Interactive Forecasting with the National Weather Service River Forecast System

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Introduction

The U.S. National Oceanic and Atmospheric Administration (NOAA) is responsible for using science and service to manage the resources of the United States. The National Weather Service (NWS) supports this mission by providing river and flood forecasts and warnings for protection of life and property, and by providing basic hydrologic forecast information for environmental and economic well being. The Office of Hydrology (OH) supports NOAA's and NWS's missions through the design, development, testing, implementation, and support of a physically-based hydrologic forecasting system - the National Weather Service River Forecast System (NWSRFS).

In general, a river forecast system (or almost any system) can be viewed as having major components of (1) forces that drive the system, or data, (2) a mechanism to analyze the driving forces, or processing, (3) the heart of the system where the physical laws of motion are modelled, and (4) products of the system, or guidance information output for decision making. The relationships of these general functions of a river forecast system are shown in Figure 1. Other papers presented in this symposium will discuss data and processing components of the NWSRFS. This paper will concentrate on the modelling and some output features which, as part of an ongoing OH project tied to NWS modernization, have been converted to an interactive, graphical form on computationally powerful scientific workstations.

There are many components which together form the NWSRFS. The next section will present a brief background and history of the evolution of the NWSRFS, including some of the rationale for the existing structure which allows NOAA/NWS to have one of the premier river forecast systems in the world.

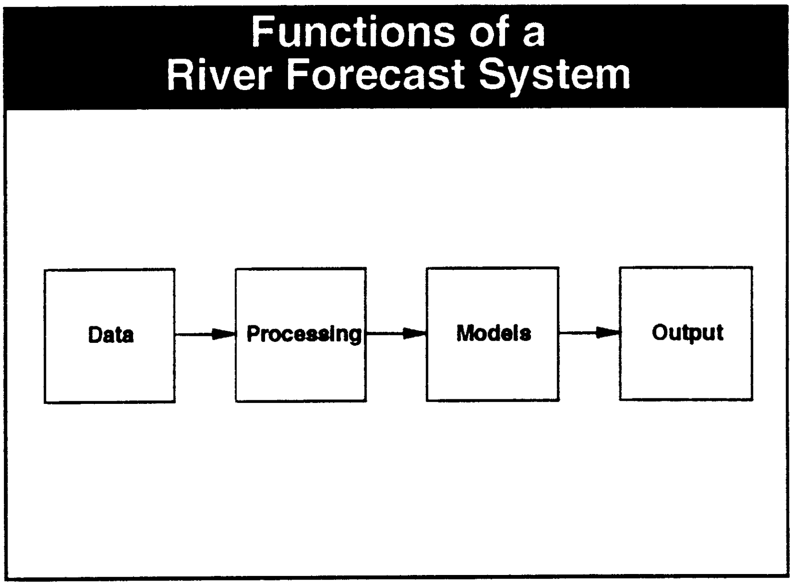


Figure 1

Background/History

Prior to the advent and availability of digital computers many graphical or hand calculation methods were used for determining the flow of water in rivers. Because the hydrologic conditions varied greatly from one portion of the U.S. to another, different techniques for forecasting river conditions were developed by River Forecast Centers (RFC) responsible for different areas. There are presently 13 RFCs in the U.S. The areas of responsibility for the 12 which cover the coterminous U.S. are shown in Figure 2. The thirteenth RFC is responsible for the state of Alaska.

In the 1960's and early 1970's computers were introduced into the RFCs. Consistent with their pre-computer activities, each of the RFCs independently developed river forecasting software. Often this software was simply a computer representation of the graphical techniques used previously. These locally developed software programs introduced two major problems into the NWS forecasting activities. First, the forecasting software was dependent on the individual who did the initial development. When that person changed jobs or retired, much of the knowledge of how to run the programs, or how to maintain or enhance the programs was lost to the NWS. Second, forecasters at one RFC were trained in forecasting software that was, in general, only applicable to that RFC. If someone moved from one RFC to another they would have to be retrained in the forecast programs used at the new RFC. This also was a major burden to the NWS river forecasting mission.

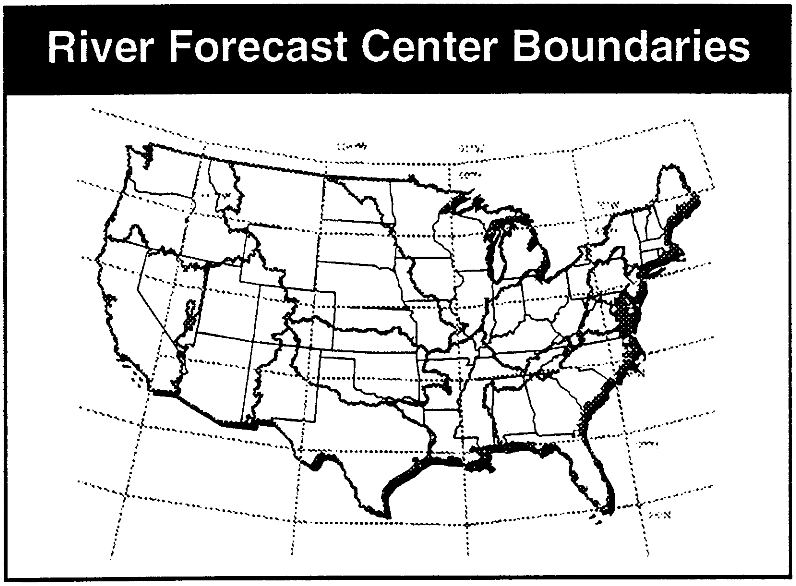


Figure 2

In the early to mid 1970's the OH began development of the NWSRFS to (1) meet the forecasting needs of all RFCs, (2) be supported and documented at the National level, and (3) have enhancements and software configuration management coordinated by OH. One of the initial goals was to design a system which included existing techniques from many of the RFCs so that a single system could be used for river forecasting throughout the U.S.

In the middle and later years of the 1970's initial versions of the NWSRFS were developed by software contractors under guidance from OH. These initial versions met some of the intended requirements of a national river forecast system, but they suffered from several basic flaws. Early versions of NWSRFS did not include all the features needed to model the flow in rivers in the varied hydrometeorologic regimes found throughout the U.S. Also, they did not account for the growth and evolution of computer technology and advances in hydrologic science. Versions 1 through 4 of the NWSRFS had a rigid program structure which made it difficult to add new modules as additional features were developed. The hydrologic modelling structure required that all basins use the same models in a fixed sequence. With the hydroclimatic variation found in the U.S. from humid to arid, and snow to sub-tropical conditions, this restriction was very limiting. New models or technology were very difficult to add to these early versions of the NWSRFS.

NWSRFS Version 5

In 1979, the OH began a project to completely redesign the NWSRFS. In addition to fixing the shortcomings found in previous versions, a major objective of the project was to develop a system structure which looked toward the future of hydrometeorologic forecasting. The initial requirements for NWSRFS Version 5 were developed from extensive interactions between designers in OH and the RFCs. Version 5 differed from previous ones in several ways, a major one being that scientific algorithms were designed to be independent of any specific computer system, and were coded by OH and RFC hydrologists who were intimately familiar with the physics of the processes being modelled. Specifications for data access and command decoding routines were developed by OH and RFC staff, and were coded by software contractors. 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 a snow, soil moisture, or river routing procedure 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.

