AWRA International Symposium
on Hydrometeorology,
Denver, CO, June 1982

TECHNOLOGICAL DEVELOPMENTS IN HYDROLOGIC FORECASTING WITHIN THE U.S. NATIONAL WEATHER SERVICE

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Abstract. The hydrologic components of the National Weather Service (NWS) consist of: elements in the NWS Regional Offices; groups at National headquarters [including the Hydrologic Research Laboratory (HRL), the Hydrologic Services Division (HSD), and the Water Management Information Division (WMID)] located in Silver Spring, Maryland; River Forecast Centers (RFC's) located across the United States; and service hydrology functions located in most of the Weather Service Forecast Offices (WSFO's). The total NWS Hydrologic Program spans applications and scales ranging from those associated with the issuance of flood and flash-flood warnings to those associated with seasonal water-supply forecasts. New technological developments underway, or planned, for the NWS Hydrologic Service are carried out as a combined effort by headquarters and field personnel. These developments basically fall into two categories — hardware and software data systems technology and hydrologic analysis and prediction technology. This paper will discuss research and development in progress in both of these categories. There are projects currently underway in the following areas: real-time acquisition of hydrometeorological data (including digital radar data), network design studies, multivariate rainfall analyses, precipitation-runoff modeling systems, river mechanics and reservoir operations, extended streamflow prediction techniques, model calibration procedures, and the application of estimation theory to optimize the use of available data in updating model states. The salient aspects of these various research and development projects will be discussed and the technological implications for the NWS Hydrologic Service Program of the future will be highlighted.

CONTENTS

1. BACKGROUND

History and Structure of the NWS Hydrologic Program. The Hydrologic Program of the Weather Bureau was born during the early development of the Federal weather services. Joint Congressional Resolution H.R. 143 of February 2, 1870, established the Weather Service and assigned it to the Signal Corps of the War Department. The Congressional Organic Act of October 1, 1890, assigned to the Weather Bureau the duties of "...the forecasting of weather, the issuing of storm warnings, the display of weather and flood signals for the benefit of agriculture, commerce, and navigation, the gauging and reporting of rivers..." In July 1891, the Weather Service was transferred from the Signal Corps to the Department of Agriculture, and the Weather Bureau was established.

In 1937, the Hydrometeorological Research Branch of the Weather Bureau was established, and the United States was subdivided into hydrologic regions for the purpose of procedural development, including analyses of rainfall-runoff relationships. Reorganization Plan No. IV of June 30, 1940, transferred the Weather Bureau from the Department of Agriculture to the Department of Commerce. Formation of the first River Forecast Centers (RFC's) with geographic areas of responsibility defined as they are today began in 1946 with the establishment of two RFC's, staffed by professional hydrologists, to prepare river and flood forecasts and to develop and refine hydrologic forecast procedures for these areas. During this same period, the river and flood service and the climate and crop weather service were consolidated into the Division of Climatological and Hydrologic Services. This consolidation was terminated in September 1951, with the establishment of the Hydrologic Services Division and the Climatological Services Division. The Hydrologic Services Division was expanded to the Office of Hydrology in 1964.

The Weather Bureau, which became part of the Environmental Sciences Services Administration (ESSA) when ESSA was formed in 1965, still resides within the Department of Commerce. ESSA became the National Oceanic and Atmospheric Administration (NOAA) in 1970, and at that time the Weather Bureau once again became known as the Weather Service (actually the National Weather Service-NWS). NOAA continues as the parent agency of the NWS.

Figure 1 illustrates the basic organizational structure of the current NWS Hydrologic Program. The scope of research and development (R&D) has been expanded somewhat from that described in the original charter of the Hydrometeorological Research Branch and is achieved through a combined effort between headquarters and field components. The principal goal of the R&D effort is to produce and implement improved hydrologic forecasting technology at the 13 RFC's (12 distributed across the lower 48 contiguous states and one located in Alaska; see Brazil and Hudlow, 1980, for a more precise description of the RFC locations and areas of forecast responsibility) and the Weather Service Forecast Offices (WSFO's). There are approximately 50 WSFO's located across the country, with at least one in most states [NOAA-NWS, 1981]. In addition, there are usually several smaller offices, the Weather Service Offices (WSO's) in each state which contribute to the Hydrologic Service Program through the collection of hydrologic data and/or the dissemination of forecasts and flood warnings in their area of responsibility.

The Hydrologic Research Laboratory (HRL) comprises the nucleus of R&D resources available to the NWS Hydrologic Service Program for developing new technology in support of field operations. The Hydrologic Services Division (HSD) coordinates requirements for new technology and carries out implementation and maintenance of both hardware and software systems. The overall responsibility for execution of the NWS hydrologic program, including its

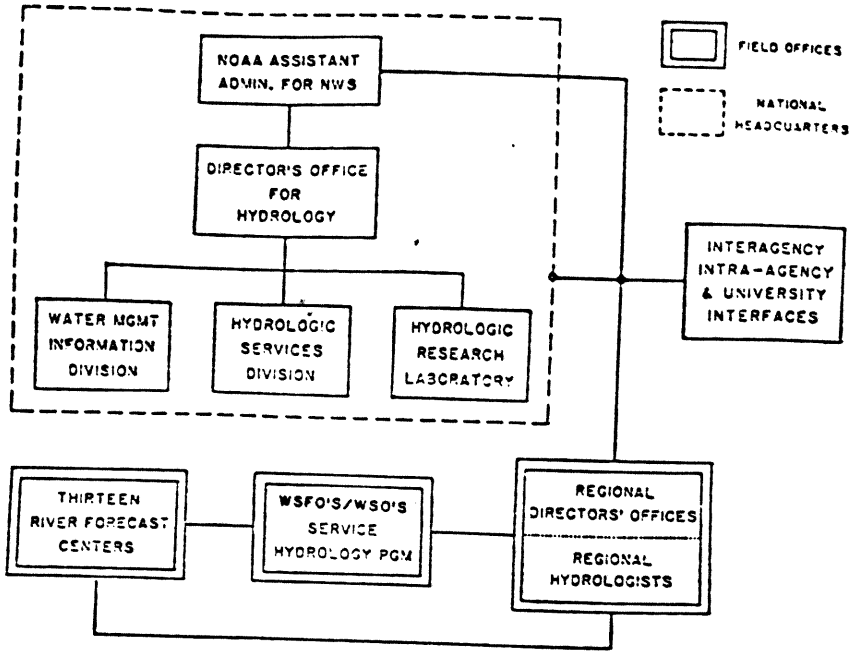

Figure 1. Basic organizational structure of the current NWS Hydrologic Program.

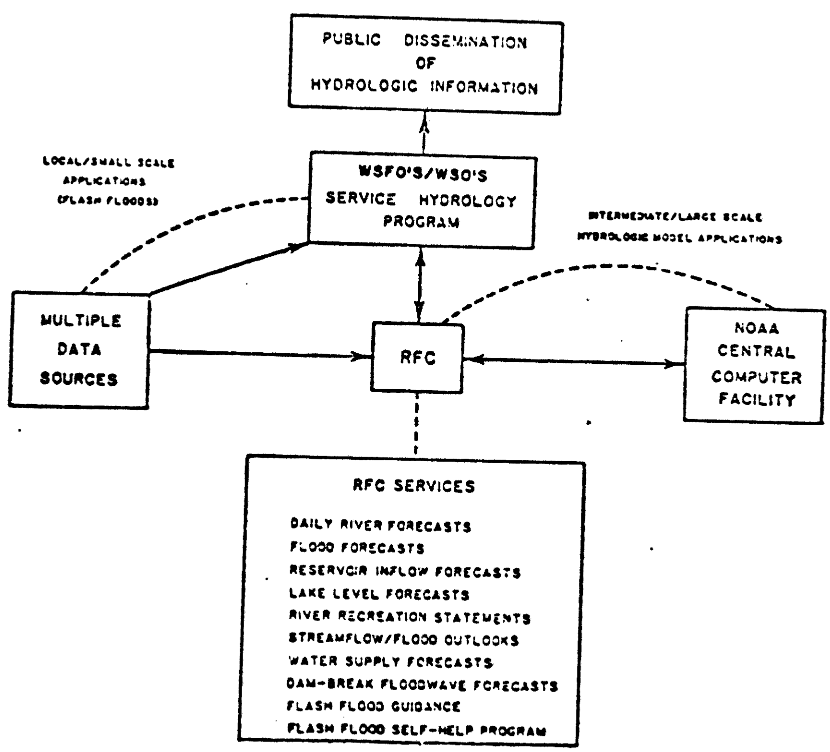

Figure 2. Principal facilities and services of the NWS Hydrologic Service Program.

technical direction, rests with the NWS Director for the Office of Hydrology, Overall management of the hydrologic program within each of the NWS regions is the responsibility of each Regional Hydrologist.

The RFC's have one or more procedural development hydrologist(s) who are involved in the development, implementation, and maintenance of operational systems. Active participation by the RFC staff in the overall development effort is not only desirable but essential, especially in the current era of rapidly accelerating hardware and software technology. Today's NWS RFC hydrologists are highly skilled professionals with expertise in data and computer systems as well as hydrologic procedures. Also, most WSFO staffs include one, or occasionally more, service hydrologist(s) who must be cognizant of data acquisition and forecast dissemination systems, as well as hydrologic procedures for their area.

Staffs of the Scientific Services Divisions (SSD's) attached directly to the Regional Directors' Offices within the Regional Headquarters (figure 1) complement the technological development and implementation activities of the NWS at the regional level. The SSD's generally focus their attention on meteorological forecasting activities, although they have developed some techniques of importance to the hydrologic forecaster; for example, improved techniques for using radar data to estimate rainfall [Moore and Smith, 1979; Mathewson, 1980] and procedures for deriving Quantitative Precipitation Forecasts (QPF's).

Hydrologic Forecasting System Considerations. Figure 2 illustrates the various products and services provided by the NWS Hydrologic Service Program and the interactions between the various offices and computer facilities. Each RFC is equipped with a gateway minicomputer (except the Alaska RFC which has a super minicomputer) that is used for data communications, limited procedural development, and backup to the remote-job-entry (RJE) function of the Automated Field Operations and Services (AFOS). AFOS, which is the primary NWS communication and display system [Klein, 1978; NOAA-NWS, 1978a; NOAA-NWS, 1981], also includes one or more minicomputers. All RFC's and WSFO's are equipped with AFOS facilities. Almost all of the RFC's use the RJE and a dedicated high-speed line to access the IBM 360/195 computers located at NOAA's Central Computing Facility (CCF) in Suitland, Maryland (figure 2), where most of the hydrologic computations are performed. Hydrometeorological data from various sources flowing over AFOS and through the RFC gateway computers (along with some manually entered data) are combined with data from other sources at the CCF where they are processed for input to the hydrologic prediction procedures and models. It is planned that the on-site computer resources at all RFC's will be increased some time in the future to include capabilities equivalent to those provided by an interactive super minicomputer with color graphics display, although such enhancements may not be possible until the late 1980's or early 1990's as part of the next generation AFOS system (System II) [NOAA-NWS, 1982]. In the interim, enhancements to the RFC gateway minicomputers and the NOAA CCF will continue to provide adequate computing resources with some improvements in the 1980's beyond the 1970's capabilities. Also, a computer prototype system for future RFC operations will undergo further development and testing at NWS Headquarters. Regardless of what the future holds in the way of RFC computer facilities, the NOAA CCF always will remain a critical resource for the RFC's because of the vast amounts of hydrometeorological data and products that must be shared in a distributed computational fashion among central and RFC computers.

As illustrated in figure 2, the RFC's prepare numerous service products spanning applications and scales ranging from those associated with flash-flood guidance information to those associated with water supply forecasts. The RFC products are used by many sectors of government, private industry, and the general public. Public dissemination of hydrologic forecast information is the responsibility of the WSFO's and WSO's. In addition, the primary responsibility for actual identification and warning for flash-flood conditions rests with the WSFO's and WSO's because of the hydrometeorological nature and associated short-time scales of flash floods. The RFC's also have designated flash-flood hydrologists who provide technical assistance for community/local flood warning systems. For a further description of the relationships and interactions between the hydrologic and meteorological components of the NWS, see Clark (1977) and NOAA-NWS (1981). Ostrowski (1979) provides a good overview through 1979 of the NWS Hydrologic Program including data collection, information distribution, and forecast methods.

