Presented at the 1993 Federal Inter-agency
Workshop on Hydrologic
Modelling Demands for the 90's,
Ft. Collins, CO., June 7-9, 1993

The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations

by Richard K. Farnsworth[1], Donna Page[2], Timothy Sweeney[2], Ann McManamon[2], George F. Smith[2], Donald P. Laurine[3], and Danny L. Fread[4]

ABSTRACT

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) is currently undergoing significant evolution. Under the program for Modernization and Associated Restructuring (MAR), NWS is establishing observing systems that increase the temporal and spatial resolution of observed data, enhancing the communication systems, and distributing the processing of the data to generate forecasts to be used for issuing watches and warnings. The new level of data observation, communication, and processing is bringing about improved procedures for making forecasts. This report will concentrate on those related to hydrologic forecasts. Specific topics include (1) the processing of rainfall data and display of rainfall fields from independent sources of varying resolution allowing the user some flexibility in adjusting these fields, (2) modularization of forecast software to make forecast programs more interactive with graphical user interfaces (GUI) to assist the forecasters in making appropriate choices, (3) the use of new graphical products to enhance model understanding (4) advancements in river routing procedures, (5) the capability of using digital elevation data bases to derive basin boundaries and geomorphologically model ungaged basins, and (6) new procedures using Geographic Information Systems (GIS) to estimate water content in snowpacks.

INTRODUCTION

The NWS has been given the responsibility to forecast watches and warnings of dangerous flood conditions on rivers. They also have the task of issuing forecast for water supplies. A third task is to provide warnings of flooding on basins that respond too quickly to gather and process precipitation to provide quantitative stage forecasts. This third service involves the preparation of flash flood guidance values which serve as the basis for issuing advisories for areas with a strong probability of flooding in a very short time (flash floods).

Over a decade ago, approximately 20,000 locations were identified as being at risk to flood damage. Even with those operations that are currently in place, the NWS is working near the

[1] Deputy Chief, NOAA, National Weather Service, Office of Hydrology, Hydrologic Research Laboratory, 1325 East-West Highway, Silver Spring, Maryland 20910

[2] Research Hydrologists, NOAA, National Weather Service, Office of Hydrology, Hydrologic Research Laboratory, 1325 East-West Highway, Silver Spring, Maryland 20910

[3] Hydrologist, NOAA, National Weather Service, Colorado-Basin River Forecast Center, 337 No. 2370 West, Salt Lake City, Utah, 84116

[4] Director, NOAA, National Weather Service, Office of Hydrology, Hydrologic Research Laboratory, 1325 East-West Highway, Silver Spring, Maryland 20910

limit of its operational capability to issue stage forecasts for about 3,000 forecast points. One of the major limitations is the size of the remaining watersheds. Many of them are small and respond too quickly to obtain the necessary input data, process a forecast, and issue the forecast to the public in sufficient time to control damage. In these situations, advisories are issued to alert the public; but the extent of the threat can not be expressed in terms that allow significant damage reduction activities. With the improved hardware and software currently under development, the NWS hopes to extend its capability to meet the public needs.

The accomplishment of this assignment requires that (1) precipitation be accurately observed with high temporal and spatial resolution, (2) that air temperature be observed and used to (a) model the separation of precipitation into rainfall which immediately infiltrates the soil or runs into channels, or snow which remains where it falls until it melts (or drifts to a new location) and (b) model the melting of the snow pack in a realistic manner, (3) that the land surface of the basin be modeled with appropriate state variables to indicate the (a) amount of the rainfall that flows to river channels, (b) the timing of runoff discharge past the forecast point (unit hydrograph), (c) the rate of ground water release to form the base flow, (d) the amount of moisture transpired from the soil, and (e) the moisture that the soil holds in storage, (4) that the flow through segments of basins be routed by an accurate modeling process to forecast points further down stream, and (5) that climatic variabilities be properly considered for making forecasts involving precipitation that has not yet been observed.

Almost all of these topics have been impacted by the NWS modernization. This impact will be described further in subsequent paragraphs. However, as this is an overview of the evolution of operational procedures by our agency, the details of several of these topics will be treated in a somewhat cursory manner.

The technical evolution in our procedures to accomplish the specific tasks listed above are strongly influenced by the following considerations: (1) the Modernization and Associated Restructuring (MAR) program of the NWS; (2) advances in the technology required to observe, record, and report precipitation and other hydrometeorological data; (3) advances in communications, data processing, and display technology; and (4) advances in the science of hydrometeorological models.

Because NWS is highly focused on its forecasting mission, our research and development is concentrated on operational models and applications. Essentially all models considered for research and development are designed to fit directly into our National Weather Service River Forecast System (NWSRFS).