NWSRFS Hydrologic Models

Snow	
HYDRO-17 Snow Model	SNOW-17
Soil	
Sacramento Soil Moisture Accounting	SAC-SMA
Ohio RFC API Rainfall-Runoff Model	API-CIN
Middle Atlantic RFC API Rainfall-Runoff Model	API-HAR
Central Region RFC API Rainfall-Runoff Model	API-MKC
Colorado RFC API Rainfall-Runoff Model	API-SLC
Xinanjiang Soil Moisture Accounting	XIN-SMA
Continuous API Model	API-CONT
Middle Atlantic RFC API Rainfall-Runoff Model #2	API-HAR2
Channel	
Channel Loss	CHANLOSS
Dynamic Wave Routing	DWOPER
Lag and K Routing	LAG/K
Layered Coefficient Routing	LAY-COEF
Muskingum Routing	MUSKROUT
Tatum Routing	TATUM
Stage-Discharge Conversion	STAGE-Q
Single Reservoir Simulation Model	RES-SNGL
Unit Hydrograph	UNIT-HG
Utility	
Baseflow Generation	BASEFLOW
Computation of Mean Discharge	MEAN-Q
Instantaneous Discharge Plot	INSQPLOT
Clear Time Series	CLEAR-TS
Add or Subtract Time Series	ADD/SUB
Weight Time Series	WEIGH-TS
Change Time Interval	CHANGE-T
West Gulf RFC Tabular Operational Display	LIST-FTW
Table Lookup	LOOKUP
Plot Time Series	PLOT-TS
Tulsa RFC Operational Plot	PLOT-TUL
Adjust Simulated Discharge	ADJUST-Q
Merge Time Series	MERGE-TS
Rain-Snow Elevation	RSNWELEV

Table 1

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 3 to be shared by the major sub-systems which comprise the NWSRFS Version 5. 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.

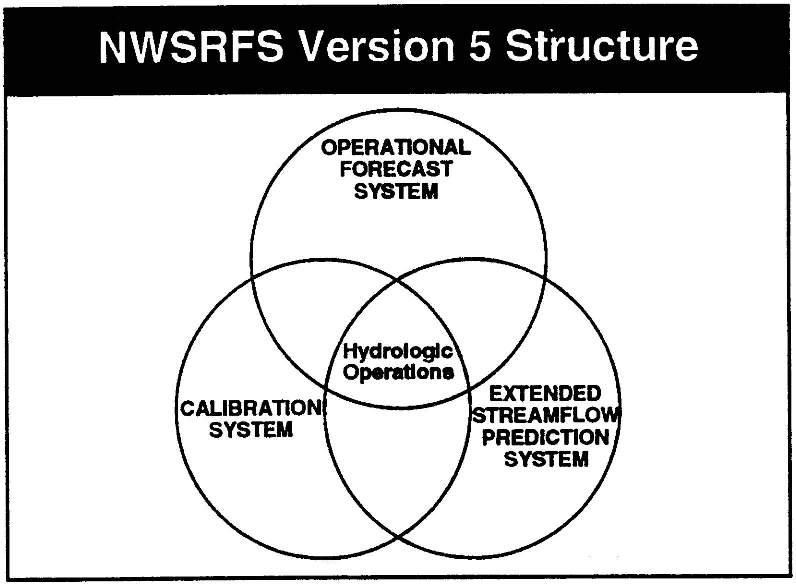
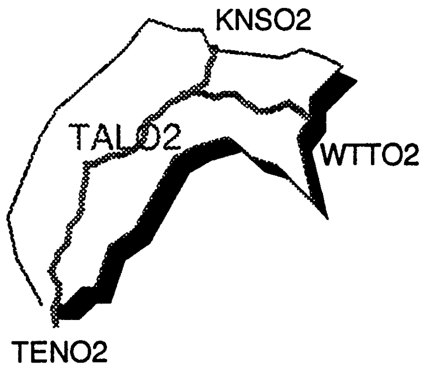


Figure 3

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. An example of the specific operations table for the Tahlequah, Oklahoma subbasin in the Tulsa RFC area is shown in Figure 4.

Initial NWSRFS Version 5 development occurred from 1979 through 1984. In 1985 NWSRFS Version 5 was delivered to the Tulsa RFC for initial operational forecasting use. Since then Version 5 has been installed in other RFCs and has been used daily to produce operational forecasts at thousands of locations along rivers throughout the U.S. New

Tahlequah Forecast Point with operations



TALO2 Operations Table

Lag/K	**WTTO2**
Clear-TS	
Add/Sub	WTTO2
Lag/K	**KNSO2**
Add/Sub	KNSO2
Snow-17	TALO2
Sac-SMA	***TALO2***
Clear-TS	
Unit-Hg	**TALO2**
Clear-TS	
Add-Sub	Routed
Add-Sub	Local
Stage-Q	**TALO2**
Adjust-Q	**TALO2**
Stage-Q	**QUINE**
Plot-Tul	TALO2

Figure 4

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 Xinanjiang soil moisture accounting model was added as an NWSRFS operation by scientists from the Yellow River Commission in 1988.

As computer technology has evolved the NWSRFS has kept pace. The initial NWSRFS design and development was on mainframe computers at the NOAA Central Computer Facility (CCF). As minicomputers became powerful enough to support the system requirements of the NWSRFS, OH made the changes needed to move Version 5 from the CCF computers to a Prime minicomputer. As shown in Figure 5, the NWSRFS Operational Forecast System (OFS) was ported to Prime minicomputers which are at OH and several of the RFCs. With the explosive growth in computational capabilities for scientific workstations, OH initiated a project in the late 1980's to prepare for modernization of the entire NWS by moving the scientific operations and forecasting component of the NWSRFS onto IBM RS/6000 workstations.

When the NWSRFS is run from the NOAA CCF, command input is sent over Remote Job Entry (RJE) lines from RFCs to the CCF as shown in Figure 6. Line printer results are sent back to the RFC for display on standard printers or on text display screens.

