operational direct access disk file system to retrieve and store information necessary to simulate entire river systems (which may include as many as 600 local catchments) on a continuing real time basis.

The operational forecast programs in the NWSRFS have been organized into three separate modules (fig. 7) /15/: (1) a data management module, (2) a pre-processor module, and (3) a forecast module. The data management module is the only interface between the user and the forecast system. The data management module allows the user to: (1) enter time series data (i.e., precipitation, temperature, stage/discharge, and potential evaporation data values); (2) enter model parameter data; and (3) display/print time series data, parameters, and forecast output. The pre-processor module uses the time series data and corresponding model parameters to compute mean areal precipitation, potential evapotranspiration, streamflows, and mean areal temperatures. The forecast module uses the values from the pre-processor module along with the model state variables carried over from previous computational periods to compute conditions at specified forecast points.

Dynamic Wave Model

The core of the operational dynamic routing program is the dynamic routing basic element described above. The modifications to that basic element of the NWSRFS consist primarily of an expanded data management package (fig. 8). A large portion of the information required to simulate a river system does not change daily. The cross sectional data, roughness coefficients, and information specifying the routing configuration will remain constant for long periods of time. It is only the hydrographs that must be updated for daily operational use. To efficiently manage these data requirements, a package of subroutines to store and retrieve the unchanging portion of the input data from disks and to update the hydrographs has been developed.

By specifying which river system is to be simulated and the period of simulation, the data are automatically prepared for use by the dynamic routing basic element. A minimum of data handling is required as only the latest values needed to update the hydrographs must be prepared.

A feature included in the operational dynamic routing program, which will improve forecasts, is the ability to bring the entire system (all computed stages and discharges) up to date with the most recent observed stages before proceeding into the future. Since all the information available about the conditions in the river is contained in the stages and discharges, by updating the entire system to present observed stages, the startup errors in a forecast of any given length can be minimized.

Extended Streamflow Prediction

Water supply forecasting is another function performed by the NWSRFS. An operational element capable of extended streamflow prediction (ESP) provides the forecast.

The ESP program makes multiple simulations with the catchment model using the current hydrologic conditions and precipitation and temperature data representing periods from numerous years. The streamflows obtained from these simulations are analyzed to provide a frequency distribution (and thereby probability) of any flow level. The probability distribution relates any flow to a specified chance of occurrence. The timespan to which a probability distribution applies, as well as the date at which the span begins, can be input into the ESP program.

With this information, the expected flow at any selected probability level can be obtained for the time period chosen. Forecast information for peak, low, and mean flow levels, as well as volume of flow, is available.

COMPUTER FACILITIES

The computational elements of the NWSRFS are being implemented on a computer facility at Suitland, Maryland. The operating system consists of three IBM 360/195 computers* with a capacity of 64 disk drives.

*Trade names are included for identification purposes only. No endorsement by the U.S. Department of Commerce, the National Oceanic and Atmospheric Administration, or the National Weather Service is implied.

Each RFC will access the computing system through remote terminals with batch processing capabilities. Input/output can be accomplished by means of punched card, paper tape, printer or magnetic tape mass storage. Limited off-line processing capabilities will also be available. The remote terminal serving the HRL will perform batch processing, as well as allow interactive access with the operating system.

EXPERIENCE WITH THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

Since 1971, the Lower Mississippi RFC at Slidell, Louisiana, has been using the initial version of NWSRFS /4/ for operational river forecasting. This RFC has forecast responsibilities for the lower portion of the Mississippi River system (fig. 2) and some adjacent systems draining to the Gulf of Mexico. Nearly 200 catchments have been calibrated by the Lower Mississippi RFC and most are forecast on a daily basis.

The use of NWSRFS at Slidell has proven to be especially effective in forecasting extreme hydrologic events. For example, in March 1973, a major flood on the Amite River at Denham Springs, Louisiana, crested at an elevation of 9.93 m (flood of record is 10.8 m) NWSRFS was used to forecast a flood crest elevation of 9.90 m. Prior to the storm, the Amite River was flowing at an elevation of 3.05 m. The time to peak of the flood hydrograph was 72 hours and the NWSRFS crest forecast was released approximately 30 hours before the crest occurred.

A similar situation was experienced on the Leaf River at Hattiesburg, Mississippi, in December 1973. A total 2-day rainfall in excess of 150 mm produced a major flood on the Leaf River. In 48 hours, the river rose from an initial elevation of 2.13 m to the crest elevation of 8.25 m. Nearly 36 hours before the crest was observed at Hattiesburg, a crest forecast of 8.07 m was generated by NWSRFS. These two examples are a good indication of the potential of a conceptual model with a strong physical base to simulate catchment response.