Until the late 1960's and early 1970's, each RFC generally had been solely responsible for establishing and maintaining its own river forecast system, although various procedures implemented by the RFC's may have been developed by Headquarters personnel or personnel at other RFC's. Around this time, the NWS adopted a policy to attempt to establish a National forecast system framework which would be common to most, if not all, RFC's. This new policy resulted in the birth of what is termed the NWS River Forecast System (NWSRFS). The initial focus for NWSRFS was centered on the premise that if one physically-based conceptual model could be adopted in lieu of an Antecedent Precipitation Index (API) type method [Linsley et al., 1982, p.242], to relate runoff to rainfall, then hopes for achieving a common framework would be heightened. Schaake (1976) discusses some of the advantages of conceptual rainfall-runoff models.

The initial version of NWSRFS, which incorporated a modified version of the Stanford IV Model [Crawford and Linsley, 1966], was completed in 1971 [Hydrologic Research Laboratory Staff, 1972]. A snow accumulation and ablation model was added to NWSRFS in 1973 [Anderson, 1973]. Subsequent testing, as part of a World Meteorological Organization project to intercompare several watershed models, led to the decision to replace the Stanford Model with the Sacramento Model [Burnash et al., 1973] in 1974.

Much was learned from the initial versions of NWSRFS. It became clear that greater modularity, flexibility, and hydrologic capabilities were essential if indeed NWSRFS was to become the basic framework for a National forecast system. A new forecast system design was needed for which hydrologic procedures developed by HRL and/or the RFC's, or anyone else, could be readily incorporated to handle the common requirements among RFC's as well as unique requirements within a given RFC's area. Also, considerable care had to be given in the design of this new system to efficient computer software and comprehensive program documentation. This new version of NWSRFS should allow the flexibility, for example, to include both conceptual and API type relationships, leaving the user to decide which rainfall-runoff modeling technique is most appropriate in a given location and situation.

During the past 3 years, headquarters and field personnel have undertaken a major redesign and development effort for what will become Version 5 of the Operational Forecast Program (OFP) of NWSRFS (figure 3). The OFP of NWSRFS should not be thought of as a model. It is, in fact, composed of: (1) a system of models; (2) utility programs and data entry, preprocessing, and processing modules required to establish and maintain data files and assemble

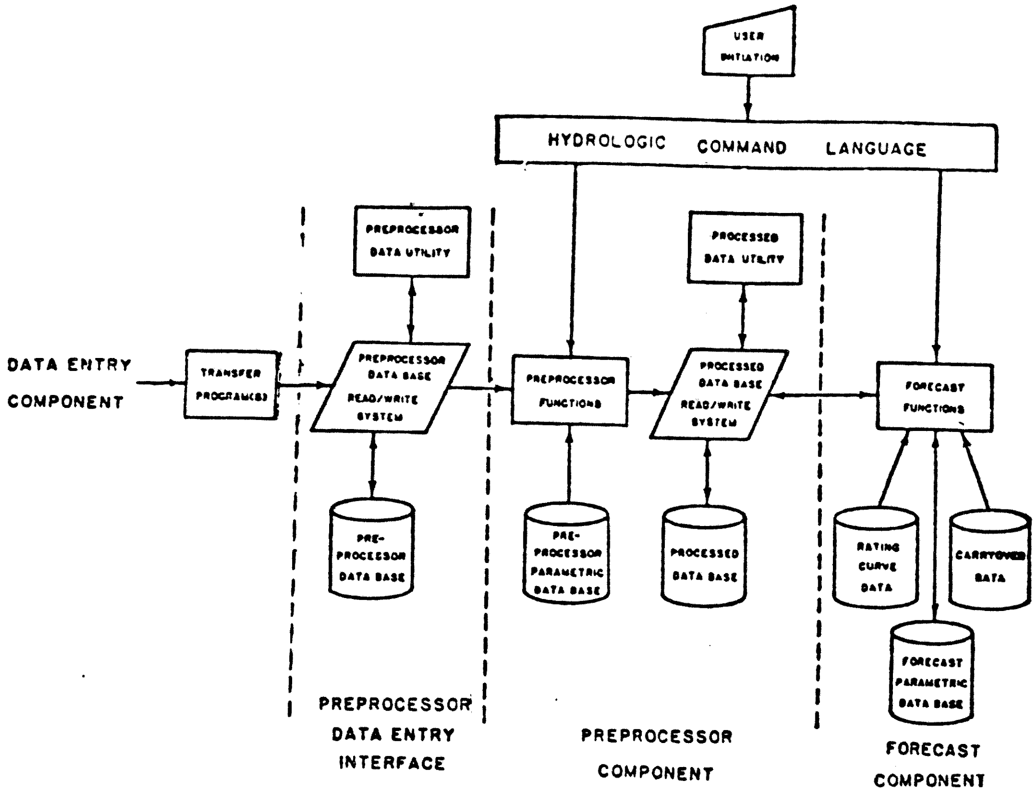

Figure 3. Basic structure and modules for Version 5 of the OFP of the NWSRFS

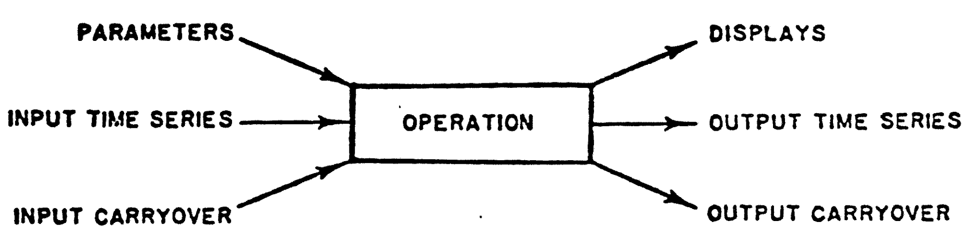

Figure 4. Possible inputs and outputs for an NWSRFS Forecast Component operation.

and prepare data; and (3) an overall Hydrologic Command Language (HCL) which provides the forecaster with the necessary flexibility for specifying forecast instructions and options to control, in the desired sequence, the execution of the various functions or programs linked to HCL. NWSRFS Version 5 is being designed for continuous river forecasting down to hourly time scales, although most RFC's currently do not forecast for time periods shorter than 6 hours.

Most, if not all, conventional data for input to NWSRFS will be communicated from various data systems in the Standard Hydrologic Exchange Format (SHEF) [Attendees at Jan. 11-15 Hydrologic Data Entry Planning Meeting, 1982; NWRFC, 1982]. The adoption of SHEF is a major step forward in standardization of data exchange formats. SHEF should facilitate intra- and interagency exchange of data and the creation of a National hydrometeorological data base, consisting of data originating from a variety of sources, which can be accessed efficiently within NWSRFS and for other uses.

At the heart of the latest design of the Forecast Component of NWSRFS is a system framework, called an operations table, which allows hydrologic procedures (operations) to be performed in a user-specified sequence. Any of the following can be classified as an operation: a hydrologic/hydraulic model, an updating or verification procedure, an arithmetic computation, or a display. Figure 4 illustrates the possible basic inputs to and outputs from an operation. All types of inputs and outputs do not apply to all operations. For example, not all operations require carryover values consisting of information that must be saved from previous forecast run(s) for use in subsequent forecast run(s). Table 1 lists the operations that are planned for NWSRFS Version 5. See Anderson (1980) for a more complete description of Forecast Component operations and their use.

Table 1. Operations planned for Forecast Component of NWSRFS Version 5.

HYDROLOGIC/HYDRAULIC MODELS

API/MKC -- Antecedent Precipitation Index Rainfall-Runoff Model for the Missouri Basin and North Central RFC's
SAC-SMA -- Sacramento Soil Moisture Accounting Model
CLS -- Constrained Linear System Rainfall-Runoff Model
UNIT-HG -- Unit Hydrograph Operation
SNOW-17 -- HYDRO-17 Snow Accumulation and Ablation Model
LAG/K -- Lag and K Routing
LAY-COEF -- Layered Coefficient Routing
MUSKROUT -- Muskingum Routing
TATUM -- Tatum Routing
DWOPER -- Dynamic Wave Operational Model
CHANLOSS -- Empirical Channel-Loss/Gain Routine
CHANLEAK -- Conceptual Channel Loss/Gain Routine
STAGE-Q -- Converts River Stage to Discharge or Vice-Versa
RES-SNGL -- Single Reservoir Control Operation

UPDATING AND VERIFICATION PROCEDURES

ADJUST-Q -- Adjust Simulated to Observed Discharge and Blend into Future
CHAT -- Computed Hydrograph Adjustment Technique
SACFIL1 -- Estimation Theory (Kalman Filter) Formulation of the SAC-SMA and UNIT-HG for Lumped, Non-Snow, Headwater Basins
STAT-OP -- Statistical Package for Measuring NWSRFS Effectiveness

ARITHMETIC COMPUTATIONS

ADD/SUB -- Add or Subtract Time Series
CLEAR-TS -- Clear Time Series
WEIGH-TS -- Weight Time Series
CHANGE-T -- Change Time Interval of a Time Series
MEAN-Q -- Computation of Mean Discharge for Specified Time Interval

DISPLAYS

INSQPLOT -- Plots Instantaneous Discharge Time Series
WY-PLOT -- Water Year Mean-Daily Flow Plot
SAC-PLOT -- Sacramento Type Mean-Daily Flow Plot
PLOT-TS -- General Time Series Plotting Utility
PLOT-TUL -- Time-Series Plotting Routine Specifically Designed for Real-Time Operational Forecasting
STAT-QME -- Computes Statistical Summary of Mean-Daily Discharge

Note: The 21 operations designated *in italics* are complete as of this writing.

The operations table is the list of operations and the order in which they are being performed. A group of operations performed as a unit is called a segment. A segment normally includes the operations necessary to compute the flow at a forecast point. Carrying the concept further, to encompass a large river system with many forecast points, a forecast group is defined as a set of segments and a carryover group as a set of forecast groups all to be executed in a specified order. A forecast run could consist of the execution of a single segment or groups of segments. Figure 5 illustrates the operations from table 1 used in applying the operations table concept to an example segment.

The operations table concept not only provides great flexibility, so that the forecaster can choose the appropriate hydrologic and hydraulic procedures to be used for each segment associated with a river system for real-time river forecasting, its modular framework allows new procedures to be added to the OFP ~~system~~ with a minimum of difficulty. This should shorten considerably the time required to implement new hydrologic forecasting technology and increase the opportunity for pertinent new procedures to be incorporated into the system regardless of who developed them or where they were developed. Similarly, the Preprocessor Component for Version 5 is being designed with considerable flexibility although not with the level of flexibility inherent in the operations table concept for the Forecast Component. Flexibility available to the forecaster through the HCL and/or preprogrammed contingency coding, for example, includes options in the Mean Areal Precipitation (MAP) Preprocessor allowing for varying levels of missing data and estimation approaches which may include information from manually digitized radar data and non-standard reports. Subsequent enhancements to Version 5 will expand considerably on the

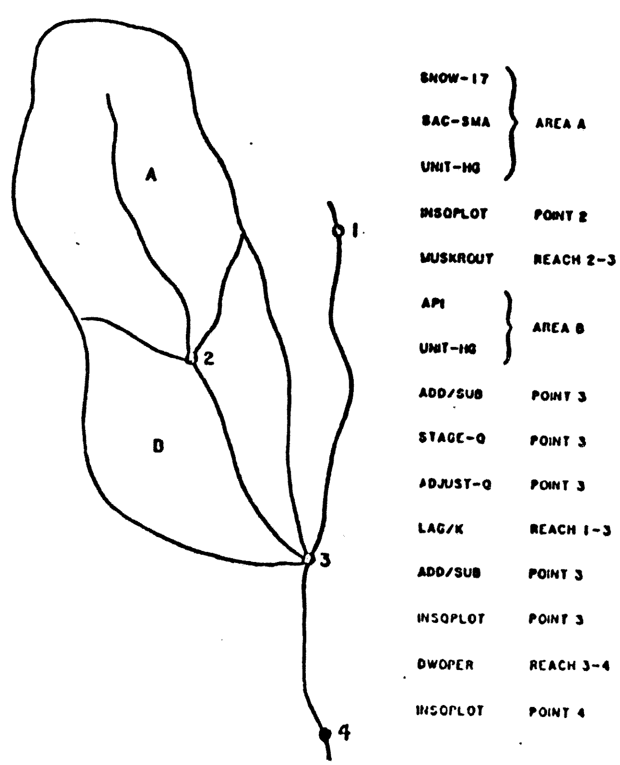

Figure 5. Schematic illustration of the operations from Table 1 used in applying the operations table concept to a segment of an example river system.