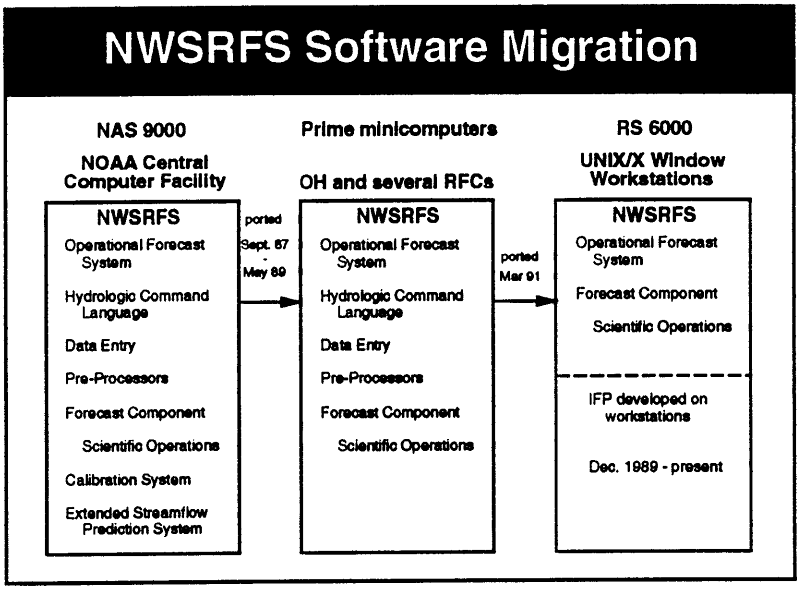


Figure 5

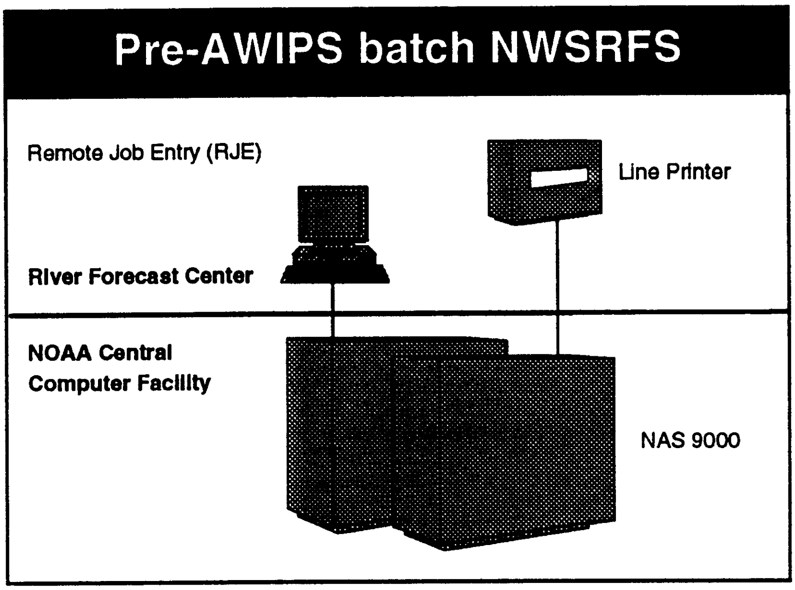


Figure 6

Beginning in 1989, graphical display and user interface capabilities were developed for the NWSRFS. The result is the NWSRFS Interactive Forecast Program (IFP) which will be discussed in more detail in the next section of this paper.

Interactive Forecast Program

The process of hydrologic forecasting requires human-machine interaction. This is 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 process we use to calibrate, or find specific parametric values for, the models does not produce perfect results, and
3. we do not perfectly observe rainfall or stream conditions as input to the models.

In order 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 NOAA CCF or a Prime minicomputer, a group 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 only way to avoid this problem is by making adjustments to reduce or remove the error in any subbasin before processing downstream subbasins. The NWSRFS IFP provides the forecaster with this capability. An additional benefit of the IFP is the enhanced display capabilities of high-resolution color display terminals above those of line printer output.

As described above, hydrologic forecasting is inherently interactive. The initial designers of NWSRFS recognized this, but were limited because computational requirements demanded that the forecast system run on a mainframe computer with little interactive capabilities. The computational capabilities of scientific workstations have evolved so that the initial design features of NWSRFS Version 5 to allow for interactive forecasting can be realized.

Graphical user interface (GUI) and graphical display capabilities were developed on scientific workstations. Figure 7 shows in heavy outlines those portions of the mainframe and minicomputer versions of NWSRFS that were ported to scientific workstations and linked with the GUI and graphical display modules. The division of components among those solely in the NWSRFS OFS, those solely in the IFP, and those shared by both programs is shown in Figure 8.

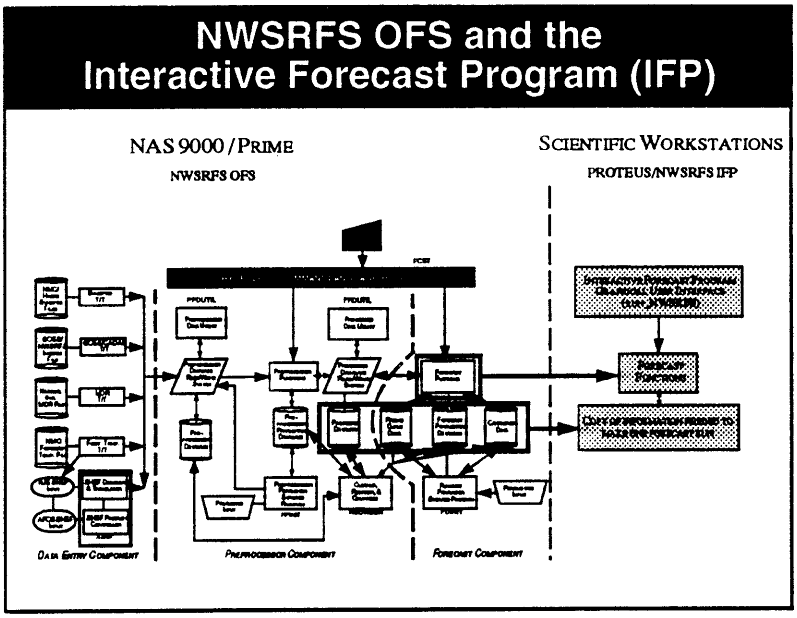


Figure 7

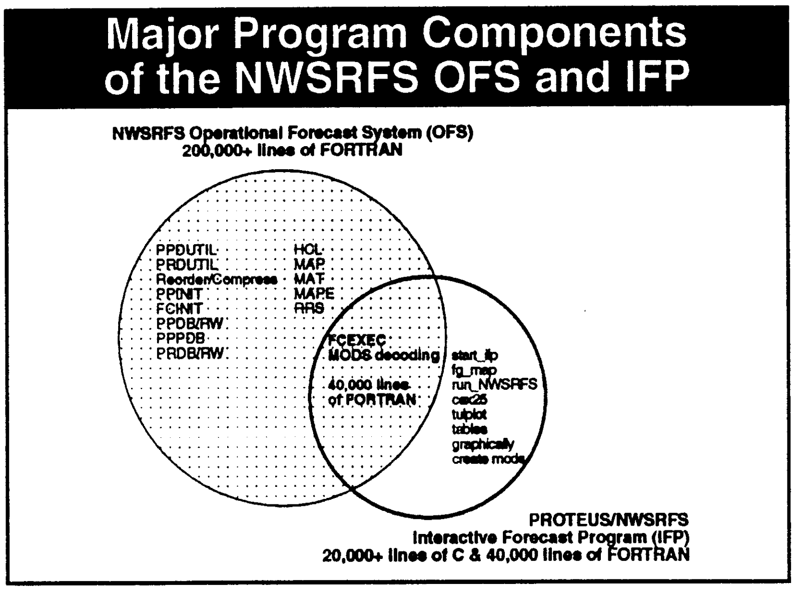


Figure 8

Important features of the NWSRFS IFP include:

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 function 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 modelling.

The IFP is currently run in the configuration shown in Figure 9. A Prime minicomputer at an RFC runs the NWSRFS OFS and creates a current set of model conditions and time series. A forecaster at a scientific workstation networked to the minicomputer begins an IFP session by asking for information about a set of subbasins. This initial information is transferred from the minicomputer to the workstations. The remainder of the IFP session with computations of the operations tables for subbasins being forecast, adjustments being made through the IFP GUI, and results being displayed for forecaster interpretation is performed on the workstation. At the end of an IFP session adjustments made for any subbasins are transferred to the minicomputer to become incorporated in further forecasting activities. Some of the graphical input and display features of the IFP are presented in Appendix A.

