R-95-06

QUANTITATIVE PRECIPITATION FORECASTING FOR IMPROVING RESERVOIR OPERATIONS

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13. ABSTRACT *(Maximum 200 words)*

The Bureau of Reclamation prepared this report under the WATER program. The first part summarizes research related to combining existing orographic (mountain-induced) precipitation and runoff models for improving reservoir operations. The study area was the American River Basin in the Sierra Nevada of northern California. The two-dimensional orographic precipitation model developed by Rhea (1978), and the HED71 headwater runoff forecast model (Buer, 1988) developed by the National Weather Services's (NWS) California-Nevada River Forecast Center and the California Department of Water Resources were used in the study. The study demonstrated the operational applicability of using quantitative precipitation forecasts (QPF) from the orographic precipitation model as input for rainfall-runoff simulation hydrologic models. Improved hydrologic forecasts are expected to result from forecasters adjusting the model QPFs based upon the latest available data and other forecast guidance.

The second part of the report assesses how applied research by Reclamation meteorologists, particularly in the area of better QPFs and flood potential forecasts, might improve Reclamation's water operations. Because Reclamation water operation managers receive hydrologic forecasts from the NWS, meteorological applied researchers must form partnerships with the NWS so that Reclamation's work will add value to NWS products.

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April 1995

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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Special recognition is herein given to Dr. J. Owen Rhea for his cooperation and work on this research study. From February 1992 to February 1994, Dr. Rhea held a meteorologist position in the Water Operations Branch of the Reclamation Mid-Pacific Region's Central Valley Operations Coordinating Office, Sacramento, California. While working in this position, Dr. Rhea adapted his orographic precipitation model to the American River Basin above Folsom Reservoir. He subsequently ran his model for selected historical major storm periods and compared the model predicted precipitation with recorded precipitation. Both predicted and recorded 6-h precipitation accumulations for the storms were input to the HED71 hydrologic headwater runoff model; Dr. Rhea then compared predicted and observed peak inflow values for Folsom Reservoir. During 1993, Dr. Rhea made the necessary arrangements and developed procedures for obtaining prognostic gridded field data from the NMC (National Meteorological Center). In February 1994, Dr. Rhea accepted a new position with the California-Nevada River Forecast Center, where he serves as the senior HAS (hydrometeorological analysis and support) forecaster.

Thanks is given to Mr. Timothy Barker of the National Weather Service's Scientific Services Division in Salt Lake City, Utah, for providing software to extract NMC model prognostic data for selected grid points, convert these data to ASCII, and store them for retrieval over INTERNET.

Special thanks is due to Mr. Chester Bowling, Chief of the Water Operations Branch, Central Valley Project Water and Power Operations Office (formerly known as the Central Valley Operations Coordinating Office), for providing the support that allowed Dr. Rhea to work on this study. Mr. Bowling also provided valuable information on water operations for the Central Valley Project, and critical areas where better flood potential forecasts are needed.

Thanks is also given to all of the Reclamation employees who took the time to complete and return the Questionnaire on Meteorological Support. Special thanks is given to Gordon Aycock (GP-450) and Susan Hoffman (MP-700), whose help in distributing the questionnaire resulted in the receipt of a representative number of responses from their respective regions. Tom Hovland, Reclamation Technical Communications Group, provided technical editing for this report.

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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

GLOSSARY AND ACRONYMS

AI: Antecedent Indexing

ALERT: Automated Local Evaluation in Real Time

ARB: American River Basin

AVN: AViatioN model

CDWR: California Department of Water Resources

CNRFC: California-Nevada River Forecast Center

CSR: Condensate Supply Rate

CVP: Central Valley Project

DOC: Department of Commerce

Eta: Greek letter - Eta model replaces LFM model

FAR: False Alarm Rate

FSL: Forecast Systems Laboratory

GIS: Geographic Information Systems

GOES: Geostationary Operational Environmental Satellite

HAS: Hydrometeorological Analysis and Support

HED71: HEaDwater 1971 hydrologic runoff model

HPC: Hydrometeorological Prediction Center

INTERNET: INTERnational NETwork

LAPS: Local Analysis and Prediction System

LFM: Limited Fine Mesh model

MAR: NWS's Modernization and Associated Restructuring

MRF: Medium Range Forecast model

NEXRAD: NEXt generation RADar

NGM: Nested Grid Model

NMC: National Meteorological Center

NOAA: National Oceanic and Atmospheric Administration

NWS: National Weather Service

OAK: Oakland

POD: Probability of Detection

QPF: Quantitative Precipitation Forecast

Reclamation: Bureau of Reclamation

RFC: River Forecast Center

SCPP: Sierra Cooperative Pilot Project

SH: Sheridan

SLC: Salt Lake City

SNOTEL: SNOwpack TELemetry

TSC: Technical Service Center

UTC: Universal Time Coordinated

WATER: WAter Technology and Environmental Research

WFO: Weather Forecast Office

2-D, 3-D: two-Dimensional, three-Dimensional

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1. INTRODUCTION

Forecast precipitation and runoff on time scales from several hours to several days in advance can be critical to the reservoir operators' decision-making process. Currently, the NWS (National Weather Service) provides QPF (quantitative precipitation forecasts) out to 24 h into the future. In addition to the QPFs, 2- to 3-d precipitation outlooks are also available. However, the NWS products do not adequately address orographic (mountain-induced) precipitation, which is the most significant contributor to wintertime precipitation in most watersheds and river basins of interest to Reclamation (Bureau of Reclamation). Given the large variability in precipitation (frequency, amount, and type) and subsequent runoff in mountainous areas of the Western United States, managing reservoir operations optimally is difficult. Better QPFs extending further into the future are needed.

The research study summarized in this report addresses the problem of inaccurate and untimely QPFs. The study was funded under the Research and Laboratory Services Division's WATER (Water Technology and Environmental Research) Program. The end objectives for this study were to develop the methodology for more accurate and timely wintertime QPFs for mountainous watersheds and river basins of interest to Reclamation, then integrate the QPFs with existing hydrologic headwater runoff models to improve forecasts of runoff (amount and timing) and the potential for flooding. More accurate and timely headwater runoff forecasts will improve Reclamation's effectiveness in making operational decisions for water resources management and reservoir operations.

This summary report is separated into two parts, which are located in sections 2 and 3. The first part summarizes the research related to combining existing orographic (mountain-induced) precipitation and runoff models for improving reservoir operations. The study area was the American River Basin in the Sierra Nevada of northern California. This area experiences occasional relatively warm winter storm episodes of heavy precipitation which produce flooding potential. Models used in the study were the 2-D (two-dimensional) orographic precipitation model developed by Rhea (1978), and the HED71 headwater runoff forecast model (Buer, 1988) developed by the NWS's CNRFC (California-Nevada River Forecast Center) and the CDWR (California Department of Water Resources).

The second part of the report is an assessment of how applied research within Reclamation, particularly in the area of better QPFs and flood potential forecasts, might improve Reclamation's water operations. Because Reclamation water operation managers are and will continue to receive hydrologic forecasts from the NWS, future meteorological applied research will require collaboration between Reclamation and NWS personnel so that Reclamation's work will result in added value to NWS products.

2. COMBINING OROGRAPHIC PRECIPITATION AND RUNOFF MODELS FOR IMPROVING RESERVOIR OPERATIONS

2.1 Orographic Precipitation Model Description

The orographic precipitation model is a simple 2-D model, originally developed by Dr. J. Owen Rhea in the mid-1970s for western Colorado, for both climatological purposes and as a QPF (Quantitative Precipitation Forecasting) aid. This section only provides a brief description of the precipitation model; a complete description is given in Rhea (1978).

Input requirements for the orographic precipitation model are (1) an actual or predicted profile of temperature, humidity, and winds aloft entered in 50-mb (millibar) intervals, (2) a set of topographic grids (obtained for every 10-degree azimuth relative to true north) with a grid interval of 10 km or less, and (3) the "period of representativeness" of the input sounding (usually set as the time interval between input soundings, observed or predicted). For this study, a 5-km horizontal topographic grid interval and a 12-h period of representativeness were used.

Fast running time and usage of upper-air soundings routinely available every 12 h as input data were key considerations in constructing this operationally-oriented computational method. Therefore, no mesoscale modeling of the flow field over complex terrain was attempted. Rather, the air was assumed to flow along gridlines, with the topographic grid x-axis aligned with the 700-mb wind direction and with the x-component wind speeds for each 50-mb layer computed accordingly. Thus, a topographic grid of different orientation may be needed for each model run that uses a different input upper-air sounding, depending upon the amount of change in the 700-mb wind direction.

A key feature of the orographic precipitation model is its simulation of upstream barrier "precipitation-shadowing" effects. Some model features, such as precipitation efficiency, can be varied if desirable, when adapting the model for use in an area. A weakness of the model is that although precipitation quantities in mountainous areas are obviously highly controlled by topographic features, nonorographic influences, which are not modeled, are also important.

The orographic precipitation model keeps track of the condensate or evaporation caused by forced vertical displacements as the air flows over the underlying topography. (Condensate is the product of condensation, which in meteorology is the physical process by which water vapor becomes liquid; evaporation is the opposite of condensation.) For rising air at a given grid point, part of the condensate precipitates. The rest moves downstream to the next grid point, where a fraction (precipitation efficiency) of it and the condensate generated by additional orographic lift precipitates. For sinking motion, part or all of the parcel cloud water evaporates. Precipitation falling into a layer from above partially (or totally) evaporates when encountering subsaturated conditions. Eventually, precipitation generated in each layer reaches the ground, provided it does not totally evaporate.

Orographic precipitation model computations are made at the pressure mid-points of 50-mb-thick layers, up to as high as the 450-mb level, depending on where the top of the moisture is found. The model's "moisture top" is defined as the highest level with at least 65 pct relative humidity which is not undercut by any lower layer(s) of less than 50-pct relative humidity. Over a given grid interval, computations are made for the highest layer first and proceed downward. When computations are completed for all layers over that grid interval, a step forward (downwind) along the grid line is made by incrementing location indices. Thus, computations proceed one grid line at a time. A printout of precipitation for each grid point gives the resulting map of amounts. Specific measurement site amounts and area averages for desired watersheds can also be calculated.

2.2 Hydrologic Model Description

The HED71 rainfall-runoff simulation hydrologic model briefly described in this section has been a key tool for flood forecasting in northern California for over two decades. A more complete description of this hydrologic model is contained in the Program Manual prepared by CDWR (California Department of Water Resources) staff (Buer, 1988). Despite great advances in flood hydrology and computer technology during the past two decades, this model has persisted because it is well formulated for California's variable storm regime, and it is stable, efficient, and simple to use.

This hydrologic model is an AI (Antecedent Indexing) regression type model that is used operationally by the CDWR and the NWS's CNRFC (California-Nevada River Forecast Center) for basin headwater runoff and flood forecasting. (The antecedent index roughly corresponds to the number of inches of rain needed to get 1 in. of runoff.) This model has also been used by Reclamation's Mid-Pacific Region in California in connection with reservoir operations during periods of heavy precipitation. HED71 was designed to effectively model the following:

- Effect of precipitation input - amount and type
- Losses caused by evaporation, infiltration, and detention
- Effect of snow on the ground upon precipitation
- Surface runoff routing
- Ground-water flow (base flow)

Input requirements for this rainfall-runoff simulation hydrologic model are: (1) a soil moisture AI, (2) an initial base flow, (3) an estimate of the rain/snow level, (4) an elevation-dependent specification of preexisting snowpack water equivalent, and (5) an estimate of the mean basin precipitation in 6-h increments out to any reasonable length of time into the future.