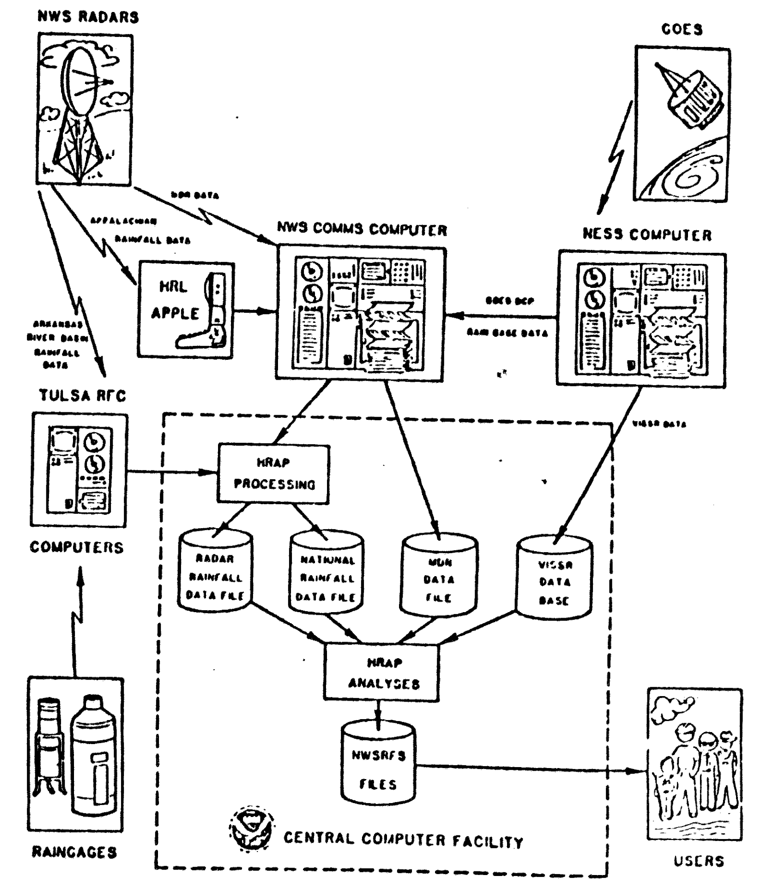

Figure 6. Basic data sources and system/computer interfaces currently being developed for HRAP.

Data Entry and Preprocessing Components as new data sources and data management and analysis procedures become available.

Virtually all of the hydrologic development activities currently underway in HRL, as well as many of those in field components, could be thought of as either immediately becoming a part of the NWSRFS or ultimately leading to a procedure to be added to NWSRFS. (This is illustrated by figure 3 which shows the broad scope of the OFP of the NWSRFS.) Possible exceptions are the development of event-oriented forecasting procedures such as those used with the NWS Dam Break Models [Fread, 1982; Wetmore and Fread, 1981] and a flash-flood forecasting system in the early stages of development. However, even the event-oriented models will probably often make use of information produced by or shared with NWSRFS and, in some cases, may actually become part of the system.

The official release of NWSRFS Version 5 should constitute a significant step forward in NWS hydrologic forecasting capability. The development effort for Version 5, for which the integration of the various components is now under the technical management of Dr. Eric A. Anderson at HRL [NWS-Office of Hydrology, 1982a], is scheduled for completion in readiness for field implementation by fall 1983. Field testing of the Forecast Component began in the summer of 1981 at the Tulsa RFC, and field testing will continue at Tulsa and other RFC's as required to validate and refine the Version 5 system before it is officially released. Sections 2-4 of this paper describe briefly some of the technology that will be incorporated into NWSRFS Version 5 or future versions, as well as certain complementing technology for event-oriented forecasting, Extended Streamflow Prediction (ESP), and data systems which will provide improved information for input to NWSRFS.

Primary-Supplemental Missions of the NWS Hydrologic Program. As indicated above in the Organic Act of 1890, the primary mission of the NWS Hydrologic Program is to provide effective issuances of river stage and flood warnings. However, as can be surmised from figures 2 and 3, considerable information is assembled which may be used for providing extremely beneficial supplemental services to the Nation in the course of satisfying the primary mission. And, these supplemental services can be provided for a negligible additional cost. Data must be continually assembled and processed for input to the soil-moisture accounting model to maintain updated states of the model in preparation for possible flood events and for selected daily river stage forecasts. A natural extension of the primary use of NWSRFS, for example, would be to use the system to provide improved probabilistic forecasts of streamflow to water managers faced with making the critical water management decisions of the future. Such a development effort is currently underway, utilizing Version 5 of NWSRFS as the basis for an Extended Streamflow Prediction (ESP 3) Program [Day, 1983]. This work will be described further in Section 4.

2. HYDROLOGIC DATA ASSIMILATION AND ANALYSIS ACTIVITES

Scope of Hydrometeorological Data Requirements and Systems. The quality of hydrologic predictions is strongly influenced by the quality of the hydrometeorological data inputs to the prediction procedures and models. The hydrologic forecasting services performed by NWS, described in Section 1 above, require access to and use of large quantities and various types of hydrometeorological data. Data are required for procedural development and model calibrations [Peck and Monro, 1977] as well as for operational forecasting. Data types range from streamflow to atmospheric wind speed. The most critical data types for operational hydrologic forecasting are temperature, precipitation, streamflow, and reservoir status. Other hydrometeorological parameters such as solar radiation, cloud cover, wind speed, and dewpoint temperature can be very useful for obtaining a more accurate assessment of potential evapotranspiration rates. However, evapotranspiration can be modeled as part of a soil moisture accounting model given only mean areal temperature and precipitation time series as inputs. Directly observed data on land use and vegetative canopy states also would be useful if such data were generally and routinely available so as to warrant adaptation of hydrologic models to make use of these types of physiographic information.

There can be many sources of data for a particular hydrometeorological parameter. For example, precipitation data used for deriving MAP values may originate from both automatic and manual in situ sensors as well as from remote sensors. Forecast data in the form of Quantitative Precipitation Forecasts (QPF's) from meteorological models also may be used in some situations. Most of the rain gage reports available to NWS offices are collected by cooperative observers. These reports normally are available once daily, and often then only on a criteria exceedance basis. Data from automatic systems and first-order synoptic stations are available more frequently but for a much smaller number of stations nationwide. The total number of rain gage stations providing data to NWS offices across the country is approximately 10,000, whereas only about 10 percent of these are automated.

One of the most critical areas in which future technological developments can lead to substantial improvements in hydrologic predictions is that of more comprehensive and representative data acquisition and assimilation for input to the hydrologic predictive procedures/models. GKY (1981) has examined various network scenarios and estimated the economic benefits that potentially could be realized with various network improvements including more automation.

More effective model input information may be obtained by implementing one or more of the following enhancements: (1) an improved network characterized by increased temporal and/or spatial sampling, (2) more effective assimilation and analysis of observed and forecast data, and (3) use of observed streamflow information in an adaptive framework to adjust model inputs and/or states. Considerable progress is being made on (1) and (2), especially for selected parts of the country in support of the flash-flood program [Barrett, 1982]. One project underway involves a cooperative effort between the NWS and the Appalachian Regional Commission to develop a prototype system, the Integrated Flash Flood Observing and Warning System (IFLOWS) [Carnahan and Monro, 1980]. IFLOWS is initially being implemented in a 12-county region at the intersection of the states of Kentucky, West Virginia, and Virginia. IFLOWS incorporates a network of cooperative observers with a significant number of radio-reporting rain gages, a variety of other automated sensors, and microprocessors at the county level to provide quick assimilation and analysis of local data. Local and state communications facilities tie the county level systems to state level and to NWS facilities and other concerned emergency service organizations. A similar approach, developed over the past 5 years at the California-Nevada RFC is called Automated Local Evaluation in Real Time (ALERT) [Hydrologic Services Div., NWS Western Region, 1981]. The basic components of ALERT consist of automated event-reporting precipitation and/or river gages, automated data collection and processing equipment, computerized hydrologic and meteorologic analysis techniques, and, through cooperation with a local warning coordinator, the distribution of warnings. Development of the ALERT system is further along than that of IFLOWS in its capability to perform computerized hydrologic and meteorologic analyses. For a local area, on the other hand, the development of IFLOWS has emphasized integration of IFLOWS components with other primary and secondary NWS systems including system interfaces to remote sensors.

As emphasized in the recent Program Development Plan for Improving Hydrologic Services [NWS-Office of Hydrology, 1982b], an Integrated Hydrometeorological Data System (IHDS) is needed to most effectively utilize the information from the many available data sources. Optimally, IHDS would efficiently link computerized data bases at the local, regional, and National levels and would manage the data to provide effective inputs for a variety of hydrometeorological applications.

A major technological advancement toward more effective data acquisition and management at the RFC's has been achieved through the development of a Data Collection software system (DATACOL) at the California-Nevada RFC [Leader, 1981a and 1981b]. Enhancements of and refinements to the original DATACOL system are continuing, with active involvement of staff members at other RFC's, notably the Missouri Basin and Colorado Basin RFC's. DATACOL was designed to run in the foreground partition of the RFC gateway computers (Data General S-140's). DATACOL automatically collects data through asynchronous ports, allows manual entry of data, files data in a hydrometeorological data base on disk, displays file data, performs local file transfers and calls stations, terminals, and other computers automatically or manually to collect or send data. Automatic data collection may incorporate data from sensors such as Data Collection Platforms (DCP's) used with the Device for Automatic Remote Data Collection (DARDC) [Flanders and Schiesl, 1972], which provides reports at a set frequency or upon interrogation, or from event-reporting rain or river gages such as those used with ALERT.

In addition to effective local acquisition and use of in situ data, greater emphasis in the future needs to be placed on objective techniques for merging and analyzing data from multiple in situ and remote sensors. Hudlow et al. (1981) discuss hydrologic forecasting requirements for precipitation data from space (satellite) measurements. As summarized by these authors, the spatial and temporal resolution requirements and accompanying accuracy expectations are a function of the application, which may range from flash-flood advisories to water-supply forecasts.

The Hydrologic Rainfall Analysis Project. To achieve the goal of effectively managing and merging data from multiple in situ and remote sensors to fulfill the mission requirements of the NWS Hydrologic Program requires an integrated design employing distributed computer processing and multivariate objective analysis systems. Such an integrated system design for rainfall data sources has been developed as part of the Hydrologic Rainfall Analysis Project (HRAP). Rainfall generally is highly variable in space and time; thus, the MAP estimates for input to hydrologic models often contain the largest source of error in hydrologic predictions. This fact prompted the initiation of HRAP. Many of the same concepts, however, would apply to other parameters, i.e, temperature.

In essence, the objectives of HRAP involve the development of improved methods of acquisition, preprocessing, quality control, and merging of multi-sensor data bases for input to hydrologic forecasting models [Greene et al., 1979]. Hudlow et al. (1981) discuss the various data sources and computer processing modules forming the current and projected Multisensor Rainfall Analysis System (MSRANS). Figure 6 schematically summarizes these sources and modules for currently available data systems, including digital radar rainfall estimates from available radar data processing systems in the Arkansas River Basin and the Appalachian region where IFLOWS exists. These radar processing systems, originally named D/RADEX (for the Digitized Radar Experiment), are now called RADAP II (Radar Data Processor -- Version II) in order to signify an upgrade from experimental to fully operational status. The RADAP II (D/RADEX) network is being expanded to include five additional radars in the Arkansas River Basin and Appalachian region. NWS plans to expand the number of radar sites that have automatic data processing capabilities by the implementation of the Next Generation Weather Radars (NEXRAD's) beginning in the late 1980's and in the interim, as resources will allow, by adding system components to existing radars such as those constituting D/RADEX and the AFOS Radar Processor (ARAP) [Mathewson, 1980].