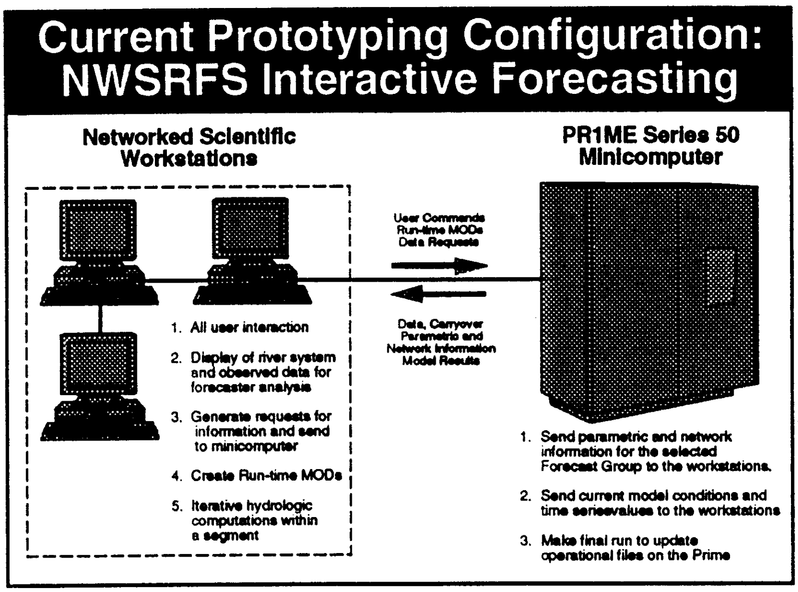


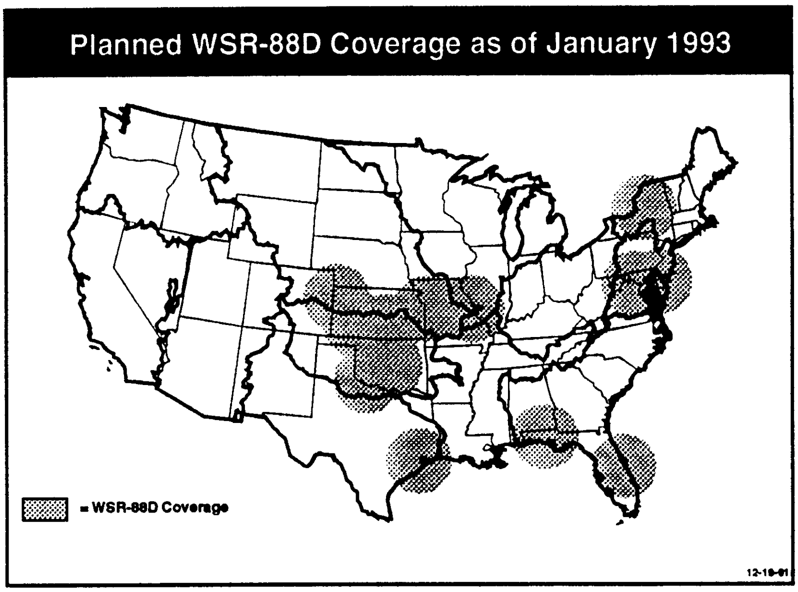
Figure 9

Future Activities

As the NWS moves forward with planned modernization activities, interactive forecasting with the NWSRFS will evolve to continue to fulfill NOAA's mission and make the best use of newly available data to provide forecasts and warnings for protection of life and property, and for environmental and economic well being. A major new data source in the modernized NWS is the WSR-88D radar data which will provide high resolution quantitative estimates of rainfall. The current computational configuration shown in Figure 9 is not adequate to process the WSR-88D data which will become available soon to the RFCs. WSR-88D radars are being installed to cover:

18% of the continental U.S. by January 1993,
41% of the continental U.S. by January 1994,
81% of the continental U.S. by January 1995, and
95% of the continental U.S. by January 1996.

Figures 10 through 13 show the areas of WSR-88D coverage for January 1993 through 1996 respectively. Enhanced computational capabilities are needed to realize the benefits of this high resolution radar data for hydrologic forecasting. The next phase of OH's modernization activities will be to demonstrate the operational use of WSR-88D radar data



Planned WSR-88D Coverage as of January 1993

Figure 10

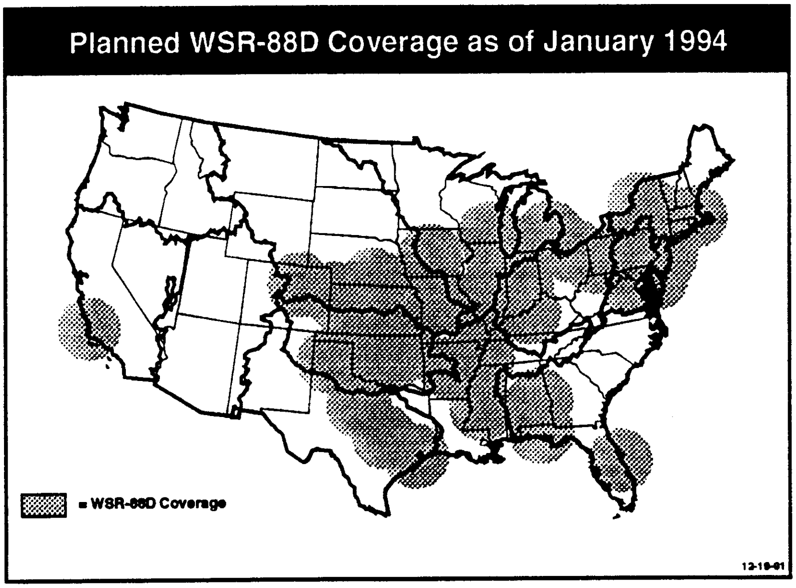


Figure 11

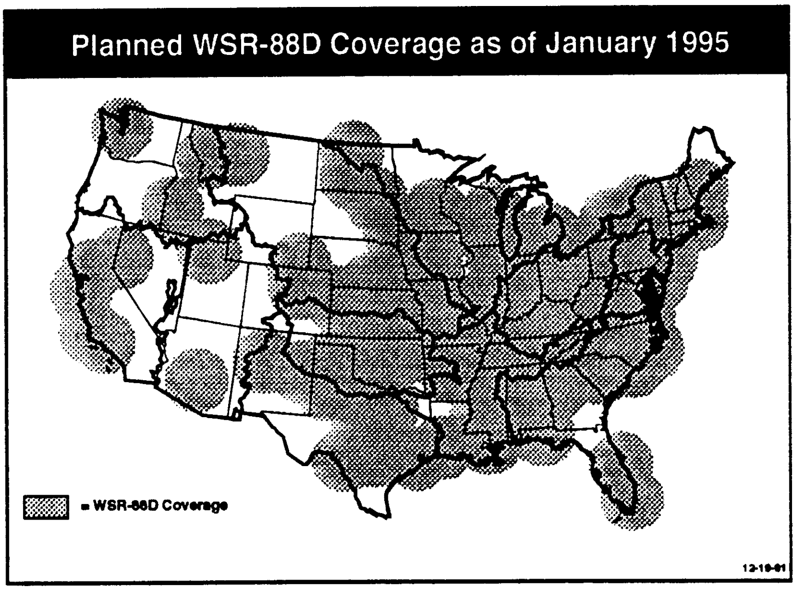


Figure 12

and the IFP. This activity will not only provide benefits to the U.S. as WSR-88D radars are commissioned, but will also allow for a smooth transition of hydrologic forecasting applications into the modernization plans for the NWS.

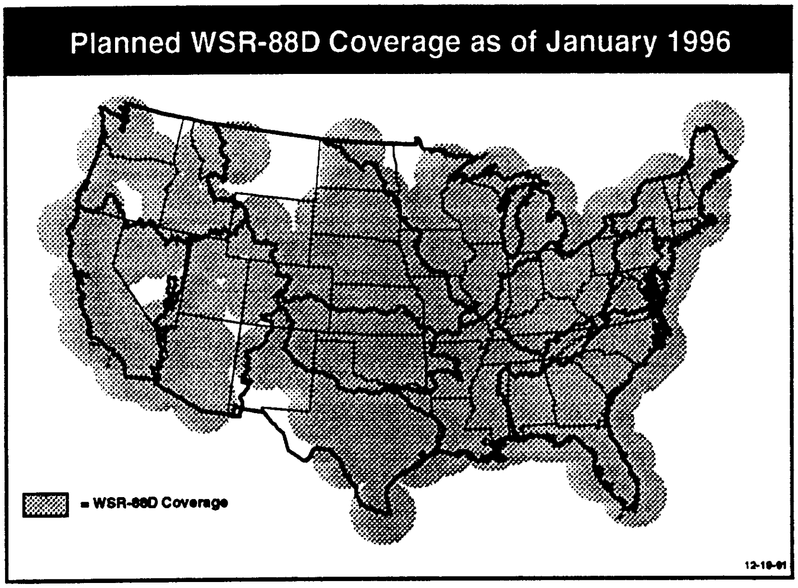


Figure 13

A configuration as shown in Figure 14 will allow NWSRFS OFS and IFP to operate efficiently. This fully networked system will process WSR-88D radar data and provide an interactive environment for hydrologic forecasting.