The experiences with NWSRFS by the Lower Mississippi RFC have been instrumental in making many of the operational modifications and improvements that are included in the current version of NWSRFS. As remote job processing terminals connected to the IBM 360/195 in Suitland, Maryland, are installed, the remaining RFC's will have the computing capacity to implement NWSRFS. It is expected that in the next 5 to 10 years the NWSRFS will be implemented nationwide.

In addition to the operational application of NWSRFS by the Lower Mississippi RFC, several other RFC's, as well as the HRL, have calibrated a wide variety of catchments. These catchments represent most of the hydrologic conditions found in the United States.

SUMMARY

The NWSRFS has been modified and expanded since its initial publication in 1971. Some conceptual components have been changed, new components have been added, and the data management capabilities have been improved.

The body of hydrologic knowledge is expanding rapidly. As new technology becomes available, the NWSRFS will continue to be updated to improve the quality of the NWSRFS.

REFERENCES

/1/ SITTNER, W. T. (1973). Modernization of National Weather Service river forecasting techniques. Water Resources Bulletin, Vol. 9, No. 4, pp. 655-659.

/2/ MONRO, J. C., and ANDERSON, E. A. (1974). National Weather Service river forecasting service. Journal of Hydraulics Division, ASCE, Vol. 100, No. HY5, pp. 621-630.

/3/ CRAWFORD, N. H., and LINSLEY, R. K. (1966). Digital simulation in hydrology: Stanford watershed model IV. Dept. of Civil Eng. Tech. Report 39, Stanford University, Stanford, California, 210 pp.

/4/ STAFF, HYDROLOGIC RESEARCH LABORATORY (1972). National Weather Service river forecast system, forecast procedures. NOAA Tech. Memo. NWS HYDRO-14, U.S. Dept. of Commerce, Silver Spring, Md., U.S.A.

/5/ BURNASH, R. J. C.; FERRAL, R. L.: and McGUIRE, R. A. (1973). A generalized streamflow simulation system: conceptual modeling for digital computers. Joint Federal-State River Forecast Center, Sacramento, California, U.S.A., 204 pp.

/6/ ANDERSON, E. A. (1973). National Weather Service river forecast system, snow accumulation and ablation model. NOAA Tech. Memo. NWS HYDRO-17, U.S. Dept. of Commerce, Silver Spring, Md., U.S.A., 217 pp.

/7/ FREAD, D. L. (1974). Implicit dynamic routing of floods and surges in the Lower Mississippi. Presented at AGU National Meeting, Washington, D.C.

/8/ ANDERSON, E. A. (1968). Development and testing of snow pack energy balance equations. Water Resources Research, Vol. 4, No. 1, pp. 19-37.

/9/ ANDERSON, E. A. (1976). A point energy and mass balance model of a snow cover. NOAA Tech. Report NWS-19, U.S. Dept. of Commerce, Silver Spring, Md., 172 pp.

/10/ LARSON, L. W., and PECK, E. L. (1974). Accuracy of precipitation measurements for hydrologic modeling. Water Resources Research, Vol. 10, No. 4, pp. 857-863.

/11/ LINSLEY, R. K., KOHLER, M. A., and PAULHUS, J. L. H. (1958). Hydrology for engineers. McGraw Hill Book Company, Inc., New York, 340 pp.

/12/ FREAD, D. L. (1974). Numerical properties of implicit four-point finite difference equations of unsteady flow. NOAA Tech. Memo. NWS HYDRO-18, U.S. Dept. of Commerce, Silver Spring, Md., U.S.A., 38 pp.

/13/ PECK, E. L. (in preparation). Catchment modeling and initial parameter estimation for the national Weather Service river forecast system. NOAA Tech. Memo. NWS HYDRO-31, U.S. Dept. of Commerce, Silver Spring, Md., U.S.A.

/14/ MONRO, J. C. (1971). Direct search optimization in mathematical modeling and a watershed model application. NOAA Tech. Memo. NWS HYDRO-12, U.S. Dept. of Commerce, Silver Spring, Md., U.S.A., 52 pp.

/15/ (1975). Interim report: operational forecast programs and data components for the National Weather Service river forecast system (NWSRFS): data files design. Prepared for the National Weather Service under Contract No. 5-35422, by Data Sciences, Inc., Silver Spring, Md., 75 pp.