Progress also has been made in recent years toward the computerized or partially computerized derivation of satellite rainfall estimates. For example, Griffith et al. (1981); Lovejoy and Austin (1979); Stout et al. (1979); Scofield and Oliver (1977); and Moses (1980) have developed procedures for estimating rainfall using data from visible and/or infrared geosynchronous satellites. Also, Wilhert et al. (1977) have developed a technique for mapping rainfall rates over the oceans using microwave data from the Nimbus polar orbiting satellite. However, none of these procedures are currently available on-line for hydrologic forecasting. The Oliver/Scofield technique has been used on a selected basis to provide accumulated rainfall maps to field offices during critical rainfall events, and plans exist to partially automate this technique using a ~~man~~-machine interactive system [Moses, 1980]. This system, called an Interactive Flash Flood Analyzer (IFFA) will be used in support of the NWS Flash Flood Warning Program. Satellite rainfall estimates from IFFA on a county-wide basis will be sent over AFOS when they exceed specified flash-flood guidance/threshold values. In addition, an experimental project is underway as a collaborative effort between the IFFA group and the West Gulf RFC to evaluate the use of IFFA-derived rainfall estimates for river forecasting applications. Plans also exist to incorporate satellite data into HRAP analyses using the multivariate analysis system described by Crawford (1978) and now being streamlined for operational use by Krajewski and Crawford (1982).

The advent of the Radar Data Communications and Processing (RADCOMP) system [Ahnert et al., 1981] has made possible the performance of real-time analysis of high resolution radar fields on the NOAA CCF, using a sophisticated multivariate analysis system such as the one under development by Krajewski and Crawford (1982). The Krajewski and Crawford analysis system will provide grid-point rainfall estimates from radar and/or other sources according to a universal grid coordinate system based on a polar-stereographic map projection as described by Greene and Hudlow (1982). The basic resolution of the grid system will be approximately 4-5 km. It has been recognized for some time that the use of a grid system for addressing the problem of irregularly spaced rainfall stations would facilitate computer processing of rain gage data by RFC's [Smith, 1975]. The polar-stereographic system will be used in NWSRFS as the basic coordinate system for referencing data for numerical computations.

Real-time assimilation and analysis of data with computers to automatically produce inputs for hydrologic forecasting models and procedures can be effectively achieved only if reliable automatic quality control procedures are incorporated as part of the processing system. Development and/or implementation of such quality control procedures are indispensible prerequisites to achieving the ultimate objectives of HRAP. Major progress toward establishing a framework for automatic screening techniques from in situ hydrologic telemetered data sensors has been recently reported by Bissell (1981). With this framework and suitable expansions to include provisions for other screening functions, especially those needed for remotely-sensed data, it should be possible to incorporate automatic quality control procedures into HRAP.

Network Design Influences on Hydrologic Modeling Applications and Accuracies. As mentioned above, the accuracy of hydrologic predictions can be strongly influenced by the quality of the data inputs to the prediction procedures and models. For example, the accuracies of the MAP time series inputs are affected by the network design of available data sources. This is particularly true when one considers that over 50 percent of the total number of rain gage observations are reported on a criterion exceedance basis (e.g., when a 0.5 inch or greater accumulation occurs during a 24-hour period). Unless rainfall exceeds the criterion amount during any 24-hour period at a particular station, a report would not be made by the cooperative observer. This poses a major dilemma since, without additional information, it becomes impossible to distinguish those stations which did not report because no rain occurred from those at which insufficient rain occurred to exceed the criterion or from those that simply were missing because the observer was unable to take the observation. Significant over-estimates of MAP can occur, especially for convective rainfall events, if the rainfall amounts are assumed missing for those stations that did not report. This is because the present areal estimation procedures tend to smear the larger rainfall amounts over too much of the watershed area. Correction of this problem, short of eliminating the reporting criterion, is not easy. One approach, which can be very useful, consists of using manually digitized radar (MDR) data [Tetzloff, 1980] to assess whether zero or some other value should be assigned to non-reporting stations.

Rainfall estimate biases, which can originate from network deficiencies such as those produced by the criterion reporting stations, can, over a period of time, produce cumulative and extremely significant errors in the values of the state variables of a continuous soil moisture accounting model. This problem is aggravated by the fact that the network used for calibration of the model often is different from (usually superior to) the operational network. A project was initiated in HRL at the request of the Southeast RFC to evaluate the magnitude and behavior of such network introduced biases and to attempt to derive correction factors where feasible [Reed, 1981]. A generalized computer program was set up at HRL by Mr. David Reed, who subsequently transferred to the West Gulf RFC but continued his work there. This program provides the capability to simulate various operational and calibration networks by conditioning the total calibration data base. (See Peck and Monro, 1977, for a description of the data available for calibration.) The program also computes MAP's and derives a host of statistical parameters which quantify the differences in MAP's between two networks. This program currently is being used in HRL by Dr. Richard Farnsworth, for a range of conditions, and error analyses are being summarized for various networks with the goal of formulating guidelines for first-order corrections.

Another dimension of the network bias problem may become relevant when an operational network density considerably exceeds the density of the network used for calibration of the soil moisture accounting model. Such will be the case when high-resolution digital radar rainfall estimates become available for watersheds for which only a sparse to moderate density rain gage network was available for calibration. This, in many instances, may not be a serious problem, depending on the distribution of errors associated with the MAP values used for calibration and the error criterion used to judge the "goodness-of-fit" during the calibration process. The difference between calibration and operational network bias errors, in many cases, may be small compared to the reduction in errors in the operational MAP values realized by use of the high resolution radar data. Nevertheless, this is another aspect of network design influences that must be evaluated as part of the ongoing network bias studies at HRL.

Quantitative Precipitation Forecast Information. Georgakakos and Bras (1982) review the state of the art of quantitative precipitation forecasting as it relates to hydrologic forecasting. Much of the material which follows has been extracted from the Georgakakos and Bras report.

Currently, operational forecasts of precipitation quantity and time of occurrence over a certain area, produced by the NWS's National Meteorological Center (NMC), are based on: (1) output from large-scale meteorological models that simulate the atmospheric dynamics, with spatial resolutions of the order of 160 km grid-size and greater [e.g., the Limited area Fine Mesh model (LFM) documented in NOAA-NWS, 1978b]; (2) use of statistical regression models [i.e., Multiple Output Statistics models (MOS), Glahn and Lowry, 1972] that correlate selected meteorological observations and the predictions from the large-scale atmospheric models with precipitation on a smaller scale; and (3) analysis by forecasters who understand meteorological processes and weather patterns. The forecast produced by NMC may be updated and modified by local WSFO's.

Recent evaluations [Charba and Klein, 1980] of operational quantitative precipitation forecasts show relatively poor performance for the purposes of providing quantitative inputs for relatively small scale applications such as those required for hydrologic forecasting. Current large scale atmospheric models fail to adequately consider the mesoscale aspects of precipitation processes and structure. The use of statistical regressions to partially bridge this gap between the mesoscale and the scales resolved by large-scale numerical models involves difficulties such as: (1) the identification of all the relevant meteorological variables that will be used as "explanatory" variables for each location and (2) the absence of high temporal correlation in the station precipitation records. In addition, no guarantee is provided regarding the invariance of the regression parameters for different storms, due to the absence of explicit physics in the statistical regression models.

The process by which local forecasters combine information from different sources to issue operational forecasts varies with each case. They often, however, rely heavily on the LFM and MOS forecasts.

In addition to the procedures described above for the derivation and dissemination of operational precipitation forecasts, descriptions do exist in the meteorological literature of numerical models which simulate some of the convective cloud processes. (For example, see review in Rogers, 1979.) These models focus on the representation of the microphysical cloud processes. Their spatial and temporal scales are significantly finer than those generally of interest for hydrologic forecasting. Their emphasis usually is on the moving storm rather than on the effects of the storm processes at a fixed location on the ground.

Georgakakos and Bras (1982) report on a precipitation model which they developed to be compatible, in mathematical structure and spatial and temporal scales, to the hydrologic models of the conceptual type. This model is a physically based non-linear precipitation model which has been formulated in the state-space form. The model uses observed or forecast values of temperature, pressure, and dewpoint temperature for a given ground station as input meteorological variables, and it produces precipitation rate as an output. The state variable of the model is the liquid water content of a storm cloud column above the station. The predicted precipitation values are assumed representative at the station or, because of the coarseness of the input data, actually representative of some area around the station. It may, in fact, be reasonable to assume that to a first approximation these values represent predictions of mean areal precipitation for a watershed in proximity to the station.

The precipitation model developed by Georgakakos and Bras provides a critical piece of the framework required to enable real-time coupling of precipitation and streamflow forecasting models. Their precipitation model should be implemented operationally so that it makes maximum use of meteorological forecast information, perhaps including certain precipitation forecast information available from other sources. And, the combined precipitation and streamflow modeling system should be applied in an adaptive framework (Georgakakos and Bras provide the necessary equations to do so for one modeling configuration) so that the states of the system can be continually updated based on observations of precipitation and/or streamflow. Such a forecast system will be especially valuable for the shorter scale flash-flood applications as described in section 4. Also described there is the possibility of using "nowcasting" techniques [Browning, 1982] as a complementing approach for deriving short-term rainfall predictions.

<u>Other Hydrometeorological Data System and Analysis Activities</u>. Numerous other pertinent hydrometeorological data studies could be described. Only a few of

them will be mentioned here. An important term in conceptual soil moisture accounting models is evapotranspiration. Accurate assessment of this term is important for model calibration as well as for operational predictions, especially for dry periods. Updated and refined maps of pan and estimated lake evaporation and tables of pan evaporation have recently been completed for the United States [Farnsworth et al., 1982; Farnsworth and Thompson, 1982] to provide data bases useful for both model calibration and operational forecasting. Other studies are continuing to determine the best guidelines for use of various sources of evaporation data.

Another important area of remote sensing that has received great attention in the past decade in the NWS Hydrologic Program is that of sensing of natural gamma radiation from a low flying aircraft. Such aerial gamma measurements can be used, with suitable flight-line calibrations, to estimate equivalent liquid water in snow packs and soil moisture values in the absence of snow cover [Peck et al., 1971; Carroll and Vadnais, 1980; Carroll, 1981]. The NWS Aerial Gamma Program became operational in 1979 and operational flights have been made in the upper midwest since that time in basins which in past years have shown high risk of spring snowmelt flooding. However, considerable development work remains to be done on how to "optimally" integrate the aerial gamma measurements with other information on areal extent of snow cover, snow depths, and water equivalents to obtain the best assessment of snow packs and corresponding estimates of snowmelt runoff.

Many hydrometeorological design studies which provide bases for planning various water resources activities or construction of structures are conducted by the Water Management Information Division (WMID) of the Office of Hydrology (figure 1). Typically these studies involve estimation of Probable Maximum Precipitation (PMP) values or frequency estimates of precipitation for return periods less than or equal to 100 years. One recent study [Richards et al., 1982] presents frequency estimates for 2 to 100-year return periods of water available for runoff due to rainfall and/or snowmelt in the northwest United States.

3. HYDROLOGIC MODELING ACTIVITIES

As described above, most of the models currently under development in HRL and in field offices will become a part of NWSRFS. For simplicity, the Forecast Component of the NWSRFS can be thought of as having two general types of programs/models: (1) hydrologic programs which simulate the runoff and in-channel routing processes, and (2) hydraulic programs which utilize the complete momentum and continuity equations, also known as dynamic routing programs. Models in these two categories will be described in the following sections and some plans will be presented for improvements in model calibration and updating procedures.

Rainfall-Runoff Modeling. A considerable amount of work has been performed in HRL in recent years in the area of rainfall-runoff modeling. The primary effort has centered on the incorporation of a conceptual rainfall-runoff model into the river forecasting procedures used by RFC's. Although the main emphasis in the past has been on implementation of the Sacramento soil moisture accounting model, the modularity and flexibility being built into Version 5 of NWSRFS will allow other models also to be used for forecasting. API [Linsley, Kohler, and Paulhus, 1982] and Constrained Linear System (CLS) [Todini and Wallis, 1974] models currently are being written in a format suitable for inclusion as operations in NWSRFS.

Throughout the years, several RFC's have developed flood forecasting procedures based on API relationships. In the late 1960's, a continuous hydrologic model based on API relations was developed in HRL [Sittner et al., 1969]. The inclusion of API operations into Version 5 of NWSRFS will allow RFC's to implement the new software without an abrupt change to their basic forecasting techniques. The version of the API method currently in use in the Missouri Basin and North Central RFC's is being added to the list of available NWSRFS operations at this time [Anderson, 1980]. Other versions of the API method are planned as future parts of NWSRFS. The capability to choose from among several types of rainfall-runoff forecasting techniques should facilitate implementation of the new programs.