Each new storm rainfall-runoff simulation assumes that any flow in the stream is base flow, which recedes much more slowly than surface runoff. Occasionally, a new AI value must be inserted in one of the simulation periods. This insertion is done during a storm if a significant break occurs in the precipitation, which allows the soil to recover part of its infiltration capacity while surface runoff is still draining from the basin.

For each simulation period, the hydrologic model program considers the effect of snowpack and temperature on precipitation reaching the ground. The model analyzes each elevation zone in turn, then integrates to get a basin wide average.

If snowpack is present on the ground in part of the basin where precipitation is falling as rain, part of the snow will be melted by the combined effect of wind and rainfall. Any snowpack that remains will delay the passage of rain and melt to the ground surface. The deeper the pack (up to 254 mm [10 in.] of water equivalent), the greater the portion of rain and melt delayed. Precipitation falling at elevations greater than the specified snow level accumulates as snow on the ground and does not contribute to runoff during the storm period.

The effective basin area and shape vary with the rain/snow level; consequently, the model uses the unit hydrograph approach to convert surface runoff to streamflow. The model breaks the basin into 12 elevation zones (at 1000-ft [305-m] increments for this study) and computes an area-elevation curve. The model references a set of 12 hydrographs (one for each elevation zone) calibrated to the basin and selects the proper unit hydrograph for the snow level.

Each of the 12-unit hydrographs has the same total streamflow volume (in ft^3/s-h). But streamflow volume will change as the snow level moves up or down on a watershed. The program achieves this volume adjustment when computing streamflow because the surface runoff increment is the area-weighted sum of runoff from each zone up to the snow level. The program properly lags and sums the hydrographs resulting from each surface runoff increment to obtain the surface runoff hydrograph.

For each period, the area-weighted sum for all elevation zones of liquid water reaching the ground is output as "MELT + RAIN." The area-weighted sum for all elevation zones of snowfall plus delayed liquid water is output as "ADDED SNOW."

Only the MELT + RAIN is effective in generating surface runoff. The soil moisture AI and basin constants determine how much surface runoff is generated by a given amount of MELT + RAIN. In effect, these constants determine a curve of cumulative MELT + RAIN versus cumulative runoff, along which the simulation proceeds, period by period. Thus, two MELT + RAIN sequences with the same total water will result in the same surface runoff, regardless of time distribution.

The hydrologic model program computes base flow for each simulation period and adds it to the streamflow. To compute the base flow, the program considers base flow in the previous period and surface streamflow in the current period. Surface streamflow results in gradually increasing base flow, corresponding to ground-water recharge and increasing discharge. The combined effect results in a base flow which increases gradually following the surface streamflow peak, then decays smoothly over many periods.

2.3 Study Area and Topography

The study area selected was the 4820-km^2 portion of the ARB (American River Basin) above Folsom Dam, which is located just northeast of Sacramento. The ARB is located on the western slope of the Sierra Nevada Mountain Range in northern California. This area experiences occasional relatively warm winter storm episodes of heavy precipitation, much in the form of rain, which produce flooding potential. Such storms are associated with basin average rainfall accumulations exceeding 50 mm (2 in.) of water below the rain/snow level. The upper-air measurement site used in this study was OAK (Oakland, CA), which is located about 225 km southwest of the center of the ARB study area.

For this study, terrain elevation information was extracted from the National Geophysical Data Center digital elevation 1-minute latitude/longitude data tape on a 2.5-km grid interval. These data were then averaged to generate smoothed, gridded elevation data with a 5-km grid interval for model use. The elevation in the ARB ranges from about 150 m (500 ft) to over 2700 m (8860 ft). Figure 1 shows the model grid points for the ARB plotted on 5 km topography; the contours are in 500-ft intervals. The grid point numbers are the percent of grid element area residing within the ARB. The numbers on the outside of the box in figure 1 are model row and column numbers that define the grid point location indices.

2.4 Data Used in Study

During the 1979-86 period, Reclamation conducted an investigation of cloud seeding as a means of increasing winter precipitation on the Sierra Nevada. This weather modification research project, known as the SCPP (Sierra Cooperative Pilot Project), was conducted almost

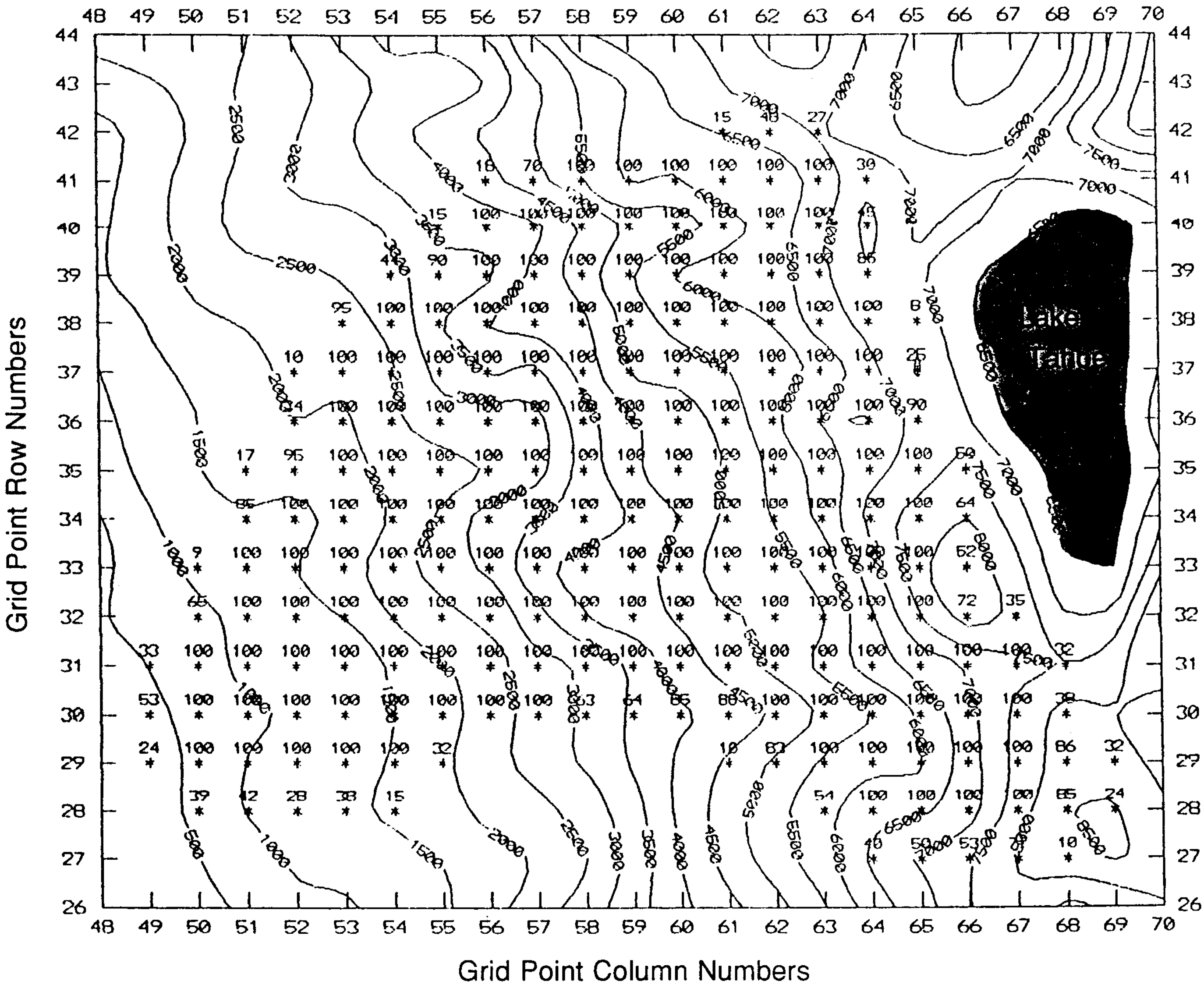


Figure 1. - American River Basin topography (500-ft intervals) and Rhea orographic precipitation model 5-km grid points used in study.

entirely in the ARB (Reynolds and Dennis, 1986). One of the products of the SCPP was a good meteorological data base from the ARB. Consequently, this QPF study was based upon SCPP precipitation and rawinsonde (upper-air soundings of pressure, temperature, moisture, and winds) data; NWS rawinsonde data from Oakland; CDWR data used in the HED71 hydrologic model; and Reclamation precipitation and Folsom Reservoir inflow data.

2.4.1 Precipitation Data

This study concentrated on heavy precipitation episodes that occurred during the SCPP winter field seasons (November through April). Heavy precipitation episodes were defined as storms where observed cumulative precipitation totals exceeded 60 mm (2.34 in.) of water equivalent over a significant area (four or more gauge sites) of the ARB, and any breaks in precipitation were less than 24 h. From mid-January 1980 to mid-March 1986, 42 such periods were selected by examining precipitation data collected during Reclamation's SCPP.

Table 1 lists the 42 storm periods selected for this study. The 6-digit starting and ending dates give the UTC (Universal Time Coordinated) year, month, and day (YYMMDD). UTC starting and ending times give the first and last hour respectively for the 12-h periods in which precipitation began and ended; each 12-h period is centered on either the 0000 or 1200 UTC atmospheric sounding time. The maximum precipitation accumulation measured within the ARB always exceeded the greater than (>) values listed in the "Max Cum" column.

Precipitation data for the major storm periods were compiled for 14 SCPP gauge sites and 8 Reclamation/CDWR gauge sites within the ARB. These 22 gauge sites, shown on figure 2, are listed in table 2. Both 6- and 12-h precipitation accumulations were compiled; however, only the 12-h values, centered on the UTC atmospheric sounding times, were used in this study. Data were not always available for all 22 gauge sites because of instrument problems.

Precipitation data recorded at remote locations only provide indices of the actual areal amounts. This limitation occurs because the gauges only represent point observations, and some of the precipitation is not measured by the gauges because of wind effects, snow capping, and gauge malfunctions.

Table 2 indicated two sites in the ARB where Reclamation/CDWR and SCPP gauges were located very close to each other. These sites are S06/BLU and S50/GRE. Comparing precipitation data from these two sets of collocated gauges provides insight into the accuracy of point precipitation data. The results of comparisons of 12-h precipitation totals, taken from the 1983/84 - 1985/86 SCPP field seasons, are listed in table 3. The data in this table indicate that the 12-h precipitation data from the collocated gauges at both sites were in close agreement; sample correlations were 0.98 and 0.97, respectively.

2.4.2 Rawinsonde Data

During SCPP, rawinsondes (upper-air atmospheric soundings) were taken at Sheridan, California, during winter storm periods. Sheridan (SH) is located just to the west of the ARB, and approximately 150 kilometers (93 miles) north-northeast of Oakland, California (fig. 3). Oakland (OAK) is the rawinsonde station operated by the National Weather Service that is closest to the ARB; both historic and real time sounding data are usually available for Oakland for the two synoptic times each day (0000 and 1200 UTC). Because Sheridan rawinsondes will not be available in the future as a real time data source, a comparative study of Oakland and Sheridan sounding data was done to determine if Oakland data could be substituted for Sheridan data in the orographic precipitation model.

For this study, atmospheric sounding times were selected from the 1981-82 and 1982-83 SCPP winter field seasons when good data were available from both Sheridan and Oakland at least through the 400-mb level. These two winter seasons were used because both were wetter than normal and had at least 10 storm periods where the cumulative precipitation within the ARB exceeded 60 mm (2.34 in.) water equivalent over a significant portion of the basin. A total of 120 Oakland/Sheridan sounding pairs was selected. These sounding pairs were subdivided based on the 700-mb wind direction at Oakland, viz., NW (northwest) flow (270° - 360°) and SW (southwest) flow (180° - 269°). The resulting sample sizes were 40 soundings for NW flow and 80 soundings for SW flow. Parameters compared were temperature (T), relative humidity (RH), wind direction (WD), and wind speed (WS) at selected pressure levels from the 1000-mb level through the 500-mb level. Table 4 lists the mean values and mean difference computed for each parameter at each pressure level.