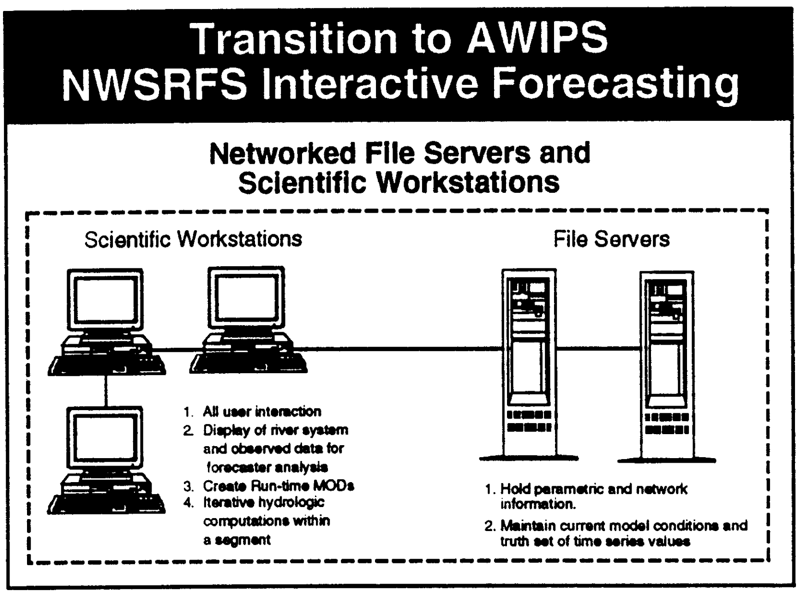


Figure 14

Appendix A.
Samples of some IFP displays

The NWSRFS Interactive Forecast Program (IFP) provides a graphical user input and display interface to the hydrologic models and techniques found in the NWSRFS. Samples of some of the input menus and display windows are presented in this appendix. The IFP runs in a UNIX operating system, under X Windows, using Open Software Foundation (OSF) Motif displays.

To begin an IFP session the forecaster chooses from a main system menu to run the NWSRFS_IFP application. The first window displayed is shown in Figure A.1. This display allows the forecaster to choose the set of forecast points and the starting time for the current IFP session. The list of forecast groups shown in the left-most column of Figure A.1 is for the Tulsa (Oklahoma) River Forecast Center area of responsibility. The forecast points are grouped by major river basin so that a single forecaster can follow the flow of water through a given reach of a river. In this example, the portion of

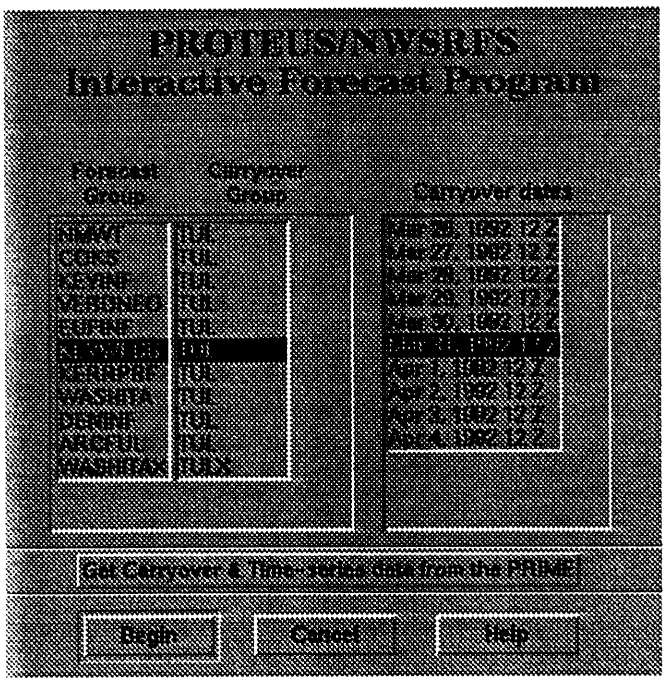


Figure A.1

the Arkansas River from the Keystone Dam to Webbers Falls (KEYWEBB) has been selected as the group of forecast points to be forecast. The forecast will begin with conditions for March 31, 1992.

Figure A.2 shows the window that appears when the Help button shown in Figure A.1 is selected. Help screens are available throughout the IFP to guide the forecaster through use if the available options.

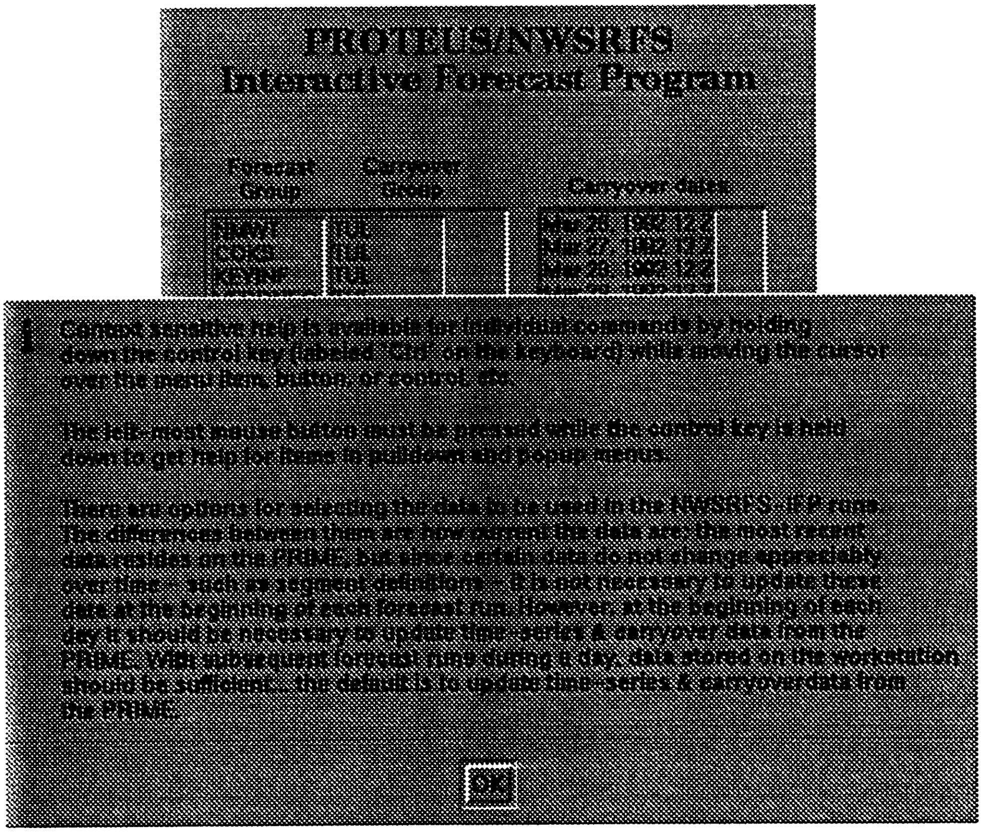


Figure A.2

Figure A.3 shows a subset of the KEYWEBB forecast group for use in this example. Each of the rectangular buttons in the main portion of the window represents a forecast point. The lines connecting the forecast points represent the flow of water through these points. The most downstream point is on the right. There is a menu bar across the top of the window which lists the options available from this screen. Figures A.4 through A.7 show the pulldown menus for the Control, Options, Display, and Modifications menu items.