The only conceptual rainfall-runoff model currently included in NWSRFS is the Sacramento model. The model is conceptual in design in that the authors have parameterized soil moisture characteristics. Numerous descriptions of the model have been published and, therefore, a detailed discussion of the model will not be included here [Burnash et al., 1973; Lawson and Shiau, 1977; Brazil and Hudlow, 1980]. The model has been modified slightly since its original release. A full description of the current NWSRFS Sacramento soil moisture accounting operation is given in the NWSRFS User's Manual [Burnash and Ferral, 1979].

Numerous studies have been conducted on the Sacramento model, both within HRL and by outside sources. Although most of the studies have dealt with calibration of the model, some work has been done in other areas. Contract work sponsored by the National Aeronautics and Space Administration has provided information concerning the use of remotely sensed data as input to the model [Peck et al., 1981]. Several case studies verifying the predictive capabilities have been published. For instance, Smith successfully used the

Sacramento model as the basis of the streamflow forecasting system in a water supply management study in the Potomac River Basin [Smith et al., 1982]. Abbi (1980) applied the model to a river basin in India to perform a water balance study. The World Meteorological Organization included the Sacramento model in an intercomparison of hydrologic forecast models [Sittner, 1976].

Work currently is underway to develop an operation for the CLS rainfall-runoff model [Todini and Wallis, 1974]. Basically, the model calculates the impulse response functions between the input and the output. As an improvement over a strictly linear system, the model preprocesses the precipitation data so that the precipitation can be assigned to separate inputs based on an API criteria. The potential primary use of the model would be in forecasting hydrologic events in small drainage basins where lead times are short. In a number of tests, the model has been shown to provide satisfactory simulation results.

One final point should be made with regard to rainfall-runoff modeling. As higher resolution rainfall data become available from systems such as ALERT and HRAP, there may be definite advantages to moving toward multizone distributed modeling techniques. Morris (1975) has studied this possibility for a basin on the Illinois River in Oklahoma and Arkansas. His conclusions were that streamflow simulation improvements could be achieved with multizone modeling of a basin subjected to intense convective rainfall when only a relatively sparse rain-gage network is available. Even greater improvements should be possible with higher resolution rainfall inputs.

River Mechanics and Reservoir Operations. Extensive work has been under way over the past decade at HRL, under the project area leadership of Dr. Danny Fread, to develop comprehensive numerical techniques and software systems capable of applying the one-dimensional St. Venant equations of unsteady flow to complex river systems. This work has led to the development of a dynamic wave routing model known as the NWS Dynamic Wave Operational Model (DWOPER) [Fread, 1978]. DWOPER is being implemented on portions of major rivers such as the Mississippi, Ohio, and Arkansas, where backwater effects and mild slopes are most troublesome for hydrologic routing methods. The entire lower portion of the Mississippi River is now being forecast with DWOPER by the Lower Mississippi RFC. Of course, hydrologic routing methods remain available (see table 1) where such methods provide sufficient accuracy or the DWOPER hydrodynamic model has not yet been implemented. Research is under way in HRL to develop objective criteria for pre-determining when various routing procedures will provide acceptable accuracies.

Some of the features that DWOPER provides include: various initial and boundary conditions including discharge hydrographs and water level fluctuations due to tides and/or storm surges, irregular cross sections at unequal intervals, off-channel storage, lateral inflows, partitioning of flows onto left and right flood plains, local losses, wind effects, internal boundary conditions (e.g., lock and dam), flow diversions, dendritic river systems, levee overtopping, subcritical or supercritical flows, and automatic calibration. Computational efficiency and user convenience has been emphasized in the design and development of DWOPER. DWOPER does include various data management functions, and the system is supported by HRL.

Another river mechanics model developed at HRL is the NWS Dam-Break Flood-Forecasting Model (DAMBRK) [Fread, 1982]. The DAMBRK development was initiated in support of the NWS responsibility to advise the public of downstream flooding when there is failure of a dam. Many past catastrophic flash-floods were produced or intensified by dam failures. Dam failures are often caused by "piping" or overtopping of the dam during a period of large inflow to the reservoir produced by runoff from heavy precipitation. Although the dam-break flood has many similarities to floods produced simply by precipitation runoff, it normally produces some important differences which make it difficult to analyze with the standard techniques. DAMBRK was developed to aid the NWS flash-flood hydrologists who are called upon to forecast the downstream flooding resulting from dam failures.

The basic components of DAMBRK are: breach description (shape versus time), reservoir routing to produce an outflow hydrograph based on either storage routing or dynamic routing, and downstream flood routing based on the same hydrodynamic model used in DWOPER. Some of the features that DAMBRK provides include: in the breach description component -- time-dependent geometry of triangular, rectangular, or trapezoidal shape which can approximate failures resulting from structural collapses, erosion, or piping; in the reservoir outflow hydrograph component -- reservoir inflow and storage characteristics considered with total reservoir outflow being composed of broad-crested weir flow through the breach (with submergence correction) and flow through spillway outlets (uncontrolled or gated and including provisions for turbine flows); in the downstream routing component -- all of the provisions inherent in DWOPER as described above. A unique feature of DAMBRK is the capability to consider the effect of a landslide-generated wave in a reservoir.

In order to provide a simplified procedure for forecasting dam-break floods for cases in which the accuracy required may not warrant the use of DAMBRK by field offices which do not have the lead time or the personnel or computer resources required to use DAMBRK, the NWS Simplified Dam-Break (SMPDBK) Flood Forecasting Model is being developed [Wetmore and Fread, 1981].

SMPDBK is based on DAMBRK in the sense that the basic expressions comprising the SMPDBK were derived from analysis of output from DAMBRK for a wide range of conditions. The SMPDBK model is being designed so that it is adaptable to the simplest possible scenario in which a forecaster wants to produce a forecast by only referring to a set of curves or a nomogram(s) and a slide rule or hand-held calculator. Also, analytical expressions are being fit to the set of curves so that the SMPDBK model can be adapted easily to a programable calculator or a desk-top microprocessor.

A project is underway within HRL to investigate floodwave movement in interactive stream-aquifer systems by coupling a numerical model of groundwater flow to DWOPER. Most open-channel flow simulation models in use today either ignore any interaction between the stream and groundwater system or treat the groundwater system externally as some simplified function of infiltration or baseflow. Studies have shown that floodwaves in alluvial channels of some river systems are significantly modified by flow exchanges between the stream and the adjacent aquifer system. The groundwater component being developed for this project is a two-dimensional, transient finite difference model that treats the entire saturated-unsaturated flow domain as one composite system [Krouse, 1982]. The results of the groundwater component research should be available within a few months.

More simplified procedures for accounting for losses or gains of water through the bed and banks of a stream or by means of evaporation from the surface will be provided in NWSRFS Version 5 for routing applications in which some stream-aquifer interaction does occur, but the seriousness of the problem does not warrant the use of the more complex coupled model treatment. The CHANLOSS operation is an empirical approach in which losses or gains are specified as a fixed or variable percentage or absolute magnitude of streamflow volume. A more conceptual type operation (CHANLEAK) was developed as an HRL-Tulsa RFC cooperative effort under the direction of Miss Kay Krouse and Mr. Bobby Armstrong, and currently is being tested at the Tulsa RFC. The flow exchanges in CHANLEAK are computed as functions of both streamflow and available storage capacity of the alluvium. Both operations should be available when Version 5 is officially released.

While several river mechanics models are currently available and others are under development, an integration of these models into a general river mechanics system was needed to provide the forecaster with the flexibility to execute on-line the options desired for a large variety of river systems and conditions. To meet this requirement, a general river mechanics program called FLDWAV [Fread, 1981] is being developed. FLDWAV incorporates a modular design (figure 7) to provide a variety of river mechanics capabilities including:

- a river mechanics control language allowing the user greater flexibility in setting up a sequence of simulation techniques,
- greatly increased capability to model floods in channel networks,
- provisions to model dam-break floods which spread onto a wide flood plain,
- convenient selection of various routing models (dynamic, diffusion, Cunge, Muskingum, reservoir, kinematic, lag and K, Puls, etc.) for any portion(s) of a river system, so that the simpler techniques can be selected when the errors associated with their use are tolerable, and
- simulation of flow which may vary from supercritical to subcritical at any location or time in the river system.

In summary, FLDWAV comprises a distillation of the features of DWOPER and DAMBRK plus additional capabilities. The modular structure of the program

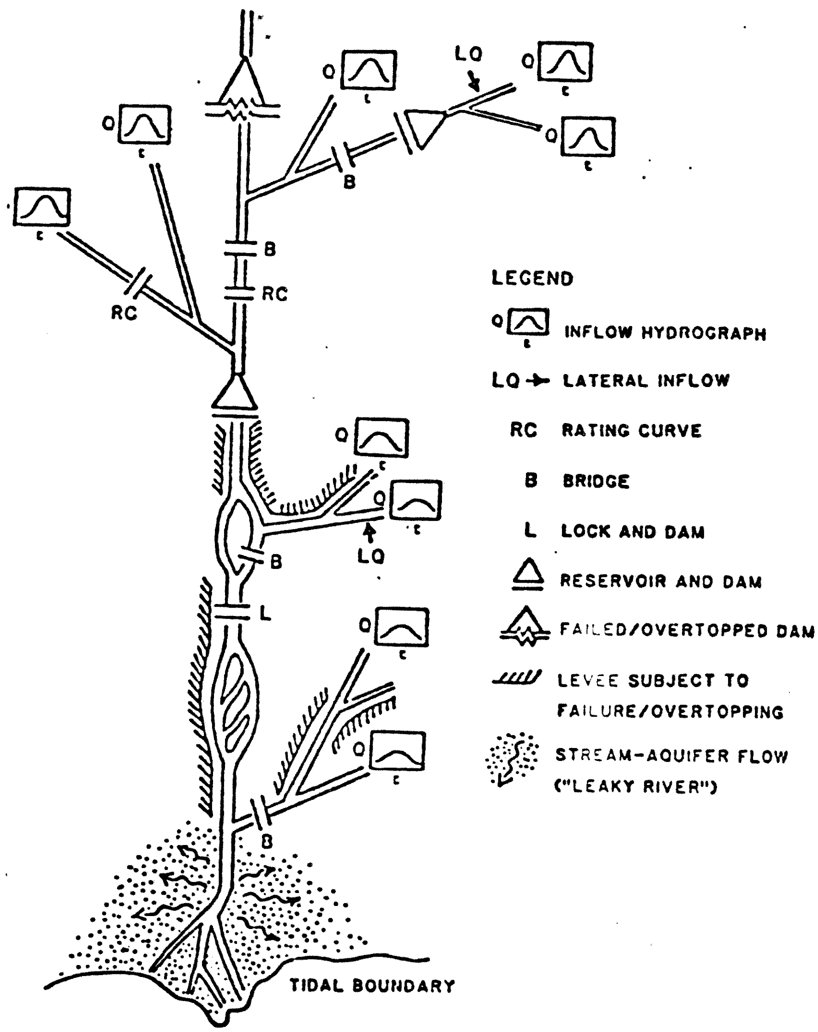

Figure 7. Schematic of a complex river system illustrating some of the hydraulic features that FLDWAV is capable of handling.

will allow for easy addition of research developments (e.g., riverine ice effects, flooding inundation mapping, the saturated-unsaturated groundwater system, sediment transport, pollutant transport, and special hydraulic applications). FLDWAV will be designed to function as a separate program, and eventually the complete system will be incorporated as an operation within NWSRFS.

When released for general use, Version 5 of NWSRFS will include an operation for simulating the regulation of an individual, independently operated reservoir [Ostrowski, 1982]. Work currently is being performed through contract with William E. Fox, Consulting Hydrologist, to develop the reservoir operation algorithms [Fox, 1982]. The computational schemes will simulate reservoir operations such as passage of inflow, maintenance of prescribed discharge or elevation, discharge from an uncontrolled spillway, pool elevation controlled discharge, discharge minimization, upstream stage minimization, flash board control, and power generation. Reservoir operating plans initially will be specified by the user through the Reservoir Command Language (RCL). RCL is being designed with the flexibility to accommodate different operating plans for each reservoir. Future development work for reservoir simulation will focus on regulation influenced by a downstream control point and multiple interrelated reservoir systems.