Table 1. - Selected SCPP storm periods with heavy precipitation.

1979-80 SCPP Winter Season (Period of Record: Nov. 1, 1979 - Apr. 30, 1980)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	800107	1900	800118	1800	600 mm
2	800213	1900	800223	1800	450 mm

1981-82 SCPP Winter Season (Period of Record: Nov. 1, 1981 - Apr. 30, 1982)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	811112	0700	811118	0600	300 mm
2	811121	0700	811125	0600	225 mm
3	811212	0700	811216	0600	60 mm
4	811218	0700	811222	0600	300 mm
5	811228	0700	820106	0600	275 mm
6	820118	0700	820122	0600	100 mm
7	820213	0700	820216	1800	275 mm
8	820301	0700	820304	0600	100 mm
9	820310	0700	820312	0600	70 mm
10	820313	1900	820320	1800	90 mm
11	820326	0700	820405	0600	300 mm
12	820410	0700	820413	0600	160 mm

1982-83 SCPP Winter Season (Period of Record: Dec. 1, 1982 - Apr. 30, 1983)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	821219	1900	821224	0600	260 mm
2	830117	1900	830121	0600	70 mm
3	830121	1900	830125	0600	130 mm
4	830126	0700	830131	0600	130 mm
5	830205	0700	830211	0600	180 mm
6	830211	1900	830214	0600	80 mm
7	830224	1900	830309	0600	300 mm
8	830310	0700	830315	1800	170 mm
9	830320	0700	830330	0600	160 mm
10	830423	0700	830426	0600	90 mm
11	830426	1900	830501	0600	100 mm

1983-84 SCPP Winter Season (Period of Record: Nov. 15, 1983 - Apr. 15, 1984)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	831116	0700	831118	0600	160 mm
2	831119	0700	831121	0600	110 mm
3	831122	1900	831126	0600	110 mm
4	831201	0700	831204	1800	80 mm
5	831205	1900	831213	0600	160 mm
6	831221	1900	831228	0600	260 mm
7	840208	1900	840217	0600	180 mm
8	840313	0700	840317	1800	130 mm

1984-85 SCPP Winter Season (Period of Record: Dec. 1, 1984 - Apr. 30, 1985)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	850207	0700	850209	0600	140 mm
2	850304	0700	850308	0600	120 mm
3	850326	0700	850329	0600	120 mm

1985-86 SCPP Winter Season (Period of Record: Dec. 15, 1985 - Apr. 15, 1986)

Pd. No.	Start Date	UTC	End Date	UTC	Max Cum >
1	851228	1900	851231	0600	60 mm
2	860104	0700	860106	1800	60 mm
3	860114	1900	860118	0600	110 mm
4	860129	1900	860204	0600	150 mm
5	860211	1900	860222	1800	800 mm
6	860307	0700	860312	1800	300 mm

Table 2. - Selected precipitation gauge sites.

14 SCPP precipitation gauges located within the ARB

Site	Name	El.(m)	Latitude	Longitude
S05	Baxter	1187	39°12'49"	120°46'32"
S06	Blue Canyon	1609	39°16'33"	120°42'29"
S10	Plavada	1818	39°18'54"	120°28'35"
S11	Sierra Snow Lab.	2087	39°19'30"	120°22'05"
S20	Onion Creek	2095	39°16'47"	120°22'43"
S21	Castle Valley	2254	39°21'03"	120°21'13"
S25	Westville	1663	39°11'08"	120°36'03"
S26	Sunflower Hill	2091	39°09'55"	120°27'33"
S27	Talbot	1731	39°11'30"	120°22'16"
S50	Pine Nut	1771	39°04'47"	120°33'00"
S59	Loon Lake Reservoir	1957	38°59'05"	120°19'43"
S64	Big Hill	1860	38°50'30"	120°24'22"
S84	Donner Grade	1976	39°20'09"	120°17'26"
S99	Yuba Gap	1760	39°18'58"	120°36'47"

8 Reclamation/CDWR precipitation gauges located within the ARB

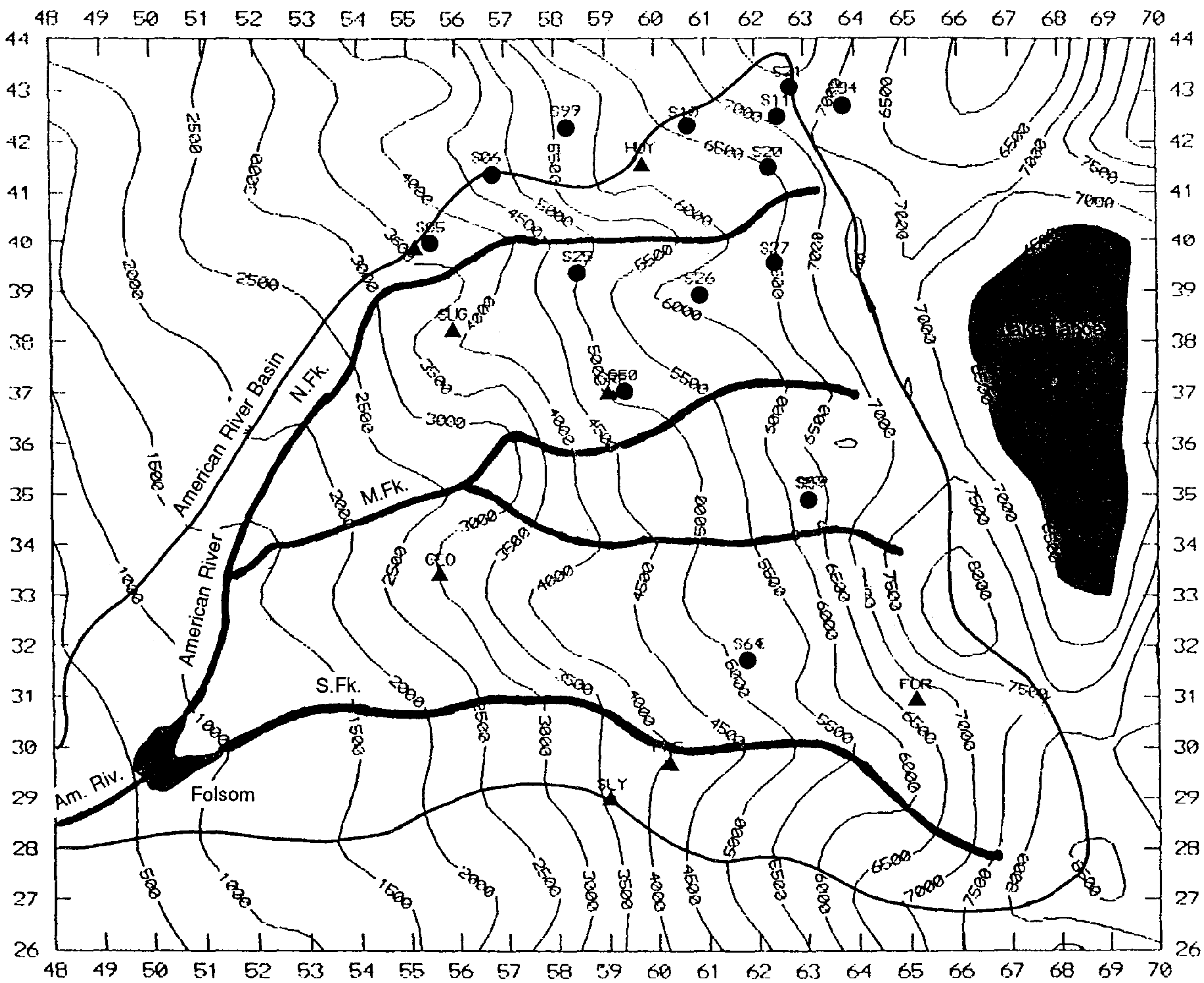
Site	Name	El.(m)	Latitude	Longitude
BLU*	Blue Canyon	1609	39°16'33"	120°42'29"
PAC	Pacific House	104	38°45'	120°30'
SUG	Sugar Pine	1171	39°08'	120°45'
GEO	Georgetown	991	38°55'	120°46'
SLY	Sly Park	1076	38°43'	120°34'
GRE**	Greek Store	1720	39°04'36"	120°33'42"
HUY	Huysink	2073	39°17'00"	120°31'36"
FOR	Forni Ridge	2317	38°48'18"	120°12'48"

* Same location as SCPP site S06

** Close to SCPP site S50

Table 3. - Comparison of 12-h precipitation accumulations (mm) from collocated gauges in the American River Basin (1 mm = 0.039 inch).

Site ID	No. Cases	Precip Tot (mm)	Precip Max (mm)	Precip Min (mm)	Precip Mean (mm)	Mean absdiff	Corr. (*r*)
S06	125	2591	110.5	0.0	20.73		
BLU	125	2695	124.0	0.0	21.56	3.67	0.98
S50	131	2357	99.4	0.0	17.99		
GRE	131	2411	104.0	0.0	18.40	3.15	0.97



● SCPP precipitation Gauge Sites (14)
▲ Reclamation/CDWR Precipitation Gauge Sites (8)

Figure 2. - Precipitation gauge locations within the ARB (American River Basin) used in study, plotted on 5-km topography.