The modernization and restructuring of the NWS has occurred in large part from the need to replace aging weather observation radars, slow and saturated communications systems, and limited observation networks. The implementation of the WSR-88D radars (also known as NEXRAD) brings about a system that will cover, within a very short time, 98 percent of the country under an umbrella of radars that makes hourly observations of rainfall fields with resolution sufficient to map them into a grid 4 km on a side. These radars will be generally collocated with the primary NWS weather and river forecast offices for the area of radar coverage.

Station surface observations are beginning to be reported hourly from a system that ultimately will consist of well over 1000 automatic stations through the implementation of the Automation of Surface Observations Program (ASOS). These automated stations will include all of the first order weather stations and over 500 locations required by the Federal Aviation Administration.

The added data collected from the radars and the ASOS stations will be communicated, stored, and processed at the Weather Forecast Offices (WFO) and River Forecast Centers (RFC) by the Advanced Weather Interactive Processing System (AWIPS). The contract for the initial phase of this system was awarded in late December of last year. This system will provide significantly increased capacity for data transmission and it will focus on local processing of river forecasts on scientific workstations, thus replacing to a significant degree, the centralized processing on mainframe computers.

The introduction of workstations will allow significantly more flexibility in operational procedures. Currently most RFCs run batch programs which model their entire area of responsibility in a single computer run. The new interactive software on the workstations will be able to identify and process individual forecast basins where flood or drought threats are greatest. The workstations facilitate the use of graphics and graphical user interfaces (GUI) for assisting forecasters in assessing, analyzing, and processing data; developing their forecasts; monitoring precipitation to issue flash flood watches and warnings; calibrating basins; and generating water resource forecasts.

This report discusses improvements that have been made in the NWS in (1) data processing, (2) hydrologic modeling, (3) the use of GIS, (4) water supply forecasting systems, (5) and model verifications. Hydrologic modeling and model verification will be discussed in some detail in this paper. Other papers by NWS staff members will cover items 2,3, and 4 in more detail.

DATA PROCESSING AND MATHEMATICAL MODELING

In accordance with its mandated mission of issuing river flood and water supply forecasts, the NWS develops models for real-time simulation and forecasting.

Precipitation is the primary process that drives our forecast models. Innovations in observing and recording precipitation are being worked on in NWS by two different teams. One team is looking at producing a hydrologically meaningful quantitative precipitation forecast (QPF). The second is working to merge data from the WSR-88D radar, rain gages, and satellites to produce a real-time, high-resolution assessment of hourly precipitation on a 4 km grid.

Quantitative Precipitation Forecasts

The Ohio River RFC (OHRFC) located in Cincinnati, Ohio has been leading the team to produce QPFs and convert them to a grid and/or to assign QPF values to the basins being forecast by the RFC. The team includes the OHRFC, forecasters at the NWS National Meteorological Center (NMC) in Camp Springs, Maryland and at the NWS Techniques Development Laboratory (TDL)

located at NWS headquarters in Silver Spring, Maryland, and meteorologists at Weather Service Forecast Offices (WSFO) within the OHRFC area of forecast responsibility. Interactive software to carry out this task has been written to operate on an IBM RISC 6000 scientific workstation.

The major problem associated with QPFs is the large areas where potentially intense rain may fall. If the total area within which relatively small, intense rainfall concentrations might occur were used (with the maximum intensities predicted) to generate a flood forecast, floods of record would occur. It is therefore important that probabilities be associated with the forecast intensities in such a way that a map of the forecast intensities can provide reasonable assessments of river runoff that might occur. Certain simplifying assumptions are being made in the initial modeling of this process. We expect that as experience is gained with the initial models and as the overall system evolves, these models will include objectively computed probabilities of occurrence of heavy rainfall intensities resulting in improved accuracies of the QPFs. This improvement will increase their value for use in forecasting floods.

Precipitation Processing

The monitoring of precipitation in real time is taking a great leap forward with the installation of the WSR-88Ds. There are only a handful of these radars that have been fully accepted at this time (February 1, 1993). However, several have been installed and are being actively tested. By January 1996 95 percent of the continental U.S. will be covered.

As of this time, WSR-88D systems produce hourly maps of gridded rainfall on a 4 km grid. The radars themselves can provide higher resolution than this. A graphical product is currently being produced on a 2 km grid. Many forecasters are pressing for digital conversion of this product for flash flood detection.

The processing of precipitation data from the radar is covered in more detail in these proceedings in the report "Precipitation Processing with the WSR-88D" by Robert C. Shedd, et al. In general terms, however, the system involves three stages. The first stage (1) detects a reflected return from the radar signal, quantifies it to a set of intensity rates which are averaged over the hour and converted to rainfall volumes; (2) compares the areal average of these rainfall volumes with an average volume derived from readily reporting rain gages and adjusts for bias in the data (the ratio of the two averages); (3) makes preliminary quality control corrections for ground clutter, anomalous propagation (AP), and range effects; and (4) maps the data from the polar coordinate system in which it is initially observed into the polarstereographic projection coordinate system. This processing takes place in the WSR-88D computer system.