Snowmelt Modeling and Other Cold Region Hydrologic Developments. The accurate simulation of snowmelt is a key element of river forecasting activities throughout much of the country. Considerable effort has gone into the development of models which can adequately simulate the accumulation and ablation of snow. In some parts of the country, the effects of frozen ground have been found to significantly alter runoff from spring snowmelt, necessitating modifications to the soil moisture accounting model. The effects of ice jams in rivers need to be considered in many locations. Research work has been performed or sponsored by HRL on each of these cold region topics, and the RFC's, especially the Alaska RFC, are faced with the operational development and implementation of a variety of cold region forecasting techniques.

Two basic types of snow models have been developed within HRL: a temperature index model [Anderson, 1973] and a point energy balance model [Anderson, 1976]. The temperature index model is the snow accumulation and ablation model currently incorporated in Version 5 of NWSRFS. The model uses air temperature as the only index to energy exchange across the air-snow boundary. Air temperature data are readily available in a real-time forecasting environment, facilitating the use of the temperature index model. A detailed description of the model is given in the NWSRFS User's Manual [Anderson, 1978]. A limited number of test cases have been run to compare the performance of the temperature index model to a more detailed energy balance snow cover model. In general, there was close agreement between the two models for normal meteorological conditions. The energy balance model provides more accurate estimates of snow cover energy exchange under extreme conditions; however, more types of hydrometeorological data are required as input to the model. The minimum data requirements are measurements of air temperature, vapor pressure, wind, and a good estimate of solar radiation. The model is based on theoretical expressions for energy exchange at the air-snow interface and for heat transfer within the snow cover [Anderson, 1976].

Experience with the Sacramento soil moisture accounting model in the upper Midwest showed that the effects of frozen ground needed to be taken into consideration during the spring snowmelt season. A research project was conducted in HRL in collaboration with the North Central RFC to incorporate frost index equations into the Sacramento model. The frost index is a function of air temperature, the simulated snow water equivalent, and combined melt and rain. The soil moisture model was modified to allow for a reduction of percolation and interflow based on the frost index. The modified model was used by the North Central RFC during the spring snowmelt season of 1982. An evaluation of the results by Pat Neuman of the RFC showed that the modifications which account for frozen ground improved the model performance; however, additional developmental work is needed [Neuman, 1982].

The simulation of ice jams in rivers is an area of research which had not received significant attention within HRL until recently. The development of DWOPER has provided a means by which the ice jamming process can be modeled in conjunction with the detailed simulation of unsteady flow in rivers. The Cold Regions Research and Engineering Laboratory (CRREL), Corps of Engineers, has worked under contract with HRL to modify DWOPER to account for ice cover in rivers. Although considerable work on the techniques remains to be done (such as simulation of ice cover initiation and breakup), the CRREL project provides a first step toward the accurate modeling of the processes of river ice and the associated transient responses [CRREL, 1981].

Model Calibration Research. Calibration research is a vital step in the effective and timely implementation of hydrologic models. The development of new calibration techniques (which allow the user to calibrate models more efficiently and gain a more thorough understanding of the simulation concepts) increases the likelihood of accurate calibrations, and helps to accelerate implementation of the models. Numerous procedures for calibrating the various models are either currently available or under development. Research is being conducted, both within the HRL and by private contractors.

Implementation of one-dimensional hydrodynamic models in natural rivers requires the determination of the roughness parameter in the friction slope term of the momentum equations. A feature developed for the DWOPER model allows this parameter to be optimized automatically. The technique is simple and highly efficient [Fread and Smith, 1978] and is based on a decomposition principle which simplifies the treatment of dendritic river systems.

Application of the hydrologic operations in NWSRFS requires the selection of suitable parameters for the snow accumulation and ablation model (in areas where snow processes are important), the soil moisture accounting model, the unit hydrograph, and the channel routing models. Calibration of the models currently can be performed with three programs: the Manual Calibration Program (MCP3), the Automatic Parameter Optimization Program (OPT2), and the Interactive Calibration Program (ICP). Presently, only MCP3 and ICP are compatible with Version 5 of NWSRFS. A new version of the automatic optimization program (OPT3) is under development and should be available within a few months. MCP3 enables users to determine parameter values through the simulation of periods of historical records. Manual adjustments can be made to parameters until simulated response agrees satisfactorily with observed values. A complete description of the program is given in the NWSRFS User's Manual [Anderson, 1981]. The optimization programs (OPT2 and OPT3) automatically adjust model parameter values based on a statistical comparison of simulated and observed data values. OPT3 will provide a variety of parameter optimization procedures, including a choice of objective functions and optimization schemes. ICP is an interactive program designed to be run on a small in-house computer system. The program allows the user to manually adjust parameter values and examine the results of the changes by viewing computer-generated color graphics displays [Brazil and Laurine, 1981; The Analytic Sciences Corporation, 1982a and 1982b].

A number of groups under contract to NWS have performed research aimed at improving the calibration techniques for the Sacramento model. Groups from The Analytic Sciences Corporation (TASC) and the Civil Engineering Department, Massachusetts Institute of Technology (MIT) have developed state-space formulations for the Sacramento soil moisture model and unit hydrographs. Both groups have examined various ways of applying estimation theory techniques to parameter estimation and have concluded that maximum likelihood estimation techniques appear to have the most potential. The work at TASC has been documented through project reports to HRL [TASC, 1980]. MIT's work resulted in several publications, including an MIT Technical Report [Posada and Bras, 1982]. A research group at the Systems Engineering Department, Case Institute of Technology, has developed new objective functions for use with the automatic parameter optimization program. The functions are designed to account for autocorrelated and heteroscedastic streamflow errors [Sorooshian et al., 1981 and Sorooshian, 1981]. A limited number of tests showed that the techniques resulted in model parameters which provided improved simulated forecasts.

Calibration research activities also have been conducted in RFC's and within HRL. Guidelines for estimating soil moisture accounting parameter values are given in the original Sacramento model publication [Burnash et al., 1973]. Peck also published a technical report [Peck, 1976] which presents steps for selecting initial parameter values based on observations of streamflow records. Armstrong has developed a procedure for deriving initial soil moisture parameters related to soil properties from soil data type [Armstrong, 1978]. Smith is working on a technique for estimating model parameters based on geologic information [Smith, 1982].

The current hydrologic model calibration work within HRL basically consists of an extension of much of the work performed in recent years. Part of the research consists of a project to incorporate many of the recently developed optimization techniques into a systematic procedure for selecting model parameter values. An analysis of the structure of the soil moisture model will be made and the parts of the model which cause calibration difficulties will be identified. The project will include in-house testing and evaluation of some of the optimization techniques derived in previous research efforts and the development of new physically based techniques designed to automate some of the current manual calibration steps. The final product should be a multi-stage program which includes a combination of the most promising optimization techniques resulting in an improved procedure for systematically estimating the hydrologic model parameters.

Model Updating Research. Automatic objective updating procedures for hydrologic models have become more important as the models have become more complex. Research within HRL on this topic has been in several different directions. One direction of research resulted in a method of updating forecasts known as the Computed Hydrograph Adjustment Technique (CHAT) [Sittner and Krouse, 1979]. The philosophy used in deriving CHAT is based on the idea that the differences between simulated and observed discharges is caused primarily by faulty input precipitation data and inaccuracies in the unit hydrograph. The approach used by CHAT to resolve the differences is to make iterative adjustments simultaneously to the precipitation inputs and the shape of the unit hydrograph until the differences are within a specified tolerance (figure 8). Although no direct changes are made to the soil moisture model states, the states are

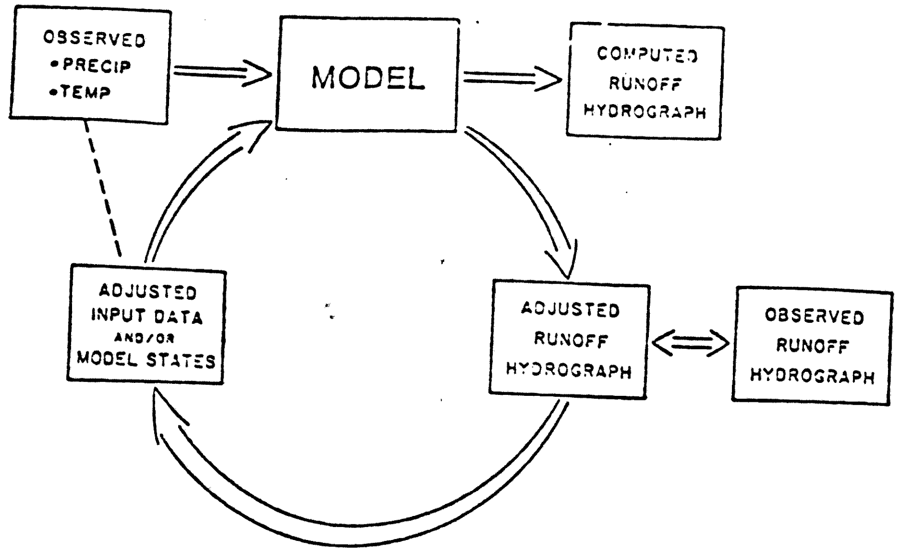

Figure 8. Illustration of general concept for updating hydrologic model predictions through adjustments using observed streamflow.

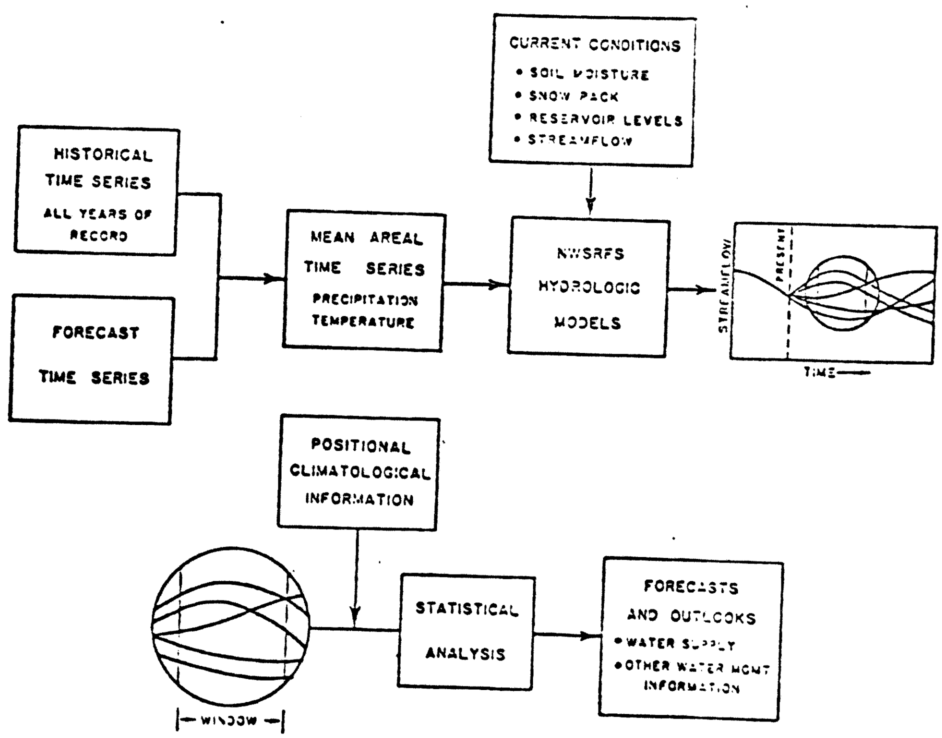

Figure 9. Block diagram summarizing the ESP system.

updated as a result of the adjusted precipitation. The program has been tested on several basins with encouraging success.

A second direction of updating research uses an estimation theory approach and has been developed through contract work with outside sources. Both MIT and TASC derived state-space forms of the soil moisture model in conjunction with their calibration research. The estimation theory approach accounts for four sources of error in resolving differences between simulated and observed outputs (input error, model structure, model parameters, and output measurement error). The algorithm directly adjusts each state of the hydrologic model in proportion to the output residuals. The Kalman filter is used to determine the amount of correction to be applied to the measurement residual at each time step, resulting in the "best" estimate of the hydrologic states. An updating program developed by Kitandis and Bras (1978), which applies the Sacramento model in a state-space formulation for a lumped input/parameter headwater situation with non-snow conditions, has been successfully applied to a few test basins. Work also is curently underway at MIT to develop a format for computationally coupling connected river basins through the use of an algorithm which considers the correlation of the mean areal precipitation estimates for the respective watersheds. The goal of this work is to produce a river forecast system with adequate automatic objective updating capabilities.