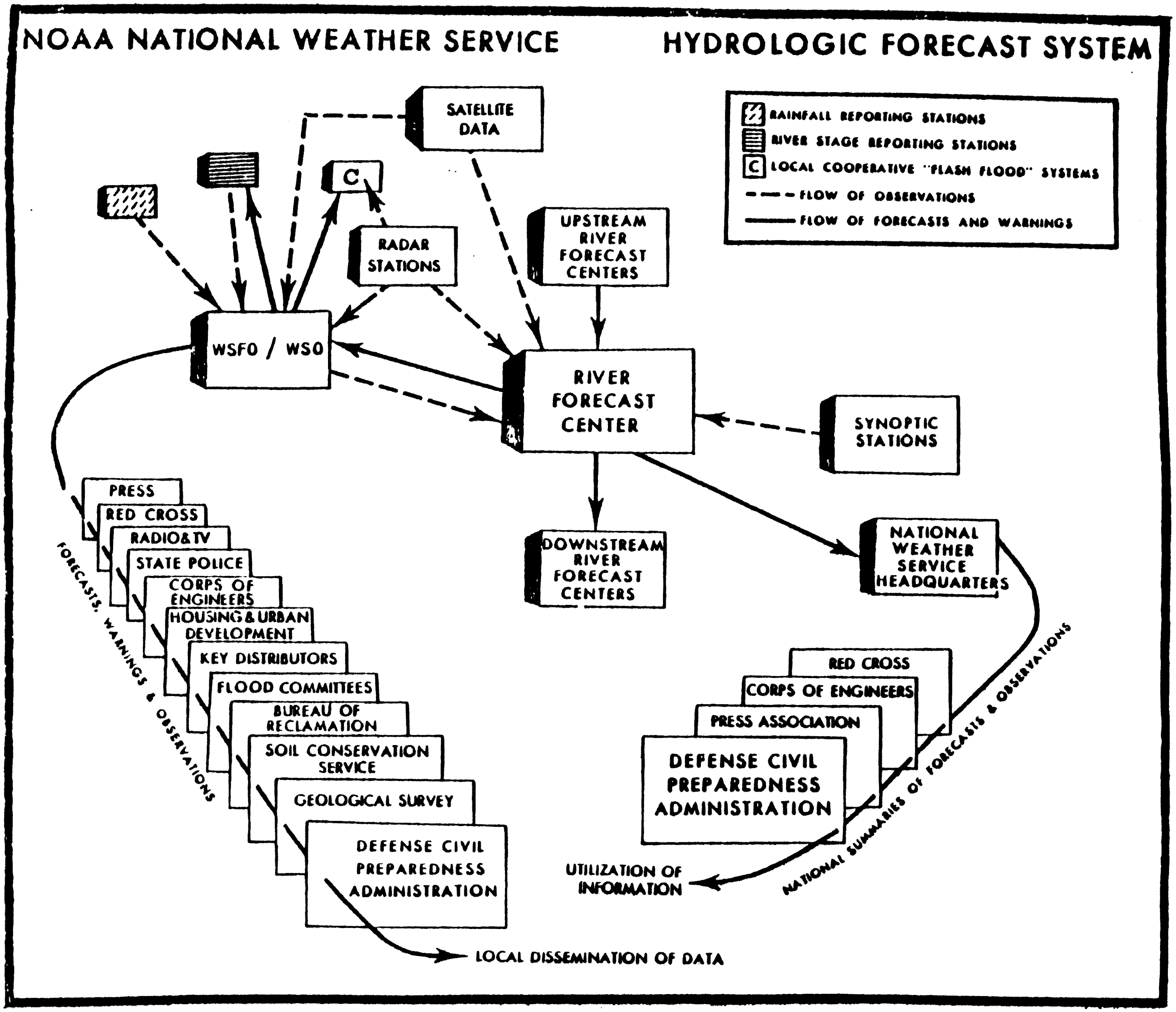

Figure 1.--National Weather Service River Forecast System.