The second stage (1) adjusts the rainfall field to conform to readings from additional rain gages, (2) makes further quality control checks by comparing thermal infrared data from satellites with areas indicated as rainfall by the radar to reduce the effects of AP occurring under cloud free skies, and (3) sets up information for further interactive quality control activities to be carried out in the succeeding step. This processing can occur on a mainframe or a scientific workstation.

The third stage performs two major functions. It creates mosaics of the mapped rainfall, i.e. merges data from several radars, resolving differences in the estimates in areas that are overlapped by more than one radar. This stage also generates graphic displays of the rainfall fields resulting from (1) the rain gages, (2) the radar, and (3) the combined field. By alternating between these views, trained hydrometeorologists can spot problems arising in the radar measurement and filter erroneous data. Stage III is run on scientific workstations at the RFC.

FORECASTING SOFTWARE

NWS River Forecast System

Once the observed and forecast precipitation are estimated, the other aspects of the hydrologic cycle that are required to develop forecasts, are modeled. All of these computations are carried out in the software system known at the NWS River Forecast System (NWSRFS). The NWSRFS has been developed over the past 20 years and is now in its fifth major revision (Version 5.0). The functional requirements which guided the design of NWSRFS Version 5 were to:

1. allow for a variety of models and procedures,
2. let the user control selection of models and sequence of use,
3. easily add new models and procedures to keep up with technological changes,
4. efficiently process large amounts of data to produce forecasts at hundreds of locations for each RFC, and
5. allow the user to flexibly control real-time processing.

Version 5 was designed to be modular, so that components could be developed by a number of individuals and then combined into a total system. References in the program code to system specific routines were isolated so that the entire NWSRFS could be ported from one hardware/operating system platform to another with minimum effort. Routines which performed scientific algorithms were separated from input/output routines so that the science could be run on any computer without needing changes in the reading or writing of information from the computer system. Scientific algorithms were organized into modular functions so that the functions could be shared, unchanged, among major components of the NWSRFS.

The functions representing one scientific algorithm, such as functions that model snow accumulation and ablation, or soil moisture accounting, or river routing, are called an operation. In general, an operation in the NWSRFS is a set of functions that performs actions on a time series. Typically an operation describes the equations of motion governing the flow of water through a portion of the hydrologic cycle. There are also operations to display results, or to perform utility functions such as adding two time series. Table 1 provides a list of some of the currently available operations in the NWSRFS.

Table 1. NWSRFS Hydrologic Models

Snow

HYDRO-17 Snow Model

Soil

Sacramento Soil Moisture Accounting
Ohio RFC API Rainfall-Runoff Model
Middle Atlantic RFC API Rainfall-Runoff Model
Central Region RFC API Rainfall-Runoff Model
Colorado Basin RFC API Rainfall-Runoff Model
Xinanjiang Soil Moisture Accounting
Continuous API Model
Middle Atlantic RFC API Rainfall-Runoff Model #2

Channel

Channel Loss
Dynamic Wave Routing
Lag and K Routing
Layered Coefficient Routing
Muskingum Routing
Tatum Routing
Stage-Discharge Conversion
Single Reservoir Simulation Model
Unit Hydrograph

The operations that model the flow of water through the hydrologic cycle fall generally into the categories of (1) snow accumulation and melting, (2) water flow on or below the ground surface, or (3) water movement from one location to another on a river. Operations form the scientific heart of the NWSRFS and are shown in Figure 1 to be shared by the major sub-systems which comprise the NWSRFS Version 5. These subsystems are: 1) the calibration system for estimating model parameters based on historical data, 2) the Operational Forecast System (OFS) for producing river forecasts for a few days in the future, and 3) the Extended Streamflow Prediction System (ESP) for producing longer range forecasts (a few weeks to months) for water supply information.

Because of the modular nature of the functions which make up any operation, functions can be shared **with no change whatsoever** among the programs which form the NWSRFS. This also allows new scientific techniques to be developed in the structure specified for an operation, and once tested to be immediately available for use in forecasting with the NWSRFS.

Hydrologic operations in NWSRFS are organized into an "operations table" to specify the physics of water movement for any subbasin. Operations can be selected from the list shown in

Table 1. The order in which they are computed depends on the hydrometeorologic conditions of the subbasin being modelled. RFC forecasters can use their hydrologic expertise to determine the best sequence of scientific algorithms (operations) to model each subbasin. In this way, NWSRFS provides a generalized river forecasting system which can be used to model basins in any hydroclimatic regime.