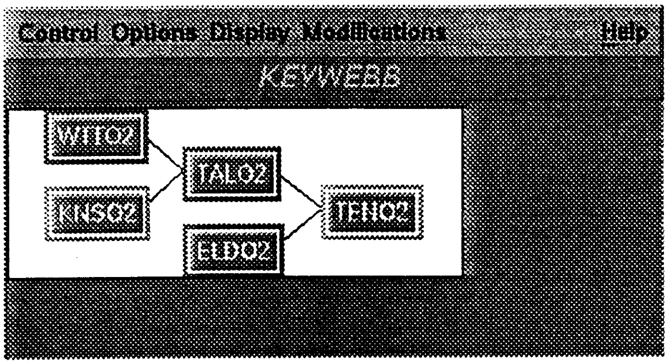


Figure A.3

The pulldown menu shown in Figure A.4 allows the forecaster to Control the sequence of hydrologic computations as the forecast points are modelled and adjustments are made. The forecaster can begin hydrologic computations then make adjustments as needed to get observed and simulated results to agree. When the differences between model results and observed data are acceptably small the forecaster can move to the next downstream forecast point. In this way errors in data or parameters are removed before they cause erroneous simulated flows to be routed downstream and corrupt subsequent forecast point results.

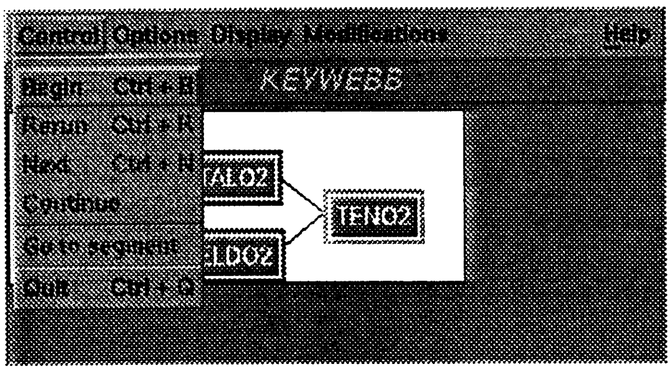


Figure A.4

Figure A.5 shows the Options pulldown menu. With this menu the forecaster can select a subset of the forecast group chosen in Figure A.1 to be modelled in the current session of the IFP. The dates for the end of observed data and the end of the forecast period can be set. Also, a number of selections such as the time zone for data input or display, or whether to use forecast precipitation can be made through this menu.

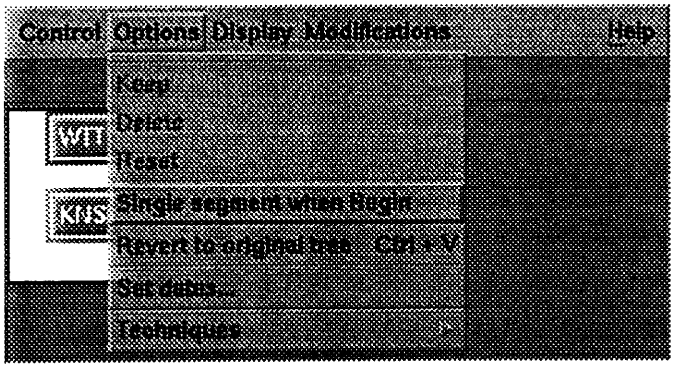


Figure A.5

The Display menu shown in Figure A.6 allows the forecaster to select additional information to be presented during the IFP session. A list of the hydrologic models, or operations, for any forecast point can be displayed, as can the parametric values for any model. The stage discharge relationship, or rating curve, at any forecast point can also be shown.

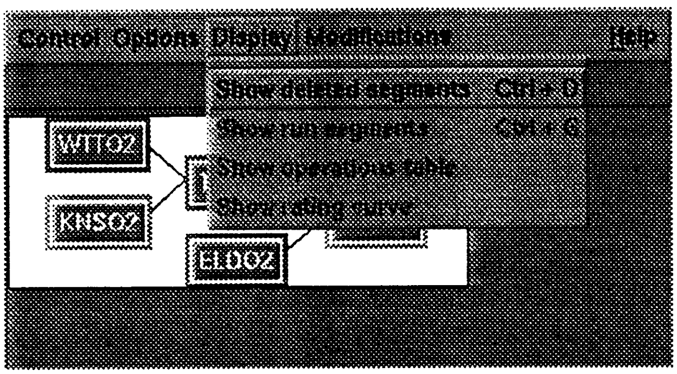


Figure A.6

With the choices shown in Figure A.7 the forecaster can choose to see plotted hydrographs for a forecast point. A tabular display is also available, as is the graphical interface to make adjustments, or modifications, to parameters or data.

In the current example, if the forecaster selects Begin in the Control pulldown menu, the hydrologic computations for all models used to simulate the first forecast point are performed. The results are plotted as shown in Figure A.8. Precipitation is shown in the topmost bar chart, with runoff just below. Observed and simulated hydrographs are plotted in the center of the window. The current time is represented by the vertical

