NATIONAL WEATHER SERVICE PRODUCTS USEFUL FOR RESERVOIR REGULATION

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1. Introduction

The National Weather Service (NWS) is responsible for the production and dissemination of hydrologic forecasts and guidances within the United States. Execution of these functions involves the cooperation of various offices and agencies, including many outside the NWS, and the integration of diverse services and components within the NWS to produce timely and accurate information to the public. The elements of NWS services and procedures which contribute to the fulfillment of the commitment of providing this information to the public are presented.

In a general discussion of the hydrologic services of the NWS, three entities must receive attention:

1) Data Collection
2) Information Distribution and Dissemination
3) Forecast Methods

Generation of daily (or more frequent) forecast products requires large amounts of data, for both forecast procedure input and forecast verification. Within the NWS's overall system of hydrometeorological and climatological data collection exist numerous techniques for gathering data needed for hydrologic operations. Techniques range from the manual measurement of precipitation, temperature and stream levels to the automated and computerized observations of these same quantities to the indirect estimation of hydrologic data via remote sensing. Emphasis on technique development for data collection is directed towards the use of automated and remote sensing methods to provide data as needed.

Communications play an equally important role in the NWS task of forecasting. Data must be quickly and reliably delivered from their source to the location where they are best utilized. Hence, national communications networks have evolved over time to meet this need. Various teletype circuits presently form the nucleus of the communications system for the distribution of hydrologic data and information. In an effort to increase the timeliness of data and forecast delivery, the NWS is consolidating most of their communications networks into a single computer-based national distribution circuit to gradually replace the teletype circuits for the delivery of virtually all NWS data and information. The performance of this modern communication system is greatly enhanced by the computerization of many of the information gathering and presentation functions of the component NWS offices. Impacts from this replacement will be felt by the hydrologic community inside and outside the NWS.

To improve the final forecast product issued to the public, the NWS has adopted the use of physically based conceptual hydrologic models. Increased service has been afforded through the development and institution of advanced techniques.

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To provide information on the hydrologic services and operations of the NWS, three major sections are presented. First, data collection sources and methods are presented emphasizing the use of automated and remote sensing techniques as they are assumed to be the future of data collection within the NWS. Second, the communications networks used to transmit essential hydrologic data and information are described, starting with the existing teletype networks and ending with description and discussion of the communications network undergoing implementation and its impacts.

Finally, the National Weather Service River Forecast System (NWSRFS) is examined, illustrating the basic hydrologic and hydraulic components incorporated. The structure of both the calibration and operational environments of NWSRFS are highlighted. Features of NWSRFS which provide products besides the traditional daily river forecast are described. Brief discussions are provided on the use of an extended streamflow prediction method as a decision-making aid, the evaluation of quantitative precipitation forecasts as a forecasting tool, the forecast updating problem and the evaluation of the overall performance of NWSRFS.

The material presented herein is an overview of the hydrologic services and operations of the NWS. Ample references are provided for the inquisitive, and a general summary of all operations of the NWS can be found in the publication, "Operations of the National Weather Service" (Commerce, 1978).

Note: Trade names are included in this paper 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.

2. Data Collection

2.1 Introduction

Data are collected nationwide at numerous locations by diverse observation systems. Surface weather reports originate at over 1,000 land stations, with slightly under 300 manned by NWS personnel (Commerce, 1978). Additional stations are manned by other governmental agencies, by private citizens or by companies contracted with the NWS. In addition, some 12,000 cooperative stations provide data as part of the National Substation Program. The implementation of computer-based automated collection sites and the use of satellite and radar imagery will add to the already vast and ever-growing NWS data base.

2.2 Surface Networks

The surface data networks can be separated into different factions based on the collecting or reporting interval. These categories are grouped as the synoptic, the basic and the substation reporting networks.

2.2.1 Synoptic Observation Network

Synoptic observation stations are manned by the NWS, the Federal Aviation Administration (FAA) or contracted parties. Data at these stations are collected at world standard synoptic times (000,0600,1200,1800 GMT) or at the 3-hour intermediate times. An observer reads gages and makes synoptic measurements by comparisons to standardized charts and descriptions. Hydrologically pertinent information received from these stations include precipitation (3 hr, 6 hr and 24 hr amounts are potentially available), period maximum and minimum and minimum temperatures, and climatological data such as wind, sky cover, dew point temperature and pressure. These data are transmitted via teletype circuit entirely in a numerical code and require the use of translation tables for decipherment.

2.2.2 Basic Observation Network

The basic observation stations, manned by the NWS, FAA or contractors, provide data at hourly intervals unless significant weather events require more frequent reports. This information is collected at manned, semiautomated, or fully-automated stations and provides such data as precipitation amounts, temperature, snow cover and snowpack water equivalent for hydrologic purposes. This information is relayed through a teletype circuit, and in contrast to the synoptic data, is readily interpretable without the use of translation tables.

2.2.3 Substation Network

The substation network consists of some 12,000 cooperative weather stations operated by private citizens who perform their duties with little or no compensation. These observers report to an NWS office on a preset

schedule or when data surpasses a reporting threshold. The data are primarily daily in nature and reported information consists of 24-hour total precipitation, daily temperature extremes and, in some cases, stream stage levels. In addition, hourly precipitation is reported from recording stations.

A major portion of the data gathered as part of the manually obtained surface observation networks described are transmitted and are available on established teletype communications networks (see section 3.) and will be included as part of the total set of information to be distributed in the communications system being implemented called AFOS (Automation of Field Operations and Services).

2.3 Automation of Data Collection

Advances are constantly being made in the refinement of automated data collection methodologies. The NWS is making a great effort to expand the automated data network to allow data to be gathered upon request and at more frequent intervals, while making data collection less labor-intensive. As existing techniques are perfected and new techniques developed, remote sensing (satellite and digital radar imagery) will become an invaluable source of data for the NWS hydrology program, providing timely information on areal rainfall intensities, storm movement, and distribution, flood extent and ice jamming.

2.3.1 Automated Meteorological Observation Stations (AMOS)

Certain stations in the basic observation network are equipped with electronic sensors and reporting facilities. These constitute the AMOS (Automated Meteorological Observation Stations) and RAMOS (Remote AMOS) networks. These stations exist to provide data from locations too remote to man, from locations not needing complete observations, during unmanned periods at staffed stations, or at stations where personnel are too busy to take observations (Commerce, 1978). The RAMOS stations are interrogated entirely by computer. A full parameter AMOS/RAMOS station will report temperature, dewpoint, wind, pressure and liquid precipitation amounts, while a partial parameter station reports a subset of the above items.

2.3.2 Automatic Hydrologic Observing System (AHOS)

Automation also exists at locations for the collections of hydrologic data. The automated hydrologic data sites were established to provide data collection services at remote locations, to make data available at any time for updating forecasts, and to reduce workloads at the data receiving locations. Hence, a data collection network labeled AHOS (Automatic Hydrologic Observing System) was developed. The NWS started AHOS on an experimental basis in 1966 using a 20-station system with hard-wired communications used for river and flood-forecasting in the Potomac River Basin above Washington, D.C. (Schiesl, 1976). The experiment proved to be successful, but expansion was economically prohibitive due to the cost of dedicated telephone lines. At this point, the AHOS concept was fully accepted and a flexible, versatile and feasible system was subsequently designed to allow communications via a number of modes.

The primary facility allowing automation at the data collection sites is a solid-state electronic package called DARDC (Device for Automatic Remote Data Collection). When requested to do so, the DARDC can collect data from a maximum of four sensing instruments, then prepare and transmit a fixed-format, variable-length message to the requesting station. Messages are sent in the industry-standard ASCII (American Standard Code for Information Interchange) Code. The DARDC can transmit information via either telephone, satellite, or radio. AHOS can therefore be subcategorized depending on the mode utilized; AHOS/T for telephone transmission, AHOS/S for satellite communications and AHOS/R for radio transmission.

AHOS/T is used where reliable direct dial automatic switching exchanges exist. Locations are determined by the need for rapid collection in quick-action situations. Interrogation of these stations is performed by mini-computers that collect and relay the information to the user/disseminator, such as an RFC (River Forecast Center) or WSFO (Weather Service Forecast Office). The minicomputers, collectively called ADAS (Automatic Data Acquisition System), are located in New York, Ohio, Georgia and Oregon. Each ADAS computer calls all AHOS sites in its area, receives the data, and stores them for later use. ADAS is also used for collection of data from RAMOS sites. The interrogation cycle normally is six hours but AHOS/T sites can be called at any time when more data are needed. Communications between the computers and the collection sites are by intra- and interstate WATS (Wide Area Telephone Service) lines. In 1978, over 400 AHOS/T sites were in existence.

With the advent of the GOES (Geostationary Operational Environmental Satellite), an operational environmental Data Collection System (DCS) became available. The DCS is operated by the National Environmental Satellite Service (NESS) of NOAA, and includes the Command and Data Acquisition (CDA) station at Wallops Island, Virginia, and the spacecraft that collects data from radio-equipped data collection platforms (DCP's) (Schiesl, 1976).

Satellite communications are used where phone service is not feasible. The data are gathered at a remote radio-equipped DCP and transmitted through GOES to the NESS CDA Station at Wallops Island, Virginia. Data are forwarded from the CDA to the central NOAA computer site in Suitland, Maryland, and then on to the RFC's and other users.

The DCP's are equipped with a transmitter if the platform operates on a self-timed basis or with a transceiver if it is an interrogated system.

The self-timed DCP operates on an internally actuated self-contained preprogrammed timer system. The internal clock switches the transmitter on at one to twelve hour intervals and data are sent to the GOES on any one of 50 available channels (Flanders and Schiesl, 1975). System design will accommodate 10,000 DCP's in a 6-hour period.

The interrogated DCP is externally actuated by a command initiated at the CDA station and received through GOES. Interrogation is on a scheduled or as-needed basis. A duplexer module, situated between the receiver and transmitter, allows simultaneous input/output of signals. Components of an AHOS/S site are depicted in Figure 2.1. In 1978, 61 AHOS/S stations were

in existence, mostly in the Pacific Northwest, Colorado and the Rio Grande Basin.

The number of AHOS stations is expected to expand to approximately 1,100 by the end of the 1980's. All of the newly installed AHOS sites will use satellite communications because of the rapidly increasing cost of telephone lines, and, more importantly, their unreliability during storm periods, exactly when reliable communications are needed the most. Initial costs for the DCP's are greater than for the hard-wired AHOS/T stations but operating costs and losses due to outages are expected to be less over the years. None of the DCP's will be interrogated but will report on a set schedule unless weather conditions dictate transmission more frequently. When precipitation surpasses a threshold level, the transmitter will send data to the CDA on an emergency channel and thereafter, will report upon prescribed shortened time intervals for the entire storm duration. An alternative reporting scheme is for the DCP to relay information at every 2 mm increment in recorded precipitation (Schiesl, 1979).

The AHOS concept of data collection is being utilized with line of sight radio communications - designated as AHOS/R. Though not implemented nationally, AHOS/R type installations are currently being tested for future use in the NWS data collection system; especially for use in the detection of flash-flood inducing precipitation events.

Presently, data obtained from AHOS are available only from the ADAS computers for AHOS/T or NOAA's central IBM 360/195 computing facility for AHOS/S. Plans have been developed to change the collection system by centralizing the hardware and forming the DADS (Data Acquisition and Distribution System). A schematic of data flow on DADS is shown in Figure 2.2. As can be seen, all telemetered stations will report to the DADS central site. The information will then be placed on the appropriate distribution circuits with the entire set of reported data eventually available on AFOS. The internal NWS functions constitute Phase I of DADS. Phase II will expand the reporting and distribution network to include other NOAA agencies and cooperating data exchange agencies such as the Corps of Engineers and the USGS (Schiesl, 1979).

2.3.3 Touch Tone

Part of the expanded automated Phase II reporting network will be what is known as the "Touch-Tone" program. The NWS has been involved in an experimental basis in the automation of data reporting by members of the cooperative observation network. Currently, data are telephoned by the observer to a collection site (a WSFO for example) where an employee records the data and then types it into the distribution network. The "Touch-Tone" program allows the observer to enter data in code to a computer through the use of a digital touch-tone pad similar to the touch-tone dial on a telephone, thereby freeing the WSO employee for other work. The data can then be immediately placed on a distribution network without any other manual processing.

2.4 Remote Sensing

The single greatest problem in producing accurate hydrologic forecast is the inadequate measurement of precipitation on an areal basis. As the response of the flood event quickens, the problem becomes more critical. Gage networks cannot provide sufficient representation as they are generally distributed at a scale larger than the convective cells that constitute a significant portion of total rainfall (Green, et al., 1979). Remotely sensed information from radar and satellites alone does not lead to improved estimates of areal precipitation as estimation techniques currently lack the refinement to provide accurate assessment of precipitation events.

2.4.1 Hydrologic Rainfall Analysis Project (HRAP)

A proposed project in the NWS, the Hydrologic Rainfall Analysis Project (HRAP), is hoped to improve the quantitative estimation of basin-wide precipitation leading to improved streamflow forecasts by integrating multiple sensor precipitation data from radar, satellite and rain gages into a central file available for use by the operational components of the NWS (Green, et al., 1979). This data file will ultimately be available to users who will have access to AFOS.

2.4.2 Radar and HRAP

The use of radar for rainfall estimation has been investigated for some time. Greene and Flanders (1976) present a historical background of radar-rainfall estimation attempts describing the manually subjective techniques of the 1940's through the semiautomated methods to the fully-automated assembly and analysis of digital radar data available today.

The NWS operational network of radar sites include 51 Weather Service Radar (WSR-57's), 5 WSR-74C's plus 15 local warning radar sites (WSR-74's), Figure 2.3. Digitization of the radar echoes is a necessity for HRAP, but only four of the sites are currently fitted for digitized output with the addition of a minicomputer and software. These sites were part of the Digitized Radar Experiment (D/RADEX) started in 1971 as an experiment but data generated by D/RADEX now are available operationally for use in streamflow forecasting. All radar sites should be converted and capable of on-site digital processing by the end of the 1980's.