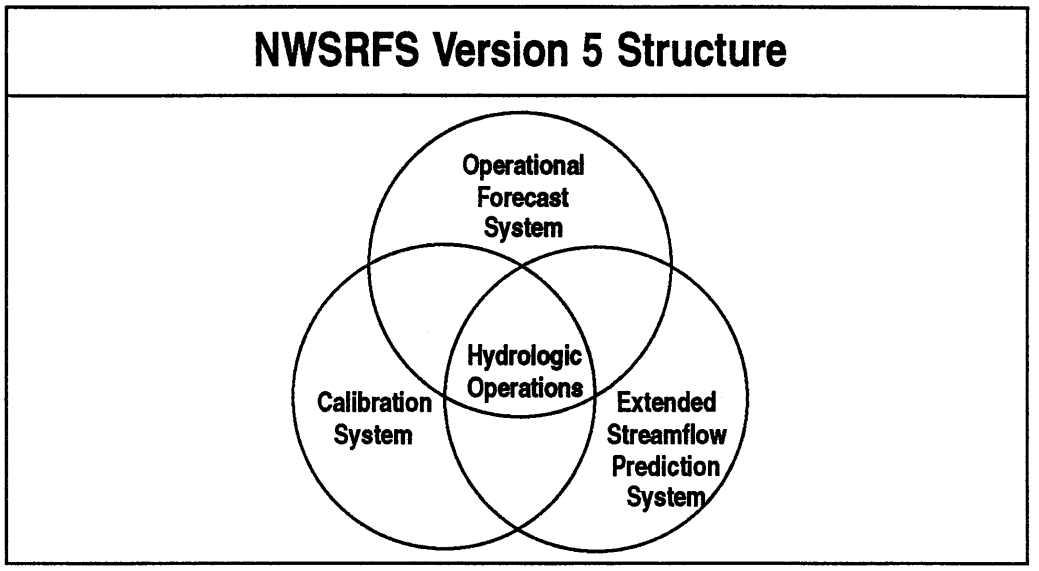

Figure 1.

A typical operations table might include: 1) the Snow operation to account for snow accumulation and ablation, 2) the Sacramento Soil Moisture Accounting operation to determine the rainfall excess, 3) the Unit Hydrograph operation to time distribute the rainfall excess, 4) the Dynamic Wave channel routing operation to route upstream flows through the forecast point, and 5) a utility operation to graphically display the resulting hydrographs.

Initial NWSRFS Version 5 development occurred from 1979 through 1984. Since 1985, NWSRFS Version 5 has been installed in RFCs and has been used daily to produce operational forecasts at thousands of locations along rivers throughout the U.S. New subbasins are continuously being calibrated and added as operational forecast locations by RFC hydrologists. Many new scientific algorithms and enhancements to existing operations have been added to improve the hydrologic modelling capabilities of the NWSRFS.

The initial NWSRFS design and development was on a mainframe computer [NAS9000s-(IBM look alikes)] at the NOAA Central Computer Facility (CCF). As minicomputers became powerful enough to support the system requirements of the NWSRFS, the Operational Forecast System (OFS), a sub system of NWSRFS, was ported to PR1ME minicomputers, located at NWS headquarters and at several RFCs. With the explosive growth in computational capabilities for scientific workstations, the NWS's Office of Hydrology (OH) initiated a project in the late

1980's to prepare for the anticipated modernization of the entire NWS by moving the OFS, the forecasting component of NWSRFS including hydrologic operations, onto IBM RISC System 6000 workstations.

When the NWSRFS is run from the NOAA CCF mainframe, command input is sent on Remote Job Entry (RJE) lines from RFCs to the CCF. Line printer results are sent back to the RFC for display on standard printers or to on-site data storage files for display on personal computers or terminal monitors.

Beginning in 1989, graphical display and user interface capabilities were developed for the NWSRFS. The result is the NWSRFS Interactive Forecast Program (IFP) which is discussed below.

NWSRFS Interactive Forecast Program (IFP)

As the practice of river forecasting has developed, it has evolved from being totally based on memory and experience, allowing a significant amount of subjectivity on the part of forecasters, toward a more object procedure where consistently observed input data is mathematically applied to physical models.

The evolutionary progress is occurring at an accelerated rate and, while machines are executing more and more of the procedures in an objective fashion, hydrologic forecasting still requires human-machine interaction because:

1. the equations with which we represent the physics of the hydrologic cycle do not perfectly model the actual movement of water,

2. the models that we use to approximate the physics of the hydrologic cycle require parameters to fit specific basin characteristics. The calibrations processes do not produce perfect results, and

3. we still have uncertainty and error in our observations and estimations of rainfall and streamflow which are the inputs to our models.