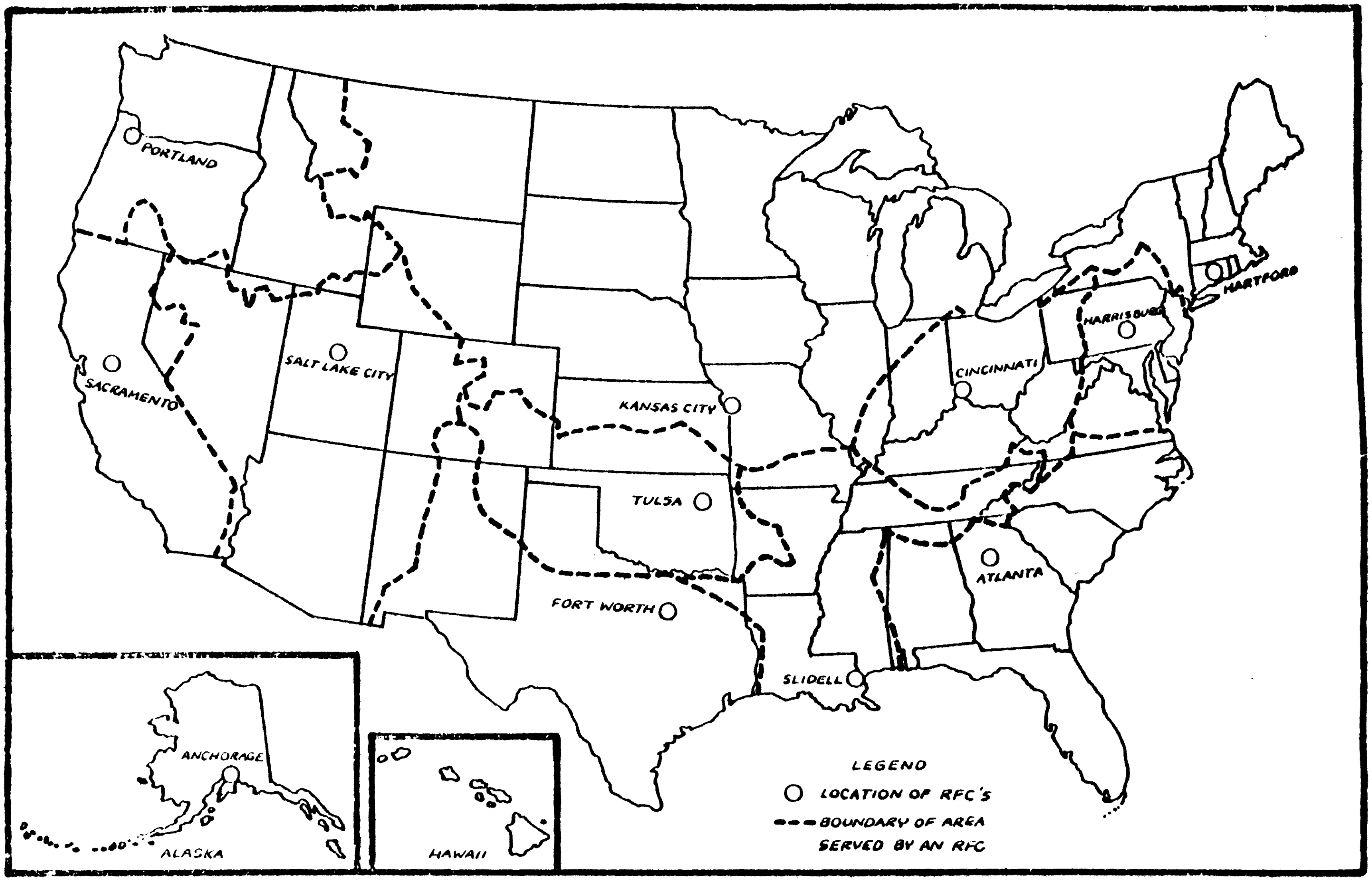

Figure 2.--River forecast areas of responsibility.