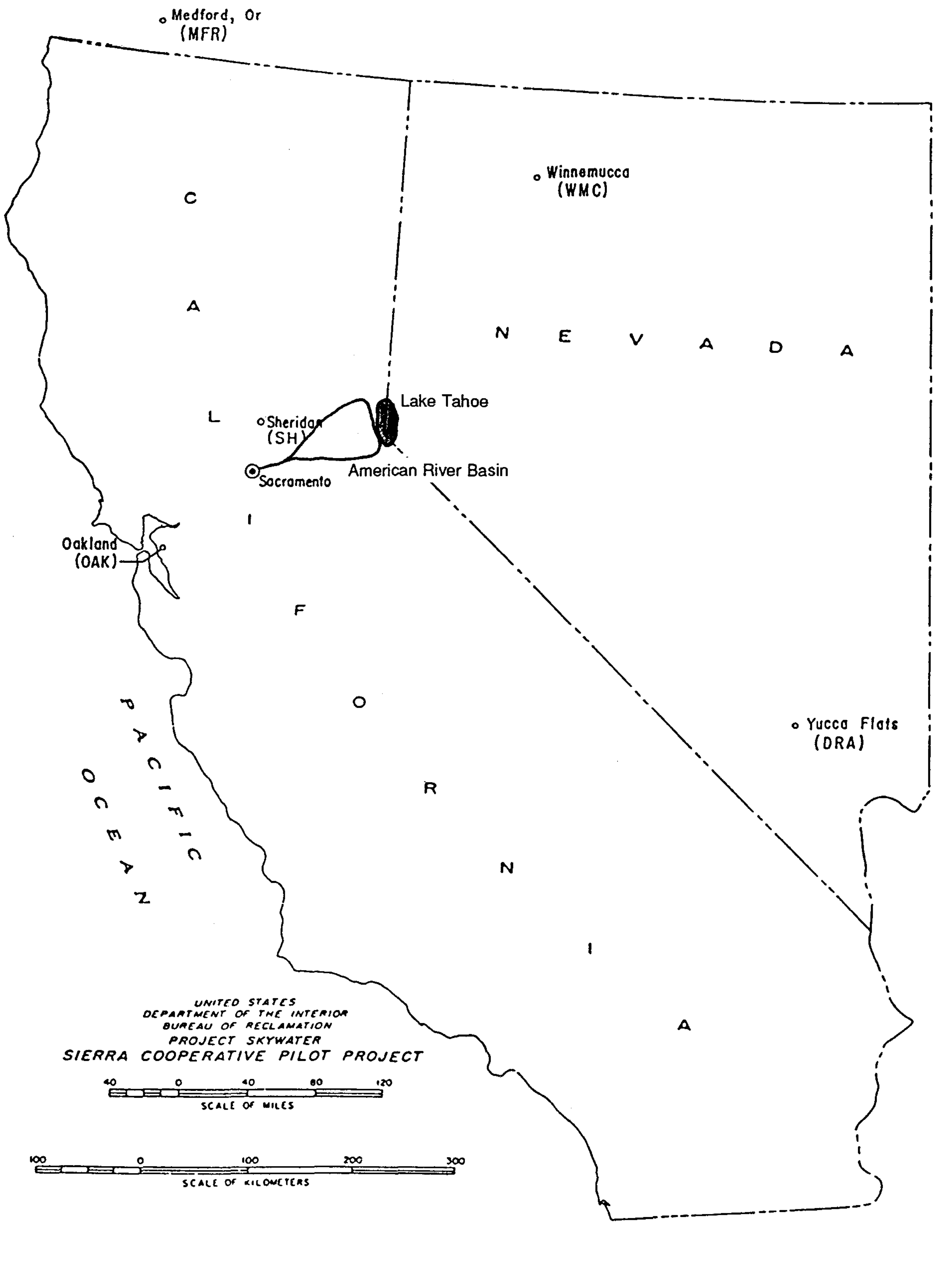


Figure 3. - Locations of OAK (Oakland) and SH (Sheridan) rawinsonde sites in relation to the ARB (American River Basin).

Table 4. - Comparison of Oakland (OAK) and Sheridan (SH) rawinsonde data; lists mean values of temperature (*T*), relative humidity (*RH*), wind direction (*WD*), and wind speed (*WS*) data.

	NW FLOW (N = 40)			SW FLOW (N = 80)		
Parameter	OAK	SH	OAK-SH	OAK	SH	OAK-SH
T (°C)						
1000 mb T	10.9	10.5	0.4	12.3	11.4	0.9
950 mb T	7.7	7.8	-0.1	9.8	9.6	0.2
900 mb T	4.5	4.6	-0.1	6.9	6.9	0.0
850 mb T	1.7	1.4	0.3	4.0	4.0	0.0
800 mb T	-0.7	-1.7	1.0	1.5	1.2	0.3
700 mb T	-6.1	-8.1	2.0	-3.9	-4.7	0.8
500 mb T	-22.6	-23.9	1.3	-20.1	-21.1	1.0
RH (%)						
1000 mb RH	72.1	72.7	-0.6	77.7	80.2	-2.5
950 mb RH	75.4	75.3	0.1	80.6	79.9	0.7
900 mb RH	72.6	75.2	-2.6	83.0	81.6	1.4
850 mb RH	64.1	74.0	-9.9	79.5	81.6	-2.1
800 mb RH	48.7	70.7	-22.0	71.9	80.8	-8.9
700 mb RH	37.8	48.9	-11.1	58.1	69.3	-11.2
500 mb RH	37.1	35.9	1.2	49.5	49.7	-0.2
WD (deg)						
1000 mb WD	248	182	66	192	166	26
950 mb WD	266	205	61	207	178	29
900 mb WD	277	220	57	214	187	27
850 mb WD	282	238	44	217	192	25
800 mb WD	287	255	32	222	199	23
700 mb WD	293	278	15	230	216	14
500 mb WD	292	289	3	238	235	3
WS (m/s)						
1000 mb WS	3.6	3.2	0.4	5.0	5.0	0.0
950 mb WS	5.6	4.9	0.7	8.1	10.2	-2.1
900 mb WS	6.2	4.9	1.3	10.4	12.2	-1.8
850 mb WS	7.2	5.0	2.2	12.1	12.8	-0.7
800 mb WS	8.4	6.1	2.3	13.1	13.3	-0.2
700 mb WS	12.5	10.3	2.2	16.1	15.3	0.8
500 mb WS	23.9	22.2	1.7	22.6	23.9	-1.3

The data in table 4 show consistent, significant differences between the two sites. The most significant differences were noted in the mid-level (800- to 700-mb) relative humidities and the lower-level (1000- to 800-mb) wind directions. Overall, the Oakland soundings were slightly warmer, had lower relative humidities in the mid-levels, and had more westerly wind directions in the lower levels; wind-speed differences were small. These findings agree meteorologically with the conclusion that the atmosphere over Sheridan had already begun its forced ascent over the Sierra Nevada. Consequently, using Oakland sounding data in the orographic precipitation model should provide reasonable precipitation estimates for the ARB, but probably did cause some error in the 12-h QPFs.

2.4.3 Other Data

Data input requirements for the HED71 hydrologic model were listed in section 2.2. For this study, both soil moisture AI and initial base flow data were available from records; rain/snow levels were estimated from Oakland upper-air soundings; the existence of a snowpack was ignored; and precipitation estimates were obtained from the orographic precipitation model.

For observed inflow to Folsom Reservoir, historical records of bi-hourly inflow were available for periods of high flow associated with heavy rains. For lesser events, records consisted of daily average inflow values. When only daily average values were available, peak inflow was estimated as 1.5 times the daily average (based on limited comparisons) in order to be able to compare to predicted peaks from the HED71 model.

2.5 Data Analysis Methods

For the periods listed in table 1, the orographic precipitation model computed 12-h total estimates of precipitation for the 22 gauge sites listed in table 2. For each storm, model precipitation average depth was also computed for the ARB above Folsom Dam. Model input was the Oakland rawinsonde data, available twice daily at 12-h intervals, assuming that the data represented conditions for the 12-h period centered on the sounding time. The 12-h model-computed precipitation estimates for the 22 gauge locations were averaged and compared to 12-h cumulative average values from the recording precipitation gauges. Gauges with missing precipitation data were ignored in calculating average observed values.

The orographic model-computed precipitation values were also used as precipitation input to the HED71 runoff simulation hydrologic model. To use the model precipitation as input to HED71, the 12-h values had to be divided into two equal 6-h amounts because HED71 requires input at 6-h time intervals. Predicted inflow to Folsom Reservoir was also computed using average values of observed precipitation as input to HED71.

The simulated hydrographs obtained using model precipitation and also those resulting from using observed precipitation were plotted along with the observed inflow to Folsom Reservoir. Figure 4 shows an example of plotted simulated hydrographs. This method allowed study of the qualitative agreement between predicted and observed hydrographs, as well as the agreement between predicted hydrographs using model-computed or observed precipitation. The storm represented on figure 4 is a very heavy precipitation event that occurred in February 1986 (table 1, 1985-86, No. 5). The orographic model precipitation estimates were too large early in the storm period; however, predicted inflow to Folsom Reservoir based upon orographic precipitation model QPFs for the ARB agreed closely with the observed inflow during the heaviest precipitation/inflow period during this storm.

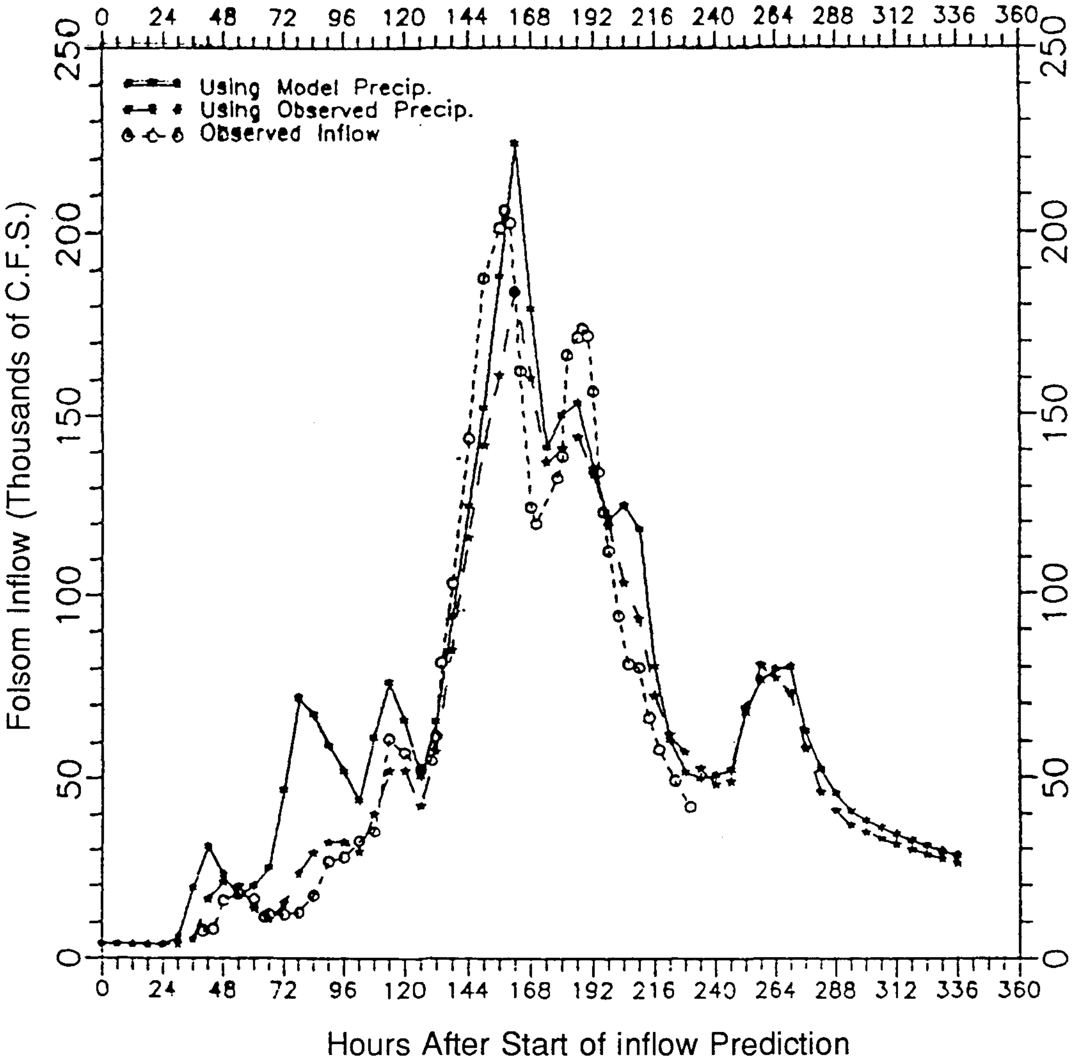


Figure 4. - Example of simulated hydrographs of inflow to Folsom Reservoir (data are for the February 1986 storm) (C.F.S = ft^3/s).

To summarize the results statistically, values of computed and observed inflow peaks were tabulated. Some leeway in timing was permitted between computed and observed peaks. Some mismatches of 12 h occurred, but most were within about 6 to 8 h (recall that 6 h is the time interval for which HED71 requires inputs).

The linear correlation between predicted and observed peaks was determined. Also, an arbitrary high inflow value of 50,000 ft^3/s (cubic feet per second) was chosen and the probability of detection (forecasting) of observed inflows above this value was determined as was the false alarm rate, i.e., the rate of predicting more than 50,000 ft^3/s when the observed inflow remained less than 50,000 ft^3/s.