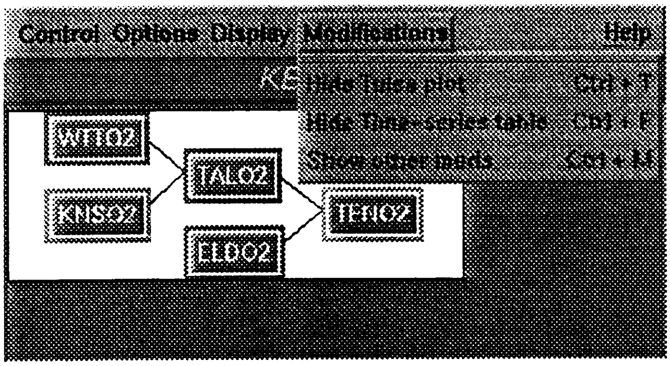


Figure A.7

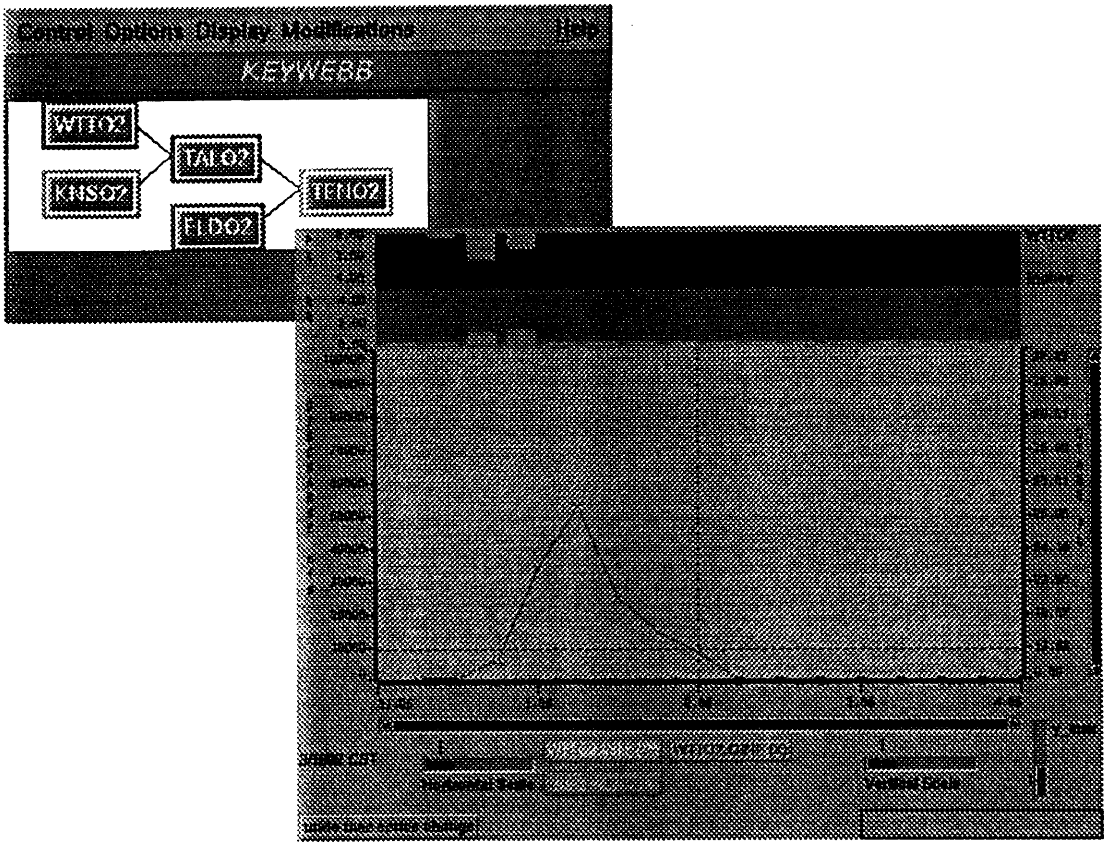


Figure A.8

dashed line. The two horizontal dashed lines represent the flood flow (the lower line) and the upper limit of the rating curve. Units of discharge (volume/time) are shown on the left axis while stage (depth) is shown on the right. In this case the simulated flow appears later and lower than the observed data. The forecaster can analyze the situation and make adjustments to reduce these differences. In this example assume that the forecaster believed that the heaviest rain had fallen near the outlet of the basin. This would mean that the assumption of uniform rain used to compute the unit-hydrograph for this area would not hold for this storm. The forecaster could try to modify the unit-hydrograph to more closely match the observed values.

The Modifications pulldown menu allows the forecaster to display the available adjustment options shown in Figure A.9. In this case the unit-hydrograph change

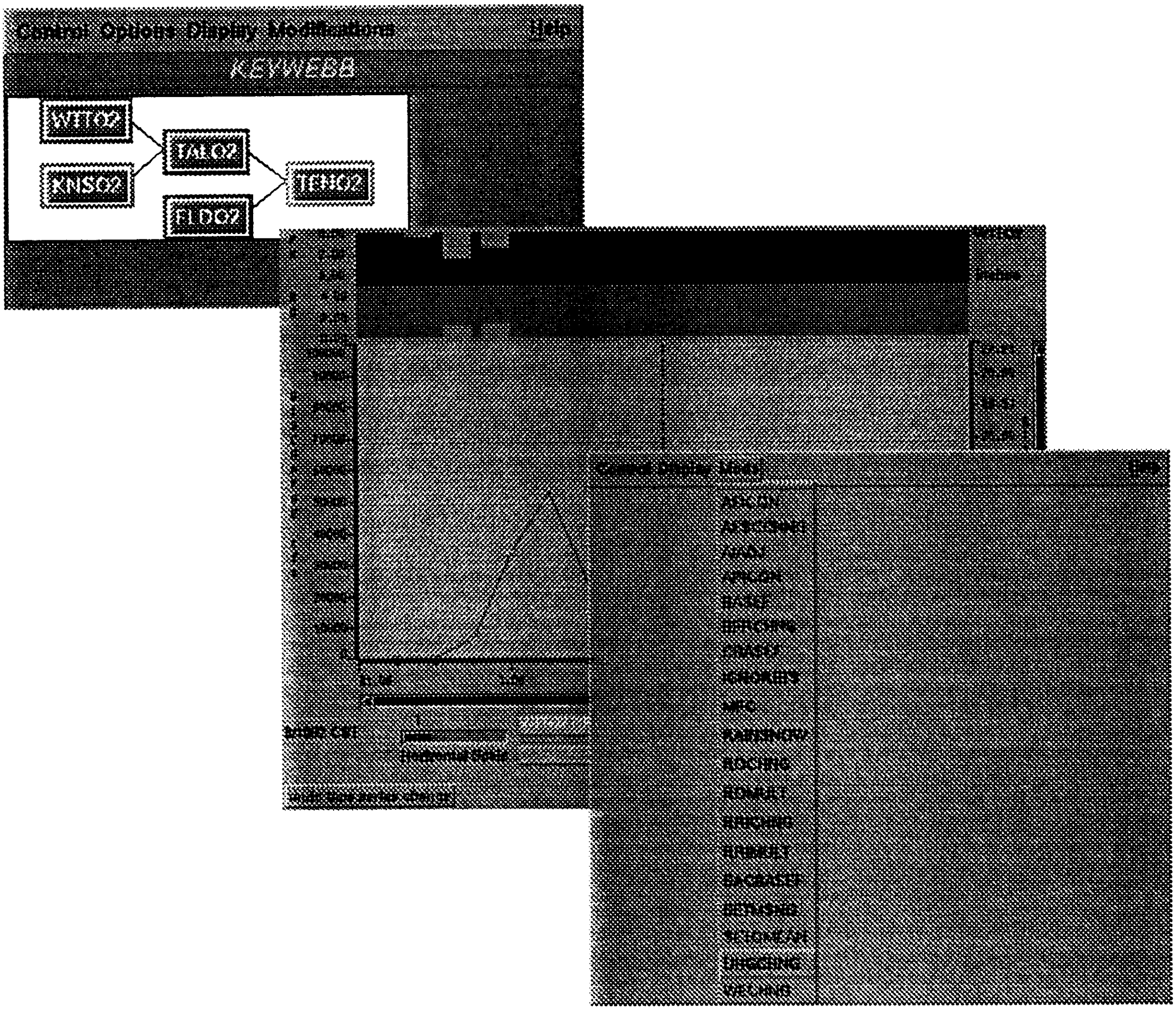


Figure A.9

(UHGCHNG) modification is selected. Figure A.10 shows a plot of the unit-hydrograph for the current forecast point. As shown in Figure A.11 the shape of the unit-hydrograph can be changed by selecting new ordinate values with the pointer device, which result in the adjusted unit-hydrograph values in Figure A.12.