With the new computer capabilities, this required human interaction may occur more frequently and effectively in the forecast process. To properly forecast a hydrologically connected series of subbasins, a forecaster must make decisions for each location along the river where observed river conditions are available. If values simulated by NWSRFS do not agree with observations, the forecaster must decide on the most likely source(s) of error, and make adjustments. When a river system is forecast with NWSRFS on the mainframe or minicomputer, large groups of subbasins are processed in a single batch run. Errors in upstream subbasins propagate into downstream basins, making forecasts for those basins less reliable. The problem can be reduced by making appropriate adjustments to reduce or if possible remove the error in a subbasin before

processing downstream subbasins. The IFP provides this capability to the forecaster. The IFP together with the workstations also provide the capability for high resolution color graphics to communicate products more clearly and effectively than the mainframe line printers.

The NWSRFS with the IFP offers:

1. an operationally proven set of hydrologic models,
2. a system configuration which uses the UNIX operating system with X Windows graphical display protocol and Open Software Foundation (OSF) Motif,
3. adherence to OSF standards to be computer hardware platform independent,
4. a GUI that provides easy, powerful user interactions,
5. scientific applications that are isolated from the operating system specific functions calls and input/output, and
6. the use of both C and FORTRAN programming languages; C for user interface and graphical display routines, FORTRAN for physical process modeling.

Currently, the NWSRFS requires input data from existing NWS data sources. With the advent of AWIPS, these data sources will be passed through the AWIPS communication system to the AWIPS workstation where the forecasting will be done.

The new interactive forecast software now being tested at two RFCs, provides the forecaster with several new capabilities. First, in beginning a forecast assignment, forecasters can review on the workstation screen the hydrologic situation for basins where they have assigned responsibility. The IFP allows them to select the assigned group of river basins and display on the screen both a schematic and a geographic map of the basins. The potential for flooding is indicated in color for each individual basin. Streams already above floodstage are marked in red, those with some possibility for flooding in yellow, and those with little or no likelihood are in green. By moving the cursor on the screen with a mouse, the forecaster can zoom in on individual basins. They can call for a window to appear on the screen listing basic basin parameters including flood stage. An example of a workstation screen is shown in Figure 2.

When the IFP begins, the hydrologic models for the most upstream basin are run on the workstation and the resulting hydrographs are displayed. The IFP then allows the forecaster, using the mouse, to point and click to make modifications to time series values or to other model inputs. A few examples of the modifications that can be made include correcting errors in observed stage data, adding QPF values, adjusting the baseflow for the Sacramento Soil Moisture Accounting operation, or temporarily adjusting the unit hydrograph for the basin.

After the forecaster is done making modifications, the hydrologic models for the basin are rerun and, within seconds, the results are displayed. When the forecaster is satisfied with the results for that basin they can move on to the next downstream basin and repeat the analysis until they are done with the chosen set of forecast points.

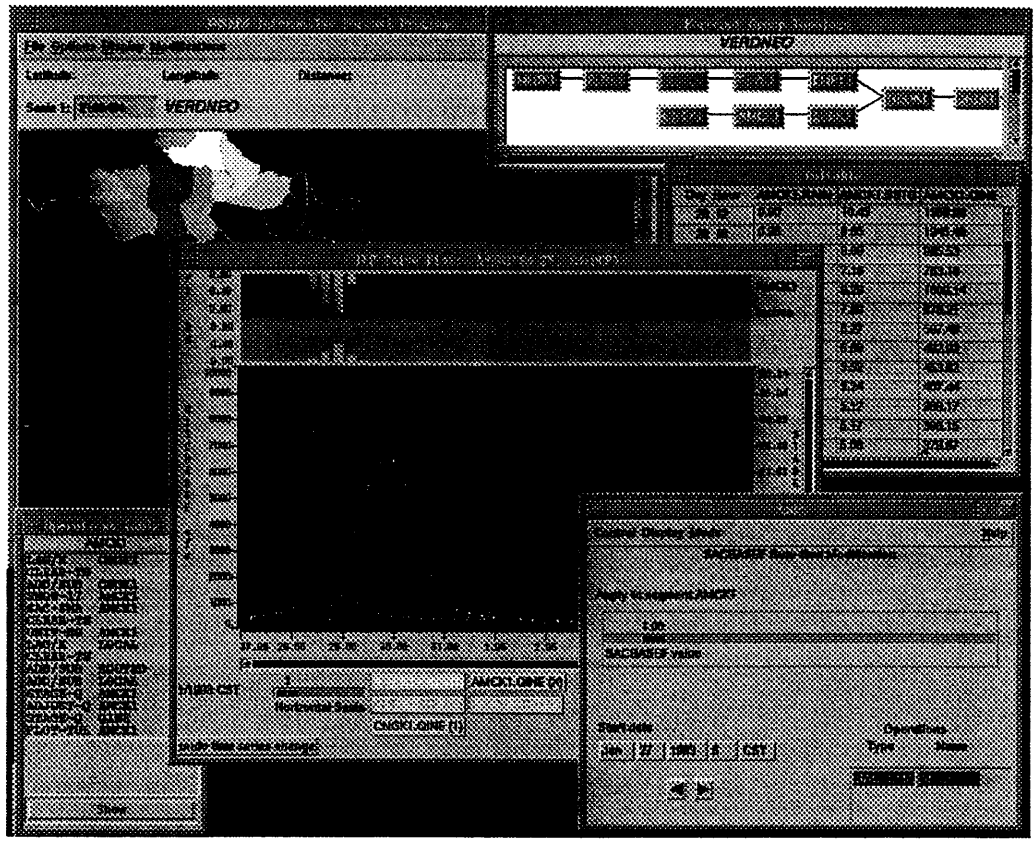

Figure 2.