2.6 Statistical Results

2.6.1 Precipitation

When comparing the orographic precipitation model estimates to the average observed (recorded) precipitation, the linear correlation coefficient, r, between model computed and observed 12-h total precipitation (for 371 periods) was 0.73. Summation to 24-h periods increased r to 0.80. This increase in correlation is believed to primarily be caused by reduced errors associated with the timing of representativeness of Oakland rawinsonde data; the longer period reduces timing errors over the longer measurement interval. The overall average ratio of 12-h observed precipitation accumulation to 12-h model precipitation estimate was 0.87. The difference could be caused by overprediction by the model, undercatch of actual precipitation because of gauge limitations, or a combination of both.

The sample size of 371 12-h periods was large enough to allow study of the results by 700-mb wind direction class (directions were rounded to the nearest 10-degree azimuth). Systematic wind direction dependent differences between the 22-site average observed and model precipitation values were found (table 5). The model overpredicted the average precipitation with southwest flow, but underpredicted precipitation with northwest flow. The correlation (r) was highest for winds most nearly perpendicular to the Sierra Nevada Range. These systematic differences can be used to good advantage for operational forecasting by adjusting model estimates based upon the observed/model ratio by 700-mb wind direction class.

Table 5. - Model and observed 12-h precipitation averages (in.) for a group of 22 precipitation gauge sites in the American River Basin.

Direction	Averages (in.)		Ratio	Corr.	Sample
Class (deg)	Obs.	Model	O/M	r	size
330-350	0.19	0.00	inf.	0.00	17
300-320	0.28	0.13	2.06	0.23	41
270-290	0.38	0.34	1.12	0.69	81
240-260	1.02	1.08	0.94	0.78	120
210-230	0.77	1.06	0.73	0.67	76
170-200	0.54	1.08	0.50	0.30	36
Overall	0.66	0.76	0.87	0.73	371

2.6.2 Simulated Inflow to Folsom Reservoir

Linear regression analysis was performed of predicted versus observed peak inflow to Folsom Reservoir (sample size = 63). Inflow predictions used orographic precipitation model estimates as input for the HED71 rainfall-runoff simulation hydrologic model. These calculations yielded a linear correlation coefficient of 0.87, a regression line slope of 0.87, an intercept of -5900 ft^3/s, and a standard error of estimate of 20,700 ft^3/s (fig. 5). This line slope is the same as the overall ratio of observed to model average precipitation noted in the precipitation analysis section above. Standard error of estimated inflow peaks is encouragingly small, especially considering that the peaks range from 6000 ft^3/s to as high

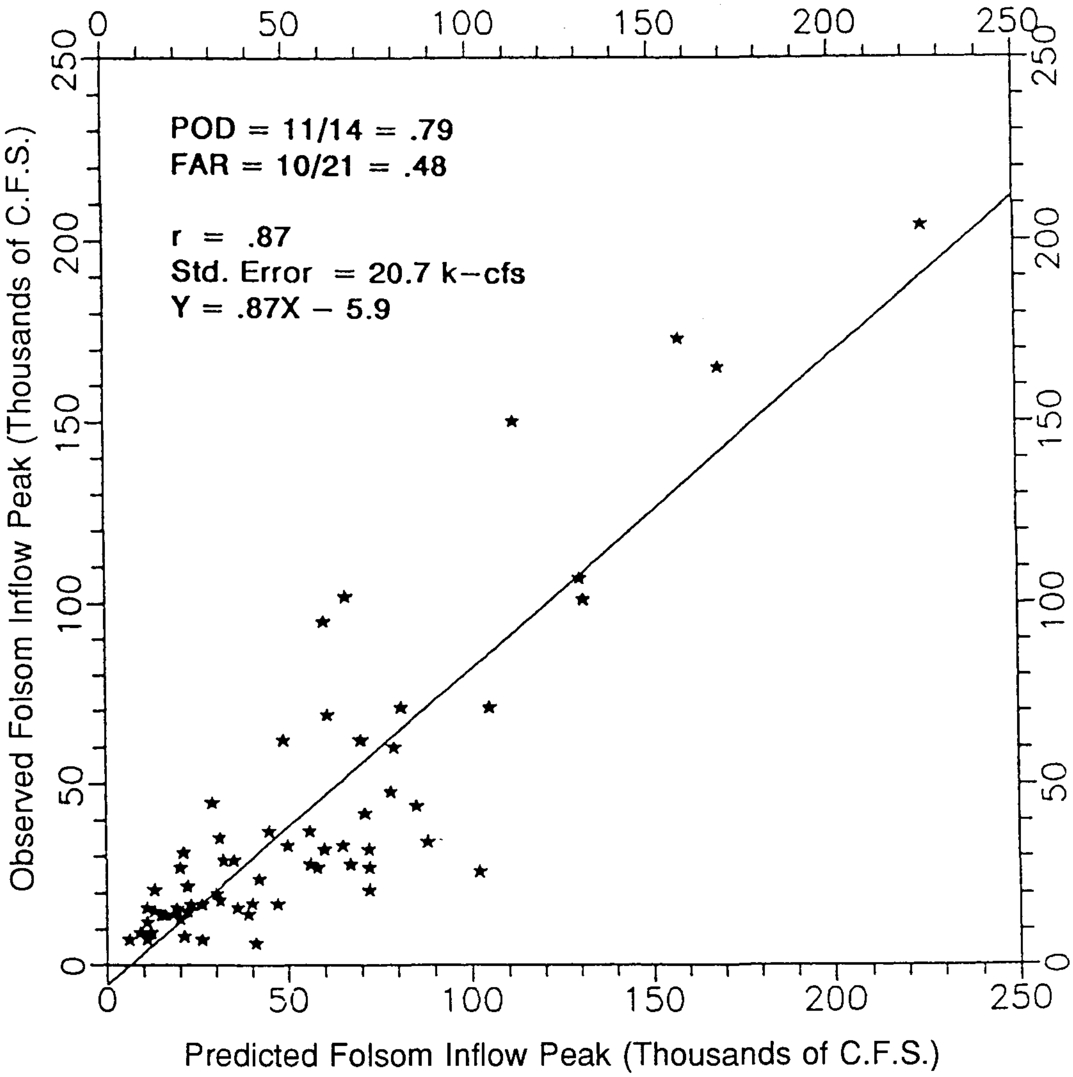


Figure 5. - Scatterplot of observed inflow peaks to Folsom Reservoir with predicted inflow peaks based upon orographic precipitation model estimates (C.F.S = ft^3/s).

as 205,000 ft^3/s. The POD (probability of detection) of peaks of 50,000 ft^3/s or more was 0.79; i.e., 11 of the 14 observed occurrences were predicted. The FAR (false alarm rate) for predicting these large flow values was 0.48; i.e., of 21 cases predicted, 10 were false alarms. Both the correlation coefficient and the POD are encouragingly high. The FAR is acceptable, though higher than desired. Also encouraging is the regression line slope and the small intercept value.

An equivalent regression analysis using predicted peaks computed with observed precipitation as HED71 input showed a correlation coefficient of 0.92, a line slope of 0.97, and an intercept of -1600 ft^3/s. The corresponding standard error of estimate was 16,500 ft^3/s, the POD was 1.00, and the FAR was 0.26 (fig. 6). Each of these numbers indicate better agreement between predicted and observed inflow peaks when using observed rather then model-computed precipitation as HED71 model input, as might be expected.

To more directly compare the effects of using orographic model precipitation to using observed precipitation, a regression analysis was performed on the predicted inflow peaks computed by these two methods. This analysis removes any HED71 characteristics that might be affecting the results of comparing to observed inflow. An encouraging correlation coefficient

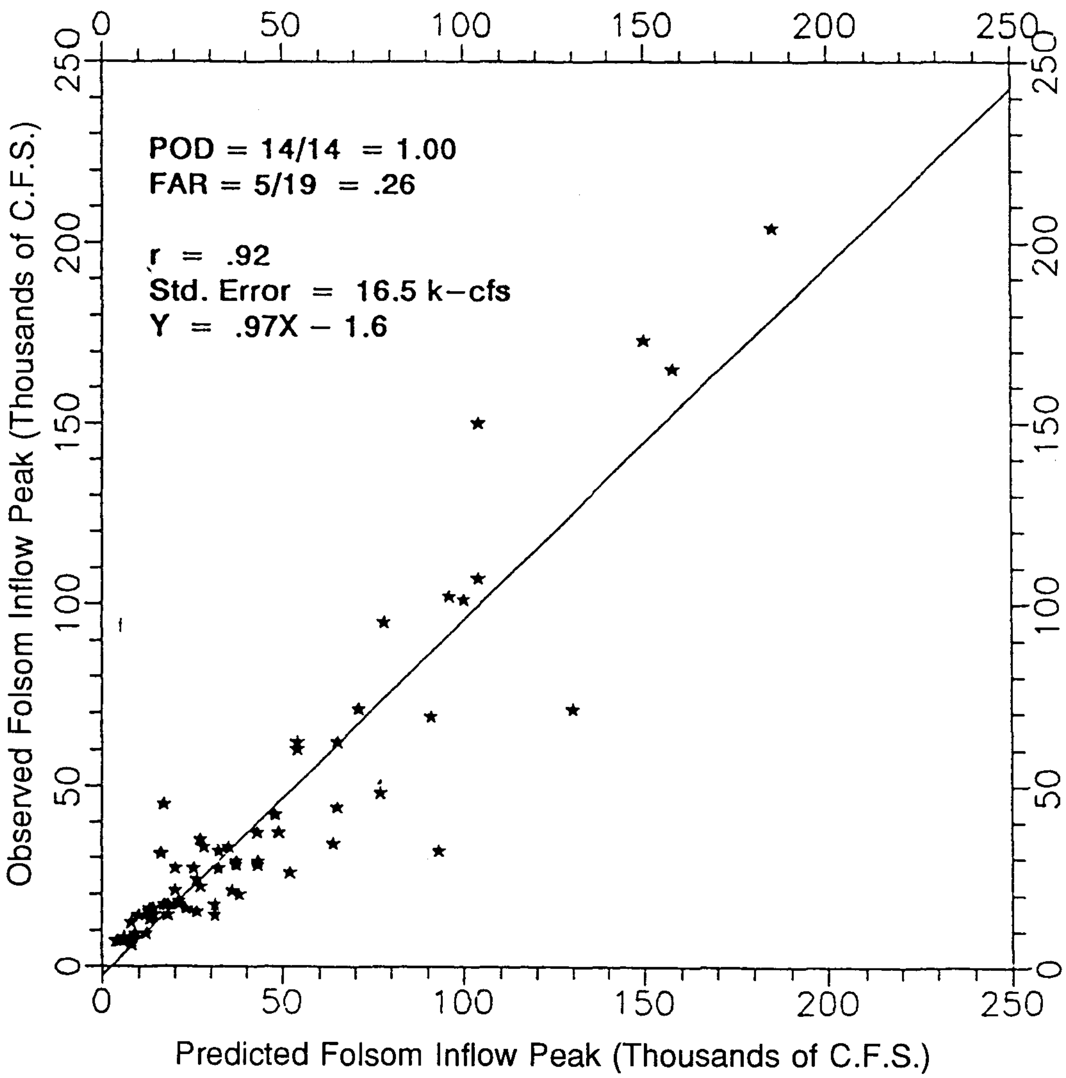


Figure 6. - Scatterplot of observed inflow peaks to Folsom Reservoir with predicted inflow peaks based upon observed 22-site mean precipitation (C.F.S = ft^3/s).

of 0.92 was found. Letting the predictor variable be the set of predicted inflow peaks from the hydrographs generated with orographic model precipitation as HED71 input, the slope of the resulting regression equation (for predicting the inflow peaks computed using observed precipitation) turned out to be 0.87, or once again, the same as the overall ratio of observed to model precipitation. A quite small intercept of -3000 ft^3/s was found (fig. 7).