As stated before, 1,100 AHOS sites are expected to be operational by the end of the 1980's. The AHOS stations will be used in support of HRAP, for dynamic calibration or joint estimation of radar precipitation estimates. Approximately 25-30 AHOS stations will be located under each radar umbrella with 1,000 in the Eastern two-thirds of the U.S. (east of the Rockies) and the other 100 on the West Coast (Schiesl, 1979). Concurrent AHOS readings will be taken to coincide with radar readings to insure measurement corroboration.

2.4.3 Satellites

The NOAA GOES satellites are two geostationary or geosynchronous satellites located at 75°W and 135°W at the equator. Images are provided by the Visible and Infrared Spin Scan Radiometer (VISSR) that can scan the full disk of the earth in 18.2 minutes, viewing in the visible and infrared spectra (Dismachek, 1977). Information is available at half-hour intervals. Resolution is approximately 1 km in the visible range and 8 km for infrared. at the earth's surface directly below the satellite (Dismachek, 1977).

The increased frequency of information from GOES versus earlier orbiting satellites made possible the development of more complex rainfall estimation techniques. Scofield and Oliver (1977) devised a technique for obtaining rainfall estimates using the IR (infrared) imagery available from GOES. It is geared more for convective storms and uses empirical relationships between cloud top heights and rainfall, and incorporates other factors such as rate of cloud growth and cloud position as input to a decision tree to evaluate rainfall amounts.

The role of GOES in HRAP will be to supplement and complement data from rain gages and digital radar. The indirect inference of rainfall afforded by GOES from the cloud imagery may restrict its use to events of long duration and large scale. However, it is expected that the information provided from GOES will be a useful addition to the data obtained from rain gages and digital radar, especially in radar void areas.

2.4.4 Aerial Snow Surveying

This past winter the NWS implemented the use of aerial gamma radiation surveys for operational purposes. Much assistance in forecasting can be gained by the accurate and timely estimate of snow cover water equivalent available for runoff. Measurement of snow cover water equivalent by gamma radiation detection has been developed over the years and is now providing information to various RFC's for forecast preparation.

The heart of the aerial snow survey program is a gamma radiation detector mounted on a low-flying airplane. The detector senses levels of specific radiation emitted from the soil surface. The natural background level from the soil is determined by snow free surveys. Reduction in this value is due to attenuation by the mass of additional water molecules in the soil mantle and in ice or snow cover. After correcting for measurement errors due to spurious radioactive sources and compensating for the changes in the soil moisture content, the amount of water in the snow cover can be computed.

The operational program was developed for the upper Mississippi and Missouri River Basins (Peck, et al., 1979). Flight lines are established for potential flood areas with a soil measurement network collocated along the flight lines to provide supportive data. Limitations to the technique

are recognized and additional research is necessary, but any improvement in the measurement and estimation of runoff contributing quantities provide increased accuracy in streamflow forecasting.

2.5 Hydrometeorological Data Base

The discussion of data collection up to this point has concentrated on the acquisition of information for forecasting purposes. For model development and calibration, extended periods of historical hydrometeorological data are required. The NWS Office of Hydrology (O/H) has designed generalized formats for the climatological records stored by the National Climatic Center (NCC) of the Environmental Data Service (EDS), NOAA (Peck, et al., 1977). The tapes on which the data are stored are known as O/H format tapes. Three climatological data sets have been prepared in O/H format:

1) Hourly precipitation data (3,000 stations)
2) Daily climatological data (10,000 stations)
3) Synoptic meteorological data (350 stations)

The formats have been designed for generalized hydrologic use and are intercomputer compatible. Records are updated on a 3-year schedule. The tapes provide the most complete, readily accessible file of hydrometeorological data for the United States and are available through the NCC for the cost of reproducing the tapes.

2.6 Additional Data Sources

Each RFC's data bank is augmented from additional miscellaneous, external to NWS, sources. State, county and local agencies maintain networks of automated and cooperator stations and provide this information to the NWS. Other government agencies such as the Corps of Engineers participate in major data exchange programs with the NWS to mutually enhance reporting networks. Information provided through external collection efforts is available to the RFC by telephone, from commercial teletype circuits, or through terminal connections to non-NWS computer systems.

3. Communications

3.1 Introduction

The communications system within the NWS has a threefold purpose:

1) To deliver observed data to the users.
2) To transmit processed information from one section of the system to another.
3) To deliver the final product to the user or mass disseminator.

Once data has been observed and recorded, it is sent to the processing location and then routed to the forecaster who needs the data not only to produce the latest forecast but to also check and verify previously issued forecasts. Once finalized, forecasts are released from the NWS to the public.

To facilitate the movement of all information among NWS offices, 19 separate major communications networks have been introduced over time, each specializing in transmitting information for different aspects of NWS operations. Those networks using teletype terminals or facsimile (graphics) machines are currently the only way to acquire hard copies of NWS data and information. Many of these teletype and facsimile circuits will be phased out and replaced by one NWS national distribution circuit utilizing computer terminals with processing and storage capabilities. This modernization is being achieved with AFOS (Automation of Field Operations and Services). The conversion is currently underway but full implementation of AFOS is still a few years into the future. Redundancy of the communications circuit will exist during the transition, so a discussion of both types of communications systems is necessary.

3.2 Teletype Circuits

The data available on the teletype circuits that are used for hydrologic operations include precipitation, air temperatures, stream gage readings, radar reports and synoptic readings. All of these data are obtainable from three of the nineteen current NWS supported/operated communication networks: Service A, Service C, and RAWARC.

3.2.1 Service A

Service A is a long-line teletypewriter system operated by the FAA in all fifty States. It consists of four subsystems, one of which serves the NWS. The NWS network is shown in Figure 3.1. Service A exists for the collection and distribution of hourly surface aviation observations. From this set of data, hourly temperatures, precipitation amounts, snow depths and snowpack water equivalents seem to be most pertinent for hydrologic functions. Entry of data on Service A is on a tightly controlled schedule with each data collection site inputting data at specified times of the day.

3.2.2 Service C

Service C also is a long-line teletypewriter circuit operated by the FAA. Service C is used to collect and distribute surface synoptic and basic data and some NWS products. The network is shown in Figure 3.2. Data relayed through Service C include the 3- and 6-hourly synoptic reports and substation reports. From these reports, precipitation, max-min temperatures, river stages, and snow depth/water equivalents can be extracted. Forecast products with hydrologic significance broadcast on Service C are QPF (Quantitative Precipitation Forecast) and max-min temperature guidances. Release of reports on Service C is also tightly scheduled.

The synoptic reports carried on Service C are also entered onto NOAA's central IBM 360/195 and can be accessed automatically and directly by each RFC, preempting the need for manual preparation of data into a computer compatible form.

3.2.3 RAWARC

The NWS Internal Radar Report and Warning Coordination System, shortened to RAWARC, is used for the transmission and collection of radar reports and storm warnings. In fact, the only scheduled reports of hydrologic concern issued via RAWARC are the radar reports. However, at times when Service A and C are overloaded, RAWARC serves as an alternate system to distribute routine information that can't be entered onto the primary circuits. Release of data on RAWARC in this supplementary fashion is very informal and unscheduled. Only the originating office has control on issuance of data in this manner.

Streamflow forecasts are transmitted on RAWARC. Although normally done without scheduling, the hydrologic forecasts are input to RAWARC before specific times and in critical situations are given higher priority for entry into the circuit.

Unscheduled releases generally receivable on RAWARC include QPF, substation reports, flash flood guidances, severe weather reports and areal snow cover reports.

3.3 Automation of Field Operations and Services (AFOS)

The basic communications mode, as previously mentioned, is in a state of conversion. Teletypes, although reliable, are relatively slow by today's standards considering their pre-WWII technology. Not only are transmission rates lacking, but all reports are received in paper form only and must be torn from the machine and posted for a forecaster's perusal. Graphical displays, which are transmitted on facsimile circuits, are treated in the same manner as the teletype reports. Relieving professionals of these tasks will help to increase productivity of NWS personnel. Also, in this age of information revolution, speed is of the utmost importance. Such occurrences as tornadoes, flash floods and other

quick striking phenomena require fast action and fast notification. In critical situations, communications should not be a hindrance but an unfailing and swift assistant. AFOS is intended to provide such a service while bringing NWS communications into the computer age.

3.3.1 System Description

AFOS will obsolete much of the NWS system of teletypewriter and facsimile machines and circuits and all the paper output generated. In its place will be substituted a computerized, national distribution circuit from which information can be stored locally (i.e., at an NWS office), retrieved upon request and displayed on a video screen with optional hard copy. Maps will arrive at offices in 15 seconds instead of 10 minutes; messages travel 30 times faster than the current 100 words per minute. Each AFOS installation will have sufficient storage capacity on disk for data collection or information retrieval. As a computer, the AFOS facility will have the ability to communicate to automated data collection sites or other computers. Complete automation of the data collection and distribution system will not only free NWS personnel from routine tasks but will enhance the whole system to the point of truly being operable in real-time.

The backbone of the AFOS system is the National Distribution Circuit (DC), see Figure 3.3. The NDC is a closed loop, full duplex (i.e., - allows simultaneous send-receive) network connecting all Weather Service Forecast Offices (WSFO's) and the three National Centers (National Meteorological Center, National Hurricane Center, and National Severe Storms Forecast Center). River Forecast Centers (RFC's) will be linked to the NDC by a high speed spur from the nearest WSFO. Each Weather Service Office (WSO) within a WSFO's region of responsibility will connect to that WSFO by a State Distribution Circuit (SDC) radiating from the WSFO.

The facilities installed at each AFOS location will vary, but minimally each office will be equipped with a minicomputer, local disk storage and an operator's console with at least one alphanumeric and one graphical display screen. The minicomputers will have between 128K and 192K character core capacity on the main processor plus at least 10 million characters in storage on disk. All information transmitted on the NDC will be available to each AFOS location. Retention of all information, however, would overload the site, so only selected portions, thosenecessary for the office duties, are intercepted and stored locally.

3.3.2 AFOS Impact on Hydrologic Operations

Here is how hydrologic operations within the NWS will be impacted by AFOS.

The current scenario for producing a forecast is thus:

1) Data are collected at the appropriate office (WSFO or WSO) from a variety of sources and in a variety of formats by telephone, from computer-called automated stations, or from other computers.

2) The data reports are manually tabulated, organized, reviewed and then punched onto paper tape. The paper tape is then fed to the teletype for entry onto one of the distribution circuits (Service A, Service C, etc.)

3) The RFC receives the reports, sorts and evaluates them and then prepares the data in a computer compatible form (cards or paper tape). Once in this form, the data are then input to the NOAA central computer for use with the streamflow forecast procedure.

4) The forecast is reviewed by the hydrologists, recomputed if necessary, and then released to the WSFO via teletype using manual or automated procedures.

5) The WSFO then reviews the forecast, adds his own modifications, or words adding local "color," and then repunches his release on paper tape before placing it on the appropriate distribution network.

Obviously, a bit of redundancy in efforts exists, especially in the data transcription. At every location, data must be retyped for relay to the next location. As a result, the production of streamflow forecasts is unnecessarily slow.

With the implementation of AFOS operationally, forecast procedures will be altered. Data will be gathered and tabulated in much the same manner, but with AFOS, the data will be entered via computer terminal (e.g., a CRT) into the SDC, (if data are received at a WSO), travel to the RFC through a WSFO, with storage occurring at each location, and then placed on the NDC. Once entered, the data are accessible to the WSFO's and RFC's in standard format AFOS files. With its computer communications facilities, the RFC's AFOS computer will link to the main computers and dump the data files to files on the main computer for use in the forecast procedure. To disseminate a forecast, a preformatted message will be completed using the forecast results and relayed to the WSFO. The WSFO hdyrologist then conditions the forecast for local use and releases it to the public.

AFOS, as can be seen, reduces the duplication of data entry at each station in its route to the RFC and subsequent public issuance. Concurrently, hydrologic data bases are built along the way. Each WSO has its local data base resulting from data collection activities; the WSFO has a larger data base gathered from all the state WSO's and the RFC assembles all WSFO information in its area of forecast responsibility. Nationally, the NDC carries all RFC information forming essentially a national hydrologic data bank.

3.3.3 External User's Policy

For non-NWS (external) users, access methods into the NWS communications network will change (Cressman, 1979). Individual negotiations are being conducted with the major governmental data-exchange cooperators and specialized set-ups will be developed for those meeting reciprocity criteria. However, for those data users who have passive drops on teletype circuits, new methods must be employed, now or in the future. Those currently connected to either Service A or Service C can continue to do so until these services are dropped by the FAA and replaced in a modernization step. NWS offices will remove their terminals to these circuits when AFOS equipment is installed. The impact on external users now linked to Services A or C at an NWS office will be increased line charges as drops may have to be made at more distant FAA locations.

The RAWARC circuit will be discontinued by the NWS with some product distribution being assumed by the statewide National Weather Wire Service (NWWS) loops. External users may consider interfacing with the AFOS system. As stated before, the large scale organization may arrange for individualized designs which will allow the non-NWS installation to become a spur originating from an NDC note. Smaller users may only need an intelligent terminal for the receipt and display of distributed data.

For the receive-only external users, the NWS has proposed that a special computer system be installed to act as a buffer so that information can be pulled off the NDC for relay to outside requests. A private company serving multiple users would connect a high speed line to a port, retrieve the requested data and sign off. The only limiting factor to the user is the complexity of his receiving equipment. The user facilities that are compatible with the service enterprise's port range from a simple high speed intelligent terminal to full-capability processors and display consoles similar to AFOS installations. An illustration of the buffer system design is shown in Figure 3.4.

4. National Weather Service River Forecast Services

4.1 Introduction

The NWS is responsible for the issuance of hydrologic forecasts throughout the United States. This program is under the direction of the Office of Hydrology (O/H) and is accomplished at 12 River Forecast Centers (RFC), Figure 4.1, each with its own area of forecast responsibility. The RFC network will soon expand to 13 with the addition of the Minneapolis RFC. Daily streamflow forecasts are produced for over 2500 communities covering approximately 97 percent of the U.S. (including Alaska). Information provided by the RFC's is not only of interest to riverside communities but also for those responsible for reservoir operations, water supply, navigation, irrigation, power production, recreation and water quality. For those areas where snowmelt runoff constitutes the majority of water supply, monthly, seasonal and water year runoff forecasts are provided as an aid in water resource management.