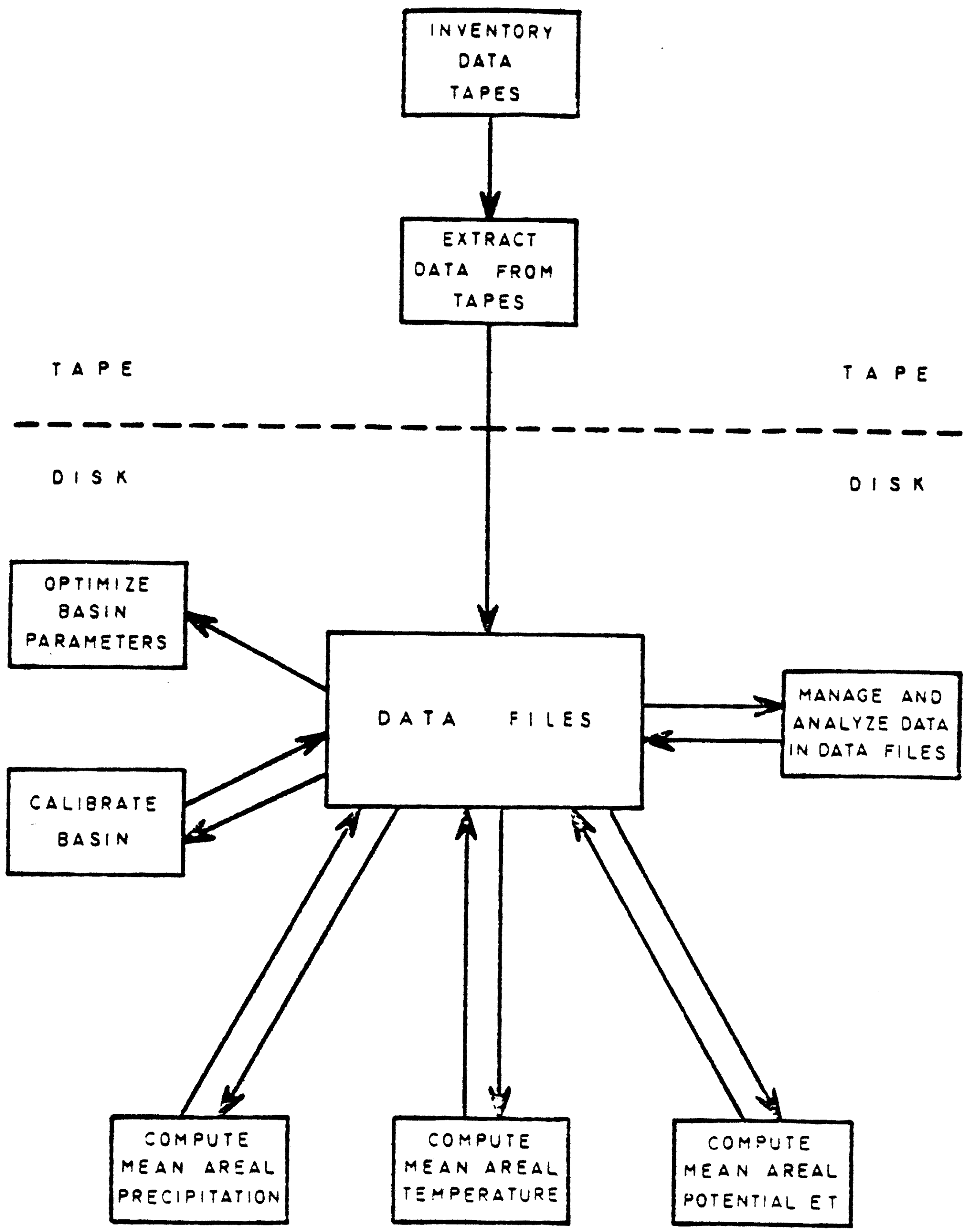

Figure 3.--Calibration data management system.