It is interesting that the orographic precipitation model seems to be even more useful as input to the HED71 hydrologic model for predicting peaks in inflow to Folsom Reservoir (correlation coefficient, r = 0.87) than would be implied by its direct correlation to observed 12-h totals of precipitation (r = 0.73). This higher correlation is caused at least in part by the leeway permitted in time when matching peaks of inflow.

These encouraging results for the ARB demonstrate the potential operational applicability of the method, viz., using Oakland rawinsonde observations for the first several hours and then using predicted upper air conditions for orographic precipitation model input for future time periods. The use of predicted conditions is discussed in the next section.

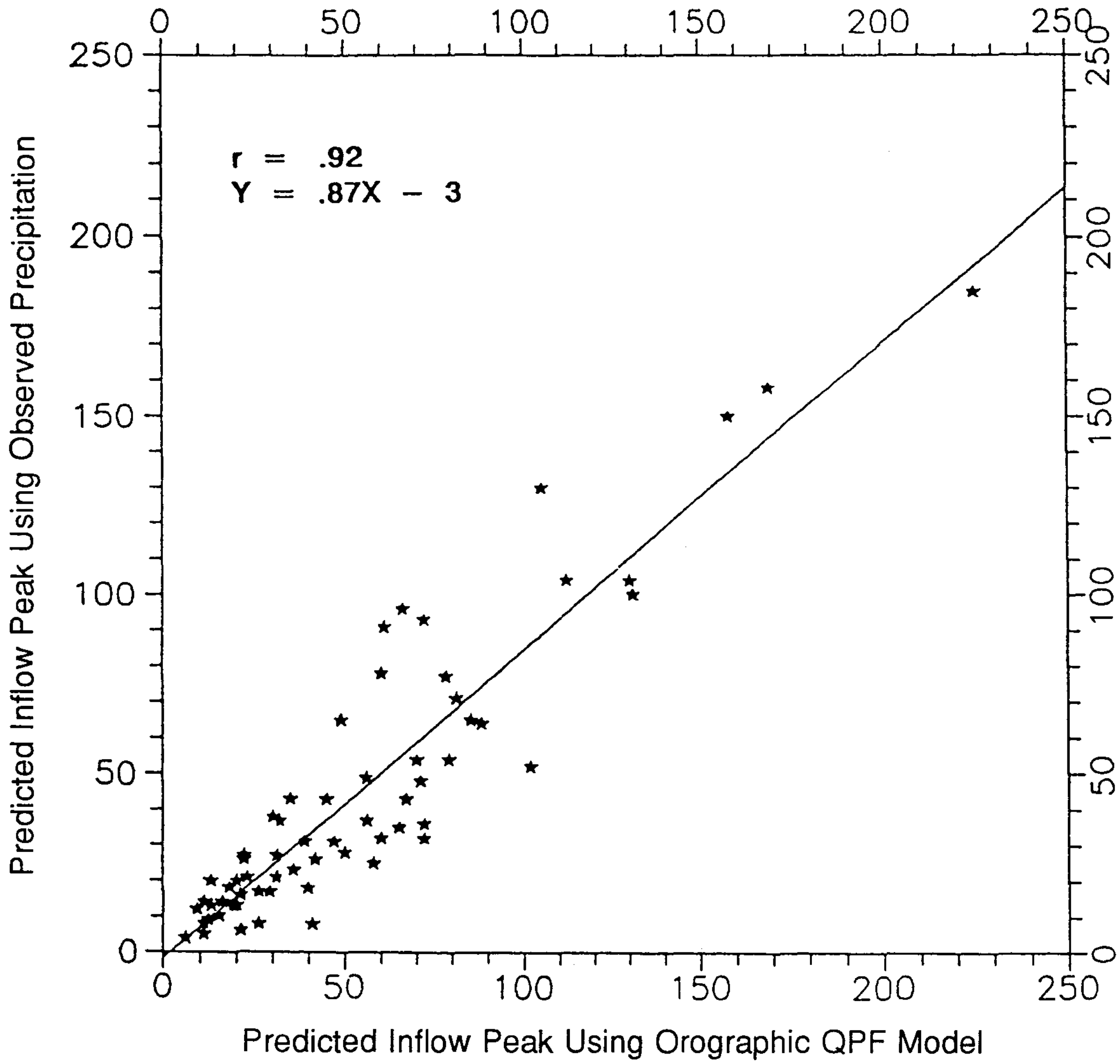


Figure 7. - Scatterplot of predicted inflow peaks to Folsom Reservoir using both orographic precipitation model estimates and observed mean precipitation.

2.7 Prognostic Gridded Field Data

Following the completion of the QPF study for the ARB based upon historic data, arrangements were made with the NWS to obtain prognostic gridded field data from the NMC (National Meteorological Center) via the NWS office at SLC (Salt Lake City). Data were available for four different models. A program was written by Tim Barker of the NWS's Scientific Services Division at SLC to extract 77 NGM (Nested Grid Model) and Eta (Greek letter - LFM replacement) model grid points, and 45 AVN (AViatioN) and MRF (Medium Range Forecast) model grid points. These data were converted to ASCII and stored for retrieval by the CNRFC in Sacramento over INTERNET. Dr. Owen Rhea then wrote FORTRAN programs to use a Data General UNIX workstation to read these gridded field data files.

The NGM and Eta model data are available for the initial time and for 6-h periods out to 48 h into the future. The 77 grid points selected for the NGM and Eta model data are spaced about 80 km apart in the north-south direction, and 160 km apart in the east-west direction (orientation is skewed from true north). The gridded field data for these two models are available in 50-mb intervals, which is the vertical spacing required by the orographic precipitation model.

Because the NGM and Eta models include the initial gridded field data, the OAK (or any other site's) upper-air sounding should no longer be necessary for the first QPF period. The grid point closest to the watershed for which the QPF is desired can be used to represent the input upper-air sounding. However, the available time of the model gridded field data presently precludes the use of the initial data when significant storms are moving into the forecast area; the Eta model data are not available until about 3 h after upper-air sounding observations are available (the NGM data are available about 30 min later). Consequently, actual sounding data must be used as orographic precipitation model input for the first 3- to 6-h QPF. The time delay in the availability of the NMC model data is expected to decrease in the future.

The AVN model data are available for 12-h periods out to 72 h, and the MRF model data are available for 12-h periods out to 120 h into the future. The grid points selected for the AVN and MRF data are spaced about 320 km apart. These models have data for only the mandatory pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 mb) and not in 50-mb intervals as do the NGM and Eta models. Dr. Rhea wrote a program that does both temporal and spatial interpolations of the AVN gridded field data to obtain representative input upper-air data at 6-h intervals for each watershed of interest; the data are then interpolated vertically to 50-mb intervals. The MRF model data are presently being used, without temporal interpolation, for days 4 and 5 for the ARB only.

Use of the NGM, Eta, and AVN model gridded field data was not limited to the ARB. As a first step in expanding the use of the orographic precipitation model to other areas by making use of the gridded field data, a procedure was set up along similar lines to the way the model had been used (for QPF purposes) in the past, prior to the operational availability of the gridded field data.

2.7.1 Past Method of Using the Orographic Precipitation Model

The past method of QPF use of the orographic precipitation model can be briefly described in the following steps:

1. The orographic precipitation model was set up for each watershed of interest with a 5-km topographic grid. Using this topographic grid and a hypothetical "reference sounding" as input, reference average watershed amounts of orographic model precipitation were computed for each 10 degrees of 700-mb direction. This computation was done one time only and the reference average watershed precipitation output data were written into a "reference table" for repeated later use. (In addition to the average values, the model could also output precipitation amounts for specific locations within the watershed.)

   The hypothetical "reference sounding" was selected to represent a warm, wet, windy, very heavy precipitation event, and included the following: (1) a 700-mb temperature of 0 °C, (2) a 50-kn wind speed at the 700-mb level, (3) saturated moisture from the surface upward to the 450-mb level, and (4) an assumed 6-h duration for these conditions.

2. Wind direction and speed were inferred from the 700-mb prognostic charts (out to 60 h).

3. Depth and duration of moist air presence were estimated from the mean 1000- to 500-mb predicted relative humidity charts.

4. The future 700-mb temperatures were estimated from the predicted 1000- to 500-mb thickness charts and the initial 700-mb temperature.

5. The estimates from steps 2 through 4 were compared to the known relevant quantities of the "reference sounding" of step 1 to derive multiplicative "correction factors" which were applied to the model reference precipitation amounts in step 1. A QPF resulted. The correction factors were for wind speed, moisture depth, temperature, and duration. The 700-mb wind direction determined which part of the "reference table" to use.

To expand this past method to other areas of California, and to use NMC model prognostic gridded field data, "reference tables" of orographic precipitation model output were established for many more watersheds in the manner described in step 1 above. However, the determination of the "correction factor" to apply for each forecast period was made in a different manner than described in steps 2 through 5 above, although the factor still amounts to a comparison of the gridded field data "predicted sounding" with the "reference sounding." The program makes no attempt to correct for a duration of less than the time interval between gridded field prediction intervals. The present method is described below.

2.7.2 Present Method of Using the Orographic Precipitation Model

The hypothetical reference sounding is used with a simple inclined plane having the dimensions of 70.0 km in the horizontal by 1.22 km in the vertical up which the air flows, to compute a "reference CSR" (condensate supply rate). Then, using the predicted sounding from the NMC gridded field data and the same simple inclined plane, the program computes a "predicted CSR." Dividing the "predicted CSR" by the "reference CSR" gives a dimensionless "relative CSR," which serves as a total correction (multiplying) factor. This correction factor is used with the 700-mb wind direction and the reference average watershed precipitation from the "reference table" to determine the 6-h QPF.

The HED71 headwater runoff simulation model requires input QPFs for every 6-h interval. The NGM and Eta model data are available in 6-h intervals and can be used directly. However, because the AVN model data are available in 12-h intervals, interpolated gridded field data are used for the intermediate 6-h intervals for all areas of interest out to 72 h into the future. These data sets are then used to predict the CSRs and QPFs for the watersheds.

The QPFs from the four NMC models provide "jumping off" points (objective aids) for assessing the weather and preparing QPFs for distribution and as input to the HED71 headwater runoff model. Forecasters at the NWS's CNRFC will need to adjust these QPFs based upon all of the latest available data, especially observed river stage and precipitation, in preparing the hydrologic forecasts.

2.8 Status of QPFs and Numerical Models

2.8.1 Rhea Orographic Precipitation Model

The 2-D orographic precipitation model computed reasonable QPFs for historical major storms in the ARB using OAK rawinsonde data. However, model accuracy, using NWS model prognostic gridded field input data out to 48 hours, needs to be verified. To examine how well the NWS large scale models estimate OAK upper-air atmospheric sounding profiles, NWS personnel at the CNRFC are comparing prognostic grid point data with observed OAK rawinsonde data. How accurately the orographic precipitation model computes QPFs depends substantially on the quality of the input data. If the ongoing NWS model comparisons are encouraging, as anticipated, the CNRFC intends to use the orographic precipitation model operationally with NWS model prognostic gridded field data for input.

As mentioned previously, the orographic precipitation model has already been set up to run for other Central Valley Project watersheds in California. However, the model still has to be "calibrated" for those individual watersheds.