4.2 Hydrologic Forecasting Techniques

In the past, River Forecast Centers were generally responsible for the formulation of their own forecast techniques. Each forecast system employed by an RFC developed independently from the other RFC's, but generally the rainfall-runoff relationship used to generate streamflow was an index type response function such as the Antecedent Precipitation Index method (Linsley, et al., 1958). As conceptual models were researched and developed, some RFC's adopted versions of these new techniques or developed their own models, but no one physically-based conceptual model was supported by O/H as best suited to fulfill each RFC's needs. In the late 1960's the NWS made a commitment to find one hydrologic model which would be useful for forecasting under all types of hydrologic conditions. This investigation resulted in the creation of the National Weather Service River Forecast System (NOAA, 1972) in 1971. Since that time, many significant improvements and additions have come to NWSRFS (Curtis and Smith, 1976) expanding its capabilities and increasing the computational accuracy of its various components.

4.3 National Weather Service River Forecast System (NWSRFS)

The National Weather Service River Forecast System is a collection of interrelated software and data interfaces capable of a wide variety of hydrologic, hydraulic and data processing functions. The interrelationship of NWSRFS software is shown in Figure 4.2.

For discussion purposes, the NWSRFS can be broken into two major segments: 1) the representation of basin hydrologic processes including the transformation of point meteorological data into areal means, the

simulation of the soil moisture adjustment and runoff processes utilizing the areal meteorological inputs and the overland and in-channel routing of the runoff and streamflow, and 2) the routing of streamflow discharges using the complete equations of momentum and continuity, known as dynamic routing.

4.3.1 Basin Representation Procedures

4.3.1.1 Hydrologic Models Overview

The basic hydrologic computational elements or models incorporated into the basin representation segment are:

a. Soil Moisture Accounting - routines to distribute and move moisture input through the soil profile.
b. Snow Accumulation and Ablation - routines to simulate the buildup and subsequent melt of a snow cover.

c. Hydrologic channel routing - various hydrologic methods for describing the movement of water through stream channels.

The processing techniques for the conversion of meteorological inputs from a point to areal basis are:

a. Mean Areal Precipitation - routines that compute uniform areal precipitation from point precipitation values.

b. Mean Areal Temperatures - routines to convert point temperature values to areal means.

c. Mean Areal Evapotranspiration - routines to compute mean areal evapotranspiration.

The hydrologic models and the processing techniques are utilized by a number of programs within the NWSRFS. These programs are:

a. Calibration program - set of routines used for the manual determination of model parameter values that accurately reflect basin and channel behavior.

b. Optimization program - set of routines to further refine basin model parameter values using automatic optimizing schemes.

c. Operational program - set of data entry, preprocessor and forecast routines to compute short-term streamflow forecasts utilizing parameter values of previously calibrated basins.

d. Estimates Streamflow Prediction - a statistical procedure to provide probability levels on longer-term forecasts for previously calibrated basins using simulations conditioned to initial hydrologic states.

e. Computed Hydrograph Adjustment Technique (CHAT) - an objective forecast updating method (discussed in Section 4.4).

f. Updating Utilizing Snow Course Data - additions to the calibration program to incorporate information available from periodic snow surveys to reduce total simulated runoff volume errors.

4.3.1.2 Soil Moisture Accounting

The model used for runoff computations in the NWSRFS is a modification of the Sacramento soil moisture accounting model (Burnash, et al., 1973), schematically shown in Figure 4.3. The model can be classified as a limited distribution deterministic model. With respect to each soil moisture accounting area, the model is of a lumped-parameter, lumped-input type, and variability of conditions within a watershed can be represented by multiple soil moisture accounting areas.

Vertically, the model divides the soil into two soil moisture accounting zones: an upper zone defining the upper soil layer and interception storage, and a lower zone representing the bulk of the soil moisture and groundwater storage.

The two zones are conceptualized as storing both "tension water" and "free water." Tension water is considered the water that is tightly bound to soil particles whereas free water is that portion which has mobility throughout the soil profile. The maximum capacities for tension and free water are model parameters with the contents described by a model variable.

The two zones are viewed as storing both "tension" and "free" water. Tension water is that water which is held tightly to the soil particles, whereas free water constitutes the portion available for movement within the soil layer. Moisture entering the upper zone must first fulfill tension water requirements before water can move to free water storage. In the lower zone, a fraction of the input can be allocated directly to free water storage before tension water capacity is reached.

Free water quantities are reduced through percolation, horizontal interflow, evapotranspiration or tension water replenishment. Tension water can only be depleted by evapotranspiration.

Movement from upper zone to lower zone is controlled by a complex percolation relationship relating contents and capacities of upper and lower zone storages in addition to the drainage parameters for both zones' free water storage areas. Moisture contents in the storage areas in both zones are effected by percolation which is, in itself, dependent on the current state of the soil moisture storage system.

Evapotranspiration can greatly influence hydrologic processes, so a close representation is necessary for accurate hydrograph simulation. Evapotranspiration is accounted for by either a seasonal evapotranspiration demand curve or an index of the actual daily evapotranspiration such as pan evaporation data adjusted to account for the vegetal cover and seasonal condition.

A portion of precipitation falling on a watershed is assumed to land on impervious areas directly connected to or adjacent to the channel system, becoming part of the streamflow without entering into the soil moisture process. As soil moisture storages become satisfied, additional soil surface area becomes effectively impervious with increased rainfall adding to the direct portion of runoff. The minimum and maximum impervious areas are specified with the current percentage of the total impervious area dependent on the state of the soil moisture storage system.

The model recognizes and generates five components of channel flow:

1. Direct runoff, resulting from moisture applied to impervious areas.

2. Surface runoff, resulting when rainfall and melt rates are greater than the upper zone intake.

3. Interflow, lateral drainage from upper zone free water.

4. Primary base flow, lateral flow from lower zone primary storage.

5. Supplementary base flow, lateral flow from lower zone supplementary storage.

4.3.1.3 Snow Accumulation and Ablation

The snow accumulation and ablation model is a conceptual model that describes the important physical processes occurring during buildup and decay of the snow cover. Output from the snow model, which becomes input to the soil moisture accounting model, is snow cover outflow (melt plus rain exiting the snow pack) plus rain that fell on bare ground.

The current version of the NWSRFS snow model uses air temperature as the only index to energy exchange across the air-snow boundary, Figure 4.4 (Anderson, 1973). The air temperature controlled snow model is used because air temperature data are readily available on a real-time forecasting environment, and close agreement has been exhibited between the air temperature index model and a more detailed energy balance snow cover model in simulating runoff in a limited number of test cases. The more complex energy balance snow cover model (Anderson, 1968; Anderson, 1976) provides more accurate estimates of snow cover energy exchange under certain conditions, provided the necessary data are available.

The air temperature model first uses the reference air temperature to determine the form of precipitation, either snow or rain, falling during storm events. Adjustments are made to snowfall amounts to compensate for snow gage inaccuracies or nonrepresentativeness.

Heat exchange at the air-snow interface is the prime controlling factor in the ablation of the snow cover. Two situations arise for which heat exchange must be estimated: (1) when air temperatures are great enough to cause melt, and (2) when the ambient air is too cold for melt to occur. During melt periods, the model must distinguish between rain and nonrain periods.

During rain periods, melt is controlled by several factors and assumptions concerning climatic and snowpack conditions (Anderson, 1973). 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 heat transfer by rainwater.

During nonrain periods, snow surface melt is assumed to be proportional to the difference between the air temperature and snowpack temperature. The constant of proportionality, called the melt factor, is used to linearly relate the temperature difference with snowmelt. The melt factor is allowed to vary between a minimum at the winter solstice and a maximum at the summer solstice.

Below a set temperature (generally assumed to be 0°C), melt is assumed not to occur, but heat gains or losses are registered, based on air and snowpack temperature differences and a seasonally varying heat transfer rate.

The areal extent of snow cover is determined from an areal depletion curve. Since snow accumulation patterns tend to duplicate themselves, a curve relating snowpack water equivalent to the extent of snow cover can be defined. Thus, once the snowpack water equivalent is known the areal extent of the snow cover can be computed from the areal depletion curve. Areal extent of snow cover is needed to determine the amount of melt generated within the snowpack and to apportion the amount of rainfall falling on bare ground and falling on the snowpack.

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.

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 solid portion of the snowpack.

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.

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 may allow a constant amount of melt to take place at the soil-snow interface.

4.3.1.4 Hydrologic Routing

The soil moisture accounting model generates volume of runoff available for channel inflow every 6 hours. A temporal distribution function is needed to link the runoff to discharge at a flow point. In NWSRFS, there are two methods for distributing runoff. In the latest version of the calibration program a unit hydrograph is used whereas the first calibration program and the current operational portion utilize a time delay histogram and linear reservoir. A project to update the operational program is currently underway and the unit hydrograph approach will be installed as the primary runoff distribution function.

Once runoff enters the stream, its movement must be described by some method; part of the general category known as channel routing. Essentially, channel routing is the anticipation of the rate of movement and change in shape of a flood wave as it travels downstream. And in a continuous simulation model like NWSRFS, all flows, large and small, must be continuously routed from one flow-point to the next.

The description of the movement of flow downstream is governed by two principles: conservation of mass, expressed as the continuity equation and conservation of momentum, described by the momentum equation.

Hydrologic routing techniques ignore the momentum term and employ only the continuity equation with either an analytic or empirical relationship between storage and discharge within the system. These methods provide quite accurate and acceptable results for most river reaches. However, for river segments where backwater effects or flat riverbed slopes greatly influence flow characteristics, a hydraulic routing technique, incorporating both the continuity and momentum equation, is required (Section 4.3.2).

Currently, the NWSRFS provides several hydrologic routing methods. The Lag and K method (Linsley, et al., 1958) is the only method available at this time in the operational forecast program. The latest calibration program offers Muskinghum Routing (Lawler, 1964), Tatum Coefficient Routing (Sullivan, 1978), and the Layered Coefficient Routing (Burnash, et al., 1973) as well as the Lag and K. Routing capabilities in the operational segment of NWSRFS will be expanded as the updating project continues.

4.3.1.5 Mean Areal Precipitation

Precipitation input to the soil moisture accounting model and snow accumulation and ablation model must be in the form of an equivalent uniform depth falling over an entire area. The mean areal precipitation (MAP) program (NOAA, 1972) objectively transforms hourly and daily point precipitation measurements into an areal mean. The MAP program also estimates missing data values from neighboring precipitation stations and temporarily distributes daily values using hourly records.

Three weighting techniques are available for distributing precipitation gage information throughout an area. A grid system can be established and the contribution of each gage in an area to the computation of an areal mean can be calculated as the sum of $1/d^2$, where d is the distance from the gage to every grid point in the area. Normalizing the sum of all gage weights results in each station's proportion of the final MAP value. In areas where an objective analysis of the precipitation gage network leads to biases in relative gage importance (e.g., areas influenced by orographic effects), predetermined weighting factors can be used to distribute point measurements. In this manner, unusual or peculiar circumstances can be recognized and appropriate adjustments can be made to be individual precipitation gage weights. The last method available to compute station weights is by Theissen weighting factors. In this technique, the area is divided into subareas, each associated with a precipitation gage, with all points in the subarea closer to that gage than to any other gage. The fraction of the total area represented by each subarea is assigned as the weighting factor for that gage.

The computation of an MAP requires complete precipitation records at each contributing precipitation gage. Periods of missing records can be filled by a technique for estimating missing data. Precipitation at the incomplete station is determined as the weighted sum of nearby stations divided by the sum of the weights. The importance (or weight) of each influencing gage is expressed as $1/d^2$, with d being the distance from the estimated station to the nearby estimating station. In this manner, stations with either missing or accumulated hourly records need not be discarded in the preparation of mean areal precipitation values.

Daily precipitation records are temporarily distributed by the application of local hourly precipitation time series. The weighting factor used to determine the relative influence of each hourly station on the daily station is $1/d^2$.

The estimating technique described will never result in a precipitation value greater or less than any observed value. In mountainous regions, orographic effects may alter precipitation patterns thereby voiding the imposed limits of the estimated values. To overcome this restriction, the MAP program applies a modification known as the "station characteristic adjustment." A ratio of the characteristics defines the relationship between precipitation amounts at a known station to those at the estimated station. For example, a characteristic of two at a station being estimated results in a doubling of the precipitation recorded at an estimating station that will be used to estimate the unknown value.

In the operational forecast program, computation of an MAP may be adjusted if knowledge of the spatial distribution of the event exists. A limit to the distance searched for influencing stations can be imposed for convective-type rainfall.

4.3.1.6 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 internal used by NWSRFS. The NWSRFS MAT (Anderson, 1973) 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 nonmountainous 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. Procedures for using observed hourly and 3-hourly temperature data from basic synoptic observation stations to compute MAT are being incorporated into the NWSRFS.

4.3.1.7 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.

4.3.1.8 Catchment Calibration - Manual and Automatic Techniques

To use the soil moisture accounting, snow accumulation and ablation, and hydrologic 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. The automatic technique for the catchment model involves the use of a direct-search optimization algorithm.

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, until an estimated optimum fit is achieved. For further refinement of parameter values, an automatic optimization 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 (Burnash, et al., 1973; Peck, 1976; Armstrong, 1978). 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" (Monro, 1972). 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 several statistical methods, one of which is 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 statistical analyses between observed and simulated values as well as the two plotted hydrographs, checking for errors or biases in low flow regimes, high flow regimes, total flow volumes, timing, and a number of other categories. Only until the hydrologist feels that the best fit between observed and simulated discharges has been achieved is the calibration considered complete.

4.3.1.9 Operational Catchment Forecast Program

Once a catchment is properly calibrated, the conceptual model is assumed to 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 for a day to 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 an entire river system (which may include as many as 800 local catchments) on a continuing real-time basis.

The operational forecast programs in the NWSRFS have been organized into three separate modules (Figure 4.5): (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 necessary routines to compute mean areal precipitation, potential evapotranspiration, streamflows from stage, 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.