With the new interactive software for the AWIPS era, forecasters will have both the Stage III precipitation processing program for interactive processing with the improved data from the WSR-88D and raingage network, and the IFP for interactive streamflow estimates on the same workstations. In a potential scenario, a forecaster looking at the Stage III display might observe heavy localized rainfall near the outlet of a basin. With this knowledge, using the IFP, the forecaster could then modify basin unit hydrograph to route the runoff to the outlet of that basin more quickly for that storm.

In summary, the new interactive forecast software will enable greater flexibility in adjusting model parameters, take less time to incorporate these modifications, and improve the accuracy of the forecast.

River Mechanics

Following, in a conceptual sense, the path of the water after it enters into the stream channel, the next computation involves routing the discharge downstream to lower basins. As noted in the previous section, NWSRFS has several channel models available for routing flows. Many of

these models are empirical and while they correctly simulate many conditions, there are many remaining situations where the routing models do not correctly describe the process. For this reason research continues in HRL.

The dynamic wave channel routing operation model is the most physically based of our routing models. It is continuously being improved to account for a wider range of hydraulic situations.

Routing models generally have several vital steps. The primary requirement is to have an accurate stage-discharge relationship. Our models generally route volumes of water downstream. Maintaining this relationship is difficult in areas where significant changes occur in the river bed or where the river slopes are very flat. Stage-discharge in these shallow slope areas are significantly influenced by changes in bedform roughness due to scouring or filling of the channel or to the change in the water surface slope with the passage of storm crests.

Studies are being conducted in our laboratory on sediment transport in order to simulate processes that influence stage-discharge relations and thereby improve our accuracy in routing flows.

In addition to forecasting downstream flows based on continuous modeling, NWS has a responsibility for forecasting damaging flows that might occur as a result of the failure of any of over 70,000 dams in the country.

To do this we have assembled catalogs and on-line data bases identifying each reservoir, its location, the river that it is on, the first downstream point of interest (community, school, power plant, hospital, etc.), general travel times of flood waves from the dam to that point of interest, and given standard conditions, the flood crest (maximum stage of the flood waters) that might be expected in the vicinity of that point. Since conditions are continually changing, to compute the flood data, a program known as the "Simplified Dam Break Model" (SMPDBK) was used. This model makes many basic assumptions and requires very little input data. This software is designed to run on the smallest of computers and give "first guess" category results. With such a large number of reservoirs, each changing continuously with inflows and outflows, it would be very difficult to maintain much greater detail than this. When conditions arise making the failure of a reservoir probable, this SMPDBK can be run with improved estimates of the relatively few input parameters or variables involved. The output from this processing can provide an improved estimate of the downstream flood crest.

The full scale dam break model can be run when time allows and when significant data such as downstream channel cross sections can be obtained.

These models are continuously being updated and improved. With the introduction of more powerful PCs and scientific workstations, many more graphics and graphical user interfaces are being introduced. Thus the software is being updated to make it more user friendly both in ease of input and in understanding the meaning of the output values.

The routing of the flows downstream can be done to many different levels of accuracy based on the extent and accuracy of the input data. When rivers or streams pass through reservoirs, the outflow becomes much more a function of the operating principals of the reservoir. During times when the outflow is most critical for making flood forecasts is when there is the least time for communication between forecasters and dam operators. There are other conditions when the operations of the reservoir are not readily available to a forecaster or hydrologic modeler that will be discussed under the section on water supply forecasting.

For these reasons, we have a suit of algorithms which seek to simulate what we think reservoir operators will do under various conditions. This model application is also evolving as we gain experience with its use.

Flash Flood Guidance

A significant fraction of the lives lost to flood events are those related to very intense storms over small but rapidly responding stream basins. We currently identify 12 hours as the minimum response time for which we can collect data and process and disseminate a forecast with enough warning lead time to be effective. For smaller basins with shorter lead times we issue "flash flood advisories."

In the past, these advisories have been developed by independent procedures in either the office issuing them or by the NWS region governing the offices that issue the forecast.

All of the procedures were based at least in part on the soil moisture conditions in each area for which the advisories were issued. The soil moisture conditions were provide by the RFCs. The different RFCs had different methods and formats for providing these data. A significant problem occurred where the soil moisture data for a single forecast office was provided by as many as three RFCs. Because their procedures differed, discontinuation would exist in the guidance values at the RFC boundries.