Of particular interest to the Mid-Pacific Region's Central Valley Project Water and Power Operations Office are the Shasta-Trinity watersheds located in the northern part of the State. The area that produces inflow into the reservoir behind Spring Creek Debris Dam is of particular interest. Once this reservoir is full, the Spring Creek Debris Dam has a high probability of spilling. Unfortunately, the topographic effects which largely control the precipitation regime in the Shasta area are quite complex. Among other things, the airflow is greatly distorted. Sample runs of the orographic precipitation model indicate that it does not produce enough precipitation in the lower elevations of the Shasta area, even when constraining the flow to be directly up-valley. Thus, other objective QPF techniques are necessary for this area. From observation, precipitation rate is still usually directly proportional to wind speed. A dependency on 700-mb wind direction also exists. Better quantification of these wind dependencies is needed. Causal mechanisms that occasionally produce slow moving to quasi-stationary narrow convective bands in the area also need to be identified.

- ***Recommendation*** - Reclamation should perform a climatological study of major storms that have occurred in the Shasta-Trinity watersheds during the past 10 to 12 yr for the purpose of calibrating existing objective aids and developing new objective aids. The data should be partitioned in 10-degree intervals based upon the 700-mb wind direction, using Oakland, California, and Medford, Oregon, rawinsondes.

2.8.2 Future NWS Hydrologic Forecasting Support

The NWS has the hydrologic forecasting responsibility for the Nation. The mission of the NWS hydrologic service program is to save lives, reduce property damage, and contribute to the maximum use of the Nation's water resources. At the present time, the NWS meets its hydrologic responsibility through the efforts of 13 RFCs (River Forecast Centers) located throughout the United States (fig. 8). The CNRFC located in Sacramento is the forecast center responsible for the Central Valley Project area. The NWS takes great care to ensure that hydrologic forecasts come from only one source so as to not confuse the public.

- ***Recommendation*** - Reclamation's research work to improve QPFs and/or runoff forecasts for specific watersheds, such as the work done in this study for the ARB, should be closely coordinated with the NWS's RFC that is responsible for the area.

A good data reporting network is the most important element required to support hydrologic forecasting. Reclamation is a close cooperator with the NWS on developing and maintaining a large part of the hydrologic data reporting network (e.g., the Early Warning Systems). Of

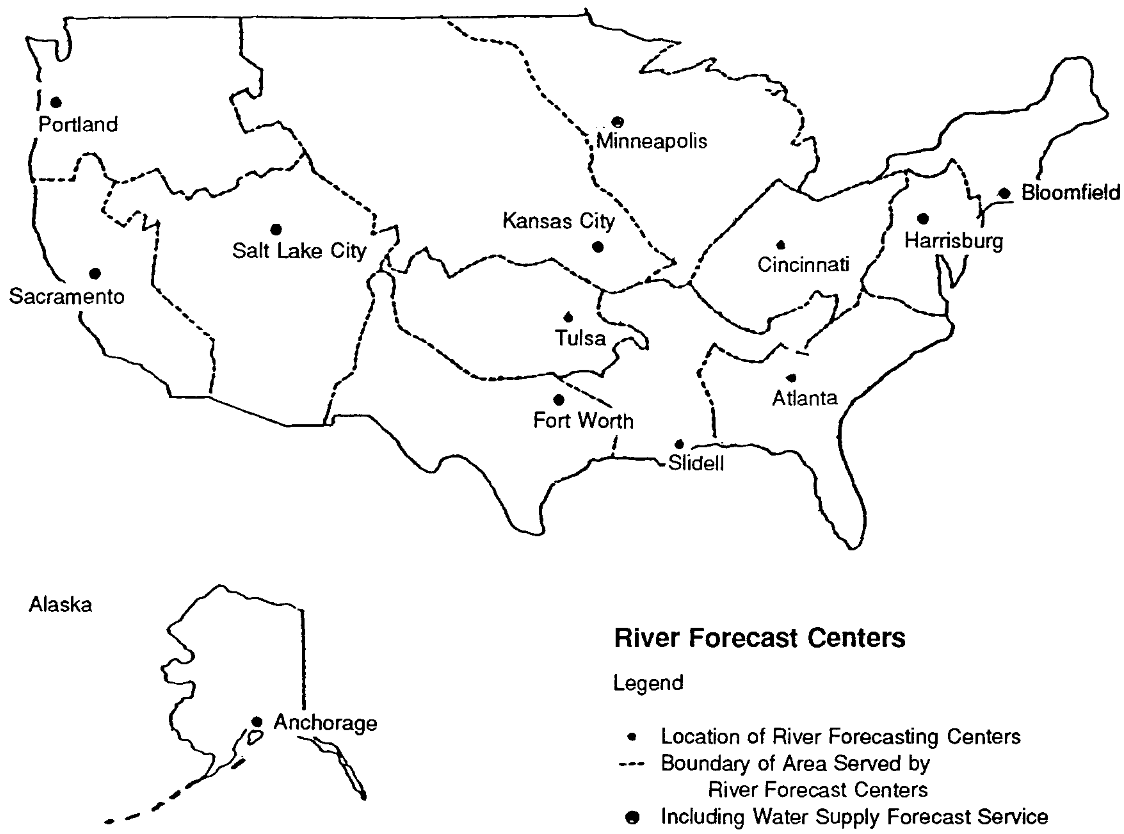


Figure 8. - Locations of NWS River Forecast Centers.

primary importance for hydrologic forecasting are precipitation and river stage data, received on a timely basis. The snowpack water content, ambient temperature, and the soil moisture antecedent index are also vital to generating a river forecast. Other types of data required to fully comprehend a hydrologic situation and make hydrologic forecasts include reservoir data (inflow, release changes, and pool elevations), radar reflectivity observations, upper-air atmospheric soundings, satellite observations, and NMC prognostic model output.

- ***Recommendation*** - Reclamation should ensure that all of its reservoir and early warning systems data needed for hydrologic forecasting are received at the responsible NWS RFC and WFO (Weather Forecast Office) on a timely basis.

New technologies and advances in remote sensing, high-speed computers, and telecommunications will be used in the MAR (modernization and associated restructuring) of the NWS to improve service to the public. One significant change is the installation of a NEXRAD (next generation radar) WSR-88D network. These changes will result in the NWS's ability to collect and process large amounts of hydrometeorological data at much faster rates, which provides the potential for more accurate, timely, and site-specific forecasts and warnings. See Friday (1994) for an overview of the NWS MAR.

- ***Recommendation*** - Reclamation should work cooperatively with the NWS on developing techniques to apply (NEXRAD) WSR-88D radar data and products to our operational water management decisions.

The NWS MAR includes the formation of the HPC (Hydrometeorological Prediction Center) in Washington, D.C. Quantitative precipitation forecasting remains a difficult problem. In the future, the preparation of QPF guidance will be the primary responsibility of the HPC, where forecasters will base their forecasts on the components of the numerical model suite, model-output statistics, and radar- and satellite-based techniques that are designed to focus on precipitation forecasting. The QPF guidance prepared at the HPC will be transmitted to the RFCs and WFOs, where local forecasters use it as the starting point for their preparation of local forecast products (McPherson, 1994).

The HPC will include an applications development group that will design and construct techniques to assist HPC, RFC, and WFO forecasters in adding value to the model output; i.e., this group will serve as a bridge between the model builders at the NWS's Environmental Modeling Center and the model users (McPherson, 1994).

- ***Recommendation*** - Reclamation should support development of value-added products (e.g., objective forecast aids) for the NWS model output which focus on specific water resources management issues. This development would likely include the testing and verification of QPFs and headwater runoff forecasts received from the RFC for selected watersheds where accurate and timely forecasts are critical for Reclamation's water operations.

2.8.3 Future Mesoscale Numerical Models

Strong indications exist of a coming revolution in computing based on massively parallel architecture. The NWS's long-range plans assume that supercomputers capable of 10^{14} operations per second will be available early in the next century. Such computing power would enable model resolutions in the HPC regional suite of 4 to 5 km. The NWS planning establishes a goal of such high-resolution mesoscale models covering the contiguous United States at that resolution in about 10 yr (McPherson, 1994). These 3-D mesoscale models are anticipated to be full physics models, with sigma-z terrain-following coordinates in the vertical axis. The future operational use of such mesoscale models will significantly improve the accuracy of QPFs.

NWS's internal research will not be able to do all that is required to develop, test, and add value to these future mesoscale models; consequently, the NWS encourages research partners in other institutions and Federal agencies.

- ***Recommendation*** - Reclamation should cultivate a partnership with the NWS to study watersheds of special interest for Reclamation water operations. Studies should include the comparison of the input prognostic grid point data for the mesoscale models with upper-air observations, assessment of model weaknesses and biases, and verification of model precipitation estimates with recording gauge observations. Case studies for heavy precipitation events would be of particular interest to Reclamation.

3. ASSESSMENT OF HOW METEOROLOGICAL APPLIED RESEARCH MIGHT IMPROVE RECLAMATION'S WATER OPERATIONS

3.1 Questionnaire on Meteorological Support

Reclamation meteorologists at the TSC (Technical Service Center) are interested in the opinions of water operations personnel and managers, among others, regarding priorities for future applied meteorological research. The TSC meteorologists should pursue research of greatest benefit to Reclamation needs. Accordingly, a questionnaire was sent out to several personnel involved in Reclamation's water operations, and to their chiefs. A copy of the questionnaire is provided in the appendix.

The questionnaire contained five questions regarding the relative importance of meteorological support for watersheds affecting Reclamation reservoirs and river system operations, or areas that use Reclamation-furnished water. Briefly, these five questions addressed:

1. Better QPFs (quantitative precipitation forecasts).

2. Better estimates of snowpack water content accumulation above Reclamation reservoirs.

3. Improved estimates of Reclamation reservoir evaporation.

4. Providing farmers with daily crop evapotranspiration estimates to aid their water application decisions.

5. Providing daily estimates of rainfall and snowfall accumulation and areal distribution using NEXRAD radar observations.

Twenty-six Reclamation personnel responded to the questionnaire by indicating their opinions about the five questions (two did not answer question No. 4, one answered only question No. 4, and one gave only a brief written comment). Table 6 lists individual rankings of questions included in the questionnaire on meteorological support for questionnaires that were returned with no more than one question unanswered. The number of returned questionnaires with answered questions ranged from two for both the UC (Upper Colorado) and LC (Lower Colorado) Regions, three for the PN (Pacific Northwest) Region, seven for the MP (Mid-Pacific) Region, to a maximum of ten from the GP (Great Plains) Region. Obviously, sample sizes of two or three are not sufficient to draw any significant conclusions for those regions.

Table 7 provides a summary of mean rating responses to the questions by region and in total. The highest mean rating was the MP Region's 4.4 for question No. 1 (better QPFs). This rating is not surprising because the northern California area frequently experiences heavy precipitation events during the winter season (November through April) where much of the precipitation falls as rain, resulting in rapid runoff into the reservoir and river systems. The other regions gave slightly more importance to better seasonal snowpack water content estimates.

Table 6. - Individual rankings of questions included in questionnaire on meteorological support.

Question 1	2	3	4	5	Region
Ranking*					
4	5	3	4	3	PN
2	4	3	2	2	PN
2	4	2	-	2	PN
5	5	5	3	5	MP
5	4	1	3	5	MP
3	3	1	2	3	MP
3	4	3	1	3	MP
5	3	2	-	4	MP
5	3	3	2	3	MP
5	5	1	5	4	MP
4	4	4	2	4	UC
4	4	2	3	3	UC
3	3	3	3	3	LC
4	5	5	5	4	LC
3	3	2	3	4	GP
1	5	3	3	4	GP
4	4	5	4	4	GP
4	5	4	4	4	GP
4	1	1	1	5	GP
4	4	3	4	3	GP
4	5	4	4	4	GP
4	4	4	4	4	GP
4	4	3	3	4	GP
4	2	3	3	3	GP

* Rankings:
1 = little or no importance
2 = somewhat important
3 = moderately important
4 = highly important
5 = should have highest priority

Table 7. - Summary of mean rating responses to questionnaire.