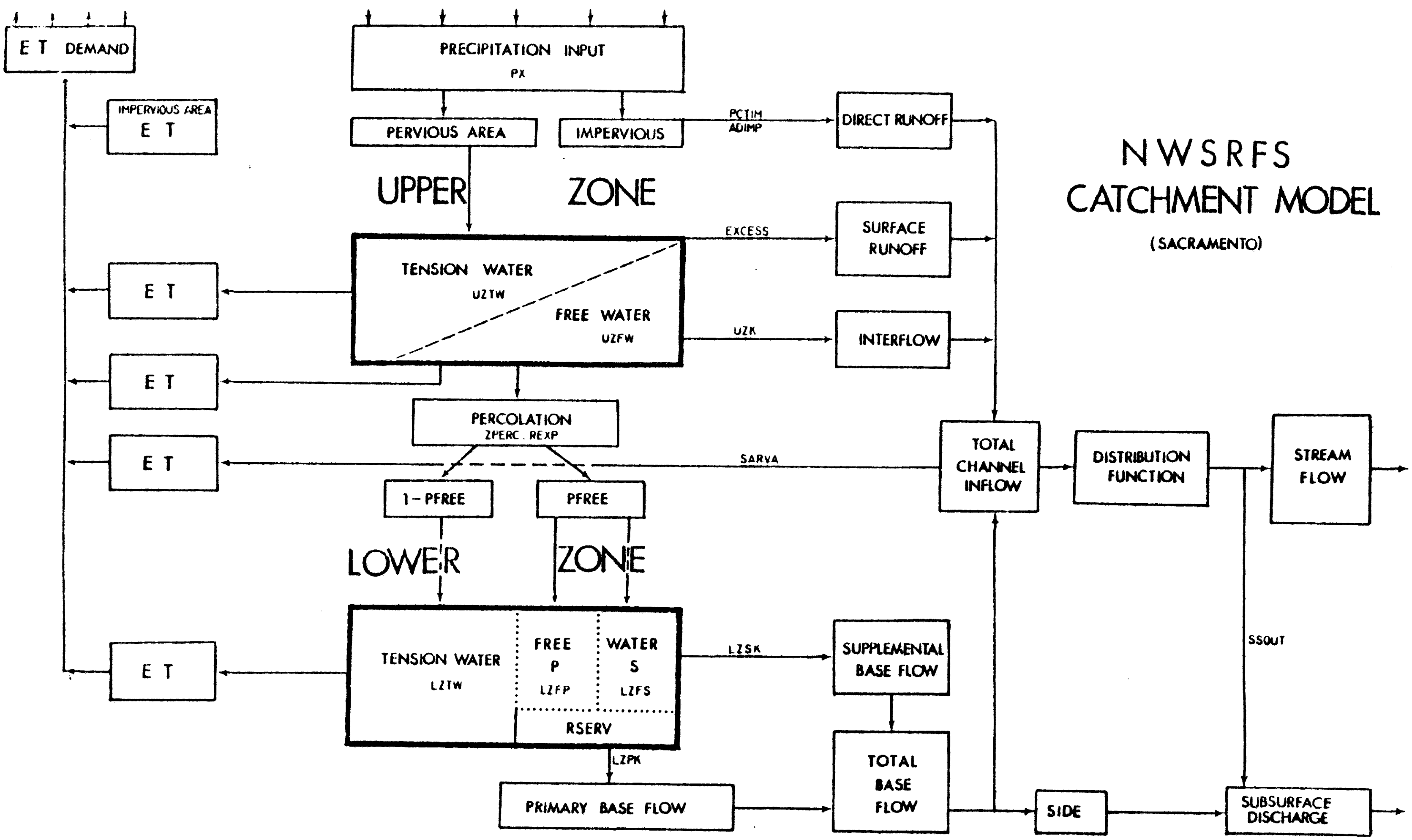

Figure 4.--Sacramento soil moisture accounting model.