4.3.1.10 Extended Streamflow Prediction (ESP)

A method for providing probabilistic streaflow prediction during any requested future timeframe is available. The method is known as Estimated Streamflow Prediction (ESP) (Twedt, et al., 1977) and provides likelihood estimates for such flow properties as total volume, peak flow, minimum flow, etc. Although primarily developed as a tool for the NWS function of water supply forecasting, ESP can provide useful quantitative probabilistic information to any decision maker where levels of risk in water use or supply are involved.

The ESP model makes two simplifying assumptions to overcome the inherent shortcomings of forecasting. The first is that the hydrologic response of a watershed can be accurately reproduced through the use of a well defined physically based conceptual hydrologic model and that the simulated flows generated by such a model are accurate replications of actual streamflows observed under similar conditions. This underlying assumption disregards errors introduced due to model inexactness.

The second is that the historical events of precipitation and temperature have an equally likely chance of occurrence in the future. Therefore, lengthy (10-20 years) records of climatological data are necessary to represent the variability of such natural processes.

The sequence of data for each year of record is used to make multiple simulations using the current hydrologic conditions as the initial state of the basin producing a range of possible streamflow events. This set of events is then analyzed to select the appropriate type of information (peak flow, total volume, etc.) for the requested time period of interest. A frequency distribution is then developed for these categories, enabling the user to relate streamflow information to a desired chance of occurrence during this period.

The ESP model is used in conjunction with the NWSRFS hydrologic computational components (Section 3.3), but can be adapted for use with any generalized hydrologic model containing a soil moisture accounting routine, a snow accumulation and ablation model and channel routing routines. Inputs to ESP include (1) historical model parameters, (2) initial basin conditions, and (3) climatological time series. The model parameters are the set of values which fit the generalized models to actual basin behavior. Initial conditions are available as current values of model state variables located in the operational forecast program files. Use of the initial conditions insures that generated flows are conditioned to the actual state of the system and are not simply historical norms. The needed climatological time series have been discussed and must be in the form of mean areal values (Section 3.3.4 and 3.3.5).

The user defines the time period or "window" over which simulated values are to be analyzed. Obviously, extended windows or starting dates far into the future will lead the statistical analyses to the point of approaching the historical, marginal distribution.

From the generated flows conditioned to the initial state, as mentioned above, a frequency distribution is formed. Assuming a normal representation of this distribution, the model determines expected values of the streamflow component at user defined probability levels of occurrence. These probability levels can be displayed in either a tabular or graphical format.

Figure 4.6 shows how uncertainty has been reduced for predicting total volume of flow for a snowmelt-fed Western River (Twedt, et al., 1977). From this information and the probability levels associated from the analysis, water resource managers would then be able to make decisions impacting long-term water-use allocations and to adjust system operations accordingly.

ESP has shown its utility as an aid in decision making for an urban water supply situation as reported by Sheer, 1979. In the late summer of 1977, a suburban Washington, D.C., public authority was faced with a critical problem of dwindling water supplies due to continued drought conditions. Decisions had to be made on the enaction of severe water-use restrictions to insure an adequate water supply for the duration of the dry period. A study was conducted by various local and U.S. agencies, employing ESP along with other risk analysis methods, to provide risk information on all possible actions for use by the public authority. The study outcome revealed that at the existing demand on storage, supplies would be quickly depleted unless stricter conservation measures or purchases from outside water companies were initiated. The methodology of the risk analysis included the calibration of the watershed using the NWSRFS and then application of 26 years of historical data for the study period using ESP. Analyzed quantities included reservoir contents given various demand levels.

The decision to enact the tighter water-use controls was short-lived as torrential rainfall saturated the dry basin and reservoir levels returned to normal. However, the critical situation proved the utility of ESP, and, although it is somewhat more computer and data intensive than other methods, the potential to provide useful information to decision makers is evident for the assessment of water-resource situations (Sheer, 1979).

4.3.2 Dynamic Wave Model

On river systems where storage routing techniques are inadequate due to the effects of backwater, tides and mild channel bottom slopes, a dynamic wave model (Fread, 1978) based on the complete one-dimensional St. Venant equation can be used to forecast stages and discharges.

The model is very flexible and can be applied to river systems exhibiting various boundary conditions and irregular cross sections located at unequal distances along a single multi-reach river or several such rivers having a dendritic configuration. Roughness coefficients needed for forecasting can be determined automatically from observed stages and discharges.

A weighted four-point nonlinear implicit finite difference scheme is used to solve the unsteady flow equations via a Newton-Raphson iterative technique. This solution technique permits irregular distance intervals between cross sections. As opposed to an explicit-type solution, the computational time step size depends solely on the desired accuracy of the solution and is not restricted due to instability problems (Fread, 1974). This property enables the model to be very computationally efficient when simulating slowly varying floods of several days duration.

The computational techniques employed in the dynamic wave model are incorporated into several structures:

a) Dynamic Wave Calibration Program - routines organized for the manual and automatic estimation of model parameters, primarily the channel roughness.

b) Dynamic Wave Operational Program (DWOPER) - data entry, pre-processing and computational routines to provide streamflow forecasts of river reaches or systems for which dynamic routing is best suited.

c) Dam Break Model - program to synthesize an outflow hydrograph resulting from a dam breach and to subsequently route the flood wave downstream.

4.3.2.1 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.

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 (Fread, 1978). 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.

The automatic calibration procedure computes a set of roughness coefficients by calibrating the river system one reach at a time. With this technique, calibration reaches are established so that test stations are 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.

4.3.2.2 Dynamic Wave Operational Program (DWOPER)

The core of the operational dynamic routing program is the basic dynamic routing element described above in section 4.3.2. The modifications to that basic element of the NWSRFS consist primarily of an expanded data management package (Figure 4.7). 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 basic dynamic routing 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.

4.3.2.3 Dam Break Model

Part of NWSRFS is the event-oriented dam-break flood forecasting model (Fread, 1977). It is comprised of two fundamental elements. The first reproduces the outflow hydrograph from the dam breach, the geometry of which is time dependent. A broad-crested weir-flow approximation which includes submergence and approach velocity effects is used to compute the outflow hydrograph while simultaneously considering the influence of the reservoir storage depletion and the reservoir inflow hydrograph by either a storage or dynamic routing technique. The second element routes the flood wave downstream using dynamic routing (Section 4.3.2).

Data requirements include the temporal and geometric descriptions of the breach, reservoir characteristics and the valley hydraulic properties.

Testing of two recent dam failures has shown good agreement between simulated model output and observed values as to magnitude and timing of the flood wave (Fread, 1977).

4.4 Forecast Updating

One of the major concerns in river forecasting has been the question of how best to use observed discharge as feedback for the final determination of a streamflow forecast. Stream gage measurements are usually used as a comparison to judge the effectiveness of a hydrologic simulation model, especially during the calibration phase; and on a real-time basis these readings are used in some manner to revise or adjust the forecast. From the operational viewpoint, observed streamflow is used as input to the forecast but is not an input to the hydrologic model.

In the past when hydrograph simulations were generated by manual methods, forecast revisions relied solely on the judgment and experience of the forecaster. With the advent of computers, updating was still highly subjective, since the simulation techniques were only the computerization of the manual techniques and model deficiencies precluded the use of objective updating methods. Any automatic techniques

were restricted to the simple blending procedures that gradually merged the observed hydrograph into the simulated without consideration of the underlying cause of the discrepancy.

4.4.1 Computed Hydrograph Adjustment Technique (CHAT)

As more complex, physically coherent rainfall-runoff models were adopted for forecasting, automatic objective updating procedures became a possibility. One method known as the Computed Hydrograph Adjustment Technique (CHAT) (Sittner and Krouse, 1979) has been developed and tested and is scheduled for includion into the NWSRFS operational forecast procedures.

Discrepancies between the values of a simulated hydrograph and discharge measurements can be attributed to four separate error sources:

1. Errors in model input data.
2. Errors in model parameters.
3. Errors in model structure.
4. Errors in discharge measurements.

CHAT considers negligible the errors introduced by model structure imperfection and measurement uncertainty. The difference in output values is assumed to be primarily caused by faulty input data and the inaccuracy of the unit hydrograph (a model parameter) to describe the runoff produced by a particular storm event.

As a model parameter the unit hydrograph is initially defined to adequately describe average storm events. Discrepancies arise during specific events resulting in unusual runoff distributions.

The approach used by CHAT to resolve hydrograph differences is to make adjustments, iteratively and simultaneously, to precipitation values and the shape of the unit hydrograph until the model produces a simulation that agrees, within reasonable tolerances, with the discharge observations. The process employs the use of an objective function as an indicator of the performance of each iteration. Contrary to normal optimization methods, CHAT does not seek a minimization of the objective function but rather reduces the objective function to an acceptable value while making the smallest possible adjustments to decision variables.

CHAT does not make a direct change to model states, but will alter these values as a result of adjusted precipitation input values.

CHAT has been applied to various basins and events with an encouraging degree of success (Sittner and Krouse, 1979).

4.4.2 Estimation Theory

In general terms, estimation theory involves an analysis of uncertainty in the use of conceptual models in forecasting; uncertainty introduced from all four sources of output discrepancy (input error, model structure error, model parameter error and measurement error) may be considered. By accounting for uncertainty, the enhanced model can:

1. Utilize real-time input and output information as it becomes available,

2. Combine and assign reliability estimates to information from various sources (measurements, forecasts guesses), and

3. Provide a measure of accuracy of the forecasts.

Basically, the updating problem using estimation theory is approached by reassessing the state of all hydrologic model variables using as input or feedback all measured and estimated quantities along with error characteristics associated with each of the quantities.

The estimation theory approach, in contrast to CHAT, directly adjusts each state of the hydrologic model in proportion to the difference in values of the observed and simulated outputs (called the measurement residual). The heart of the procedure is the computation of the gain matrix. The gain matrix is the amount of correction applied to the measurement residual to determine the correction of the value of each model state.

The uncertainties associated with the four error sources must be quantified as the gain computation is dependent on the reliability (or weight) given to the different sources of information (i.e., input, model structure, observations, etc.). The degree of uncertainty is time varying and dependent on hydrologic conditions.

The Kalman filter provides a technique to compute the gain at each time step accounting for the various sources of uncertainty and the time-varying nature of hydrologic conditions. It produces, in theory, the best (i.e., minimum variance) estimate of the hydrologic states. Problems associated with Kalman filter application are the transformation of the conceptual models into a stochastic state-space formulation, and the estimation of error characteristics (e.g., variance) of input data, measurements and model accuracy.

Kitanidis and Bras (1978) have successfully applied a Kalman filter to the soil moisture accounting model of NWSRFS. The application of Kalman filtering techniques to other hydrologic models is an active research area.

4.4.3 Incorporating Observed Snow Course into the NWSRFS Data

The Soil Conservation Service (SCS) periodically records observations of snowpack depth and water equivalent at numerous snow courses throughout the country. Carroll (1978) has presented a method to utilize the observed water equivalent readings to improve simulated water equivalents and incorporate the revised values into the snow accumulation and ablation model of NWSRFS (Section 4.3.1.3) for the improvement of simulated monthly runoff volumes.

The snow model calculates a simulated water equivalent based on mean areal temperature and precipitation time series and any nonrepresentativeness of these time series to the actual processes may result in differences between the simulated water equivalents and an index to the observed snow water equivalent. Observed snow course data serve as a check to the snow model computations and offer an empirical basis to adjust the simulated water equivalent.

Appropriate snow courses are selected and the simulated water equivalents are regressed on the snow course data for a sufficient period of record, resulting in a regression water equivalent. The update procedure results in a revised estimated water equivalent using a three parameter weighting function to position the estimated value between the simulated and regression water equivalents. The three parameters place a relative weight on the simulated and regression water equivalents, account for the shape of the weighting function and assess the normality of the monthly snow cover accumulation patterns.

Application of this updating procedure to three western snowmelt-fed rivers show reductions in monthly volume errors in discharge simulations from 18 to 40 percent.

4.5 Use of Quantitative Precipitation Forecasts (QPF) in River Forecasting

Quantitative Precipitation Forecasts (QPF) are produced by the National Meteorological Center, providing predicted precipitation depths for selected time periods into the future. Various River Forecast Centers currently use QPF values to prepare a priori peak flow forecasts particularly when potential flash-flood producing precipitation events are detected. The forecasts are forwarded to Weather Service Forecast Offices for public release in the event that the forecasted precipitation becomes reality, spawning flash floods.

The objective analysis of the value of QPF in a river forecasting environment is an area of research within the NWS. Young, et al. (1979) presented techniques to quantify the reliability of QPF estimates and the improvement needed in QPF estimates to improve river forecasts. The study results are inconclusive as the QPF estimates used in the research were generated in the early stages of QPF techniques

development and results confirm the relatively poor QPF performance at that time. The methodology formulated, however, is generalized and allows the use of any QPF values as test data. Further research is aimed at evaluating more recent QPF series in application at basins within varied climatic zones.

4.6 Operational Forecasting Hazards

One of the major hazards associated with operational forecasting is the use of a data collection network that differs from the network used for procedure development. The biases introduced through the use of a nonrepresentative network can create completely erroneous forecasts. The forecaster must continually be aware of this situation and act accordingly to rectify the inaccuracies.

The operational data networks may differ from those used in basin calibration in effective network density or station location or both. The reporting characteristics of operational network stations, in terms of reporting time-frames and reliability and of station location with respect to precipitation patterns, may detrimentally affect the computation of mean areal inputs to the runoff model, and hence, influence river forecasts. Also, the addition of aperiodic reports from spurious sources, referred to as "stranger reports," alters network characteristics. The inclusion of data from any newly instituted, regularly reporting source (e.g. - radar) introduces effects which must be considered. Whatever the cause, a change in the reporting network properties most probably will result in a computation of mean areal model inputs that are not representative of the actual events. The analysis of the degree of the effects of partial or enhanced networks is under investigation by the NWS to help river forecasters in this severe problem.

Another area of concern to the forecaster is the change in basin characteristics. The forecaster must be able to recognize when changes in basin properties, such as increased urbanization or channel scouring, cause a significant enough shift in a flood hydrograph to warrant changes in model parameters. These changes must be determined by either an intuitive estimate or by recalibration. Any estimate is heavily dependent on a forecaster's experience, whereas a recalibration can ascertain the modifications in a more objective fashion. An effective recalibration may be unattainable, however, as generally, an insufficient period of data is available to reflect altered basin properties. The solution seems to lie in the combination of both experience and objective analysis.