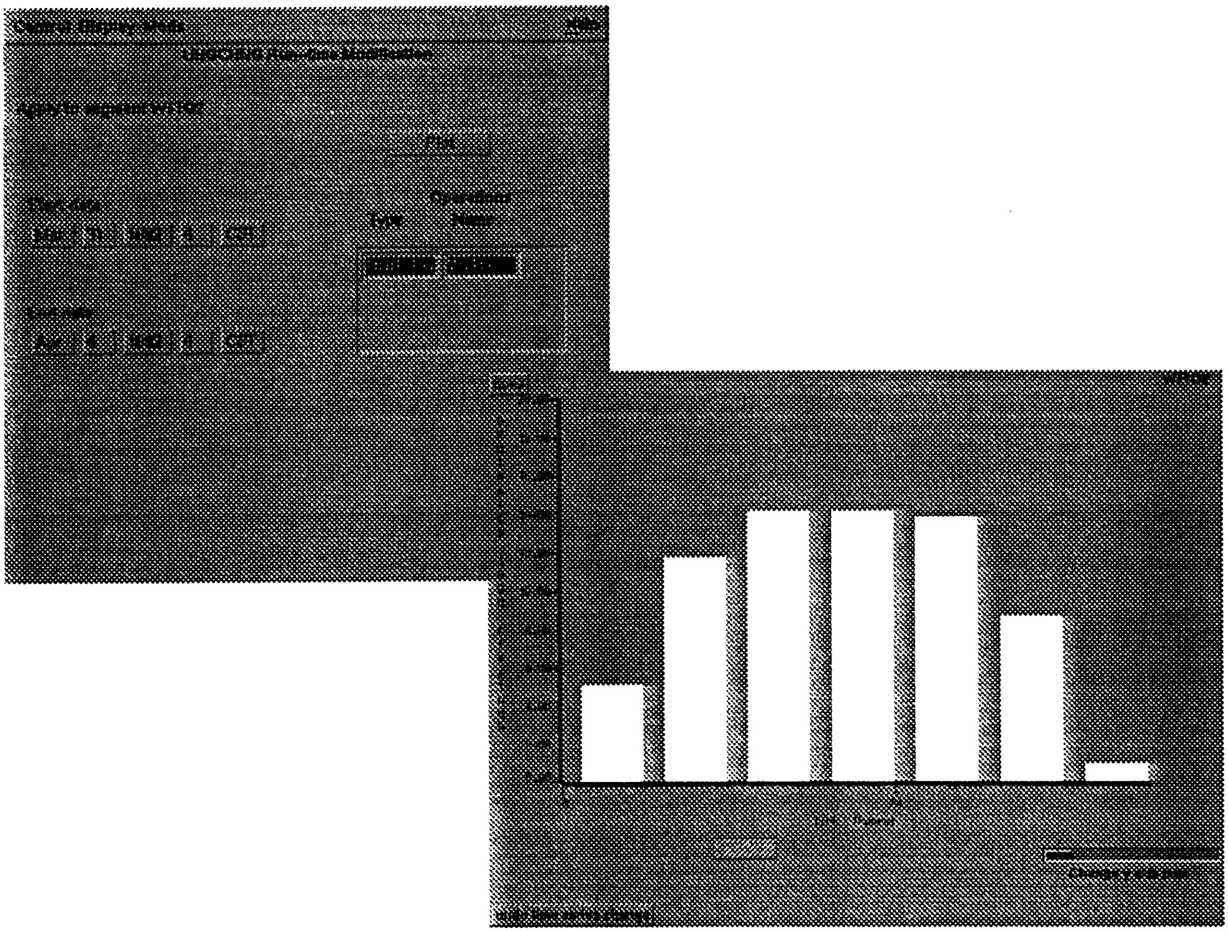


Figure A.10

Now selecting Rerun in the main menu bar Control menu recomputes the outflow for the forecast point with the changed unit-hydrograph values. As shown in Figure A.13 the simulated results improve significantly. Additional modifications could be made as desired.

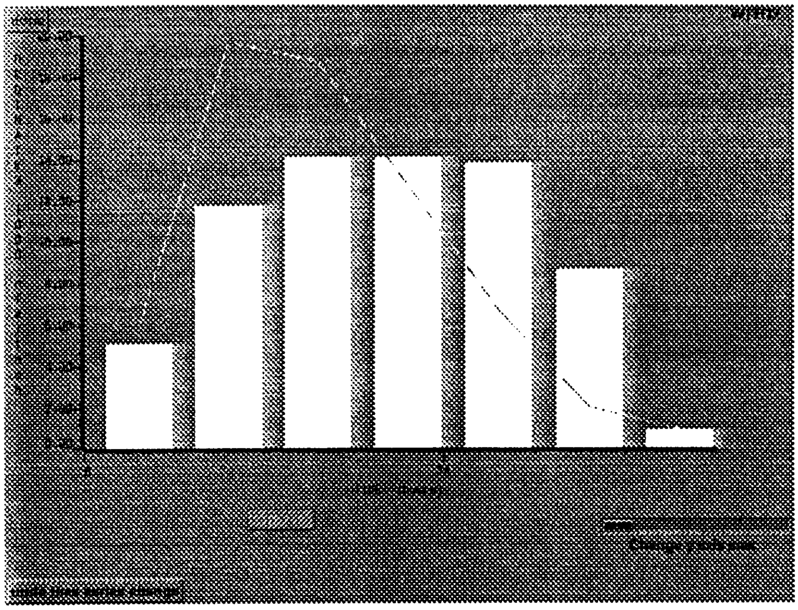


Figure A.11

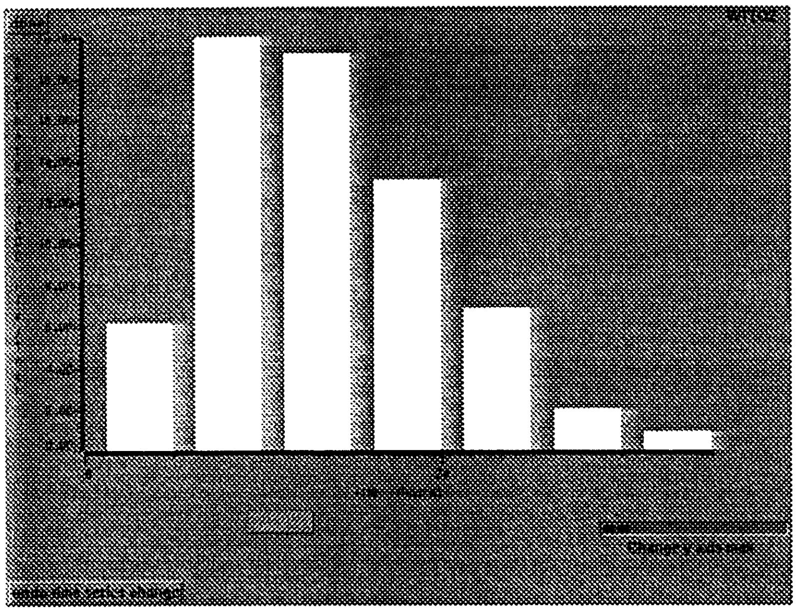


Figure A.12

When the forecaster is satisfied with model results, selecting Next in the Control pulldown menu will move to the subsequent downstream forecast point. Similar cycles of adjustment can be made for each forecast point in the group. When the forecaster

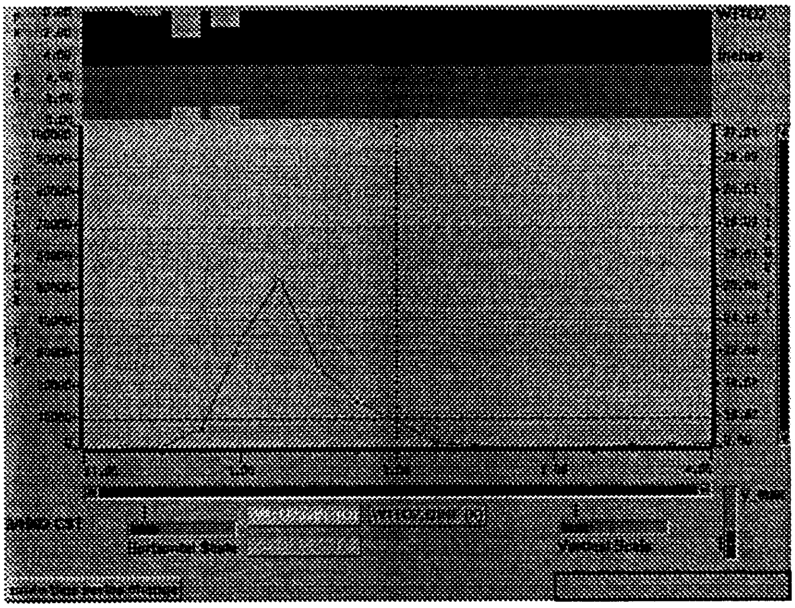


Figure A.13

finishes an IFP session the simulated flows for each forecast point can match as closely as desired to the observed data. In this way errors are minimized to that forecast flow values will be as accurate as possible.