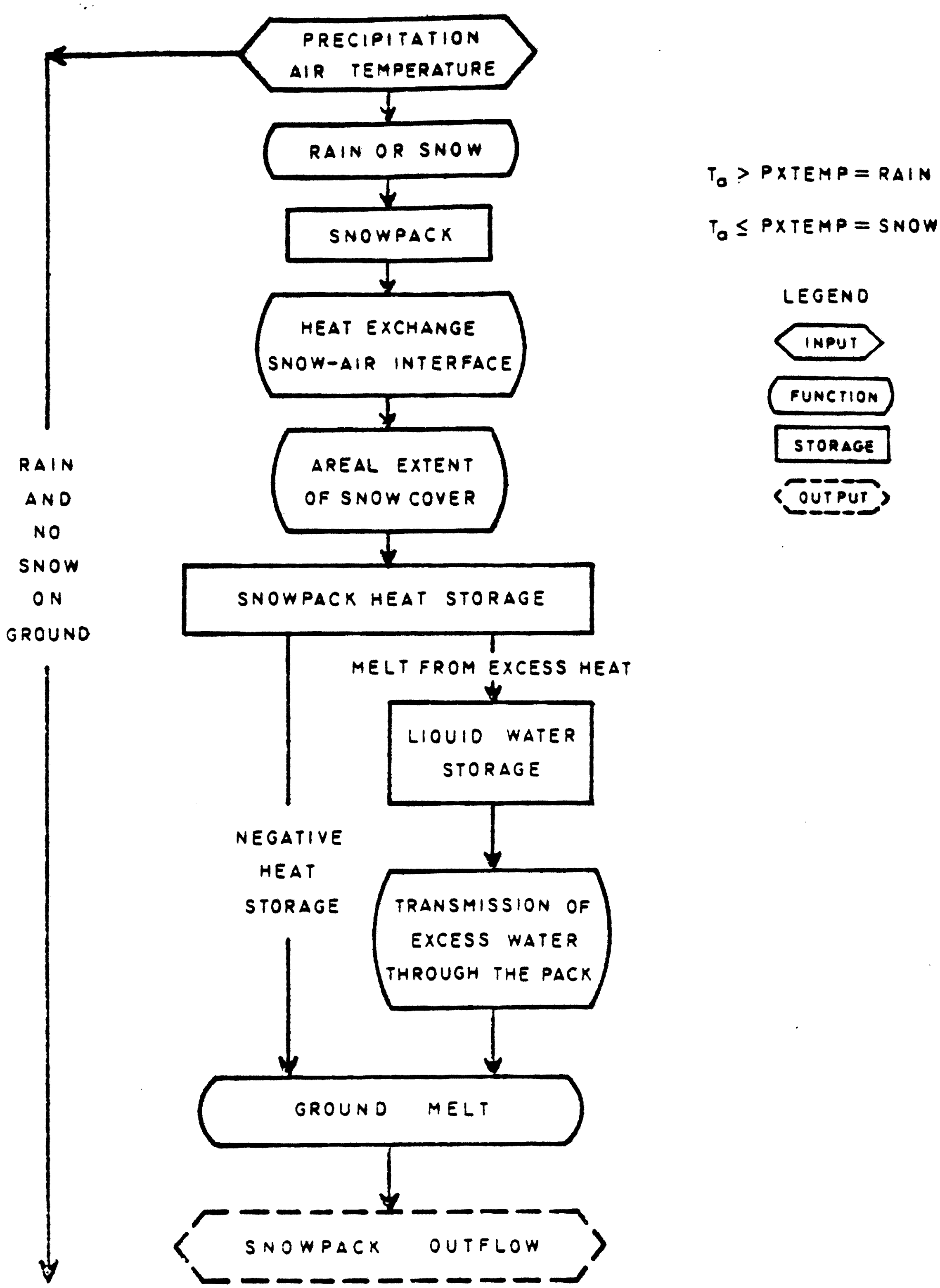

Figure 5.--Snow accumulation and ablation model.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha Q^2/A\right)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f\right) - qv_x + W_f B = 0 \qquad (2)$$

where:

- x = distance along the channel axis, positive in downstream direction;
- t = time;
- A = cross sectional area of flow;
- Q = average discharge across a section;
- B = width of cross section at the water surface;
- h = water surface elevation;
- q = lateral flow per unit length along the channel; positive in inflow and negative in outflow;
- v_x = velocity of lateral flow in the direction of the channel flow;
- α = velocity distribution coefficient;
- S_f = resistance slope given by the Manning equation for uniform turbulent flow;
- W_f = energy loss due to wind per unit width of channel; and
- g = acceleration of gravity.

Figure 6.--Unsteady flow equations.