4.7 Evaluation of NWSRFS

The justification for the adoption of conceptual hydrologic models is well documented (WMO, 1975). An objective evaluation of the effectiveness of NWSRFS river forecasting is a much-discussed but difficult to develop analysis (Sittner, 1977). Experience at the Slidell River

Forecast Center has shown it to be especially effective in forecasting extreme events (Curtis and Smith, 1976), and the ability of NWSRFS to accurately recreate historical streamflows under a variety of hydrologic conditions was one of the fundamental reasons for its implementation as a forecasting tool. A thorough investigation of the performance of NWSRFS depends on the formulation of adequate evaluation methodology (which is being researched) and its nationwide implementation. Successful implementation implies successful basin calibrations and that process is the biggest hurdle to overcome. The final verdict on the benefits gained through the use of NWSRFS has not been delivered but preliminary feelings and findings are very encouraging.

5. Concluding Remarks

An overview of the river forecasting operations and services within the NWS has been presented highlighting the efforts being made for the improvement of products and services.

The future of hydrologic operations within the NWS has been shown to be closely linked to the advances of computer technology. Data collection techniques have extended into the realm of automatic operation of data stations; computers are communicating with computers. Satellites and their attendant computers will play a large part in data collection and information relay. Communications systems will be greatly dependent on computers for system operation and data retrieval for forecast preparation. The development and use of more sophisticated hydrologic models will also require a continued commitment to sophisticated computing machinery as an integral part of hydrologic forecast procedures.

Computers are hoped to increase the productivity of the existing work force by assuming many routine tasks now performed by NWS personnel. More effective presentation of data and improved computer guidance should provide forecasters with deeper insights into the current status of the hydrologic system enhancing their forecasting abilities.

An additional benefit derived from the computerization of NWS operations is total system-wide compatability of data. With computers storing and relaying data along all points in the overall operation, manual intervention is reduced. With the increased speed afforded by computers, forecast production can be expedited, achieving one goal of the mission of NWS - the timely release of forecasts and warnings.

It is hoped that the information presented has enlightened some readers and is sufficient to arouse interest in a few to augment their own operations through the use of NWS services. Hopefully, it will also stimulate further cooperation between external organizations and the NWS for the benefit of all water-related concerns.

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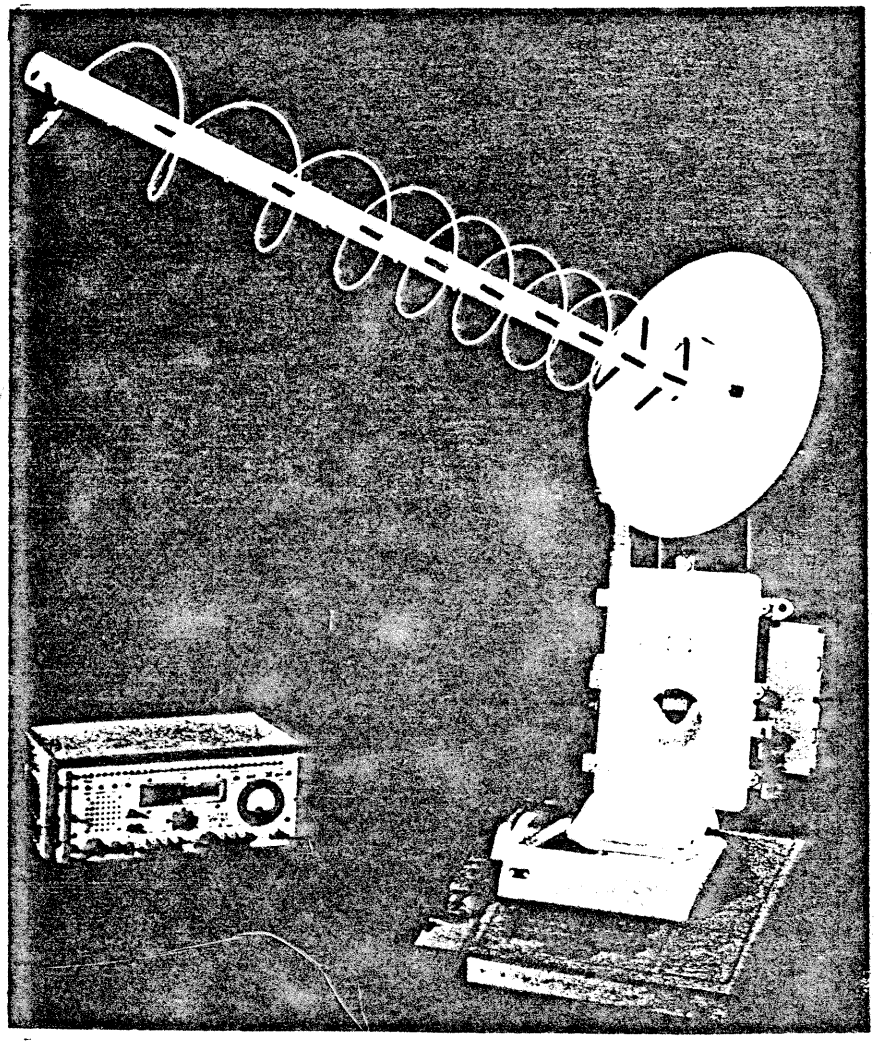


FIGURE 2.1 AHOS/S DCP depicting the antenna, radio package mounted below, test set on left and teletypewriter readout device for the user. Solar cell panel for trickle charging batteries not visible in figure.

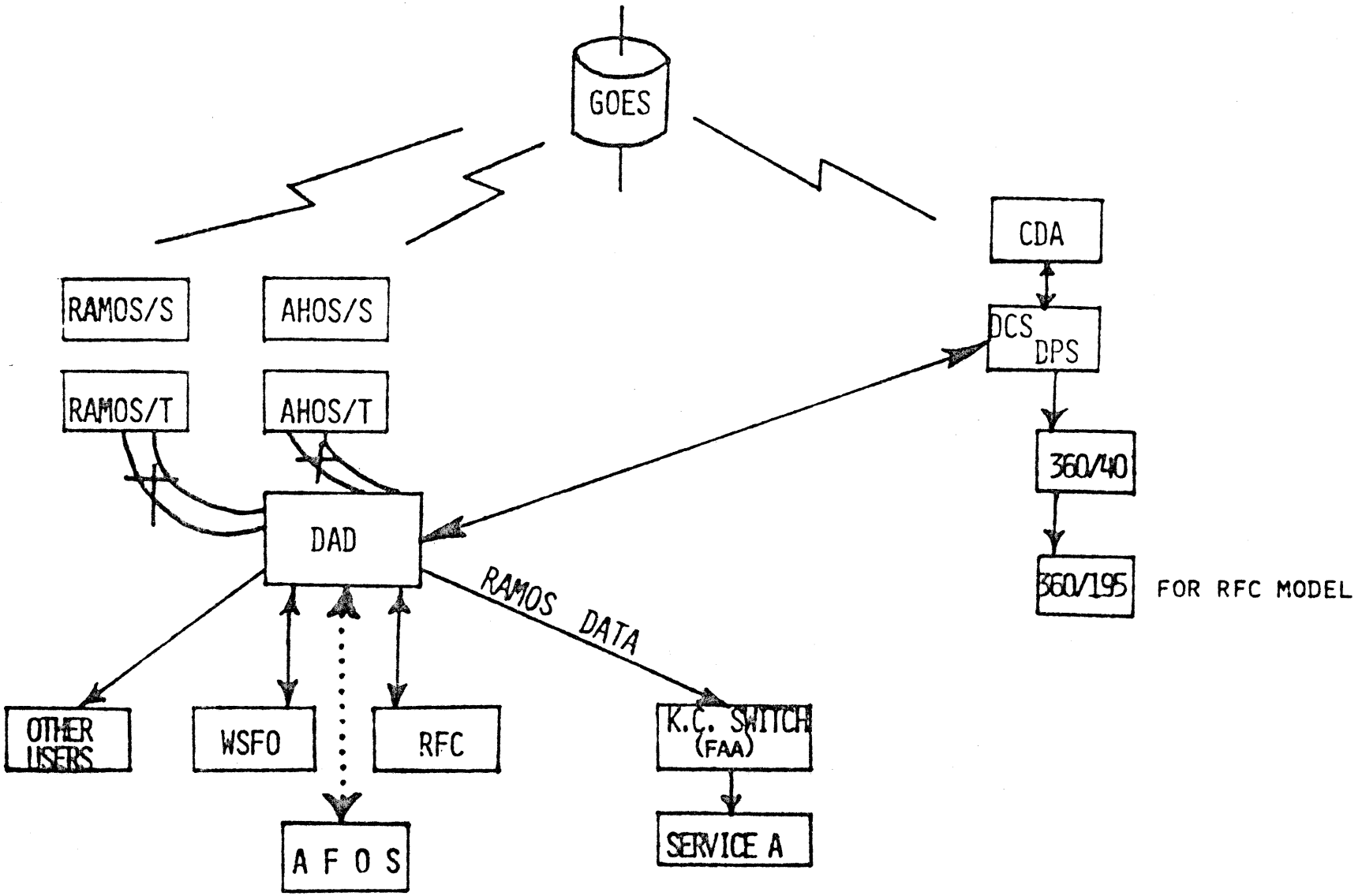


FIGURE 2.2 Proposed Data Acquisition and Dissemination System - Phase I

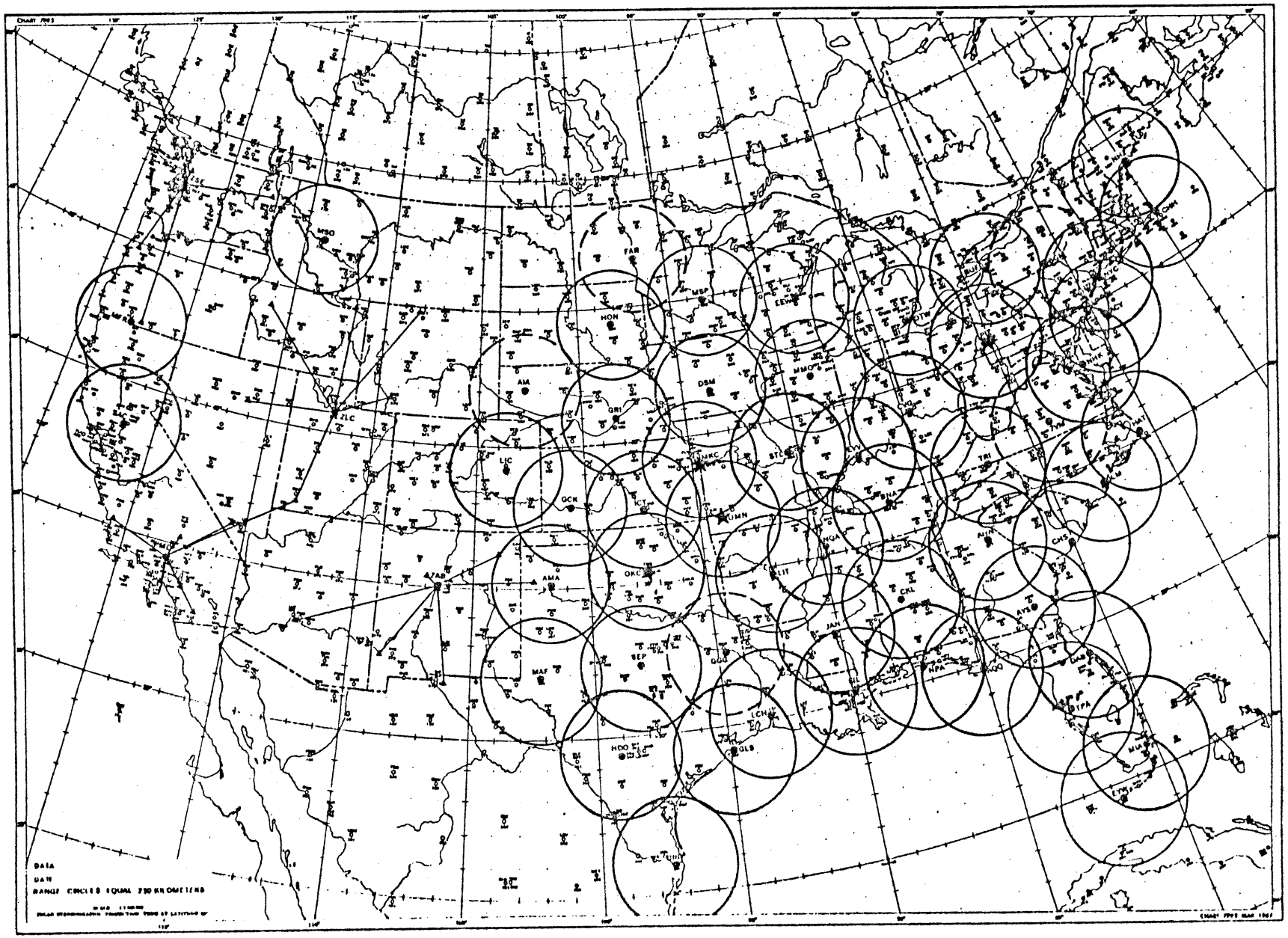
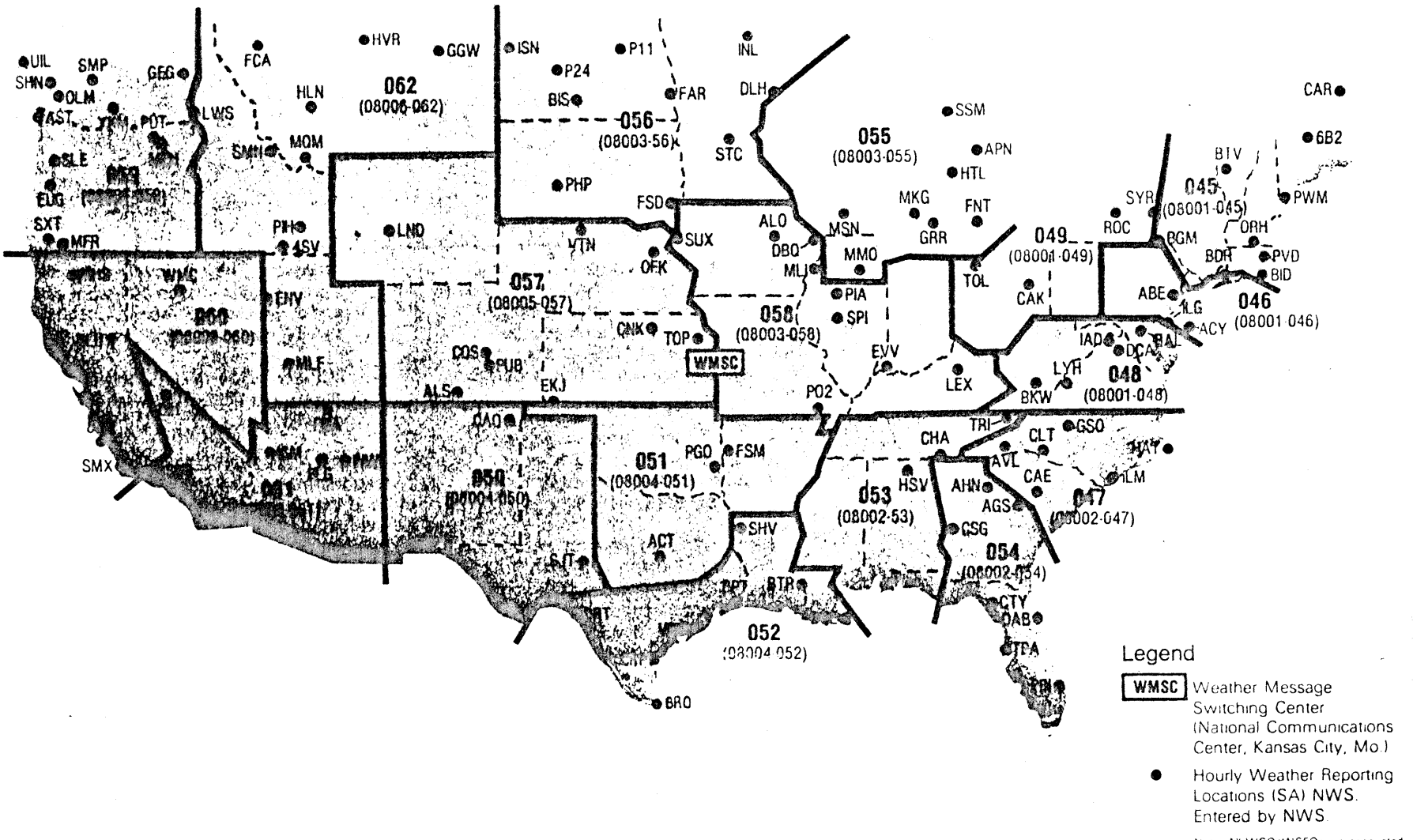