With new communication and processing capabilities, the Office of Hydrology plans to support a single standard procedure. The standard system would reduce discontinuation at RFC boundries. In this procedure, threshold runoff values will be determined for 1-, 3-, and 6- hour rainfall durations. Threshold runoff is defined as the runoff from a rain of specified duration that causes the streams located within a local geographical area to slightly exceed bankfull.

Since bankfull is not constant along a length of stream, these threshold values must relate to particular points in the basin. Further, since the small streams for which these advisories are issued are rarely gaged, and since there are a very large number of them, physical observations can not be made for each basin. For that reason, the procedures are developed using digital elevation data bases (DEDB) and GIS. Details of this development work are included in the paper "GIS Application in the NWS Flash Flood Guidance Model" by Timothy L. Sweeney, Danny L. Fread, and Konstantine Georgakakos, included in this publication and reported through a poster paper.

WATER SUPPLY FORECASTING

Water supply from surface water sources generally requires projections which extend several months into the future. Deterministic forecasts of precipitation have usable skill only a few days into the future. Climatological forecast for months or seasons are based on observable conditions such as those associated with the El Nino-Southern Oscillation but the accuracy of those forecast is quite limited.

Extended Streamflow Prediction (ESP) System

Long term flow forecasts based on averages of river flows also suffer a loss in accuracy caused by changes in the basin over the period of record. Channels are modified, basin surface areas are urbanized, agriculture and/or forestry practices are changed, etc.. All of these changes can be observed to one degree or another but their effect is difficult to model and use in making predictions of future runoff. The NWS long term forecast component of NWSRFS known as ESP uses the same hydrologic models used for standard river forecasts instead of a model based on long term averages of flow. The forecasts of flows or flow volumes up to a year into the future use current conditions for the model states and historical rainfall and temperature time series as inputs to the models.

First, however, these data are checked and corrected for internal consistency over the period of record. Each year of historical data is processed as if it were occurring in the current year. In this way, a set of streamflow traces are developed for each year of data. Considering each trace as an equally likely occurrence, a probability density function (PDF) is constructed indicating the probability of a given flow for the coming year. With this PDF, probabilities can be estimated for a range of flow levels.

When regulated rivers are forecast some distance into the future, then the rules for regulation, i.e. reservoir operating instructions, etc., must be extrapolated or "modeled" into the future. Thus the study of reservoir simulations that were briefly described in the section on river mechanics is vital for extended forecasting of streamflows.

The NWS also is interested in modeling snow pack conditions for large portions of the country. In the western United States up to 75 percent of the water used for irrigation comes from snow melt. Accurate estimates of water equivalent of snow packs are important observations for use by NWS.

Just as the NWS must depend on other government agencies for observing precipitation, the water contained in the snow pack is frequently observed by others, notably the Soil Conservation Service (SCS). Such observations include over 40 years of observations from over 1500 snow courses. The SCS has also been collecting snow-water related data at approximately 650 sites which it identifies by the name SNOTEL. These have been in operation for about 10 years.

Based on data from snow observations, regression models have been used for over 70 years to estimate seasonal runoff from regions with significant snowpack. The regression models provide estimates with the greatest accuracy for mean values. Confidence can drop significantly during the occurrence of extreme conditions, when runoff estimates are usually the greatest concern. Regression equations are developed to include coefficients relating the independent variables to that being predicted. These coefficients are defined only for the condition that values are present for all of the independent variables used in the development of the equation. A basic assumption made in developing the regression equation is that correlations between snow at various index points and the flow at the mouth of the stream remain constant year after year. In fact there are many changes occurring in basins that influence changes in that relationship. Because of these limitations, the NWS uses a physically based snow accumulation and ablation model (Anderson, 1978). This model also requires an adequate level of input data but can compensate more readily for missing data.

In addition to the data from the SCS, the NWS uses data generated by the National Operational Hydrologic Remote Sensing Center (NOHRSC) that is collocated with the North Central RFC in Minneapolis, Minnesota. The NOHRSC, with interagency support, directs the monitoring of snow pack conditions with low altitude aircraft flights that record the natural gamma radiation of the soil. The sources of this radiation exist naturally in the soil. The radiation essentially occurs at a constant rate but is attenuated by moisture in the soil and the overlying snowpack. By measuring the difference in radiation during the no snow condition to that observed with snow present, the mean value of the water equivalent can be determined in transects 80 meters wide and several kilometers long. Over time these transects can be indexed to the effective average of water held in the snowpack for a given area.

Also at the NOHRSC, the areal extent of snow cover is routinely mapped. These data can be used to determine areal depletion curves as a further index to the amount of water in the snow in a basin.