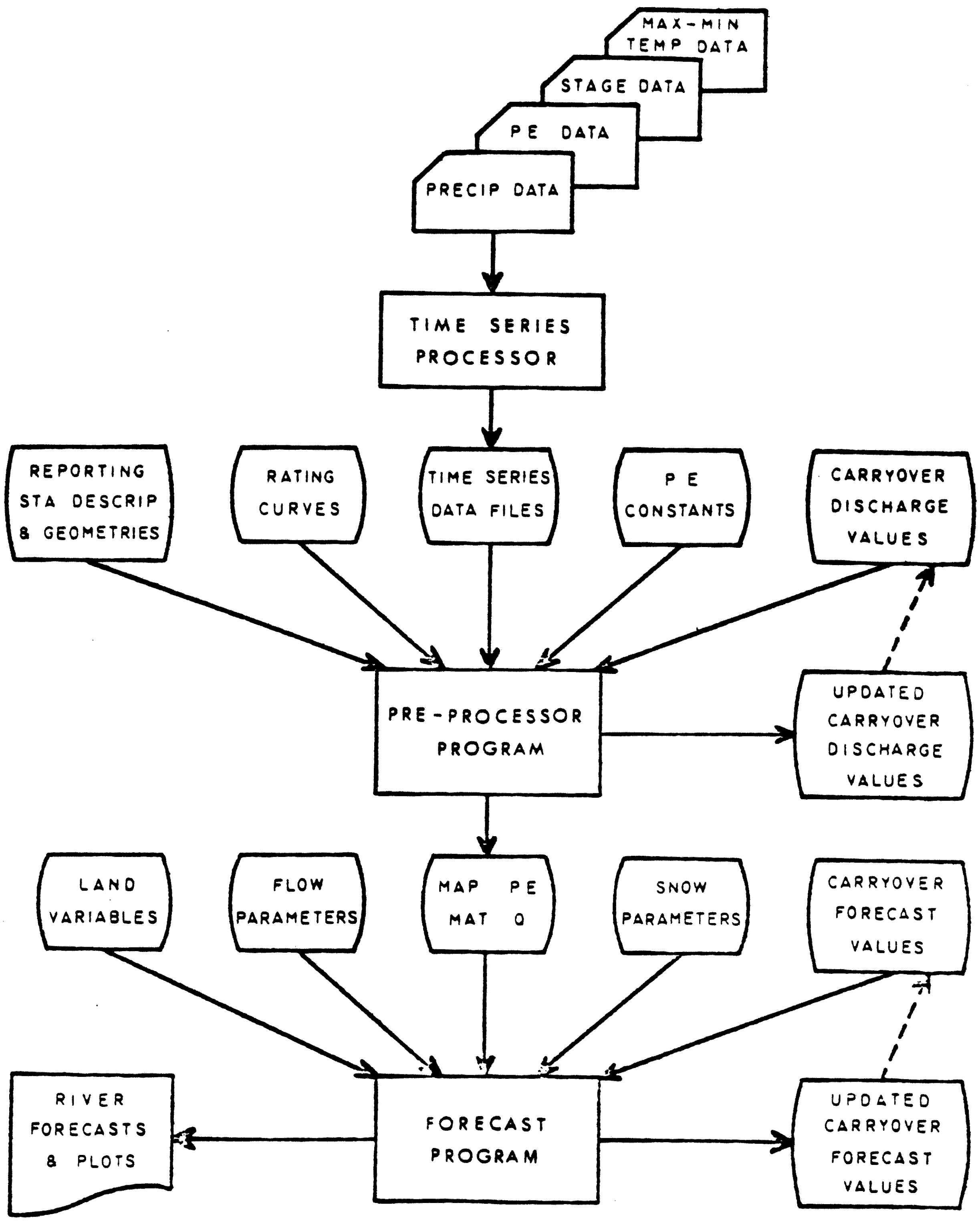

Figure 7.--Operational catchment response model.

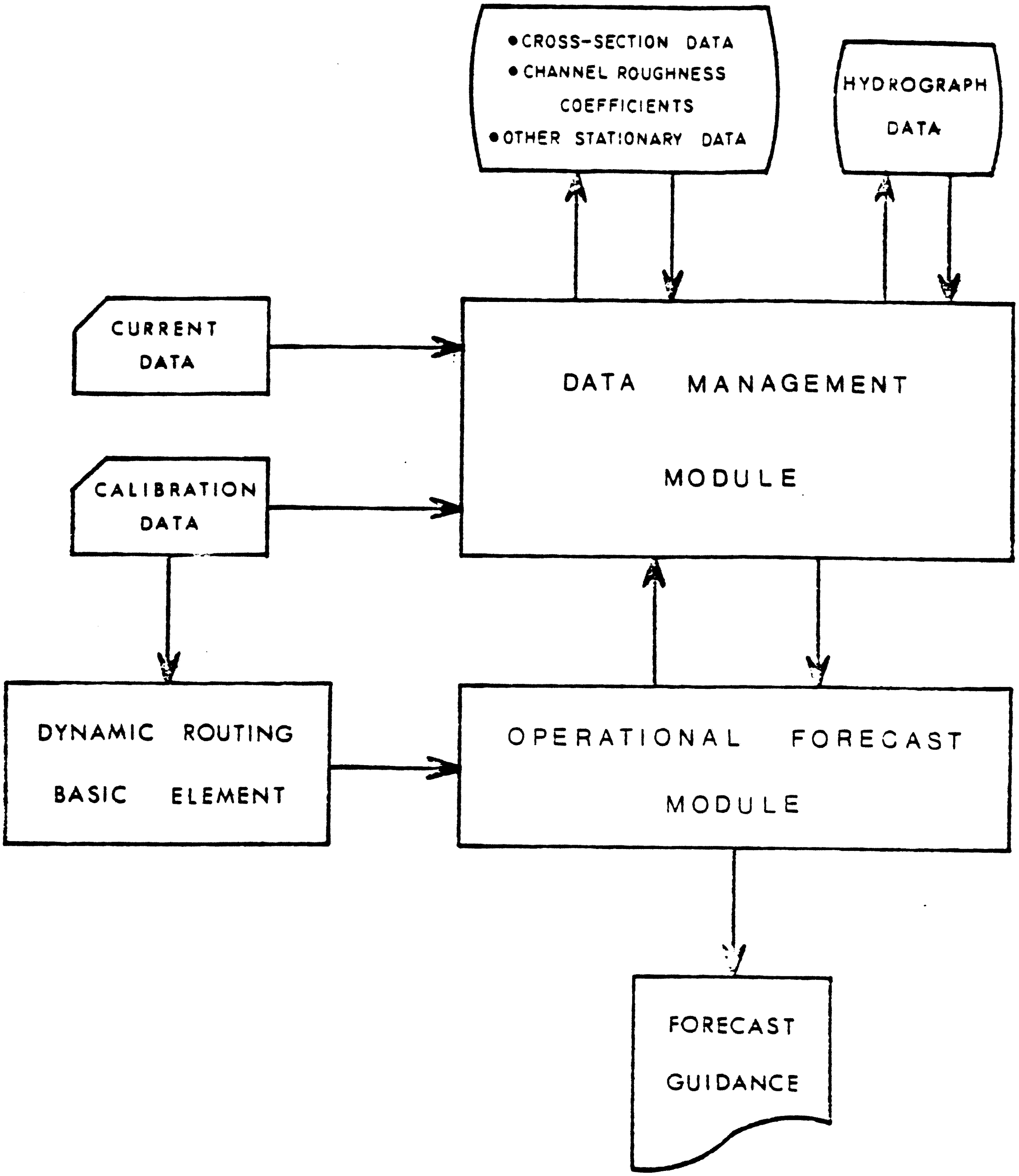

Figure 8.--Operational dynamic routing model.