Research also has been performed on the development of an updating procedure for the snow accumulation and ablation model incorporated into NWSRFS. While working as a National Research Council Research Associate at HRL, Carroll devised a means for using snow course data to update the simulated snow water equivalent calculated by the snow model. This procedure allows the model to more closely reflect the true areal snow water equivalent in basins where snow course data are available. The method has been shown to reduce mean monthly simulated runoff volume errors by as much as 40 percent in some test basins [Carroll, 1978].

A more detailed discussion of planned future directions related to hydrologic modeling activities for the shorter mesoscales and longer extended scales is given in section 4. In particular, future technological developments in support of flash-flood warning and water management information applications are described there.

4. FUTURE RESEARCH AND DEVELOPMENT DIRECTIONS

General. The purpose of this section is to summarize how the technological developments described in the first three sections will be refined and expanded in the future. Also, information is presented on plans to develop improved technology for prediction of short-scale and long-scale hydrologic phenomena. As the implementation of the technology for intermediate scales proceeds (which is the primary subject of sections 1 through 3), a gradually increasing proportion of development resources will be turned toward the flash-flood (short-scale) and water-supply forecasting (long-scale) problems. At the same time, enhancements in forecast procedures for the intermediate scales will continue as an essential part of maintaining a state-of-the-art operational river forecast system. Continued evolution of the forecast system will be made easier with the completion of NWSRFS Version 5 and of FLDWAV, which, because of their modularity, flexibility, and comprehensiveness, should allow for the addition of new hydrologic and hydraulic forecasting procedures without major system design changes.

As described in above sections, the technological development thrusts, currently as well as in the future, can be thought of as falling into two broad areas: hardware and software data systems technology and hydrologic analysis and prediction technology. Development work for the NWS River Forecast System spans both of these areas (except for system hardware development, which falls outside the umbrella of NWSRFS). However, even for this exception, the characteristics of data sensors and computer hardware must be considered in the design of NWSRFS software structure and input data interfaces.

Hardware enhancements for the future will fall primarily into two categories: improvements in data acquisition systems and improvements in computer systems. New data systems will range from automated event-reporting rain gages, such as those being used for ALERT, to land-based and satellite-borne remote sensors. One of the potentially most promising remote sensing technologies of the future should be realized from weather radar measurements which can be analyzed to provide high-resolution precipitation estimates for input to hydrologic forecasting systems. By the end of this decade, the entire United States should be covered with radars capable of providing such quantitative measurements (i.e., the NEXRAD network). By that time, as a part of HRAP, objective data assimilation and analysis techniques will have been developed to optimally use the data from NEXRAD together with data from other remote as well as in situ sensors.

Once NWSRFS Version 5 is complete (fall 1983), it will provide the basic framework for the future NWS River Forecast System, for most, if not all, RFC's. At that time, attention will be directed toward continued enhancements to NWSRFS in the data assimilation and analysis parts, as well as in the modeling portions of the system, and toward further development of model calibration and updating procedures which should allow for more efficient implementation of

NWSRFS with accompanying improvements in forecasting. Future directions also will include the R&D required to maximize the use of information from NWSRFS in support of additional hydrologic services provided by the RFC's and WSFO's, such as flash-flood advisories and extended forecasts for navigation, water supply, recreation, reservoir inflows, and pollution abatement.

Flash-Flood Warning Techniques. Improvements in flash-flood warning services nationwide will depend on the development and integration of a hierarchy of techniques [Williams et al., 1972]. Improvements in the timeliness and accuracy of flash-flood predictions will not only depend on the implementation of local flash-flood warning systems, such as ALERT, and the use of hydrometeorological information from NWSRFS to enable the RFC's to provide the best possible flash-flood guidance values to the WSFO's and WSO's, but also will depend on additional R&D work to develop a Hydrometeorological Analysis and Prediction System (HAPS) capable of running in real time on a relatively small mini- or micro-computer and of using computational time steps considerably smaller than the hourly time step limit inherent in NWSRFS. HAPS will be designed in a modular fashion, and will be developed in such a way that various system configurations can be used, depending on available computational resources and specific applications. This approach will allow for implementation of application modules, at various stages of the development of the system, as they become available. In fact, certain components exist now that will ultimately be used in HAPS, e.g., the SMPDBK model, flash-flood guidance criteria provided by the RFC's, and observed rainfall plotted on map backgrounds. Available components will be used whenever feasible, concurrent with the evolution of the HAPS system.

It is envisioned that HAPS, which will be designed with sufficient compactness and efficiency to generate streamflow predictions using time steps commensurate with resolving the most rapid flash floods (possibly 15-minute steps), will be analogous in many ways to NWSRFS except that it will be more compact. The compact HAPS software system might be thought of as a mini NWSRFS.

HAPS will be similar to ALERT in some respects. ALERT was designed as a local community flash-flood warning system, whereas HAPS will be designed as an integral part of the WSFO system capability, making it possible for WSFO forecasters to respond more quantitatively to flash-flood situations. The exact magnitude and location of the computer resources needed for HAPS are not well defined at this time, but alternatives include provisions for the software to reside at the WSFO's and/or the RFC's on special processors or System II. Access to the communication circuits required for data entry must be available, and if the software resides only at the RFC's, the computer facilities at the RFC's should operate essentially automatically since, under the present organizational structure, the RFC's are not routinely staffed around the clock. In any event, the system should be planned so that HAPS could be linked with required outputs from the RFC's, such as flash-flood guidance information available from NWSRFS, and so that the service hydrologists and forecasters at the WSFO's would have real-time access to the software and output products from HAPS.

The compactness required for HAPS can be achieved by restricting the number of options and the complexity of the prediction procedures. For example, a less accurate and simpler watershed model should be acceptable in many cases for an event-oriented flash-flood prediction system, whereas greater accuracy and accompanying complexity is required for a continuous river forecasting system which includes provisions for a hydrologic model with long-term memory designed to handle a range of forecast situations and conditions. In the dam-break flood forecasting area, a simple, compact model, such as SMPDBK, should be a component of HAPS since a large percentage of past catastrophic flash floods have resulted from dam failures.

HAPS will be designed in a modular fashion to include data entry, data preprocessing, and forecast functions analogous to those comprising the large-scale NWSRFS (see figure 3). The data entry component should include provisions to receive and assimilate data in real time from in situ sensors and remote sensors such as NEXRAD and GOES (Geostationary Operational Environmental Satellite). The development of an IHDS will facilitate the data assimilation and analysis portions of HAPS.

Sources of in situ data will range from cooperative observers to automated data platforms. HAPS should include the objective analysis concepts (for rain-gage, radar, and satellite rainfall estimates) being developed as part of HRAP and the capability to incorporate QPF information. Most effective use of remotely sensed data may require modification of existing, or formulation of new, hydrologic models. The possibility of a decision theoretics approach to the flash-flood identification problem also will be considered [Zevin, 1983]. This approach would provide useful probabilistic information on the likelihood of flash flooding. It is envisioned that HAPS, as a major component of the System II applications software, will be developed in conjunction with System II, NEXRAD, and PROFS (the Prototype Regional Observing and Forecasting Service).

The communications media, by means of which the in situ and remotely sensed data will enter HAPS, are not defined fully at this time, but it is clear that provisions must be made for data from multiple sources, including:

(1) hydrologic data in SHEF via AFOS (or System II) or directly from the hydrometeorological data base within DATACOL on the RFC gateway computers; (2) rainfall estimates from D/RADEX (or NEXRAD) via RADCOMP and appropriate communication links; (3) rainfall estimates from HRAP data files on the NOAA CCF or RFC computer facilities via appropriate communication links; (4) other remote sensor data bases, particularly rainfall estimates from GOES satellite data, either via the HRAP files or through other interfaces; and (5) QPF data. PROFS, which was initiated in the late 70's [NOAA-ERL, 1977], has as part of its mission the development of system components capable of assimilating data and meteorological products from multiple sources. Experience gained in PROFS will significantly influence design considerations for System II and HAPS, which will become an integral part of the future NWS operations.

With the improvements in mesoscale rainfall measurements and analysis that will be possible with the implementation of technology such as that currently being developed as part of HRAP, NEXRAD, and PROFS (and that being planned for HAPS), a significant improvement in rainfall inputs for hydrologic forecasting should result. Precipitation inputs are typically the most significant input to hydrologic forecast modelling procedures. Additional improvements in lead time and forecast accuracy could be achieved if reliable precipitation forecasts were available as input to the hydrologic forecast models. Unfortunately, current quantitative precipitation forecasting models and procedures generally do not provide sufficiently accurate values (at least for forecast periods exceeding 30-60 minutes) for direct input to hydrologic models (see section 2). Although current QPF products from NMC provide generalized guidance information which is very useful in roughly indicating rainfall amounts and locations of rainfall areas, they do not provide the detail and accuracy required for assigning QPF values to individual watersheds.

There is a need for more direct incorporation of QPF information into the hydrologic models, which potentially can be achieved through the development of a dynamically coupled hydrologic modelling system which: (1) includes predictive capability for mean areal precipitation values for individual watersheds, 2) makes optimum use of meteorological forecast information, and (3) applies the combined precipitation and streamflow modeling system in an adpative framework so that the states of the system can be continually updated based on observations of precipitation and/or streamflow [Georgakakos and Bras, 1982].

Another promising approach for improving short-term (less than 1 hour) rainfall predictions, which should be especially useful for flash flood applications, is the use of so-called "nowcasting" procedures [Browning, 1982]. Simply stated, nowcasting refers to any of a variety of techniques which use recent past and/or current conditions as a basis for establishing trends for use in extrapolating conditions a short time into the future. For example, rainfall accumulation patterns, and their translations, estimated from radar for the first and last 30 minutes of the current hour could be used to obtain extrapolated rainfall estimates 30 minutes in the future. Such nowcasting capability should be planned as part of System II and HAPS.

<u>Extended Streamflow Prediction Program</u>. In a report to the President entitled "Global Future: Time to Act" [Council on Environmental Quality and U.S. Department of State, 1981], recommendations are provided for alternative actions to be taken in an attempt to change some of the trends toward environmental degradation as described in the Global 2000 Report [Council on Environmental Quality and U.S. Department of State, 1980]. It is pointed out in these reports that it will become increasingly important in the future for man

to do a better job of managing the earth's fresh water resources. According to the Global 2000 Report, if current trends continue, all the fresh water on the globe would still provide 3.5 times more water per person than needed in the year 2000. (The ratio of available water to water demand in 1981 was estimated to be 10 to 1.) However, serious repercussions are indicated if such a projection should come to pass since the water is very unequally distributed over the earth's surface. Regardless of how effectively we conserve our water resources in the future, it seems very likely that available fresh water supplies will continue to shrink as the world population, and related demands for agricultural products and energy, as well as water, increase. One corollary to this likely trend will be an urgent requirement for more effective management of available water supplies. Therefore, the use of NWSRFS and, in particular, the Extended Streamflow Prediction (ESP) program, to provide improved extended forecasts of streamflow to water managers across the Nation, will become an increasingly important secondary mission of the NWS.

Development of the first experimental version of the ESP program was begun in October 1975 [Twedt et al., 1977]. The current version (ESP 3), which will be officially released together with the OFP of NWSRFS in fall 1983, is illustrated in figure 9 [Day, 1982]. Version 3 of ESP is being designed with sufficient capability and flexibility to enable it to overcome most of the limitations of the first two experimental versions which prevented them from becoming fully operational [Laurine, 1982].

ESP uses the same hydrologic and hydraulic models as the OFP of NWSRFS. The ESP program has been designed as an integral part of the forecast system. The program obtains parametric information, as well as the current states of the system, from files kept up to date by the OFP. The same command language (i.e., HCL) used to execute the OFP is used to execute the ESP program.