Snow Estimation and Updating System

Even with all of these data, there are difficulties in estimating basin averages of water equivalent in the snow pack. A method for interpolating between observed points and thereby estimating areal values is being developed. This system, known as SEUS for the Snow Estimation and Updating System, also dynamically models the changes in the snow pack with the passage of time.

The software algorithm which computes snow melt contributions to runoff in NWSRFS is the conceptual snow model. It relies on estimates of mean areal precipitation and mean areal temperature to compute estimates of current snow cover conditions. These mean areal estimates of precipitation and temperature are developed from point observations. As indicated earlier, because of the difficulties in accurately estimating precipitation in the mountains, it is essential that all possible snow water equivalent observations be used to update model simulated snow cover conditions. SEUS is used to interpolate observations of snow water equivalent to produce

gridded estimates of snow water equivalent. These grids are summed to develop estimates of the areal snow cover conditions needed by the NWSRFS conceptual snow model. These estimates are weighted with the model simulated conditions based on their relative uncertainties to compute updated snow conditions.

A paper describing this snow melt updating procedure in detail is included in these proceedings. The paper is entitled "Estimating Snow Water Equivalent Using a GIS" by Ann McManamon of NWS, Gerald N. Day (RTi) and Thomas R. Carroll (NWS).

The conceptual modeling of the physical basin where the snow accumulation and ablation will occur, is made in terms of geophysical factors which include slope, aspect, vegetative cover, elevation, etc.. This work is done most effectively using a Geographical Information System (GIS). The GIS used in our development work is the Geographic Resources Analysis Support System (GRASS) developed by the U.S. Army Corps of Engineers at their Army Construction Engineering Research Laboratory (USACERL). Based on this work, melt relationships are determined for the various combinations of geophysical classifications in the basin. With these factors, melting of the snow pack in the basin is modeled dynamically in the NWSRFS snow model as a function of air temperature and seasonal factors relating to the length of the day.

Briefly described, the SEUS has three components, one for calibration, one for real-time operations, and one for updating. The calibration component analyzes historical observations and develops the model parameters required to estimate a gridded map of snow water equivalent. It further processes the data to obtain areal or basin averages. The operational component uses real-time observations to develop gridded and areal estimates of snow water equivalent. The updating component uses information developed in the calibration phase to remove model bias and update snow conditions based on subsequent data, weighting such data according to the reliability that the input data has demonstrated as an effective index to the snow estimate.

Water Supply Forecasting Services Pilot Project

The economic effects of effective water supply forecasts which include probabilities for forecast realization have been described in conceptual terms for several years. As a quick example, the benefit from the dynamic operation of multiple use reservoirs using long-range probabilistic forecasts is rather easily recognizable. When large inflow volumes of water are expected into a reservoir that has been designed for both water supply and flood control, the long-range forecast provides the opportunity to water managers to lower the storage pool gradually several weeks in advance of any anticipated large inflows, thereby increasing the flood control capacity of the dam. They can do this knowing in advance the probability that a sufficient volume of water to restore the reservoir to the same capacity will occur as during the inflow period. Using the long-range forecast, excess water would not need to be spilled in an emergency manner potentially causing flooding in downstream areas. For these dams equipped with power-generating turbines, the systematically spilled water could be beneficially used to generate power following a set schedule. The competing uses can be taken into consideration and strategies can be developed to optimize dam operation for all uses.

To demonstrate this service in a practical manner, the NWS, with the cooperation of the Bureau of Reclamation has joined with the Denver Colorado Water Department, Riverside Technologies inc, and the Colorado State University to execute a pilot project. This project is described in more detail in these proceedings in a paper entitled "Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast." by Donald Laurine and Dr. Larry Brazil.

The project is applied to water management systems operated by the Denver Water Department which bring water from the Colorado Basin to the Denver Metropolitan area. The referenced paper details the economic value of operating these systems using long range forecasts to optimize the operation strategy to comply with water rights, serve the water needs of the City of Denver, while increasing sales of hydroelectric power and reducing other costs.

The use of scientific workstations to accomplish these water supply forecasts allows the complex factors involved in decision making and the graphics required to understand possible options to be simultaneously available to the forecaster.

SUMMARY

The introduction of scientific workstations and improved communications capabilities that are becoming available to NWS under MAR programs are allowing many opportunities to improve forecasts through improved higher spatial and temporal data observations, faster and more uniform data transmission, interactive processing involving more computer support in terms of graphics and GUIs and GISs, and to implement technologies related to QPFs and flash flood guidance values. These systems are being developed and managed so that as the technology increases, hydrologic innovations can also be applied at an accelerated rate. These systems also enhance the ability of the NWS to communicate its products more rapidly to the public and to exchange vital water related data with other sister agencies of the Federal Government.
The NWS is now on a faster track to better warn the public at risk to flooding and drought and better execute its assigned mission.

REFERENCES

Anderson, Eric A., National Weather Service River Forecast System Users Manual, Section II.2, pp.1-6, 1978.