FIGURE 2.3 Weather Service Radar Sites



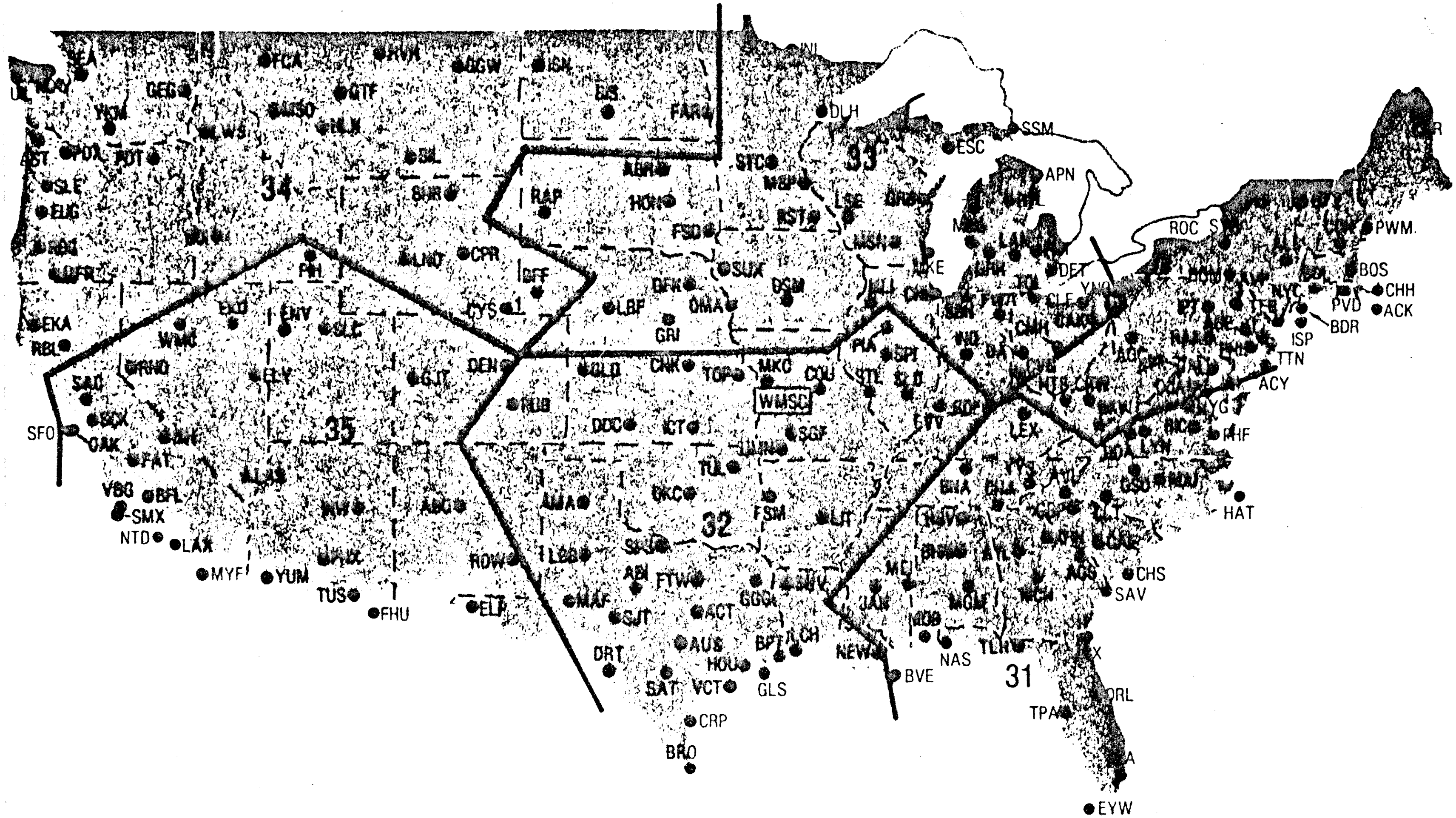
Legend

WMSC Weather Message Switching Center (National Communications Center, Kansas City, Mo.)

● Hourly Weather Reporting Locations (SA) NWS. Entered by NWS.

Note: All WSO/WSFOs are connected to these circuits. The above stations are send/receive locations.

FIGURE 3.1 Service A Teletypewriter System (NWS Circuits)



Legend

● Teletypewriter Station (Send/Receive)

WMSC Weather Message Switching Center (National Communications Center, Kansas City, Mo.)

FIGURE 3.2 Service C Teletypewriter System

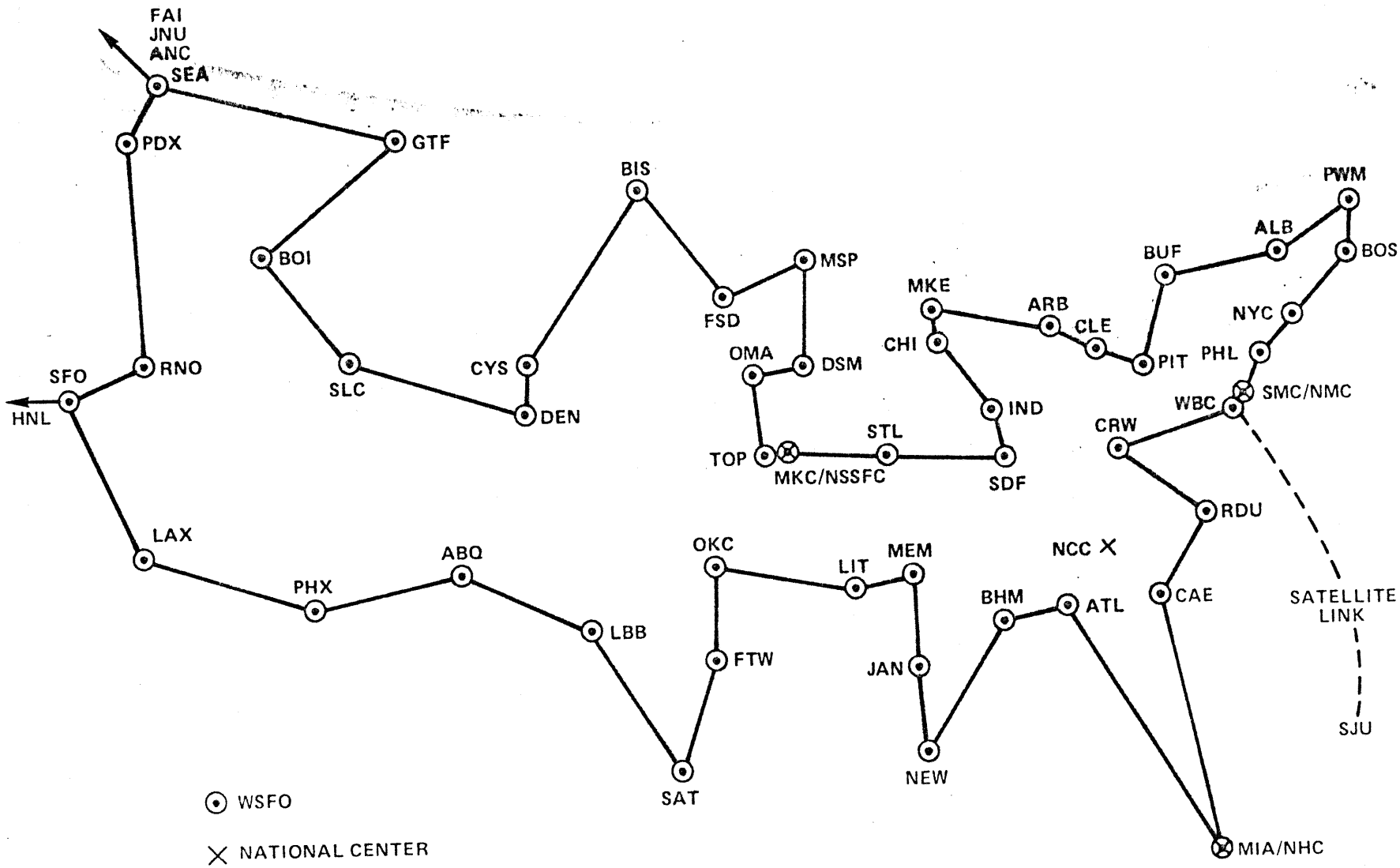
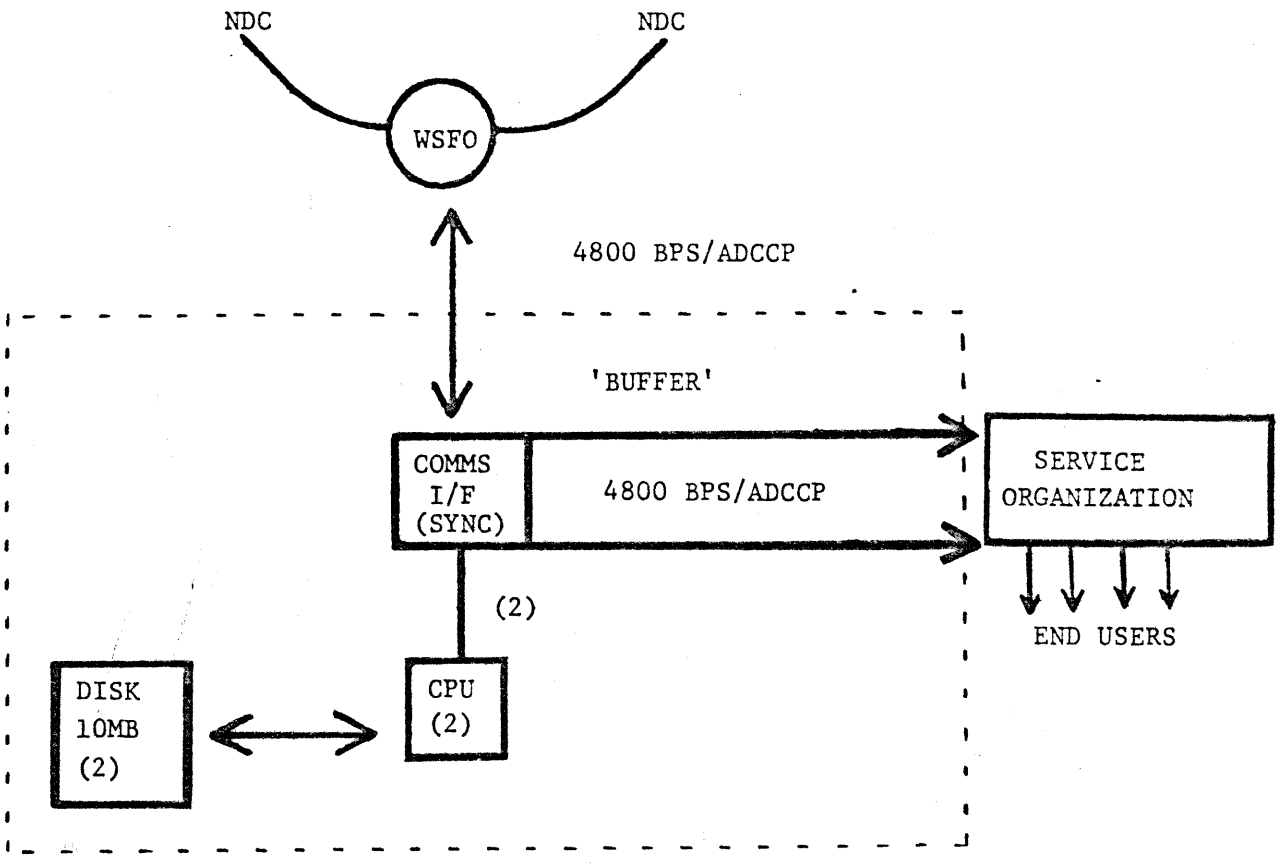