Question	Region PN	MP	UC	LC	GP	ALL
1 - Precipitation forecasts	2.7	4.4	4.0	3.5	3.6	3.8
2 - Snowpack estimates	4.3	3.9	4.0	4.0	3.7	3.9
3 - Reservoir evaporation	2.7	2.3	3.0	4.0	3.2	2.9
4 - Crop evapotranspiration	3.0	2.7	2.5	4.0	3.3	3.1
5 - NEXRAD precipitation	2.3	3.9	3.5	3.5	3.9	3.6

For all regions combined, question No. 2 (snowpack estimates) received the highest overall response, with a mean value of 3.9 (median 4), followed closely by question No. 1 (QPFs) with a mean value of 3.8 (median 4). These values approximately correspond to "highly important." Question No. 5, addressing NEXRAD precipitation estimates, had a mean value of 3.6 (median 4). Question No. 3 (reservoir evaporation) received a mean value of 2.9 (median 3), and question No. 4 (crop evapotranspiration) received a mean value of 3.1 (median 3). The values for these latter two questions approximately correspond to "moderately important."

The questionnaire results suggest that TSC meteorologists should give highest priority to improving QPFs and estimates of snowpack water content accumulation (questions No. 1 and 2). Providing NEXRAD-based precipitation estimates (question No. 5) was also considered to have significant importance by many respondents, although the rating for this question was somewhat below the ratings for questions No. 1 and 2.

Selected Comments from Returned Questionnaires:

> "We receive significant support from the National Weather Service Offices, especially the Sacramento River Forecast Center. They provide QPFs and reservoir inflow forecasts to the Central Valley Project operators on a regular basis with close coordination during major precipitation events. We do recognize that current QPF models experience difficulties in predicting Shasta-Trinity precipitation because of the complexity of wind speeds and directions that occur. Flash floods in the valley floor and foothills below Shasta can be extremely hard to predict so that more reliance on monitoring of hydromet stations in the area is necessary." (MP Region)
>
> Better QPFs are highly important, "especially in light of early warning system requirements." (UC Region)
>
> "Having the capability of providing information addressed in this questionnaire can be useful in determining flood inflows and water use requirements. The question is, does the information increase the accuracy of existing methods enough to offset the additional cost. In most cases adequate information can be obtained from the National Weather Service and the Corps of Engineers, and we would not support any added cost." (GP Region)

These comments confirm that QPFs, runoff forecasts, and flood potential advisories are and will be obtained from area NWS RFCs and WFOs. In most cases, the information is "adequate;" however, better information would be useful. Consequently, *a key guideline for TSC meteorological research work in these areas must be to form partnerships with the NWS so that Reclamation's work will result in added value to NWS products.* These partnerships will ultimately improve QPF and runoff forecasts provided by the NWS to Reclamation water operations managers.

3.2 Potential for Collaboration on Meteorological Applied Research

Precipitation is the primary input for forecasting floods and river stage; consequently, the best possible real-time quantitative estimates of precipitation are needed. In addition, better short-term (3- to 24-h) QPFs will provide more lead time for decision-making. The real-time precipitation estimates are and will be primarily based upon NEXRAD (NEXt generation RADar) and ALERT (Automated Local Evaluation in Real Time) data. Better QPFs will result from faster computer workstations which run higher-resolution mesoscale models, and the application of GOES-I (Geostationary Operational Environmental Satellite) data coupled with conceptual models. The future benefit of better mesoscale models in precipitation forecasting was stated earlier in section 2.8.3; information on the higher resolution and sounding capabilities of GOES-I is provided in Menzel (1994).

Because the QPFs and headwater runoff forecasts used by Reclamation's water operations managers are received from the NWS, many of the managers seem to believe that any improvement in the real-time precipitation estimates and short-term forecasts is the sole responsibility of the NWS. However, with the modernization and associated restructuring of the NWS (see section 2.8.2), the Nation is entering a "new era" of weather monitoring and prediction. The NWS is attempting to work on many things simultaneously, but like all Federal agencies, they too have limited resources. Who will ensure that Reclamation's hydrological needs and problems are being addressed? This concern should be Reclamation's own responsibility.

Much of the new remote sensing technology equipment is just being installed. For example, in the northern California area, the NEXRAD radar system at Sacramento will be commissioned in November 1994; two additional NEXRAD systems, at Beale Air Force Base and Eureka, are scheduled for commissioning during the fall of 1995. The first new generation of GOES satellites (GOES-I) was launched in April 1994. More ALERT systems, which are essentially the same as Reclamation's Early Warning Systems, are being installed. Tremendous quantities of data will be available; consequently, new computer workstations are being installed at the NWS's WFOs and RFCs to process the data, as well as to use NWS analysis and display products, and to access NMC prognostic gridded field data for input to local scale models.

The tasks of incorporating all of the new technology data into operational nowcast and forecast procedures, and then to verify the forecasts, are numerous and generally time-consuming. For example, the NEXRAD precipitation algorithms still need much work. Presently, only one algorithm for convective rain is being used. Algorithms have to be developed for stratiform rain, orographic rain/snow, and snowfall resulting from mesobeta-scale (20 to 200 km) and mesoalpha-scale (200 to 2000 km) weather systems.

NOAA's FSL (Forecast Systems Laboratory), located in Boulder, Colorado, focuses on research that will lead to the development and transfer of new technologies and scientific advancements to the NWS and other operational organizations (MacDonald et al., 1994). One system under development and testing is LAPS (Local Analysis and Prediction System). The primary objective of LAPS is to provide real-time, 3-D, mesobeta-scale analyses, and short-range forecasts (0- to 12-h) for NWS WFOs, RFCs, or other operational facilities. LAPS is designed to fuse data from existing and future data platforms (e.g., NEXRAD Doppler radar, wind profiler, ALERT systems, GOES-I, and aircraft observations), provide analyses of common weather elements, and generate real-time, high-resolution forecasts of precipitation and other weather parameters.

These short-range forecasts are currently not operationally available, but the potential for significantly improved QPFs and flood forecasts for individual watersheds, reservoirs/dams, and river systems is exciting. Analyzing the NEXRAD, automatic remote precipitation gauge, GOES-I, NOAA polar orbiting satellite, airborne snow survey, SNOTEL (SNOwpack TELemetry), and GIS (Geographic Information Systems) data together over time will also improve areal estimates of accumulated snowpack water equivalent content and snowpack melt.

Management at NOAA's FSL has expressed strong interest in working with Reclamation to implement and operationally test LAPS over an area that is of concern to the NWS, Reclamation, and others. However, the request for setting up LAPS in a new area for testing must be made by local NWS WFO and/or RFC management. One good possibility for collaborative studies is the California area from about Sacramento northward to Medford, Oregon (fig. 3). This area includes both the ARB, which was the focus of the study reported in section 2, and the Shasta-Trinity Watersheds that annually experience heavy winter-season precipitation events. Because much of the precipitation from these storms falls as rain in the lower elevations, the threat of flooding is of great concern for some reservoirs (e.g., Spring Creek, Folsom, Stony Creek, and New Melones).

The NWS personnel at the CNRFC in Sacramento have been very cooperative and supportive during the ARB study. They have stated that continued collaboration with other agencies and organizations is very important. With the implementation of new generation remote sensing and prediction technology, they lack personnel resources to verify their QPFs over Reclamation watersheds. In addition, existing objective forecast aids have to be calibrated, and new objective aids and conceptual models have to be developed.

The Hydrologist-in-Charge of the CNRFC recommended that any collaborative studies within the CNRFC's area of responsibility focus on northern California. In addition, the focus should be on systems and products that can be used in a real-time mode, and that provide a "real world" view. It was suggested that the studies include a "marriage" of physics and dynamics to the local orographics. Also, any products developed for operational use must run on the existing computer workstations available at the CNRFC and the Sacramento WFO.

In summary, several opportunities exist for Reclamation meteorologists to collaborate with other agencies, the NWS in particular, to add value to existing and emerging nowcast and forecast products. Many of these products need to be tested over watersheds of interest to Reclamation, and improved where appropriate. Several of the products would be of significantly more value to Reclamation if they were "tailored" for Reclamation needs. However, obtaining the maximum benefit from the new and exciting meteorological tools and approaches, primarily being developed by other Federal agencies, will require a sustained commitment from Reclamation management.

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APPENDIX

Questionnaire about how Meteorological Support Might Improve Reclamation's Water Operations

This questionnaire is being distributed as part of a WATER (Water Technology and Environmental Research) project administered by the TSC (Technical Service Center) in Denver. The questionnaire's purpose is to access how TSC meteorologists can better assist regional and area offices in their management of Reclamation's water resources. More specifically, how can TSC meteorologists help improve the efficiency of reservoir and river system operations, and water conservation? Your help in taking a few minutes to fill out this brief questionnaire is appreciated.

Please mail the completed questionnaire to:

Bureau of Reclamation
Technical Service Center
D-3720, attn. Curt Hartzell
P.O. Box 25007-0007
Denver CO 80225-0007

As general background, TSC meteorologists have a varied range of experience and expertise including the following topics:

- Application of numerical computer models from cloud-scales to regional weather scales
- Climate change investigations
- Conducting field programs to collect meteorological data by direct and remote sensing
- Development of high resolution environmental variable data sets through 3-D climate models
- Environmental reviews
- Precipitation investigations from data collection to analysis
- Statistical analyses of weather and related phenomena
- Studies of evaporation, evapotranspiration, and related micrometeorological topics
- Studies of orographic precipitation, runoff, and related hydrometeorological topics
- Weather forecasting
- Weather modification

Please answer the following questions by indicating your opinion about the importance particular subject areas should have for Reclamation reservoir and river system operations, and for water conservation goals. Use a scale of 1 to 5 where:

1 = little or no importance
2 = somewhat important
3 = moderately important
4 = highly important
5 = should have highest priority

Please circle the appropriate number with each question. If you have no opinion about a particular question, or it is not applicable to your region, do not circle any number with that question.

Question No. 1: Assume that the capability existed to accurately predict 6-hour basin average precipitation amounts over watersheds above Reclamation reservoirs, and that QPFs (Quantitative Precipitation Forecasts) and rain/snow level forecasts were accurate out to 3 days in the future. Moreover, these forecasts could be provided automatically by electronic mail network for use with hydrologic runoff models. How important would this capability be in your Region?

1 2 3 4 5

Question No. 2: Assume that the capability existed to significantly improve estimates of snowpack water content accumulation on watersheds above Reclamation reservoirs. How important would this capability be in your Region?

1 2 3 4 5

Question No. 3: Assume that the capability existed to significantly improve the accuracy of reservoir evaporation estimates. How important would this capability be in your Region?

1 2 3 4 5

Question No. 4: Assume that the capability existed to provide accurate estimates of daily crop evapotranspiration for areas irrigated with Reclamation-provided water. Further, assume these estimates would be made readily available via newspapers, local radio stations, computer modem, recorded message on a 1-800 phone number, etc. so that water users could use this information in deciding how much irrigation water to apply. (A similar system, Agrimet, has been implemented over the past decade in Idaho.) How important would this capability be in your Region?

1 2 3 4 5

Question No. 5: Assume that the capability existed to provide accurate estimates of the daily areal distributions of rainfall and snowfall over watersheds above Reclamation reservoirs, based on NEXRAD data from the new radar network being installed nationwide by the National Weather Service. How important would this capability be in your Region?

1 2 3 4 5

Please note any specific problem areas in your Region for which meteorological support or investigations would be helpful, and make any other comments you care to:

Nature of your job: ______________________________

<u>Optional:</u>

Name: ______________________________

Phone: ______________________________

Address: ______________________________

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.