As indicated in the preceding paragraph, application of ESP requires that the OFP of NWSRFS be run routinely so that parametric data and current hydrologic conditions (i.e., the states of the NWSRFS models, which may be updated with recent hydrometeorological observations, e.g., streamflow and snow water equivalent) are available from the parametric and carryover files of the forecast component (see figures 3 and 9). Starting with the current conditions and using historical precipitation and temperature time series data as input, the models are used to simulate possible future streamflow traces. One output trace is produced for each year of available historical precipitation and temperature data. If forecast time series of precipitation and/or temperature for a few hours or days into the future are available, provisions exist to merge the forecast and historical time series by weighting the two series in specified proportion out to the end of the weighting period, and then by blending the resultant series with the historical series out to the end of the specified blending period, at which time the historical series is used directly.

The forecast period (window) for each of the streamflow traces can be scanned for the output variable of interest, e.g., volume of streamflow, maximum streamflow, minimum streamflow, etc. The window lengths are specified by the user and can range from hours to seasons. The ESP program outputs the mean, maximum, and minimum of the output variable values obtained from the traces. A frequency analysis for each output variable can be performed with the ESP program, so that forecasts can be made at any exceedance probability level. Specific questions also can be asked, such as: For how many days is the flow expected to be below or above a certain flow value(s)? Other types of simulated traces, such as stage, can be analyzed in addition to the streamflow traces to produce probabilistic forecasts of other data types. ESP can be easily modified in the future to provide probabilistic forecasts of other output variables that might be desired and which can be derived by scanning the simulated traces. Thus, the ESP approach will give the NWS RFC's and WSFO's an extremely flexible and comprehensive method to provide decision-makers with water management information.

To realize maximum potential benefits from the use of the ESP functions of NWSRFS in the future will require additional R&D efforts. As pointed out by Laurine (1980), some of the most pressing issues associated with the operational use of ESP relate to data preparation and handling problems. Needed improvements in data techniques range from more efficient basic data preparation for model calibrations to improved capabilities for processing and analyzing large volumes of data. One of the problems associated with the operational application of the current ESP approach is that considerable computer resources are required for executing the input/output (I/O) functions necessitated by the use of possibly 20 to 30 years of historical time series data for 1 to 200 forecast points (watersheds) in a river system. This represents a massive data handling job even when the larger river systems are broken up into component parts. Also, disk storage for these data can be a problem, depending on mass storage availability. One possible approach is discussed below which has the potential of contributing significantly toward improving various data management problems and also of performing analyses useful for determining positional climatological information. Positional climatology in this context is that climatological information which allows one to position or weight historical time series of hydrometeorological data, in relation to the degree of similarity between the current year's meteorological patterns and those corresponding to each of the historical years, for the purpose of using these time series in hydrologic simulations leading to probabilistic extended streamflow predictions. For computational simplicity, the positional climatological weights actually are applied as part of the analysis of the ESP output traces, as illustrated in figure 9.

A general data analysis system known as Asymptotic Singular Decomposition (ASD), which has been used by Jalickee and Klepczynski (1977) and Jalickee and Hamilton (1977), may have applicability to several ESP-related problems. The use of ASD as a data compaction procedure is one approach to reducing significantly the data volumes required for ESP. If, for example, the time series required by ESP can be represented with sufficient accuracy by a relatively small number of terms and coefficients for the Empirical Orthogonal Functions (EOF's) provided by the ASD approach, then tremendous data compaction will have been achieved, and considerable savings in the computer resources required for applying ESP should occur. Such mathematical characterization of the time series data offers other potential advantages in the use of the ESP approach. Often, the available period of record of the historical time series may vary among stations within the areas of a river system. The same period of record generally is required for all historical time series needed to make an extended forecast for a river system. It may be feasible in many cases to use the EOF's to fill in missing data periods in order to produce a standard record length for all historical time series.

Another, and potentially extremely important, use for the ASD will be as a method to classify historical years based on similarity, or dissimilarity, of the coefficients of the EOF's for the current year compared to those for the historical years. Jalickee and Hamilton (1977) have used such an approach to objectively analyze and classify oceanographic data. This approach to classification is an objective one which should prove important for determining positional climatological information to be used with ESP as illustrated in figure 9.

Another more subjective approach for obtaining positional climatological information is being pursued. The NWS Climate Analysis Center (CAC) currently prepares and issues long-range weather outlooks (temperature and precipitation) for periods of 1 to 3 months. During the course of performing the analyses required to prepare the outlooks, which includes a consideration of current and historical weather patterns, the CAC analysts assign the historical years into three classes, depending on the analogy of the current year's weather patterns to those that were observed for the individual historical years. The three classes are analogue cases, anti-analogue cases, and indeterminate or weakly analogous cases. These classifications will then be used to assign weights for the positional climatological step (figure 9) of the ESP analysis.

Such an analysis was performed for part of the Potomac River basin in response to a drought situation which developed in late 1977 over a limited area of Northern Virginia [Curtis and Schaake, 1979]. In this case, 5 years, which were judged to be anti-analogue years, were withheld from the record used for the ESP analysis. However, for this case, the mean and variance of the precipitation series without the 5 years of record were not significantly different from the mean and variance of the precipitation values for the total period of record. This implied that no significant increase in skill in the ESP predictions would have been realized, in this particular case, by positioning or conditioning the historical time series by withholding the 5 years of data. Whether this resulted from insufficient discrimination by the classification procedures, or simply from happenstance for this particular data set, is not clear. Many additional cases need to be investigated as the data base is expanded by the CAC.

Plans for improving the utility and prediction accuracies of the ESP system include other R&D efforts such as: (1) accounting for the effects (on the probabilistic outputs) of uncertainty in the inputs, (2) automatically adjusting the forecasts for model bias, (3) improving low flow simulations, (4) objectively incorporating forecast precipitation and temperature data, and (5) investigating other, and possibly simpler, hydrologic modeling and prediction procedures to be used within the basic ESP analysis framework.

5. SUMMARY

In this paper, we have attempted to provide an overview of technological developments (past, present, and future) in support of the NWS Hydrologic Service Program. The original Congressional Organic Act of 1890 assigned the responsibility of river and flood forecasting for the benefit of the general welfare of the Nation's people and economy to the Weather Bureau which subsequently became the National Weather Service. The beginning of the structure of the NWS Hydrologic Service, as we know it today, occurred in 1946 with the establishment of two RFC's. Since that time, the number of RFC's has been expanded to 13 to provide coverage for all of the 48 states and Alaska. In addition, most of the approximately 50 WSFO's are staffed with one or more service hydrologists and several meteorologists who are responsible for interfacing with the RFC's, especially in regard to flash-flood services, and for disseminating hydrologic forecast information to the public. The level of technology in the NWS Hydrologic Service has grown extensively since 1946 with respect to computer applications, data acquisition and assimilation procedures, and hydrologic and hydraulic modeling and prediction procedures. Yet, there is still much progress to be made in all of these areas if we are to meet our Nation's future requirements for hydrologic forecast information.

Technological developments in the last decade have brought us closer to an integrated systems approach to forecasting from the perspective of data and computer systems and hydrologic and hydraulic modeling systems. Developments such as SHEF, DATACOL, and RADCOMP are significant examples of how computer technology can be applied to increase the collection efficiency, timeliness, availability, quality, and comprehensiveness of in situ and remotely sensed hydrometeorological data. Development of such technology must be not only continued but expanded in the future in order to provide the hydrometeorological inputs required to support the hydrologic modeling systems. Also, multivariate analysis systems such as the one under development as part of HRAP, must be perfected in order to "optimally" integrate and use data from conventional and remote sensors. And, more effective data base management and distribution procedures must be devised which, in a distributed processing environment, will link hydrometeorological data bases at the local and/or regional and national levels.

NWSRFS Version 5 and FLDWAV will provide the most generalized hydrologic and hydraulic forecasting systems ever available to the NWS Hydrologic Service Program. The modularity of these systems should make it easier to add refinements and should shorten the time between the research and development phases and the field implementation of new technology.

As we maintain and enhance the basic NWS hydrologic forecast system, we must also improve quantitatively our ability to predict short-scale hydrologic events (flash floods), as well as to provide information relevant to long-scale river and reservoir water supplies. Development of much of the technology to do this will be based on experiences and capabilities gained from NWSRFS, FLDWAV, and HRAP. Because of the modularity of these systems, it will be possible to incorporate new developments by both headquarters and field personnel. Technology for addressing the short and long scales will be packaged in systems such as ALERT, IFLOWS, HAPS, and ESP. These components of hydrologic technology must effectively integrate meteorological information such as precipitation and temperature forecasts and must be planned as integral parts of the enlarged NWS "systems picture" for the future, which will include such elements as System II, NEXRAD, and an upgraded CCF.

Finally, it must be pointed out that while the technological developments described in this paper are essential to providing a continuing modern and effective NWS Hydrologic Service Program for the future, such developments can not be achieved without sufficient resources. Especially important will be the maintenance of a highly trained staff of hydrologists in both headquarters and field components.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of all the scientists and engineers within the NWS Hydrologic Program who have provided many valuable comments and suggestions during the preparation of this paper. We are especially grateful to Dr. Robert A. Clark, who provided encouragement to produce this paper, to Dr. Danny Fread and Ms. Kay Krouse who provided advice and consultation in river mechanics areas, to Dr. Eric Anderson for invaluable consultation on the technical capabilities and operational features of NWSRFS, to Mr. Gerald Day who provided important guidance on the Operational Program of NWSRFS and the Extended Streamflow Prediction Program, to Mr. Joseph Ostrowski for advice on reservoir operations, to Drs. Richard Farnsworth and Douglas Greene for their input in various areas pertaining to hydrologic data, to Dr. Konstantine Georgakakos who provided information on QPF and model updating procedures, and to Dr. Jack Jalickee for providing information on the ASD approach.

The authors also express their appreciation to Mrs. Lianne Iseley who assisted with much of the editorial and graphics work, to Mrs. Ruth Ripkin for editorial and word processing support, to Ms. Rosalie Ryan for typing, and to Mr. Stephen Ambrose who also assisted with graphics.

7. LIST OF ACRONYMS AND ABBREVIATIONS

AFOS	Automated Field Operations and Services
ALERT	Automated Local Evaluation in Real Time
API	Antecedent Precipitation Index
ARAP	AFOS Radar Processor
ASD	Asymptotic Singular Decomposition
CAC	Climate Analysis Center
CCF	Central Computing Facility
CHAT	Computed Hydrograph Adjustment Technique
CLS	Constrained Linear System
CRREL	Cold Regions Research and Engineering Laboratory
D/RADEX	Digitized Radar Experiment (recently changed to RADAP II)
DAMBRK	Dam-Break Flood-Forecasting Model
DARDC	Device for Automatic Remote Data Collection
DATACOL	Data Collection Software System
DCP	Data Collection Platform
DWOPER	Dynamic Wave Operational Model
EOF	Empirical Orthogonal Function
ESP	Extended Streamflow Prediction
ERL	Environmental Research Laboratories
ESSA	Environmental Sciences Services Administration
FLDWAV	Floodwave Model -- a generalized river mechanics system including, among other elements, a synthesis of DAMBRK and DWOPER features
GOES	Geostationary Operational Environmental Satellite
HAPS	Hydrometeorological Analysis and Prediction System
HCL	Hydrologic Command Language

HRAP	Hydrologic Rainfall Analysis Project
HRL	Hydrologic Research Laboratory
HSD	Hydrologic Services Division
ICP	Interactive Calibration Program
IFFA	Interactive Flash Flood Analyzer
IFLOWS	Integrated Flash Flood Observing and Warning System
I/O	Input/Output
LFM	Limited area Fine Mesh model
MAP	Mean Areal Precipitation
MCP	Manual Calibration Program
MDR	Manually Digitized Radar
MIT	Massachusetts Institute of Technology
MOS	Multiple Output Statistics models
MSRANS	Multisensor Rainfall Analysis System
NEXRAD	Next Generation Weather Radar
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OFP	Operational Forecast Program
OPT	Automatic Parameter Optimization Program
PMP	Probable Maximum Precipitation
PROFS	Prototype Regional Observing and Forecasting Service
QPF	Quantitative Precipitation Forecast
R&D	Research and Development
RADAP II	Radar Data Processor, Version II
RADCOMP	Radar Data Communication and Processing

RCL	Reservoir Command Language
RFC	River Forecast Center
RJE	Remote-job-entry
SHEF	Standard Hydrologic Exchange Format
SMPDBK	Simplified Dam-Break Flood Forecasting Model
SSD	Scientific Services Division
TASC	The Analytic Sciences Corporation
WMID	Water Management Information Division
WSFO	Weather Service Forecast Office
WSO	Weather Service Office

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