FIGURE 3.3 AFOS National Distribution Circuit



Other Functional/Operational Characteristics

- All Service Organizations receive same 'Data Stream'
- Data Transmitted By Priority As Complete Message

ACRONYMS:

ADCCP:	Advanced Data Communications Control Protocol
BPS:	Bits Per Second
COMMS I/F:	Communication Interface
CPU:	Central Processing Unit
NDC:	National Distribution Circuit
SMCC:	System Monitoring And Coordination Center
SYNC:	Synchronous
WSFO:	Weather Service Forecast Office
10MB:	Ten Megabyte

FIGURE 3.4 Proposed AFOS Buffer System Design

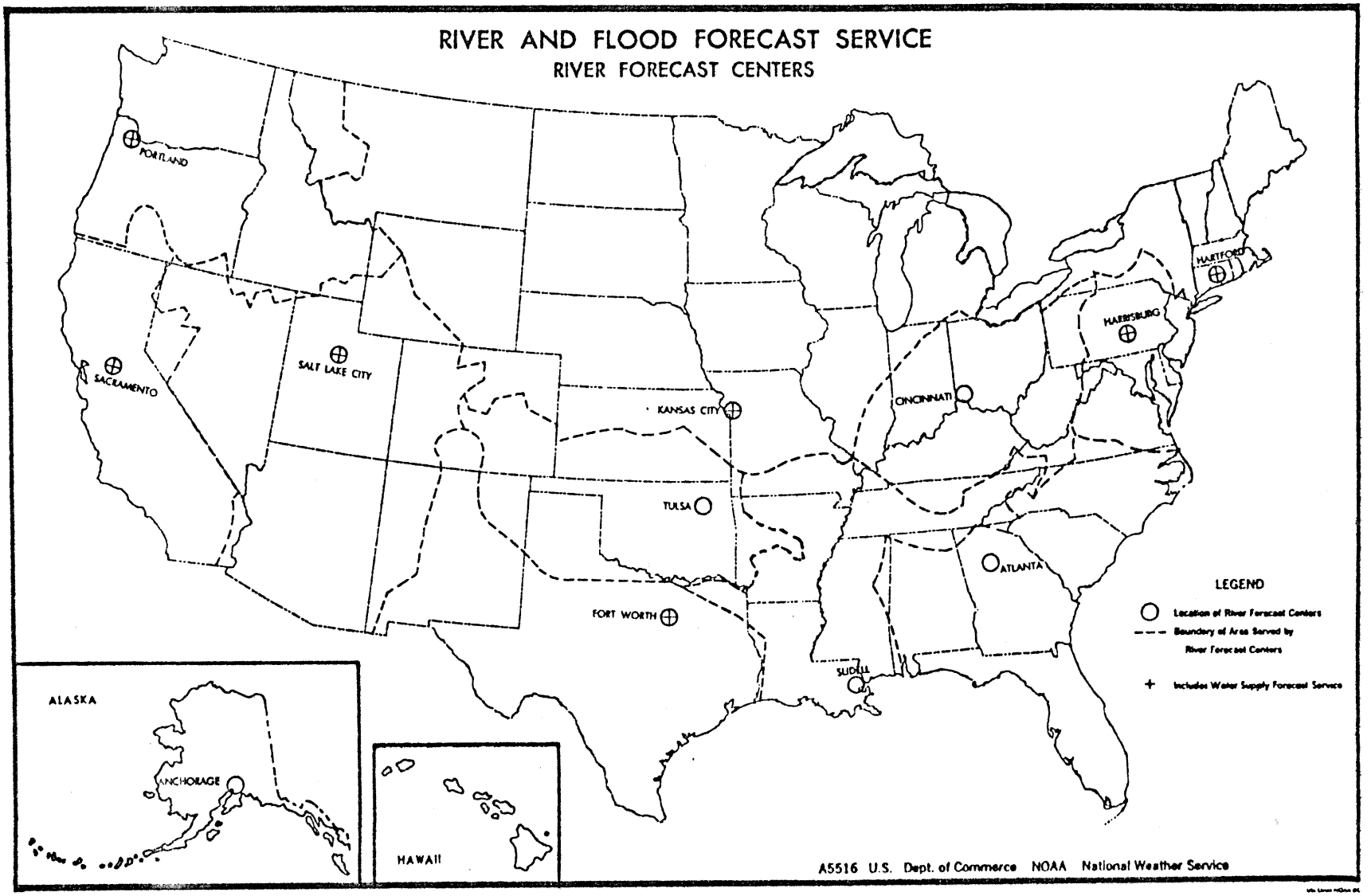


FIGURE 4.1 River Forecast Centers

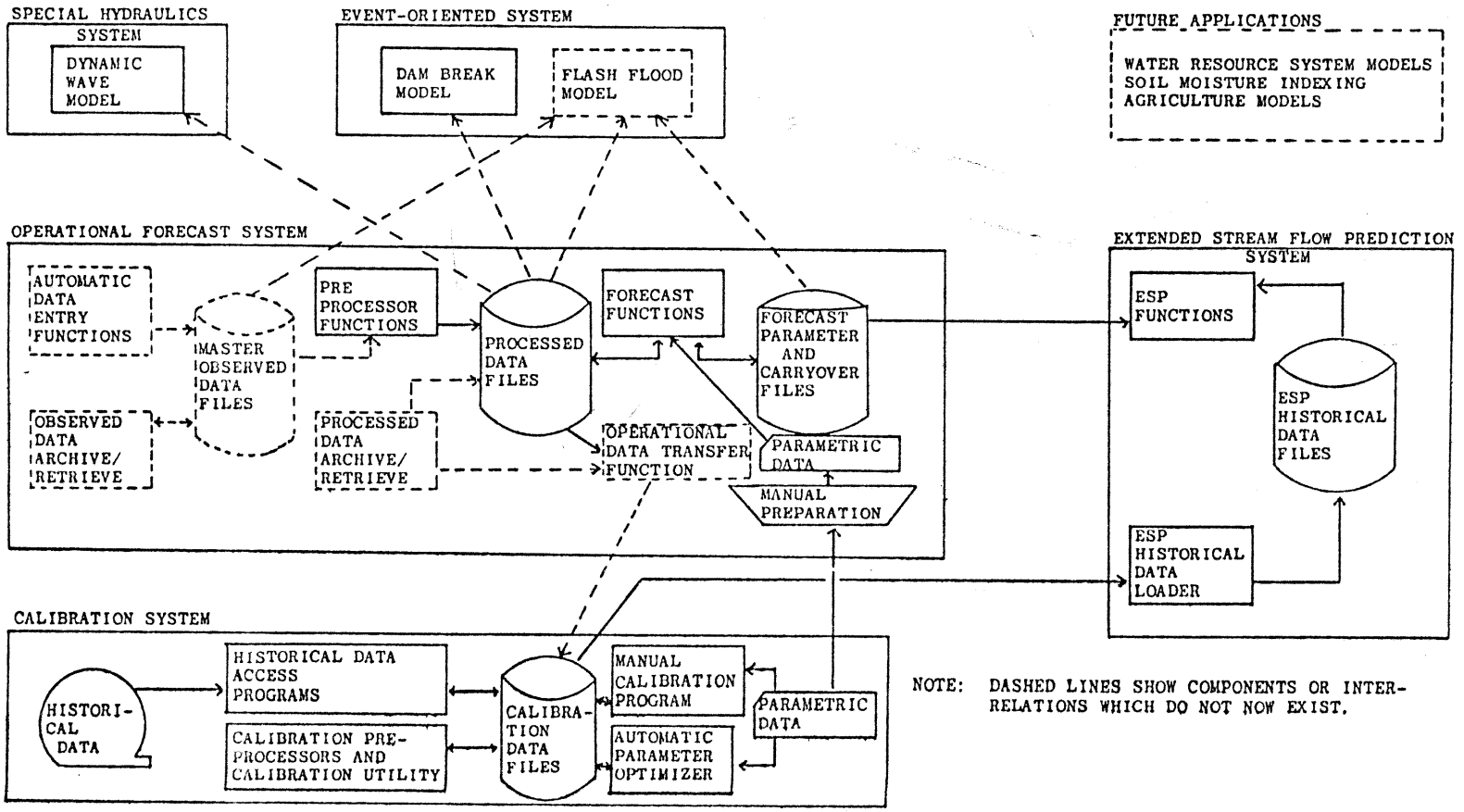


FIGURE 4.2 NWSRFS Software Overview

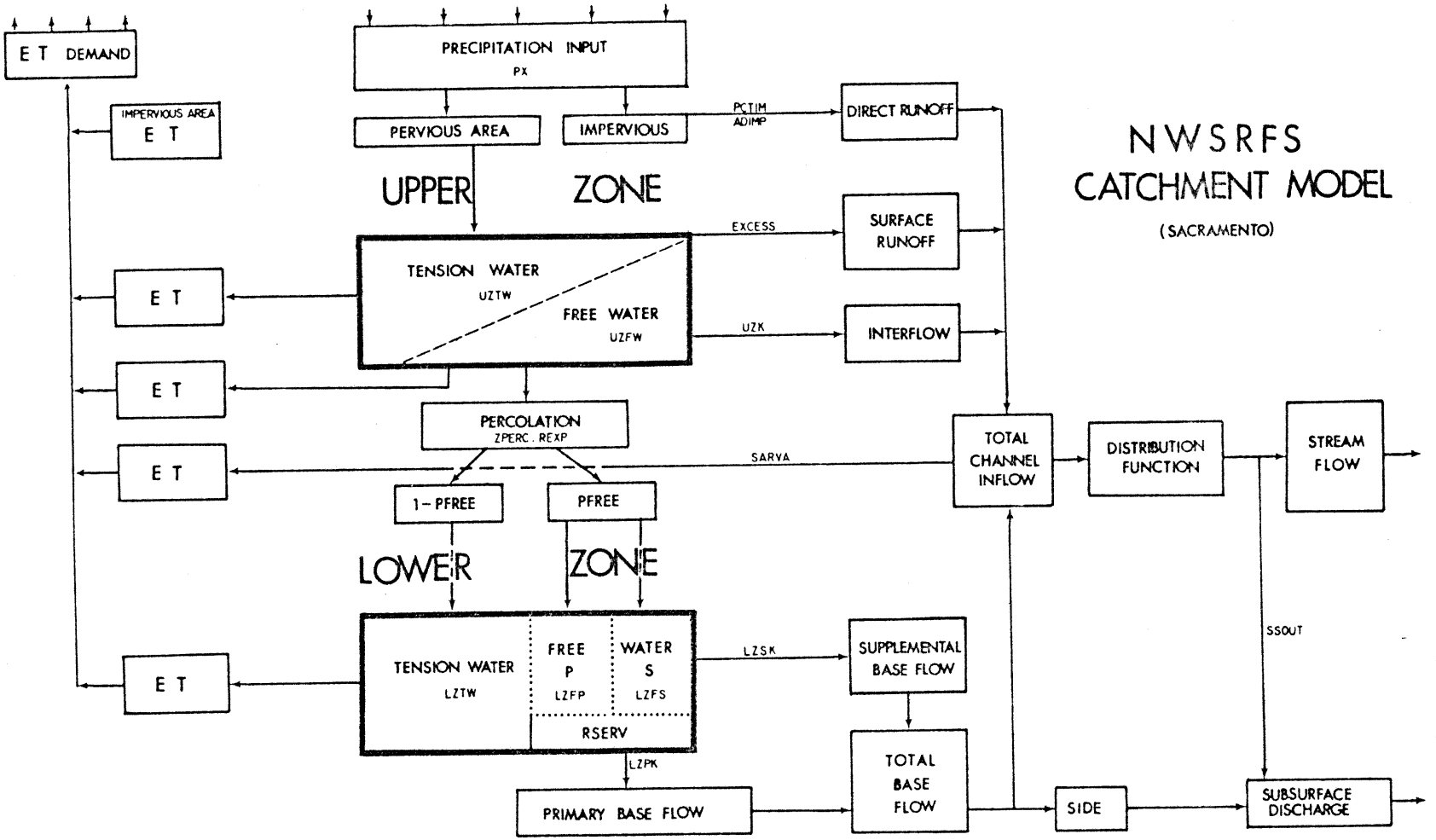


FIGURE 4.3 NWSRFS Sacremento Catchment Model

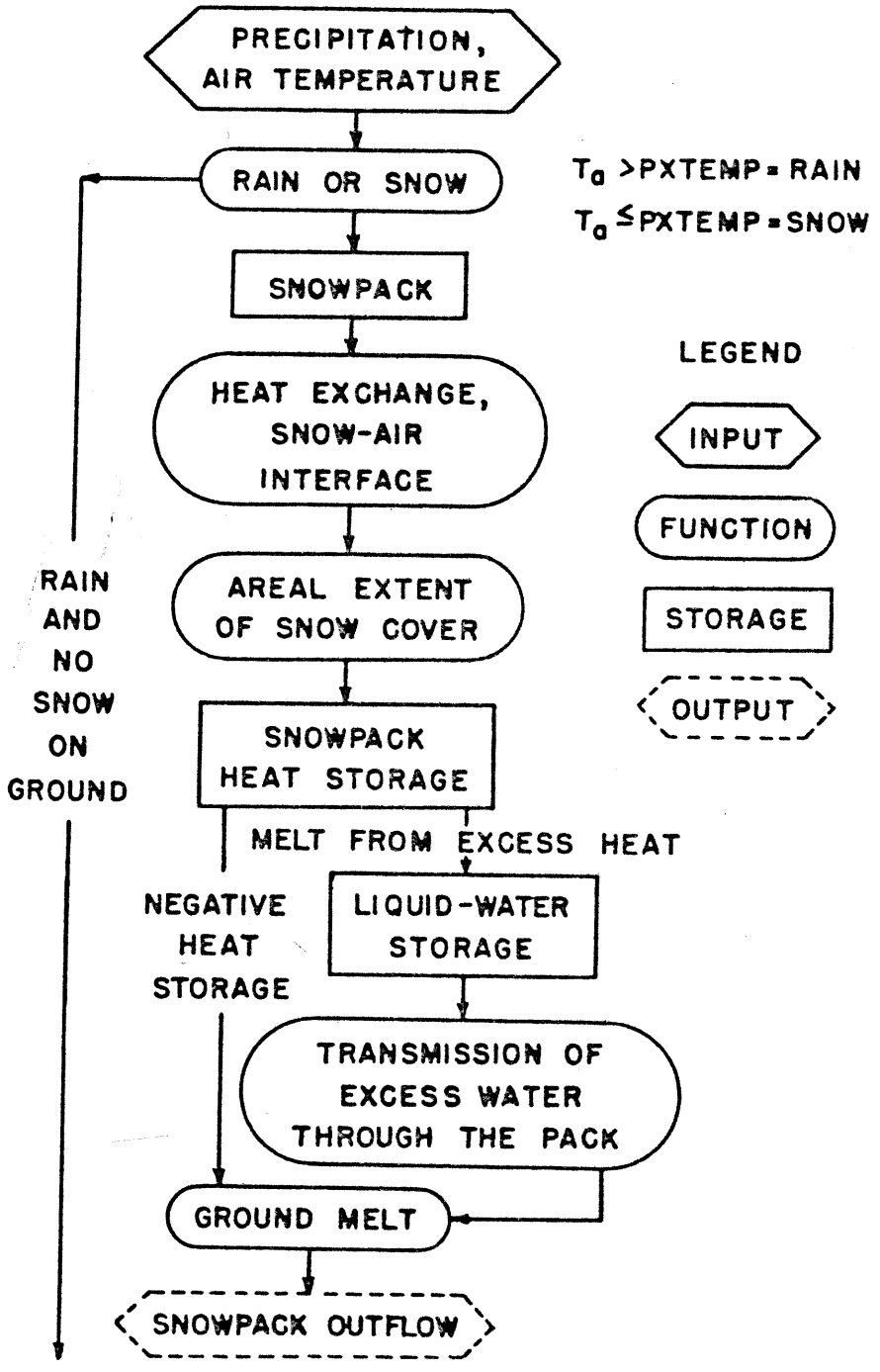


FIGURE 4.4 Flow Chart of Snow Accumulation and Ablation Model

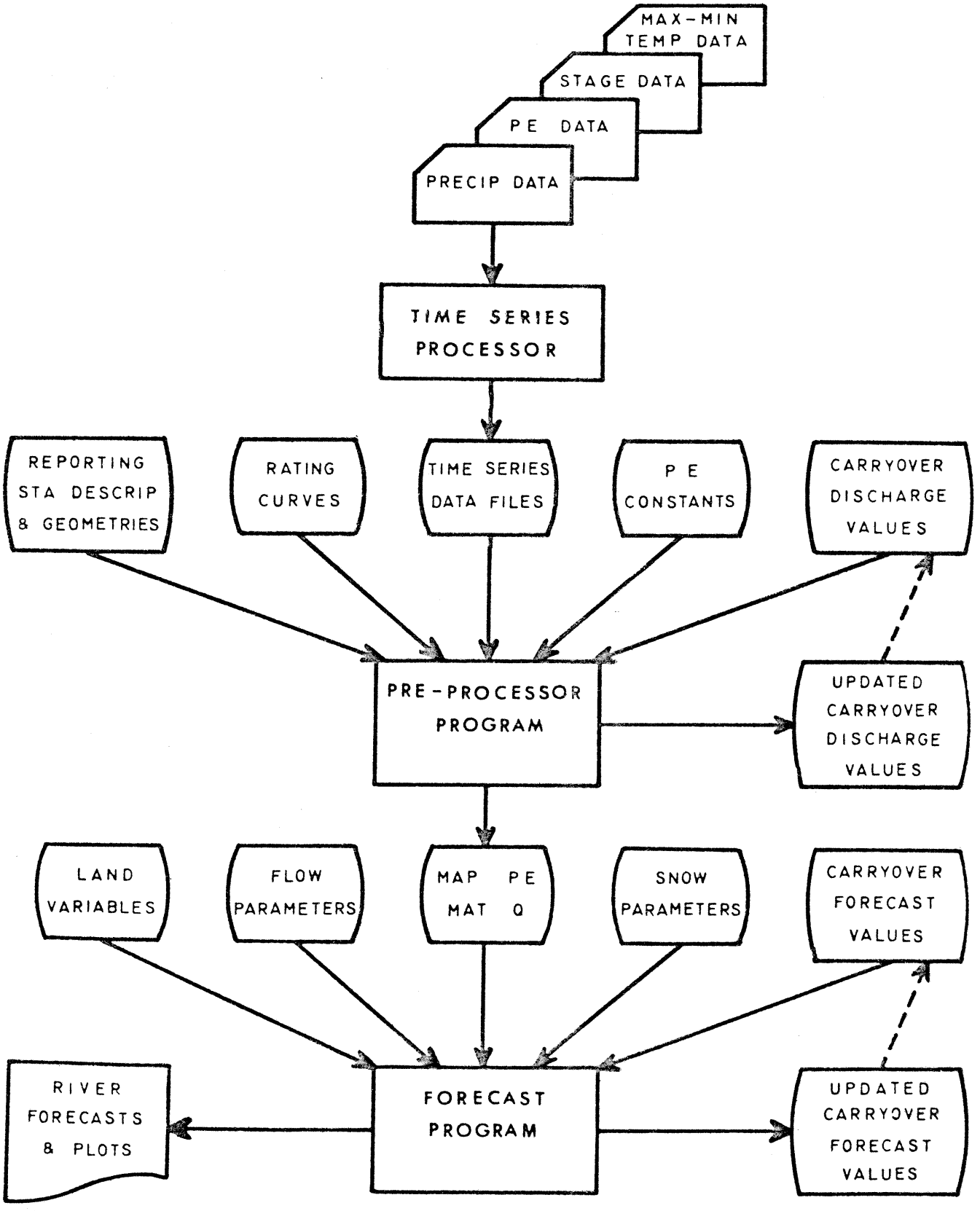


FIGURE 4.5 NWSRFS Catchment Operational Program

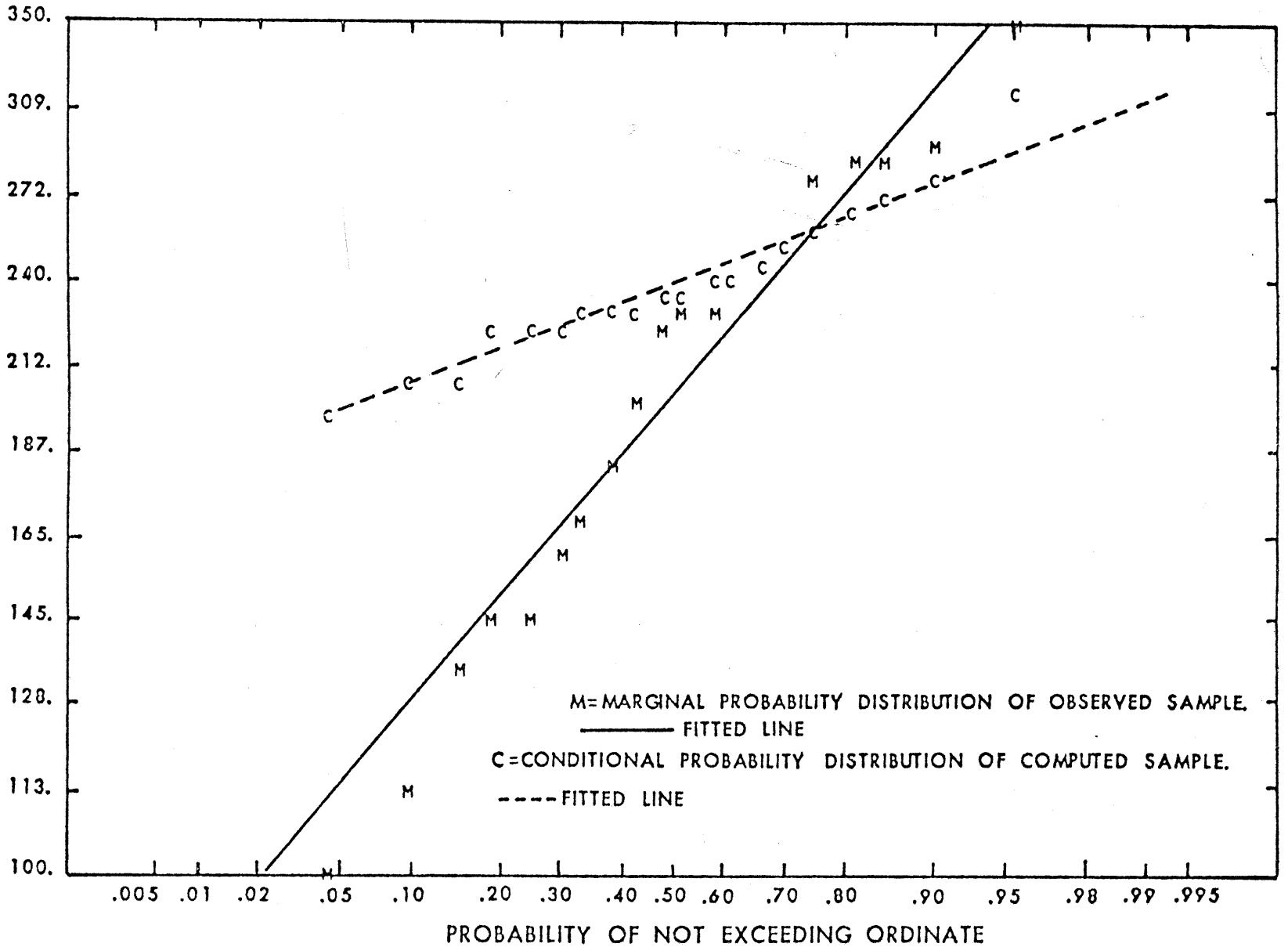


FIGURE 4.6 Marginal and conditional probability distribution plots for Eagle River total volume of flow (thousands acre-feet) during May and June 1971, predicted as of May 1, 1971.

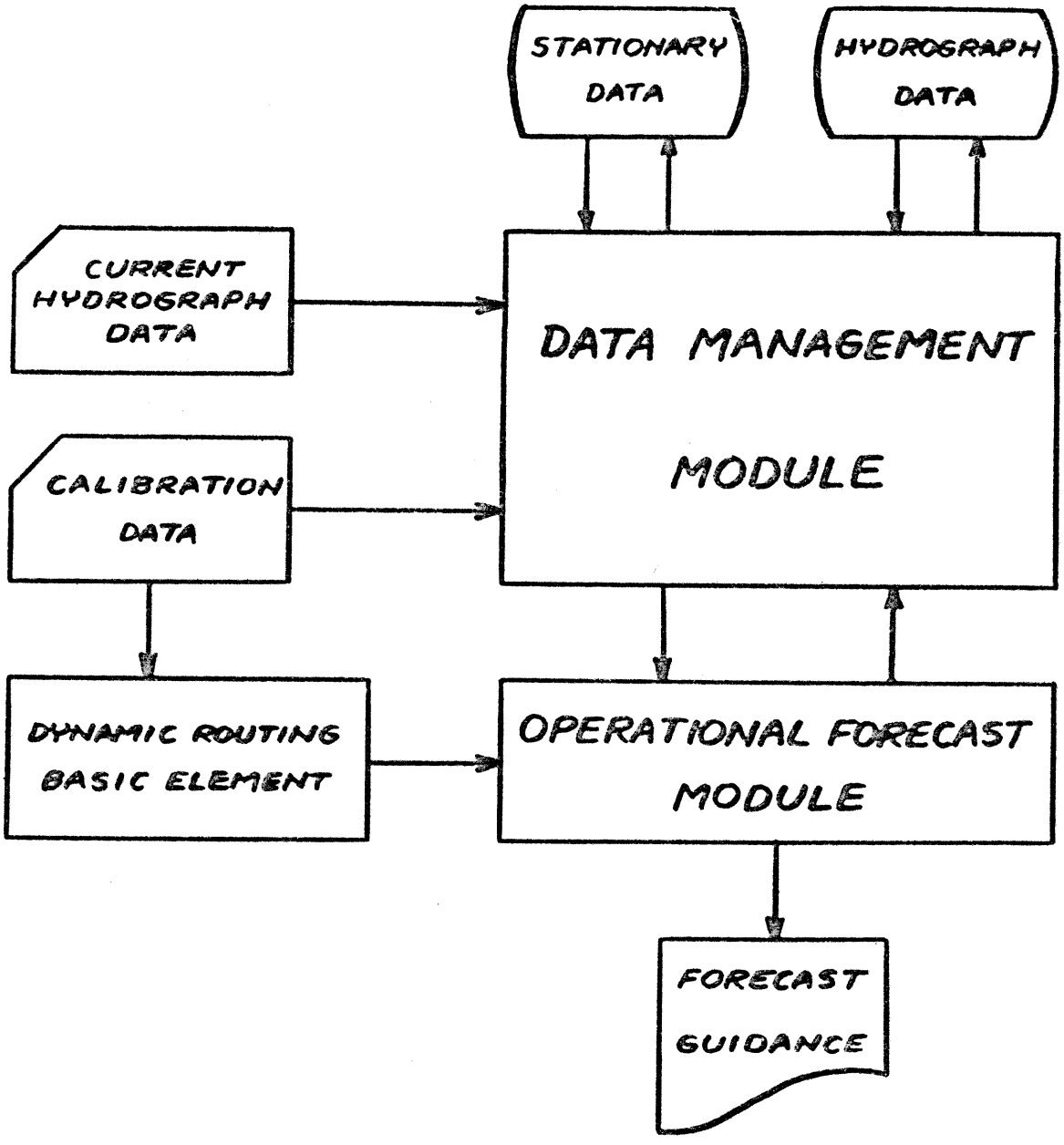


FIGURE 4.7 Operational Dynamic Wave Forecast Program